TRANSCARPATHIAN PETROLEUM PROVINCE IN ROMANIA

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Abstract. The Transcarpathian Zone, a modest hydrocarbon province so far, is part of the Inner Carpathians and is shared across northern Romania, Ukraine and Slovakia. Iňačovce-Kričevo, Pieniny and Magura nappes emplacement over the Dacia Mega-Unit's, Petrova and Botiza sedimentary covers started in the Oligocene and finalized during the Burdigalian collision of ALCAPA and Tisza-Dacia mega-units, now separated by the Bogdan-Dragos Vodă Fault. The nappe emplacement triggered the Oligocene source rocks maturation, expulsion-migration and accumulation of hydrocarbons. A broad review of structural and lithostratigraphic framework of Petrova and Botiza foreland basins is integrated in the description of oil habitat of this province. The oil bearing Petrova foreland is narrow and less extended than the oil-prone Botiza foreland. In the latter foreland, Oligocene-early Miocene backbulge, forebulge and foredeep depozones were first recognised and characterised. The foreland basins fill consists of late Cretaceous – early Miocene successions which include clastic reservoirs and Maikopian bituminous source rocks belonging to two independent thermogenic petroleum subsystems. The unconformable mid-Miocene-Quaternary Megasequence of the Transcarpathian pull-apart basin is the post kinematic cover of the Transcarpathian Zone. It bears a thermogenic (and locally, a biogenic) gas petroleum system that extends up to the East Slovakia Bassin. The main purpose of this paper is to detail the basin forming and fill of the area and to evaluate of the petroleum systems, previous exploration work and to asses resulting resources.

Key words: Transcarpathian Zone and Basin, Pieniny Klippen Belt, Magura Units, forelands lithostratigraphy, petroleum systems, resources, oil and gas accumulations, history of exploration

1. INTRODUCTION

The Transcarpathian Petroleum Province extends from the North Transylvania and Maramureș regions of Romania towards the ENE into Ukraine and NW into Slovakia (Fig. 1). It is separated in the SW from the Pannonian Basin System by the crustal-scale Peri-Pannonian Line (with the Ukrainian Gechensk and Romanian Preluca fault segments), while towards the E and NE, the Transcarpathian Line and the Pieniny Klippen Belt suture separate it from the Inner Carpathian/Middle Dacides nappe system. South of the Bogdan-Dragos Voda Fault (BDVF), in the west, is delimited by the Meseş Line. and in the NE is also rimmed by Median Dacides. The southern boundary of the habitat is represented by the maximum onlap edge of the Hida Formation, nowadays concealed by the Badenian unconformity of the overlying Transylvanian Basin.

This habitat is divided by the suture between ALCAPA and Tisza-Dacia Mega-Unit by the Bogdan-Dragos Vodă Fault (BDVF), that possibly merges westwards into the Mid-Hungarian Fault Zone. The nappes of the Transcarpathian Flysch Zone or Transcarpathian Trough according to Ukrainian authors, thrust over the unconformable late Cretaceous-Burdigalian deposits overlaying the continental unit of Median Dacides. Of interest for oil accumulations are foreland basins: Petrova and Botiza.

The Oligocene-Early Miocene nappe and foreland sediments are unconformably covered by the younger Mid-Miocene Transcarpathian Basin. Extending up to the Hernád Fault to the NW, the Transcarpathian Basin is sub-divided in Mara-Solotvino, Khust, Uzhgorod (Chop-Mukachivsk) and Trebišov subbasins.

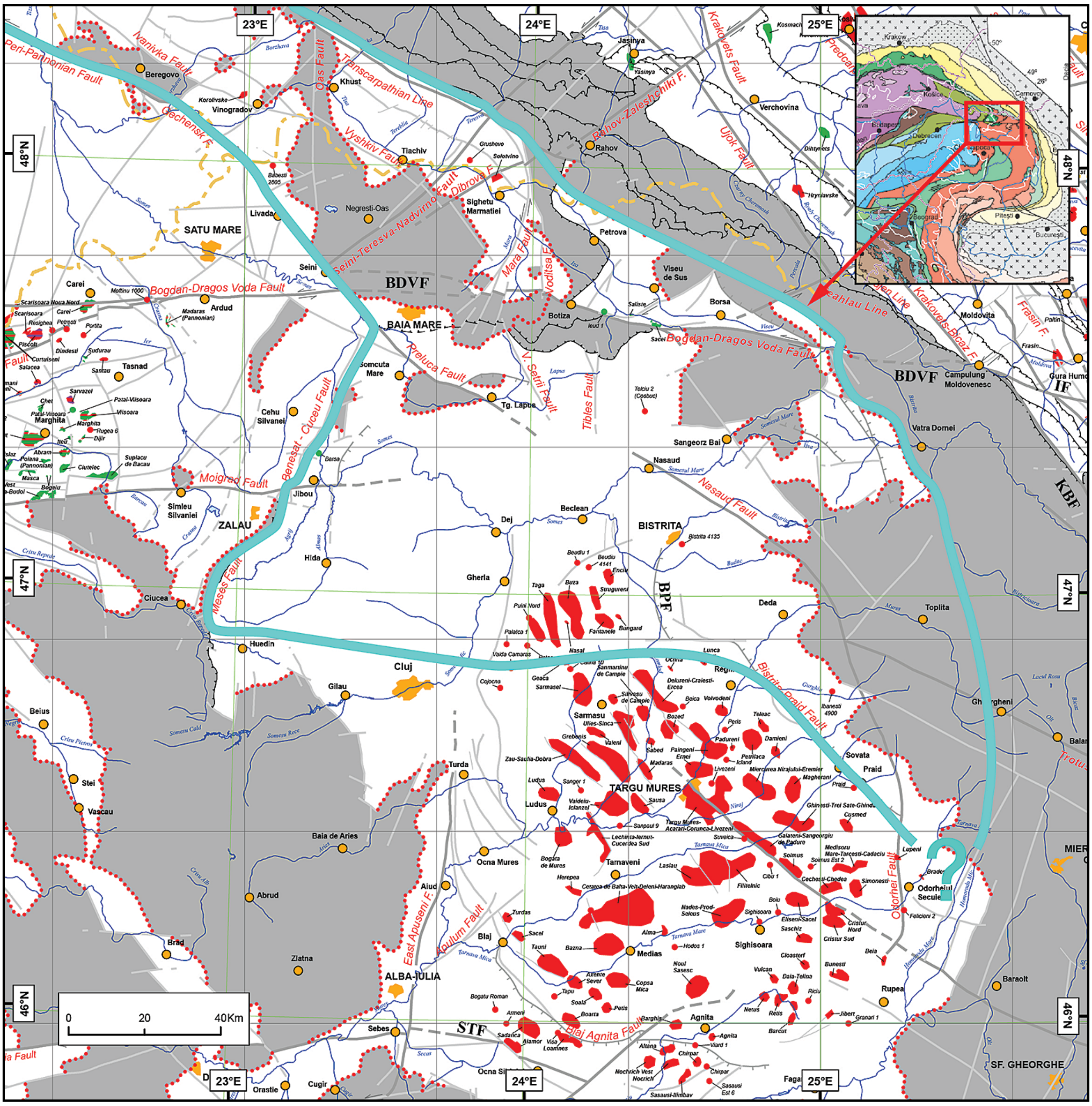

Fig. 1. Map of the Transcarpathian Zone in Romania (modified after IGG 1:50,000 geological map series, Dicea *et al.*, 1980a, b, Tischler *et al.*, 2008 Lozyiniak and Misiura, 2010 Ukrainian State Geological Survey, Khust 1:200,000 map, Seghedi *et al.*, 2019). The southern limit is the present pinch-out extension of the Hida Formation sedimentary wedge in the Botiza foredeep. The grey area is the non-prospective exhumed Apuseni and Carpathians pre-Tertiary formations. The oil habitat extension based on Ciupagea *et al.*, (1970), Popescu (1984, 1995), de Broucker *et al.*, (1998), Rusu (1989).

The Romanian area of the Mara-Solotvino Subbasin (Fig.2) is thus a subunit of the Transcarpathian Basin (*e.g.*, Prikhodko *et al.*, 2019) and not of the Pannonian Basin System as it has been proposed by several authors such as Sandulescu (1984) or Haas (2001). Similarly, to the Transylvanian Basin, gas has been explored for and produced in the Transcarpathian Basin, from the Miocene post-salt clastic rocks.

The sedimentary sections of the Transcarpathian folded units and the post-tectonic basin, as well as the northern portion of the Pannonian Basin were cut by important volumes of intrusive and effusive rocks, as protractions of the volcanic chain extending from central Eastern Carpathians.

2. PRE-TERTIARY STRUCTURAL FRAMEWORK AND BASIN-FORMING

The Transcarpathian petroleum habitat includes the Iňačovce-Kričevo Unit, Pieniny Klippen (*i.e.*, olistoliths) Belt and Magura Unit thrusted over their late Cretaceous-early Miocene forelands. These forelands stand for the extensive and best preserved post-kinematic cover of the Median Dacides (Săndulescu, 1984).

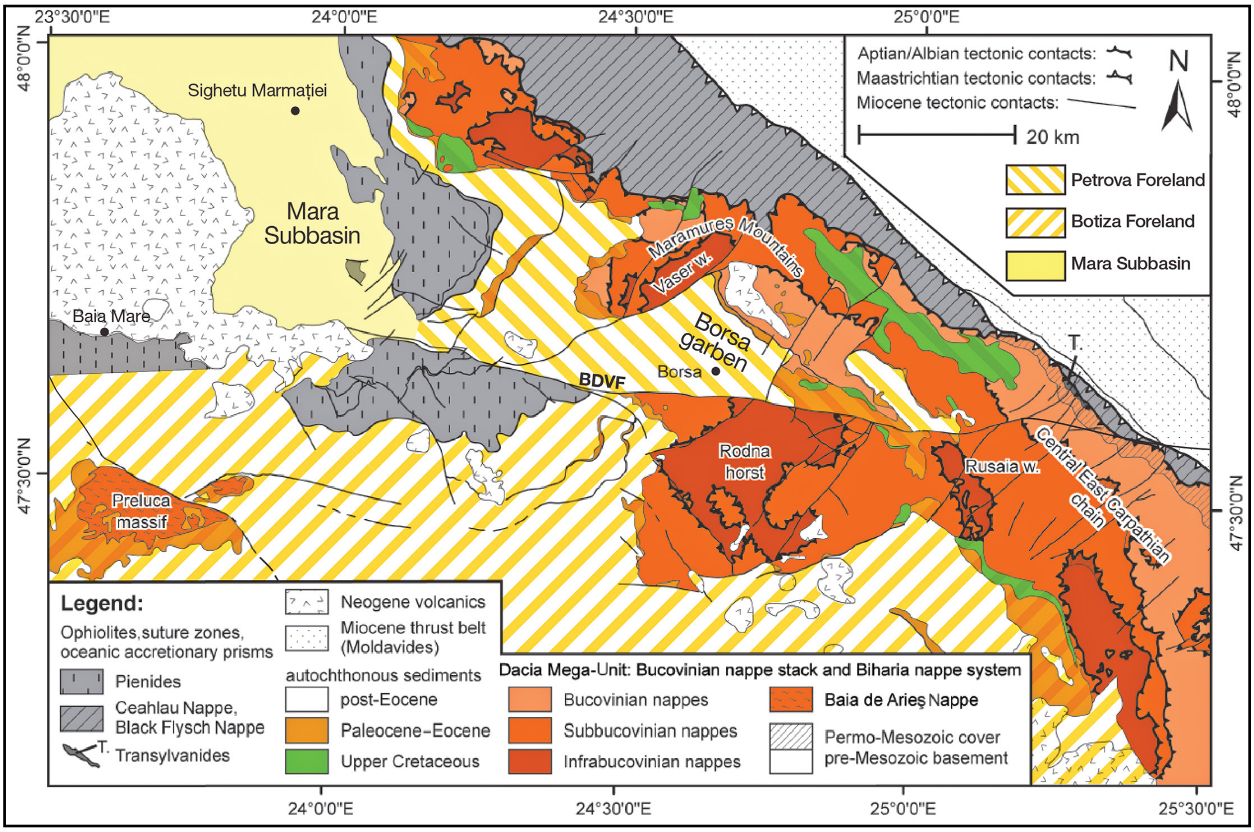

Fig. 2. Tectonic map of the Transcarpathian Habitat in Romania (adopted after Gröger *et al.*, 2013).

The Transcarpathian area has a complex and still not quite understood structure in Romania, Ukraine and Slovakia. A geological model for the Maramureș area proposed that the Pieniny Klippen Belt (PKB), generally interpreted as the fronts of ALCAPA and Tisza-Dacia Mega-Units started to collide in the late Oligocene (*e.g.*, Györfi *et al.*, 1999), and finally thrust onto Tisza-Dacia Mega-Unit during the Burdigalian (*e.g.*, Csontos 1995, Györfi *et al.*, 1999, Tischler *et al.*, 2007). The main phase of overthrusting of the ALCAPA Mega-Unit started around 20Ma and ended around 18.5Ma, (Márton *et al.*, 2007, Tischler *et al.*, 2007). According to an alternative proposal, in Hungary, the juxtaposition of ALCAPA and Tisza Mega-Unit occurred around 17Ma, but not earlier than the Karpatian (Csontos *et al.*, 2002, Kovács *et al.*, 2010). Collectively, the Pienine/Magura overthrust represents the tectonic load, while the Petrova and Botiza forelands, the flexuring plate (*e.g.*, Krézsek and Bally 2006).

Both Tisza and Dacia mega-units are Europe-derived allochtonous blocks, while ALCAPA is an Adria-derived block, which together invaded the so-called Carpathian Embayment (ample description and references in Schmid *et al.*, 2020). Separated in the late Jurassic, Tisza and Dacia blocks started common internal structuring in the late Cretaceous-Paleogene as a final stage of a convergent movement prior to the early Miocene above mentioned tectonic deformations and continent-continent collision.

In the early Paleogene, Tisza-Dacia Mega-Unit moved in the clockwise (CW) direction (Ciupagea *et al.*, 1970, Balla 1987) in the Carpathian embayment and ALCAPA, counter-clockwise (CCW) to the north (*e.g.*, Balla 1987, Márton *et al.*, 2007 and references therein).

The Burdigalian Petrova, Leordina and Wildflysch nappes belong to the Magura Unit (Săndulescu, 1980) and overthrust a basement of Dacia Mega-Unit origin, which is dissimilar of the contemporary Botiza and Poiana Botizii nappes and their original ALCAPA basement (Fig. 3). These two nappes glided together with the Wildflysch Nappe, again, over a Dacia Mega-Unit basement. It appears that the respective foreland sedimentary sequences below overthrusts are insignificantly different (Figs. 7, 8, 11), both being laid down, at least since the mid-Eocene in the same sedimentary basin with a Dacia Mega-Unit (Figs. 2, 4).

The description of main blocks of the lower plate and of tectonic units of the upper plate that shall be further used in this paper are in the next paragraphs.

The **ALCAPA Mega-Unit** represents Adria derived Austroalpine nappes and their Carpathian equivalents extruded in the northern side of the Carpathian Embayment. There, extrusion and rotation took place along the Pieniny Klippen Belt suture. In the area of this study, Marton *et al.* (2007) suggest that since the beginning of the Miocene until the Sarmatian (12 Ma) , ALCAPA started to dismember along the Hernád Fault, followed by an estimated 30⁰ CW cumulative rotation of its eastern tip, solidary to the Tisza-Dacia (Fig. 3). An additional 30⁰ CCW rotation from the Sarmatian until the Pontian (Pătraşcu 1993, Marton *et al.*, 2007) took place in the whole area north of the BDVF, including the Dacia Mega-Unit fragment of the Maramureș Massif, after which, it became inactive. These translations were accommodated mainly along the Transcarpathian Line and other Transcarpathian Zone longitudinal faults, including the arcuate Mara Fault.

The **Tisza-Dacia Mega-Unit**, frequently quoted here as Dacia Mega-Unit is composed, in the study area, of two outcropping subunits: the Bucovinian one (Median Dacides) and the Biharia one with the in-between, the Transilvanid sector of the Eastern Vardar Ocean. The intra-Dacia Mega-Unit closure of the Eastern Vardar oceanic basin during the obduction of the Transilvanid ophiolites onto the Bucovinian nappes of the Median Dacides took place in the mid-Cretaceous (Săndulescu, 1984). In the late Cretaceous, this mega-unit moved in the Carpathian Embayment, eastwards and south-eastwards (Balla, 1987), translation that continued in the early Tertiary (Marton *et al.*, 2007). At least from the late Eocene, this mega-unit rotated 75⁰CW and translated eastwards until late Burdigalian (Márton *et al.*, 2007), but this rotation should indeed be traced back from the late Cretaceous time since both present-day above-mentioned forelands cut by BDVF have the same Dacia (Bucovinian) basement and pre-Tertiary sedimentary succession (Fig. 7).

It appears that the northwards extension of the Dacia Mega-Unit ends in the Maramureș Massif, at the N/S Voditsa Fault (Fig. 1). During the late Sarmatian, similar to the ALCAPA block (Márton *et al.*, 2007), the Tisza-Dacia Mega-Unit recorded an additional 30⁰ CW rotation. These rotations and translations were accommodated in Romania along the crustal-scale Preluca Fault, Gechensk in Ukraine and adjacent Transcarpathian Zone longitudinal faults. New studies show a similar rotational behaviour at least for the Dacia Mega-Unit was recorded about 125 km south of BDVF, in the central Transylvanian Basin, where 26⁰ CW rotation was documented from the Sarmatian until the Pannonian (de Leeuw *et al.*, 2013). These clockwise translations of the Tisza-Dacia Mega-Unit south of the BDVF are further confirmed by the early intraplate shortening, whereby Tisza Unit thrust over Dacia Unit along the Meseş overthrust (Răileanu *et al.*, 1964 and 1:50,000 maps of Stefan *et al.*, 1974, Rusu *et al.*, 1977, 1994, Marinescu *et al.*, 1982) in the Aquitanian/Burdigalian. The northward Benesat-Cuceu Fault (Figs. 1,9) does not represent the late Miocene expression of the Meseş Line reactivation, but is provisionally construed as an extensional fault the Pannonian domain to the Transcarpathian one (see Rusu *et al.*, 1994, 1:50,000 geological map,). It could alternatively be interpreted as a late Miocene listric fault with the exhumed Ţicău core complex in the footwall as elsewhere described in the Pannonian Basin System (*e.g.*, Tari *et al.*, 1992).

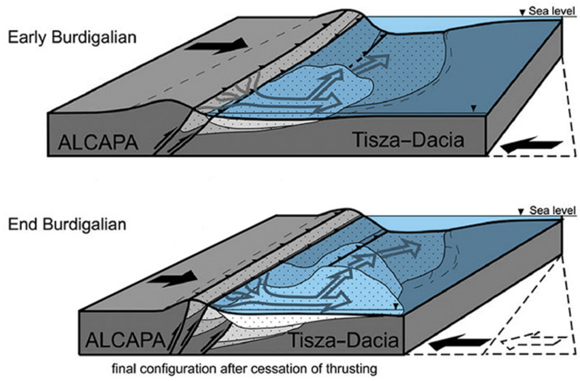

Fig. 3. Conceptual bloc-diagrams showing the tectonic load and basin flexuring, rotation and migration of Botiza Basin axes in the Burdigalian due to Tisza-Dacia rotation. The possibly emersed coeval Petrova Basin, over the ALCAPA is not shown (modified after Tischler *et al*., 2008).

The **Iňačovce-Kričevo Unit**, is a term coined by Durica in 1982 (see Sotak *et al.*, 1993) that combines the name of an internal unit from Slovakia with one from Ukraine. In Romania, it is known only in the subsurface and was called Băbesti-Tiacovo (internal) and Kricevo (external) blocks (Săndulescu *et al.*, 1993). They are the most southwestern located tectonic units of the Transcarpathian Zone and have an ALCAPA-type basement. The Iňačovce-Kričevo unit, or the Vahicum was dynamo-metamorphosed in the post-Eocene and was corelated with the southern Penninic units from the Alps (Sotak *et al.*, 1993), and with the Szolnok unit (Schmid *et al.*, 2020). It is also synonymous with, "Peninic-like" or "peri-Peninic" and is not ultimately genetically related to the PKB (Fig. 6) because it originates from the Piemont-Liguria Ocean (Schmid *et al.*, 2020).

In Romania, Săndulescu *et al.*, (1993) identified Kričevo Nappe deposits in the Sarasău wells with a position internal to the Magura (Petrova) Nappe. The Băbeşti-Tiacovo Nappe was described by the same authors more internally, in the Băbeşti 2805 (Fig 1), well that cut a sedimentary sequence comprised of andesites, Cenozoic black mudstones that unconformable covers Jurassic limestones and weathered ultrabasic Triassic rocks a succession similar to that described in the Iňačovce-Kričevo unit in Slovakia (Sotak *et al.*, 1993) and shown in Fig. 6. These nappes might be contained in the Vyshkiv Block of Prikhodko *et al.* (2019).

The **Pieniny Klippen Belt** (PKB) is a narrow belt separating the Central and Outer Western Carpathians characterized by the large presence of olistoliths and olistostromes. Most authors considered the present-day arcuate and 650km-long PKB represents the ALCAPA plate accretionary margin of the southern Magura Ocean (*e.g.*, Oszczypko *et al.*, 2015), deformed and shortened in the Cretaceous and Paleocene, and subsequently affected by early Miocene wrench tectonics and refolding (*e.g.*, Jurewicz, 2018), due to the CCW rotation.

The PKB changes its structural character, from the northwest (Slovakia) to southeast (Romania), from an initial oblique convergent boundary to a transpressive-transtensive strike-slip wedge with sub-vertical dips as described in the Western Carpathians (*i.e.*, Birkenmajer, 1986, Nemčok and Nemčok, 1994, Oszczypko *et al.*, 2015, inter alios) to a low-angle, cover nappe system in the Romanian Eastern Carpathians (Fig.6). In the northern part of Romania, it is presumably overriding at low angle a Dacia Unit slightly deformed foreland.

Săndulescu (1980, 1984, 1993) include Băbeşti-Tiacovo, Botiza-Kričevo, Poiana Botizii-PKB nappes in the Pienine *s.l.* cover nappes that are discriminated in this paper from the Iňačovce-Kričevo units. The PKB, supposedly present in subsurface north of BDVF, would develop in outcrop south of BDVF, at an angle to the structural trend of the Eastern Carpathians. This tight arcuate loop would connect to the Szolnok Unit from the Mid-Hungarian Fault Zone (*e.g.*, Nagymarosi and Baldi-Beke, 1993, Schmid *et al.*, 2020).

The **Magura Unit** was allotted by Săndulescu (1980, 1984, 1993) to external nappes of the Transcarpathian Zone namely: Petrova, Leordina and south of BDVF, the Wildflysch, as the main occurrences of Magura Unit in this zone. As a remark, the Ukrainian geologists prefer to assign the Magura Nappe, as described in Romania, to the Monastyrets Nappe (Fig. 6). However, this nappe is only an equivalent of the Rača Subunit, while the Leordina Nappe could correlate with the Fore-Magura Vezhany Unit (Oszczypko *et al.*, 2015). The Magura Nappe is an equivalent of the Valais Ocean sedimentary zone (*e.g.*, Schmid *et al.*, 2020) whose main overthrust phase occurred in the Oligocene. Of a special importance is the Šariš, (Slovakia) or Grajcarek (Poland) unit, that was initially included in the peri-Pieniny Klippen Belt (*e.g.*, Birkenmajer, 1986) and now is considered as a frontal transitional unit consisting in strongly deformed slices of Jurassic-Cretaceous deposits associated with wildflysch and olistoliths (Jurewicz, 2018).

In the Romanian sector of the Transcarpathian petroleum province, the emplacement of Petrova and Botiza nappes was followed by deformation phases, characterized by compressional-to-transpressional displacements in both foredeep and wedge zones (*e.g.*, Ratsbacher *et al.*, 1993), that ended during the late Miocene (Pătraşcu, 1993). The emplacement of Magura nappe is followed by a late Burdigalian NE-SW particular extension episode (Tischler *et al.*, 2007).

The area of these nappes was detail-mapped at various scales by many geologists since the early fifties of the last century (see extensive review in Aroldi, 2001) and synthetised in several Institute of Geology and Geophysics (IGG) maps at the scale of 1:50,000 (see list after the bibliography). It should however be mentioned that several Romanian geologists have challenged the presence of the Pieniny Klippen Belt in Maramureş preferring to assign the Botiza nappes to the Inner Carpathian Nappe zone, *i.e.,* to the Magura Unit (see a detailed discussion in Bombiţă and Müller, 1999).

The **Transcarpathian Basin** which hosts the last sedimentary cycles in the area of study, opened as pull-apart basin (*e.g.*, Vass *et al.*, 1988, in Sotak *et al.*, 1993) during the Neogene. It was filled with "molasse"-type sediments after the resumption of strong sediment supply in the Middle-Upper Miocene, during the maximum exhumation in the Median Dacides area, that amounted up to 7km in the Maramureş Massif (Gröger *et al.*, 2008). The Romanian part of the Mara-Solotvino Subbasin (Fig.2) is a subunit of the Transcarpathian Basin (*e.g.*, Prikhodko *et al.*, 2019) and not of the Pannonian Basin System as it has been proposed by several authors (Sandulescu, 1984, Haas *et al.*, 2001), of which it is separated by the crustal Peri-Pannonian Fault. The Transcarpathian Basin experienced a major extension episode and calc-alkaline volcanism during the Badenian-Sarmatian period (Seghedi *et al.*, 2004).

The **Bogdan-Dragoş Vodă Fault** (BDVF) is one of the most important post-tectonic components of the Transcarpathian area, separating basement Mega-Units and the subsequent nappe-foreland system of the northern Petrova and the southern Botiza units. It might continue far away in the east where it would merge in the Iasi Fault known on the Moldova Slope (more in the inset below). Furthermore, it appears that BDVF also separates two different hydrocarbon subsystems.

Another crustal-scale fault, the **Preluca Fault** (Fig. 1) is situated southwest of the BDVF and could continue into the Năsăud-Odorhei Fault south-eastwards of it (Fig. 1), another major fault in the east Transylvania. In our view, Preluca Fault is a segment of another important crustal fault, the Peri-Pannonian Fault running under different names from Slovakia, Hungary and Ukraine to Romania. The Preluca Fault shows dextral displacement and roughly 5km downward throw of the north-eastern hangingwall compartment at the level of the Moho (*e.g.*, Săndulescu *et al.*, 1993). These authors incorporated this fault in the conceptual North Transylvanian Fault (NTF) that deflected south of the Somes River westwards towards the Debrecen town, approximately on the BDVF trace shown in our Figs 1, 9. In the subsurface, the Preluca Fault limits towards southwest the ophiolite bearing Iňačovce-Kričevo Unit (Băbeşti-Tiacovo Nappe) and to northeast, the East Vardar ophiolite suture of the Transylvanides, thus meeting the characteristics of a transform fault. The Preluca Fault is also active at the present, as suggested by an alignment of seismic epicentres (*e.g.*, Polonic, 1980).

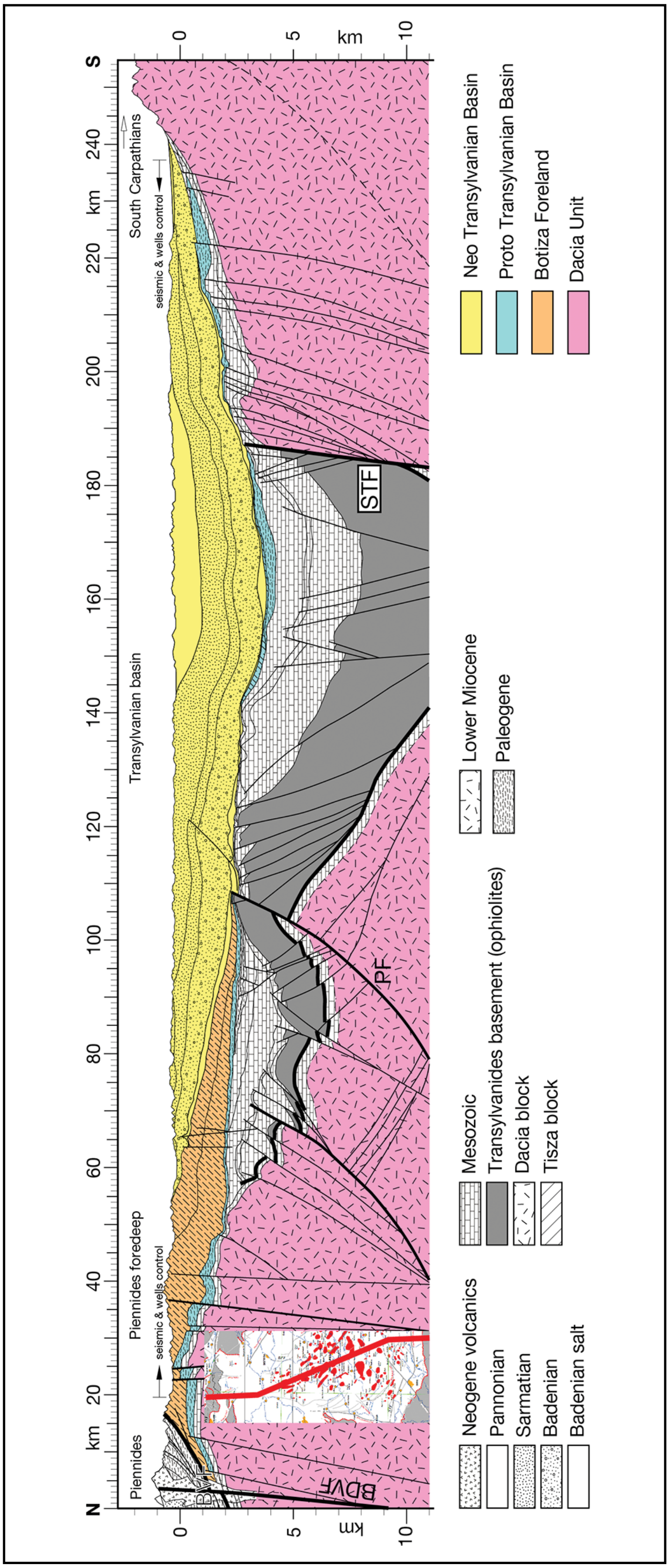

Fig. 4. N/S regional cross section in Maramureş and Transylvania, showing the Lower Miocene wedge-shape deposits of the Botiza Foredeep basin and the overlying (neo)Transylvanian Basin. **BDVF** = Bogdan-Dragoş Vodă Fault; **PF** = Puini Fault; **STF** = South Transylvania Fault (modified after Tiliţă, 2015).

Bogdan-Dragoş Vodă and Iaşi faults – The trace of the Bogdan-Dragoş Vodă Fault (BDVF) had different names in the eastern (initial Rodna, then Dragoş Vodă) and the western (initial Iza, then Bogdan Vodă) segments. It was first identified as a regional crustal fault by Gavăţ *et al.*, (1963) who named it the Borşa Pass-Baia Mare-Carei Line, a quite accurate regional representation, still generally valid today. In the Maramureş area, Dicea *et al.* (1980a) have shown for the first time the two above mentioned segments integrated into a single, broad fault. Tischler *et al.* (2007) noticed that transpression at Bogdan Voda Fault between 16-12Ma changed to transtension along the coupled Bogdan-Dragos Voda Fault system between 12-10Ma. Starting 10 to 2Ma (Györfi *et al.*, 1999, Tischler *et al.*, 2007, Gröger *et al.*, 2008) the Bogdan Voda and Dragos Voda amalgamated segments having a sinistral displacement. It appears that the BDVF has also controlled the post-Sarmatian circulation of hydrothermal fluids on extensional fissures (Ciulavu, 1999) and the resulting mineralization in the Cavnic-Baia Mare volcanic rocks (Kovács and Istvan, 1994). BDVF is still seismically active mainly to the west of the intersection with Preluca Fault (*i.e.*, Halmeu in Polonic, 1980). The total sinistral displacement along BDVF in Maramureş was estimated at 12km by Bombiţă and Müller (1999) or 25-40km by Tischler *et al.* (2008).

Nagymarosy and Baldi-Beke (1993), Csontos and Nagymarosy (1998), Györfi *et al.* (1999), Tischler *et al.* (2007) proposed that the BDVF line could be kinematically coupled with the Mid-Hungarian Fault Zone (MHFZ) at least since the late Miocene after the CCW rotation around 12Ma (see ALCAPA rotational movements above). New research suggests, the BDVF could merge into the MHFZ, possibly in the Hajdú Fault Zone, a splay of the MHFZ (*e.g.*, Petrik *et al.*, 2019), although in the Romanian border area with Hungary, the available seismic data could not yet identify the trace of this important crustal fault. One of the rationales behind this interpretation is that the Szolnok Basin is bounded to the north by ALCAPA and that the Botiza foreland basin stratigraphy would have similarities with the Szolnok Basin hinterland (*e.g.*, Bombiţă, 1972 and the above-mentioned authors). BDVF, however, is the expression of a young reactivation of an important, older, and not-fully constrained crustal fault system.

BDVF is apparently coupled with the Iasi Fault (IF) located on the European plate. This alignment was reached in the early Sarmatian when both BDVF and IF were pointing to the NW. In a map-view (Fig. 2), BDVF seemingly terminates in a splay of extensional faults in the Middle Dacides (Bucovinian) nappes (Tischler *et al.*, 2007). To the east, same trending strike-slip faults were identified in the Moldova Valley flysch deposits by Dicea *et al.*, (1980b). These are connected further east with the crustal Iasi Fault recognized on the Moldova Slope by Popescu *et al.* (2016). This configuration is probably post-early Sarmatian, after the BDVF flexed to the south 30^0 (see rotational movements of Tisza-Dacia above) at the intersection of the East European Craton Krakovets Fault with the Iasi Fault (IF) at Câmpulung Moldovenesc.

The IF was possibly an active crustal fault since the late Jurassic-early Cretaceous on the sub-thrusted European margin, and probably offsets the Greenschists Unit and Tornquist-Teisseyre Zone situated presently at depth, in front of and beneath the Moldavides. The IF was re-activated several times, the late one being during the Sarmatian-Meotian and is seismically active today. In map-view it records approximately 10km of Sarmatian sinistral displacement on the Moldova Valley area (Dicea *et al.*, 1980b) and at Câmpulung Moldovenesc, then dying-out east of the Prut River (Popescu *et al.*, 2016).

The aim of this paper is the investigation of hydrocarbon maturation, expulsion and accumulation in both **Petrova** and **Botiza Foreland Basins** located in front of Magura thrust wedges. These basins were initially identified as "the autochthonous" (Dicea *et al.*, 1980b) or as the "post-tectogenetic cover" of Dacides and Transylvanides (Săndulescu, 1984). Actually, they represent the foredeep depozone of the respective sedimentary basins (Tischler *et al.*, 2008). The south verging Botiza overthrusts load caused isostatic uplifts and re-equilibration of blocks in the foredeep (Krézsek and Bally, 2006) and in the forebulge/backbulge depozones (Fig. 9) as happened in the foredeep of the east verging Petrova Nappe, north of BDVF.

2.1. Petrova Basin

The Petrova Basin system (nappe and foreland) is situated north of the Bogdan-Dragoş Vodă Fault (figs. 1, 2) and comprise Cenomanian- early Miocene deposits outcropping eastward of the Petrova and Leordina Nappe fronts. These "Austrian" and "Laramian" post-kinematic formations cover the Maramureş Massif (Bucovinian Nappe), up to 50km eastwards of Petrova nappes.

The Petrova Basin display a slightly folded and faulted homoclinal structure except for the eastern narrow belt of the overturned Cretaceous-Paleogene, in front of the Toroioaga crystalline on the right bank of the Vişeu Valley. An alternative interpretation of the sedimentary basins behind the Middle Dacides (Bucovinian) nappes as a retroforeland, could associate an early Miocene-aged retro-wedge remnant of the East Carpathians (*e.g.*, the backthrusts of Tischler *et al.*, 2007).

The opening of the Borşa pull-apart basin (Fig. 2) in the same area is possibly related to the Tisza-Dacia above-described CCW rotation during the late Miocene. The Borşa graben recorded a progressively increased subsidence from east to west, under the nappe load.

2.2. Botiza Basin

This is a larger basin, located south of the BDVF (Figs. 1, 2, 4, 9), and represents a relatively short-lived flexural basin developed to the northeast of the Preluca crustal fault. Previous authors (including Popescu, 1984) described the Paleogene-Burdigalian deposits from NW part of Transylvania as belonging to the Transylvanian Basin depositional area (here defined as only the middle-late Miocene megasequence). de Broucker *et al.* (1998) noticed that sedimentation patterns change after the Eocene. As an example, the deposition trend changed from a SE direction during the Oligocene to an E-W direction in the early Miocene again, due to the rotation of the lower plate.

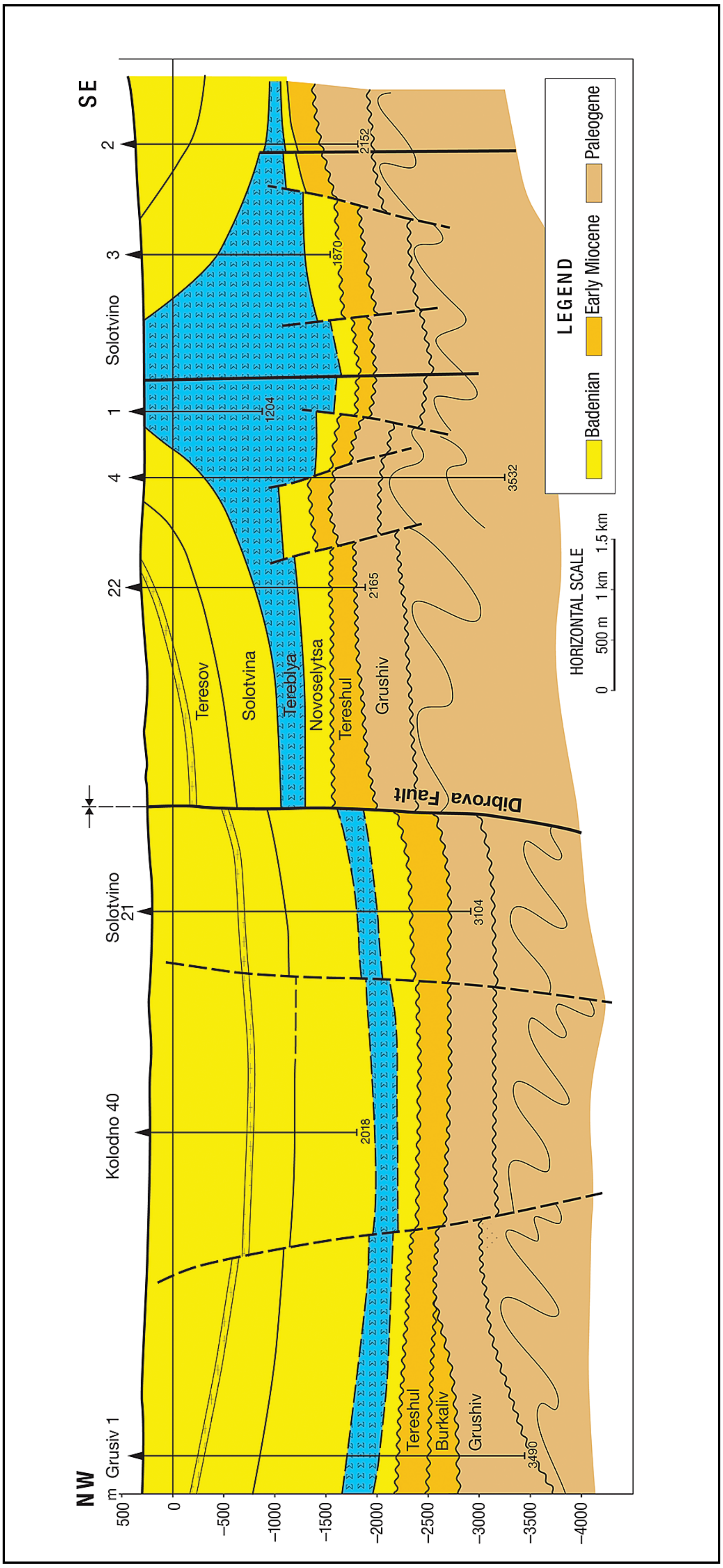

Fig. 5. On strike cross-section through the Mara-Solotvino Subbasin showing the general SE shallowing towards the basin border (see figs. 1, 2). Note the high offset of Dibrova Fault. The Solotvino gas field is sealed by the Tereblya salt in blue (modified after Lozyniak and Misiura, 2009).

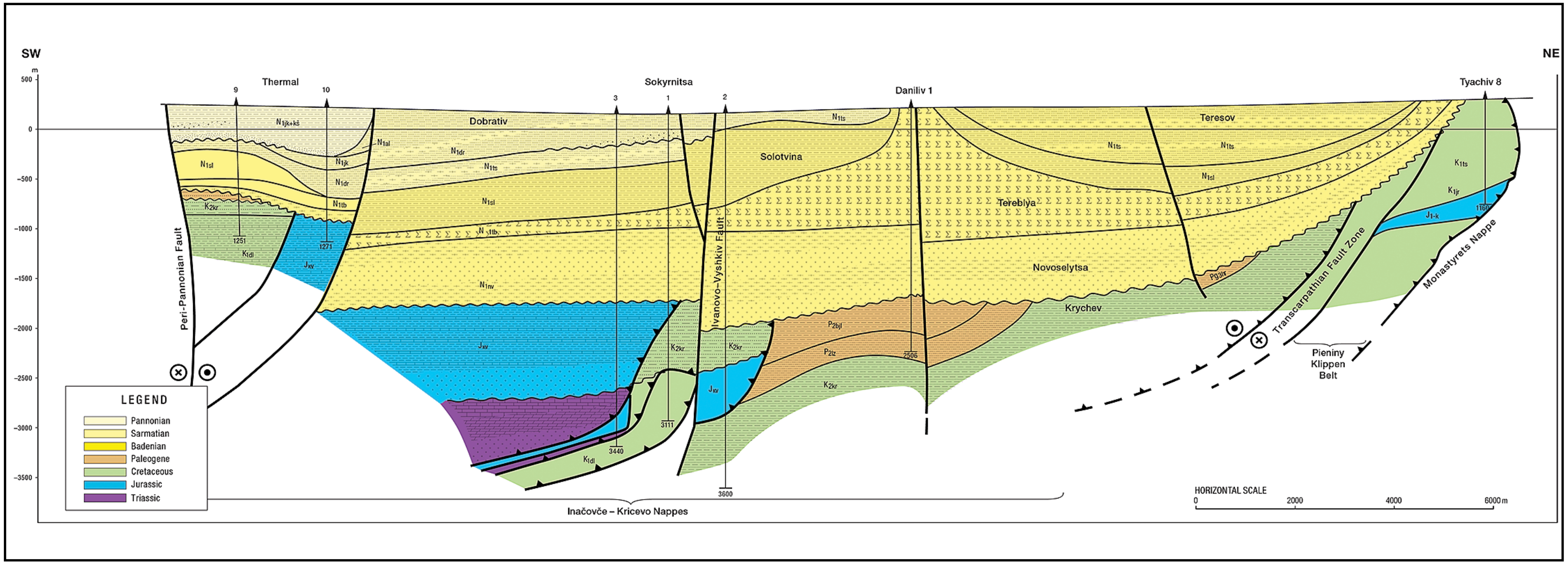

Fig. 6. SW-NE cross-section between Vysokovo and Dragovo in the Khust Subbasin. The basement structure is represented by the well-defined Iňačovce-Kričevo and Pienine thrusts, both extending towards southeast, in Romania. Note the strike-slip character of the Transcarpathian Zone boundaries defining also the rotational behaviour of this area (modified after 2009 Geological Map of Ukraine – Pre-Quaternary Units – Khust 1:200,000).

As early as the Rupelian, the Botiza Basin can be divided into distinct depozones: backbulge forebulge and foredeep, that were active until the early Miocene (Burdigalian). Therefore, the post-Priabonian sequences cropping out in the NW Transylvania described by Rusu (1989) were interpreted as the *backbulge*-depozone of the Botiza Foreland (Figs. 7, 9, 10) . The outcropping facies distribution and lithology of the backbulge are fairly well known, their basement being made up of Senonian to Lower Oligocene deposits belonging to the Proto-Transylvanian Basin, also known from outcrops.

The somewhat narrow and shifting *forebulge* has a NW-SE trend, linking the Preluca massif to Beclean, south Bistrița and west Deda localities (Fig 9). The forebulge orientation is better constrained to the SE continuation of the Preluca Massif, where the shallow crystalline basement is followed by Coroieni-Măgoaja-Strâmbu-wells (Dicea *et al.*, 1980b). It is suggested that SE extension of the Preluca Fault played a role in the flexural processes of the footwall compartment of the Botiza foredeep, covering the NE Transylvania.

The sediments of the Botiza *foredeep* basin were intensely folded and faulted, especially in the Sălăuța area, in part due to the Upper Miocene CW push of Tisza-Dacia (de Leeuw *et al.*, 2013) during the Cenozoic. Apatite (U-Th) data from the Rodna Massif suggests fast cooling during 12-13.3Ma coeval last stages of exhumation (Gröger *et al.*, 2008). The uppermost sedimentary wedge of the Botiza foredeep depozone consists of undeformed Hida Formation that lies over the folded and faulted Oligocene-early Miocene, south of the Botiza nappes (Figs. 4, 10, 12). After a short subaerial exposure, erosion and substantial tilting in the northern Transylvania region, the region situated south of this sedimentary wedge becomes the northern margin of the future middle-late Miocene Megasequence of the Neo-Transylvanian Basin, the main gas province of Romania.

2.3. Mara-Solotvino Subbasin

The extensional Neogene Mara-Solotvino Subbasin (Figs. 2, 5, 6) is a part of the Transcarpathian Basin that extends northwest until Slovakia. It unconformably overlaps folded Pienine/Magura nappes and their forelands. This subbasin is bordered eastwards by outcrops of the Petrova nappe and the Voditsa Fault, south-westwards by the calc-alkaline volcanics of Neogene arc, while in the south it is bounded by the Bogdan-Dragoş Vodă Fault. NW of the Sighetu Marmației there is the Dibrova strikeslip fault (Lozyiniak and Misiura, 2009) with a vertical throw of 600m. Not far away, the regional Seini-Teresva-Nadvirna strikeslip zone (Fig.1) seems a good candidate to discriminate in the larger Transcarpathian Basin, two units: Khust and Mara-Solotvino subbasins. Mara-Solotvino would measure 45 km on strike, of which, about 15 km in Ukraine. The sedimentary cover belongs to the Badenian-Quaternary Megasequence, characterised here by the presence of salt and widespread calc-alkaline intrusions.

3. LITHOLOGY AND BASIN-FILL

Geological and stratigraphic evidence shows that the sedimentary sections of Petrova and Botiza foreland basins (Fig. 2) are rather similar (*e.g.*, Dicea *et al.*, 1980a, b) suggesting again that sedimentation occurred on the same upper plate at least since late Cretaceous, *i.e.*, the rigid Bucovinian (Dacia) basement. Moreover, the respective nappe wedges have Paleogene sedimentary sequences that are, at least partly comparable to those of their foreland (Fig. 7). Thus, since the late Cretaceous, the initial sedimentary domain was quite large westward in the inner Eastern Carpathian sector across the Romanian-Ukrainian border.

The sedimentary section of the previously mentioned two foreland basins bears hydrocarbon accumulations. To the present-day no hydrocarbons were discovered in the thrust wedges of the foreland basins, and therefore they are considered non-prospective.

A few recent papers were published on the general stratigraphy and petrology of the Maramureș sedimentary foreland sequences. For description of Petrova and Botiza forelands lithologies, there were considered: Dicea *et al.*, (1980a), Bombiță and Müller, (1999), and the more recent facies analysis of Tischler *et al.*, (2008), as well as, older explanatory remarks of the national geological 1:200,000 scale-maps of IGG – Baia Mare, Bistrița and Vişeu, as well as lithostratigraphic columns of the 1:50,000 maps published by the same institution.

3.1. Petrova Basin

The Petrova basin is located north to the Bogdan-Dragoş Vodă Fault, and its sedimentary infill overlies unconformably the Middle Dacides metamorphic basement in a narrow foredeep depocenter that enlarges towards SW, in the Borşa pull-apart basin. The approximative 3,250m thick, <u>late Cretaceous-lowermost Miocene</u> sedimentary sequence (Figs. 7, 8) shifts from a shallow water facies in the eastern sector to deep-water facies in the western sector. The late Miocene shortening episode conducted to exhumation and subsequent erosion.

The oldest post-tectonic sediments covering the Middle Dacides nappes are the <u>Cenomanian-Lower Turonian</u> polymictic conglomerates. They are overlain by the Upper <u>Turonian-Coniacian</u> conglomerates and mudstones with *Inoceramus sp.* of the *Ajmaru Mare Formation* (Szász, 1974) altogether summing-up 750m in thickness. The red marlstones in slope facies of the Senonian-Paleogene (Danian) *Red "Puchov" Formation* (125m thick) were first described in the Şetrev Pass, south of the BDVF, but they were encountered also north of the BDVF in several outcrops up to Poienile de sub Munte (*e.g.*, Dicea *et al.*, 1980a).

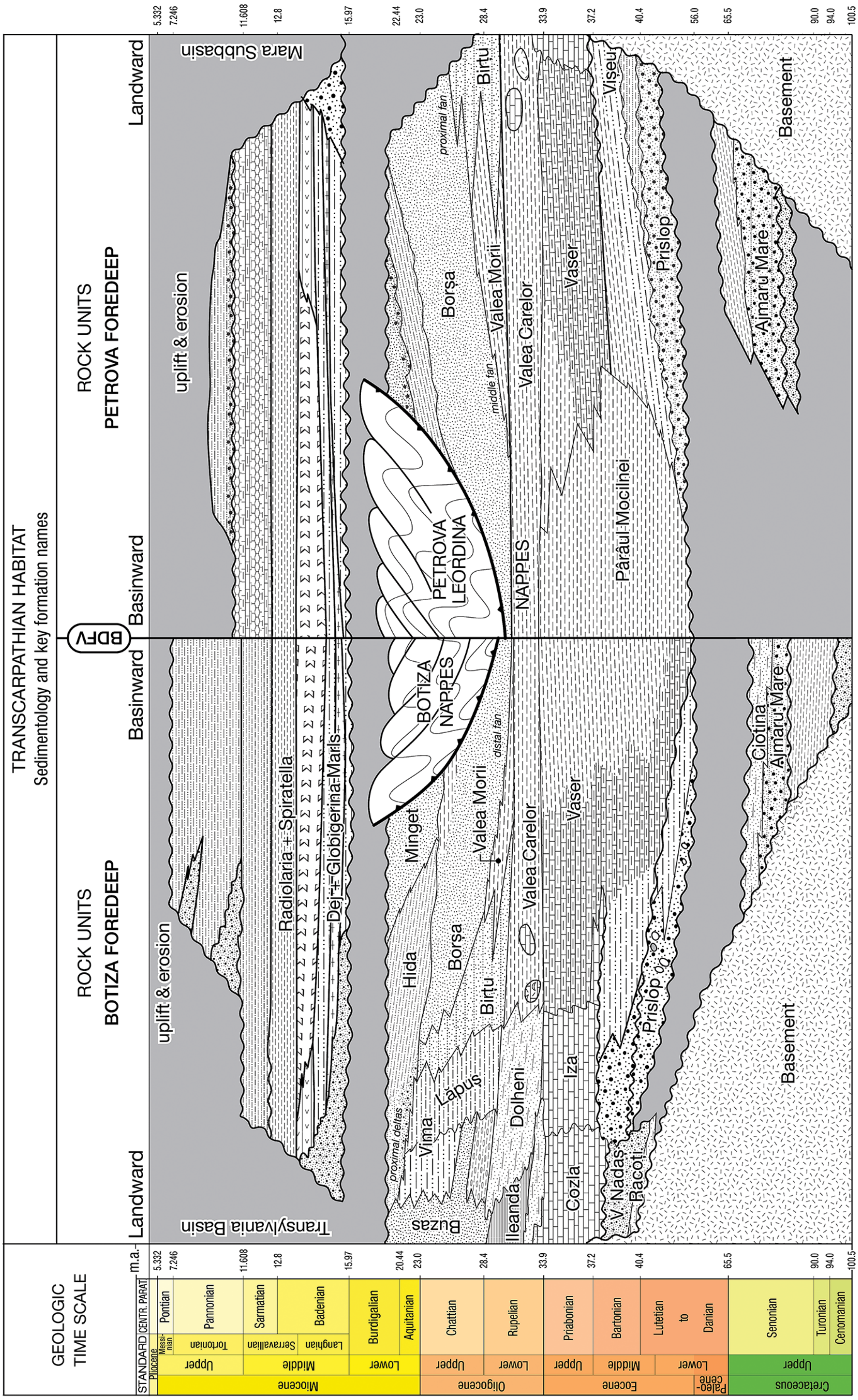

Fig. 7. Chronostratigraphic chart of the Petrova and Botiza forelands, without volcanics (based on Dicea *et al.*, 1980a, Rusu, 1989, Bombiță and Müller, 1999, Krézsek and Bally, 2006).

3.1.1. Middle Eocene (Lutetian) - Lower Miocene Megasequence

This cycle starts with the strongly transgressive (Dicea *et al.*, 1980a) *Prislop Formation* of Lutetian age represented by approximately 500m thick polymictic sandstones and conglomerates passing laterally to sandstones and flysch-like sequences (Figs. 7, 8). This formation was described mainly in the eastern part of the Borşa pull-apart basin on the western flank of the Maramureș crystalline massif. Its conglomerate facies was also found farther east, in the Șesuri Syncline, over the Bucovinian metamorphic series of the Maramureș Mountains, now exhumed at an elevation of 1,450m, 500m higher compared to nearby Borşa Graben coeval sediments. The Prislop Fm. and the terminal flysch-type deposits are continuously well-developed both to the south and to the north of the BDVF in the Bistrița Aurie Valley, and on the eastern slopes of the Rodna Mountains (Kräutner *et al.*, 1983). Westwards, overlaying the Prislop Formation, the mudstone-arenitic *Vişeu Formation* (350-50m), followed by the deeper water facies of the *Vaser Formation* (175-50m). It consists of *Upper Eocene* (Bartonian-Priabonian) marlstones and marly-limestones, representing the proximal facies of the distal *Pârâul Mocilnei Formation,* basal-slope turbidites (Săndulescu *et al.*, 1999). Their uppermost part shows the bloom of *Globigerina* foraminifera, as in the Brebi Marls or in the East Carpathians Moldavides where it is a separate lithostratigraphic unit: the *Globigerina Marlstone Formation*. These mudstones were deposited starting the latest Eocene -NP21 indicative of the starting base level drawdown facies during the Priabonian-earliest Rupelian times. This transcontinental marker also signifies the onset of the anoxic Maikop facies in the Central and Eastern Paratethys. The time-equivalents of the deeper shelf facies Vaser Formation are in the NW Transylvania Cozla Limestone and the Iza Formation from the Botiza Basin are nearshore skeletal or bioconstructed carbonates facies that grade into the deeper shelf facies. Their shoreface equivalents are microconglomerates with Nummulites and marlstones.

The *Valea Carelor Formation* (250-100m) marks the firm installation of Maikopian facies in this province. It consists of highly deformed grey and black clays, dysodiles, menilites and thin arenitic turbidite packages of Lower Rupelian age. The Valea Carelor Formation is paraconformable on the shelf and outer shelf, but can be unconformable in near shore sectors. The formation covers tipically both north and south areas separated by the BDVF, such as Sacel-Valea Carelor Valley, upper Iza Valley and Sălăuța Valley. It consists of dark mudstones, that are considered the main hydrocarbon source rock for of the local petroleum system. The Rupelian sedimentation continues with the *Birțu Formation* (400-50m) which has a turbiditic origin (Fig.8) and is made up of thick litharenite beds with dark mudstone streaks comparable to the Fusaru Formation from the Tarcau Nappe from the Moldavides. The formation exhibits sharp and large varitions in thickness and represents the principal reservoir of some local small-scale oil accumulations. Above the Birțu Sandstone, Dicea *et al.*, (1980a) described two bituminous sedimentary successions: the Marly and Menilite Formation, and the Marly, Dysodile and Spherosiderite Formation. The first one correlates with the conformable *Valea Morii Formation* (300-200m) and represents a recurrence of the Maikopian bituminous shale environment (Fig. 8) making it another source rock candidate. The formation also hosts the Jaslo-type marker level of coccolithic limestones (Dicea *et al.*, 1980a, Bombiță and Müller, 1999) and analogous to the coeval marker of the Chattian age from the Upper Menilites and Dysodile Shale from the Moldavide nappes.

The sedimentary cover of this foredeep basin ends with widespread *Borşa Formation* (up to 2,000m), that is mainly made up of folded litharenites, comparable to some extent with the underlying Birțu Fm. (Fig.8). The exception is represented by the frequent interbeds of spherosiderite, menilite and thin coal seams in the Borşa Formation. It represents the overfill, proximal facies compared with the shelf edge/slope position of the Birțu Formation. The facies analysis of the lower part of the section of the sequence suggests a mass-flow dominated progradational outer fan, whereas its mid-upper part is interpreted as a mid-inner fan depositional environment (Chira *et al.*, 2018).

An additional "Upper Bituminous Complex" package of Borsa Formation was described in the Ruscova embayment without information regarding its age. Borşa litharenite was more recently defined as Chattian-Aquitanian in age, *i.e.*, NP25 to N2 nannoplankton zones (Bombiță and Muller 1999, Chira *et al.*, 2018), coeval with the Starchiojd Formation from the Bend Zone of Eastern Carpathians. The late Aquitanian uppermost section of the Borşa Formation shows molasse-type characteristics (Chira *et al.*, 2018) displaying poorly-sorted coarse clastics located in the basal section of a deltaic cycle. This basin overfill facies was caused by exhumation at the beginning of *Burdigalian* compressional stage.

3.2. Botiza Basin

South of the Bogdan-Dragoş Vodă Fault lays the Botiza basin bearing up to 4,000m of sedimentary sequences deposited in a significantly larger foreland basin with distinct foredeep, forebulge and backbulge depozones (Fig. 9). The Botiza Basin covers a wider area that extends southwards from BDVF up to the Turda-Reghin line marking the southward extension of the Oligocene deposits as earlier pointed out by Ciupagea *et al.*, (1970). Here, the depositional trends were controlled by the NW-SE oriented forebulge, while the foredeep part represents a supposed hydrocarbon kitchen positioned below to the front of the Botiza thrust. In the NE part of Transylvania, and ESE of the Botiza nappes, in the so-called Bârgău Embayment, the Paleogene reaches maximum thickness and is characterized by marine and anoxic facies.

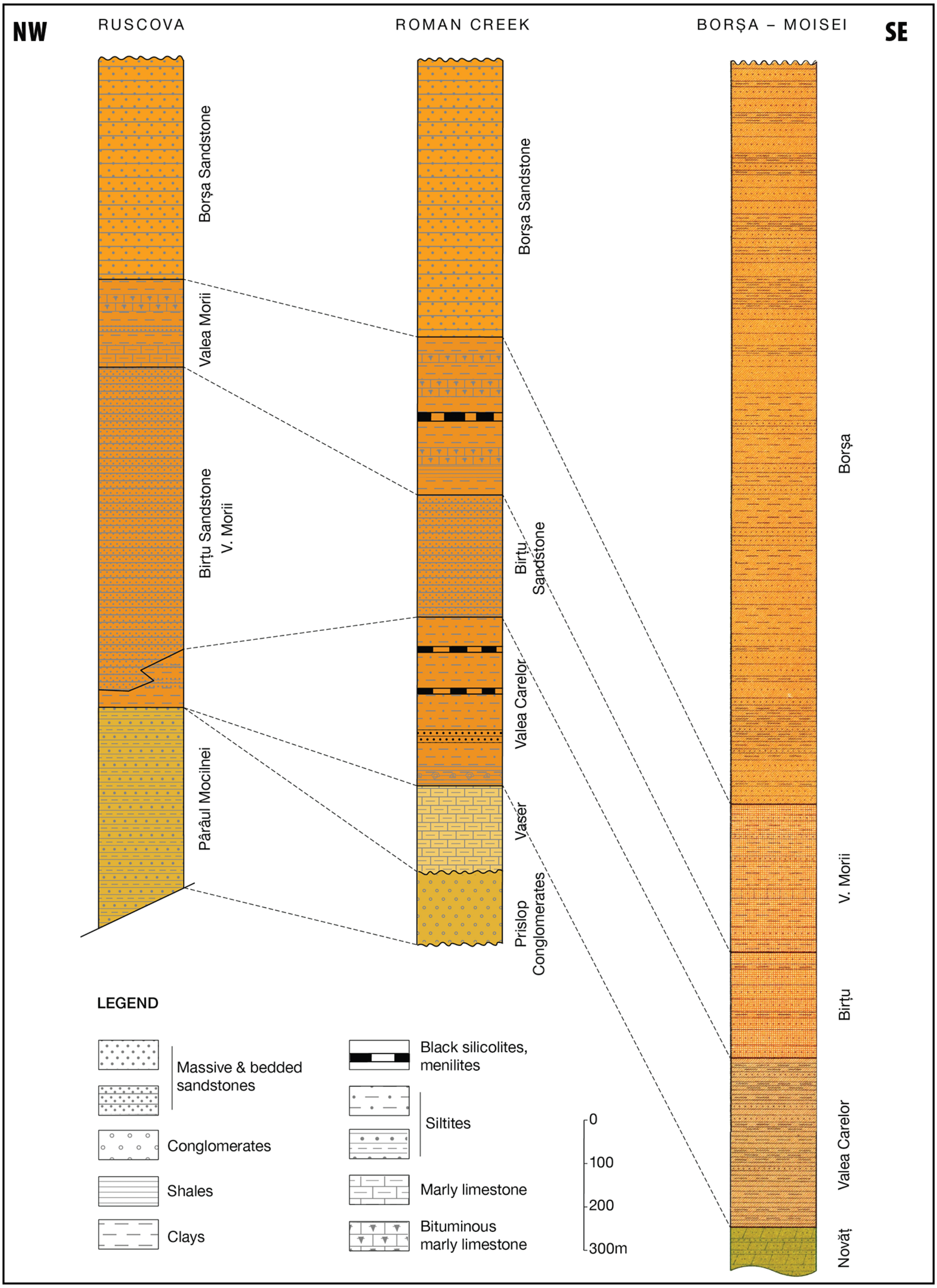

Fig. 8. Lithostratigraphic columns in the Petrova Foreland (adapted form Geological Map Pietrosul Rodnei, Kraütner *et al.*, 1982; Vişeu, Săndulescu *et al.*, 1991).

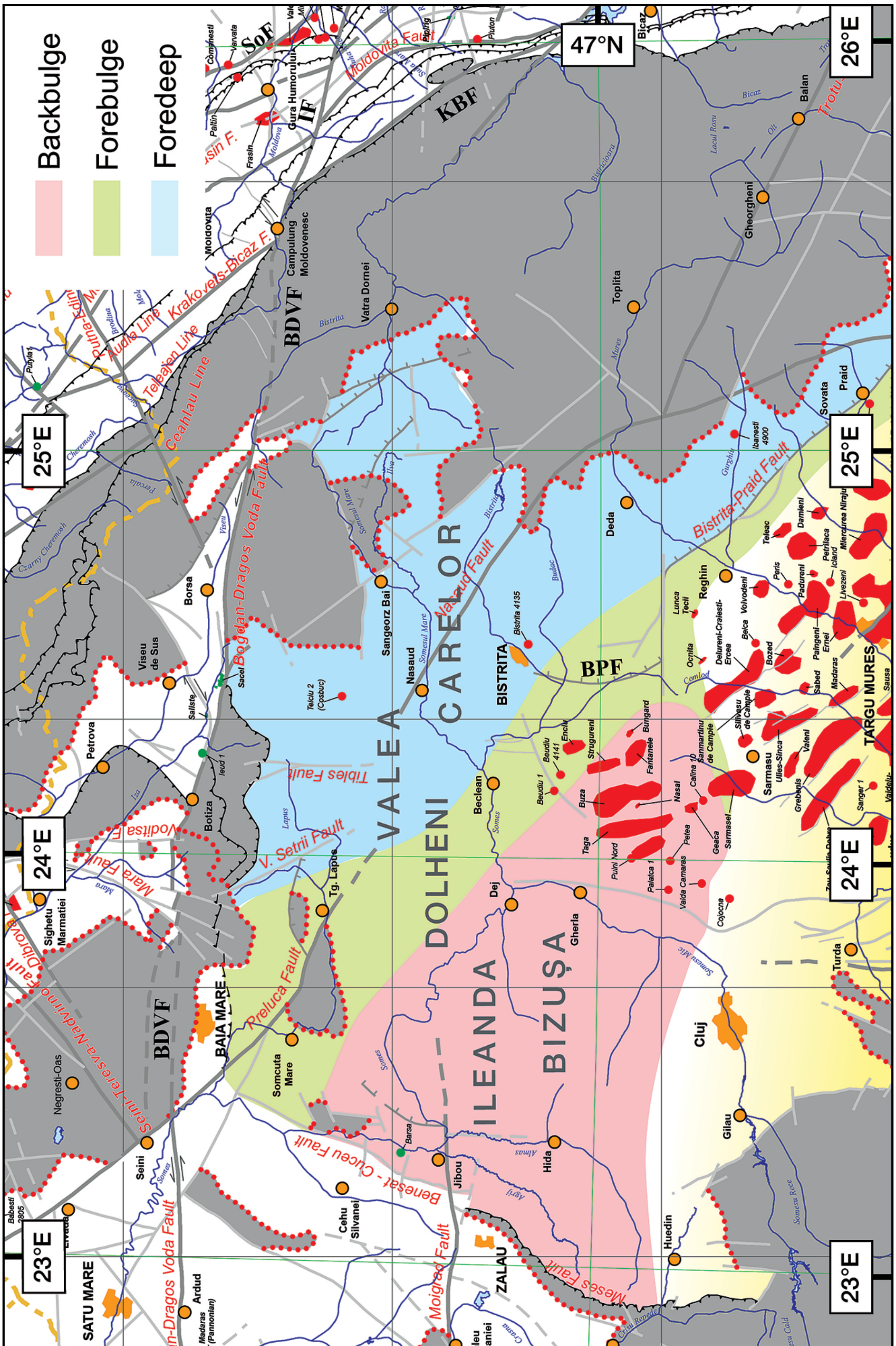

Fig. 9. Depozones of the Botiza Foreland in the Rupelian. The backbulge and the forebulge developed in the footwall of the Preluca Fault, and the foredeep in the hangingwall. The southern yellow color area represents the dryland (redrawn and modified after Rusu, 1989, de Broucker *et al.*, 1998).

The backbulge depozone (Fig. 9), as a novel interpretation covers a large area extending towards S and SW of the Preluca Fault and crystalline massif, which represents an exhumed part of the basin forebulge. The backbulge sediments consists of sequences with wide facies variations, limited areal occurrence, alternating from continental to shallow marine environments, therefore marked by numerous unconformities and facies changes. The forebulge zone overlie a basement uplift trending NW-SE, starting from Preluca Mountains in the north and ending in probably Sovata-Praid area towards SW (see Fig. 9). The foredeep is the largest area within the Botiza basin and is located eastwards to the previous mentioned Preluca forebulge. This part of the basin was filled mainly with flysch-like deposits whose continuity SE from the Mureş River, if any, up to South Transylvania Fault (STF) is not yet defined. Its sedimentary history is believed to have had an impact in the still debated formation mechanisms of the younger Transylvanian Basin (Sanders, 1999, Tiliţă *et al.*, 2013).

3.2.1. Backbulge and Forebulge Depozones

The little subsurface information does not allow yet a thorough evaluation of the pre-Oligocene succession relationship with the Transcarpathian Zone. Hence, the beginning of the sedimentation in the NW Transylvania backbulge of the Transcarpathian Zone is assumed to be Oligocene. Indeed, after a short period of subaerial exposure due to the worldwide base-level low, clearly imprinted at the top of the Cozla Formation, in the Preluca area, the first Oligocene strata deposited in the Transcarpathian backbulge already display a mosaic of facies (Fig.10). This reflects changes in the water-level, salinity changes and paleogeography during early Rupelian (Merian age in Transylvania). Starting the first separation of Paratethys in the Rupelian (Rusu, 1983) the backbulge and forebulge depozones Zone become distinctive marked by the Maikopian black organic shale facies. Ages assigned to formations described below are based on the nannoplankton zonation for the Eocene of Popescu *et al.*, (1978) and Oligocene by Iva and Rusu (1982), Gheţa (1984), and Bombiţă and Müller (1999).

3.2.2. Paleogene (Lutetian) - Lower Miocene Megasequence

The Eocene formations largely outcrop in NW Transylvania and were described in certain detail by Popescu, (1984), but are here assigned to the Proto-Transylvanian Basin. Until further dedicated studies, they could only conjecturally be assigned to the backbulge of the Transcarpathian basin and shall be not detailed in this section. The sparse subsurface data from the Someş Valley junction area (*e.g.*, Cluj-Bistriţa counties) and further south in the central Transylvania, hinders the complete interpretation of the Eocene package.

The Rupelian lower limit (top NP 21) is located in the upper section of the thin (60-30m) Brebi and *Cozla* formations (Fig. 10). The NP 22 nannoplankton zone is lithologically marked by the thin, highly regressive *Hoia Member* (2-0.5m), in fact a parochial lowstand facies of the uppermost part of these formations. The Priabonian-earliest Rupelian Cozla carbonate hardgrounds, calcretes and local thin coal beds (Popescu, 1984) suggest that it was emerged in the early Rupelian times. The shallow-marine *Mera Formation* (70-12m) overlie the formations previously described, and bears a typical NP 22 Rupelian nannoplankton flora. Its equivalents are a variety of confined formations with patchy developed in the whole area of the backbulge. Brackish water arenites, coals, gypsiferous to kaolinite-rich clays, redbeds and thin marine carbonates form the bulk of formations deposited during the Lower Rupelian.

Towards west, the often overfilled near-shore backbulge depozone is draped over by the unconformable *Moigrad* and *Gruia* sands and conglomerates, while to the east, *Bizuşa* (15m)-*Ileanda* (60-30m) bituminous mudstones (of reduced Maikopian-type facies) were deposited, extending for a short time, the whole NP 23 zone across large areas of the basin (Fig. 9). The maximum thickness of these latter formations is reached in the proximity of the forebulge. Their particular chemistry given by the lowstand dysoxic or anoxic events make them good potential source rock of this petroleum habitat. Subsequent investigations (*e.g.*, de Broucker *et al.*, 1998) showed that these formations are immature across their whole depositional area. Laterally, the sandy *Dolheni Formation* was deposited on the outer forebulge and innermost foredeep sections, being contemporary with bituminous Bizuşa and Ileanda formations (Fig.7). Their fauna was correlated by Rusu (1989) with the Rupelian's Solenovian sedimentary series that were later renamed at the Maikop Group stratotype section as the Polbian Beds (NP 23). Towards the foredeep section of the basin, the *Dolheni Formation* rapidly grades, into the shaly Valea Carelor Formation, another possible source rock candidate

Westwards, in the proximal sector of the foreland backbulge, above the Ileanda Formation, the Upper Rupelian-Chattian series consist of fine-to-coarse sands and conglomerates, that corresponds to the *Valea Almaşului Formation* (600-500m) and other equivalent lithostratigraphic units developed towards the central backbulge depozone (Fig. 10). The *Buzaş Formation* (500-350m thickness), with a larger depositional span Upper Rupelian-Aquitanian, was conformably deposited over the Ileanda Formation in a limited areal of the forebulge and NE of it. Its marly sandstone marine facies contains the Upper Chattian NP 25 nannoplankton zone. Here, the Buzaş Formation replaces Valea Almaşului Formation and *Coruş Formation* (20-10m), the latter deemed of Aquitanian in age. Restricted just to the forebulge-foredeep basin interface follows the Chattian-Lower Burdigalian *Vima Formation* settled in continuity of sedimentation.

During the overfill phase, the backbulge and forebulge areas were largely covered by the unconformable *Chechiş Formation* (120-50m) marlstones belonging to the NN2-3 nannoplankton zones and *Hida Formation* (max. 1,000m) of Lower Miocene (Aquitanian-Upper Burdigalian) age (Fig.10).

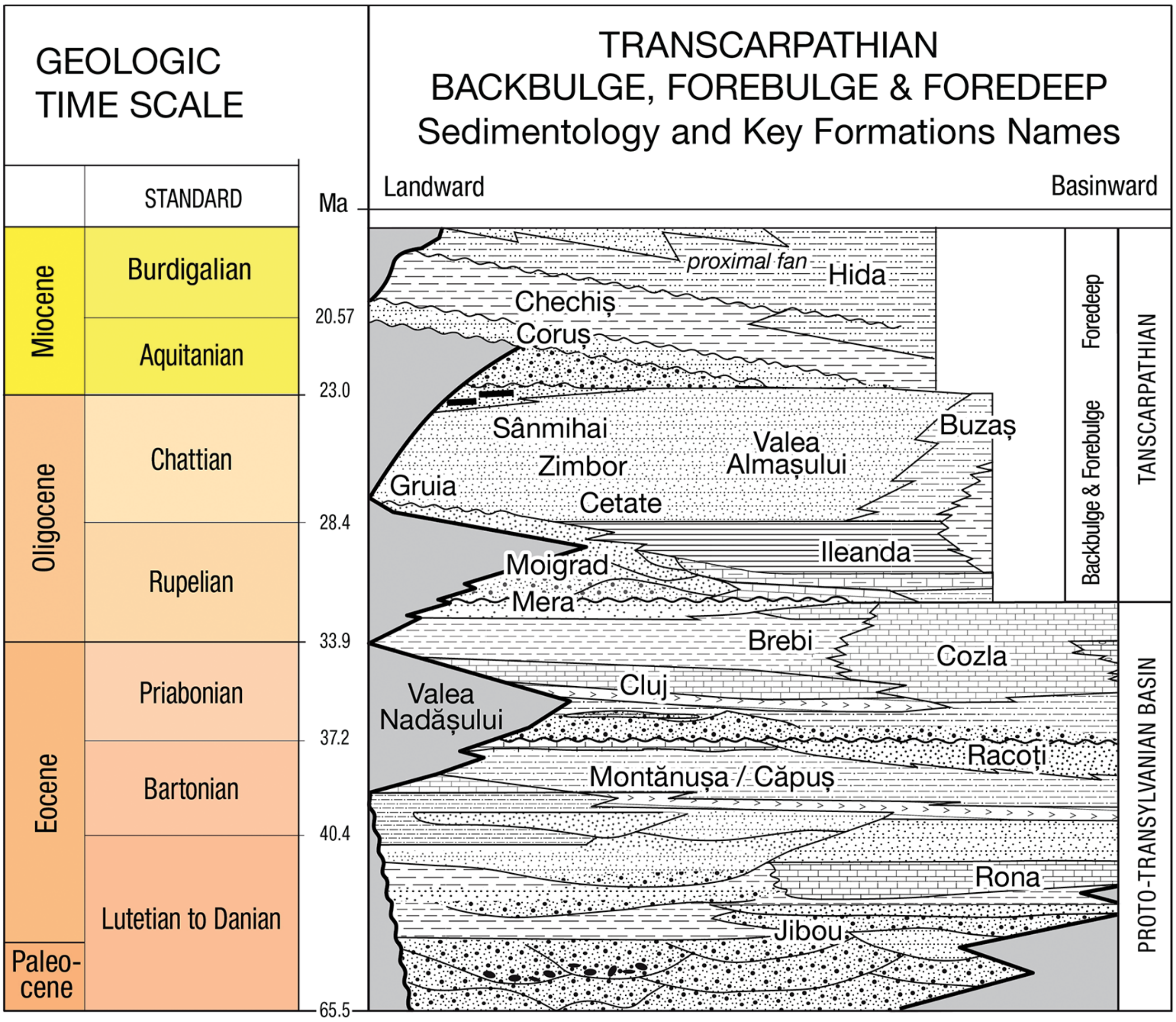

Fig. 10. Lithostratigraphic chart of the NW Paleocene-Eocene Transylvania Proto-Transylvanian Basin and of the Oligo-Miocene Transcarpathian Zone (Botiza Basin) backbulge, forebulge and foredeep depozones (redrawn and modified after Popescu, 1984 and Krézsek and Bally, 2006).

3.2.3. Foredeep Depozone

South of the BDVF, the sedimentary basement of the Oligo-Miocene foredeep consists of similar formations as described for the Petrova Basin, *i.e.*, the Cenomanian-Turonian conglomeratic series of the *Ajmaru Mare* and sandy shales of the Senonian *Ciotina* formations that could pass in distal facies to "*Puchov*" Marls (Fig.7). The deep-water facies of the Senonian *Red "Puchov" Marls,* (70-50m) likewise described on the Petrova Foreland, is encountered here in the Șetrev Pass, Maria Valley and Dorna Cândrenilor area. The occurrence of increased grey clays and marlstones into its succession of red and purple clays shows that the formation extends into the Paleocene (*e.g.*, Dicea *et al.*, 1980a). These formations outcrop in the southern and eastern slope of the Rodna Massif, in the upper Someș Valley stretching eastwards up to the Maria Valley.

Little is published about the Paleogene of the so-called "Bârgău Embayment", here assigned to the Botiza Basin foredeep. Some information can be found in the in Explanatory Notes of the 1:200,000 geological maps or in the representations from the 1: 50,000 maps. On the southern slope of the Rodna Mountains and in the Bârgău Mountains the Oligocene foredeep infill is extending some 50km to the eastward of the forebulge over the Median Dacides, preserving the same extent south-westwards of the BDVF. Besides the southern flank of the Rodna crystalline, the Eocene-Oligocene deposits are shown on 1:50,000 maps at Sângeorz Bai, north of Mureșenii Bârgaului, to the Poiana Negrii sector and in the Glodu Syncline (see the geological maps 1:50,000 Rodna Veche, Pietrosul Rodnei, Ineu and Rebra, Kräutner *et al.*, 1978, 1982, 1983, 1989). Extensively faulted and deformed and crossed by the numerous sub-volcanic bodies, the foredeep sedimentary infill consists of conglomerates, Priabonian carbonates and Oligo-Miocene black mudstones sealed by almost 2,000m of sandy and marly turbidites of the Borşa Formation (*e.g.*, Marinescu and Pelz 1967, Alexandrescu, *et al.*, 1968).

3.2.4. Paleogene (Lutetian) - Lower Miocene Megasequence

The lithology of this megasequence was described in the Petrova Foreland sub-chapter, and will not be described again in this section, except several details on specific facies, correlative possibilities and new formations.

The first Cenozoic series corresponds to the transgressive *Prislop Formation* (max. 200m) of Lutetian-Bartonian age made up of coarse polymictic clastic rocks of discontinuous and sparse metric-sized flysch-like lenses that can be found mostly in the western and southern slope of the Rodna Mountains. The Prislop Formation is maybe partly coeval with the *Stejera* and *Jibou* formations from NW region of Transylvania. In a more distal position, the *Vaser Formation* silts and mudstones, are unconformably covering the Cenomanian-Turonian from the Maria and Glodului valleys or a possible flysch package which replace the upper part of the Prislop Formation (also described in the Petrova Foreland). Moreover, the Vaser Formation laterally interfingers with the *Iza Limestone,* closing the Priabonian succession (Fig. 7, 11). Dicea *et al.*, (1980a) mentions several outcrops where the transition from the Valea Carelor Formation to Vaser Formation shows thin grey marlstones marked with a *Globigerina sp.* bloom (belonging to NP 21 nannoplankton zone), similar with the same formations of the Petrova Basin, but also elsewhere in the Alps and Carpathians.

The *Iza Formation* (150-45m) is a highstand nearshore facies of the Vaser Formation. It lies unconformably over the metamorphic series of the Rodna Mountains and Prislop Formation, and conformably over the Vaser Formation. Located beneath the Iza's main carbonates, Dicea *et al.*, (1980a) assigns the first 8-10m clastic section (black bituminous siltic marls) to the Eocene. On the western slope of the Rodna Mountains, the Iza Formation (45m) shows typical carbonate build-up ramp facies (Sahy *et al.*, 2008) that can reach almost 150m in thickness in the Iza Valley (Dicea *et al.,* 1980a). The formation age is mainly Priabonian, but in the topmost meters of the section yields a Rupelian age as shown by nannoplankton zone NP22 (Bombiță and Müller, 1999). Therefore, the formation correlates well with the Priabonian-Lower Rupelian Cozla Formations from the "basement" of the forebulge depozone (Fig. 10). Possibly they have shaped an E/W carbonate barrier (and forebulge depozone with backreef facies as backbulge?) of the basin at that time. On the Teilor brook, situated south of BDVF, Dicea *et al.*, (1980a) described several sections of carbonates impregnated with oil.

In the foredeep area, south of the BDVF, especially in the actual drainage area of Valea Caselor Valley and upper section of Iza Valley, the *Valea Carelor Formation* (400-100m thickness) displays a Rupelian-style sedimentation with typical Maikopian facies. At the stratotype site, located on the western slopes of the Rodna Massif (Fig. 11), the formation shows a more marginal facies with subjacent Vaser Formation marlstone boulders, breccia of metamorphics and Iza limestone elements, and other collapsed, considerable size blocks from subsequent formations. The distribution of this facies is restricted to shore-face because, not far in the same area, the Iza Limestone is paraconformably (*e.g.*, Sahy *et al.*, 2008) overlain by the black shales and thin turbiditic sandstones of the typical upper facies of the Valea Carelor Formation. This formation is contemplated to have a large subsurface areal coverage over the mid- and outer foredeep.

The lithology of the Valea Carelor Formation is defined, as stated above, by the presence of Maikopian facies type exhibiting thick bituminous marlstones or dysodile shales, marly limestones and menilites, which probably are the main source rock of all known oil accumulations of this province. As a side remark, the Valea Carelor Formation was correlated by Dicea *et al.*, (1980a) with the deep-water wildflysch facies of the overthrusted Wildflysch (or Lăpuş) Nappe of the Botiza nappes stack and with the same Rupelian age Lower Menilites and Brown Marlstone Formation of the Maikopian Group of the East Carpathians' Tarcău Nappe.

Of the same age and situated in the distal foredeep outcrops, above the Valea Carelor Formation, follows the *Birțu Formation* (100-200m), that represents an arenitic channel-type deposit thinning to 60-75m in deep basinal areas (Figs.7, 11) where it is gradually replaced by the Valea Mare mudstone facies. The *Valea Morii Formation* (250-100m) has a similar lithology as described in the Petrova Basin, but appears to slightly thicken in deeper Botiza Basin areas. Towards East Carpathians crystalline core, the basal Birțu arenites and Valea Morii black shales form a continuous sequence of up to 750m as can be observed on the Cormaia Valley (Fig. 11). Much the same as in the Petrova basin, Valea Morii shales represents another good source rock candidate, while Birțu arenites are the main known reservoirs.

To the SE, between Târgu Lăpuş and Bistrița, the *Borşa Formation* (1,500-350m thickness) represents the bulk of the whole central and far-eastern foredeep deposits. These Borşa sediments consists of bedded litharenites and arkosic arenites with carbonate cementation interbedded with claystone streaks. The lowstand facies implies a shallow-up of the Botiza basin, being again, comparable with the Petrova Foreland basin succession. In this basin, planktonic foraminifera were found characteristic to the Upper Chattian-Lower Miocene (*e.g.*, Dicea *et al.*, 1980a).

During the Upper Oligocene, the sediments showing an "on-off" separation of the forebulge depozone consist of the Chattian-Lower Burdigalian *Vima Formation* (300-150m) mudstones interlayered with sandstones, and are in part coeval with the Buzaş Formation from the forebulge (Figs. 7 and 10). In the Lăpuş area, the Vima Formation change to the *Valea Lăpuşului Formation* (up to 600m), that is a marly and sandy sequence deposited on the near and mid-shelf proximal deltas, with Jaslo-type limestone interbeds in its upper part (Bombiță and Müller 1999).

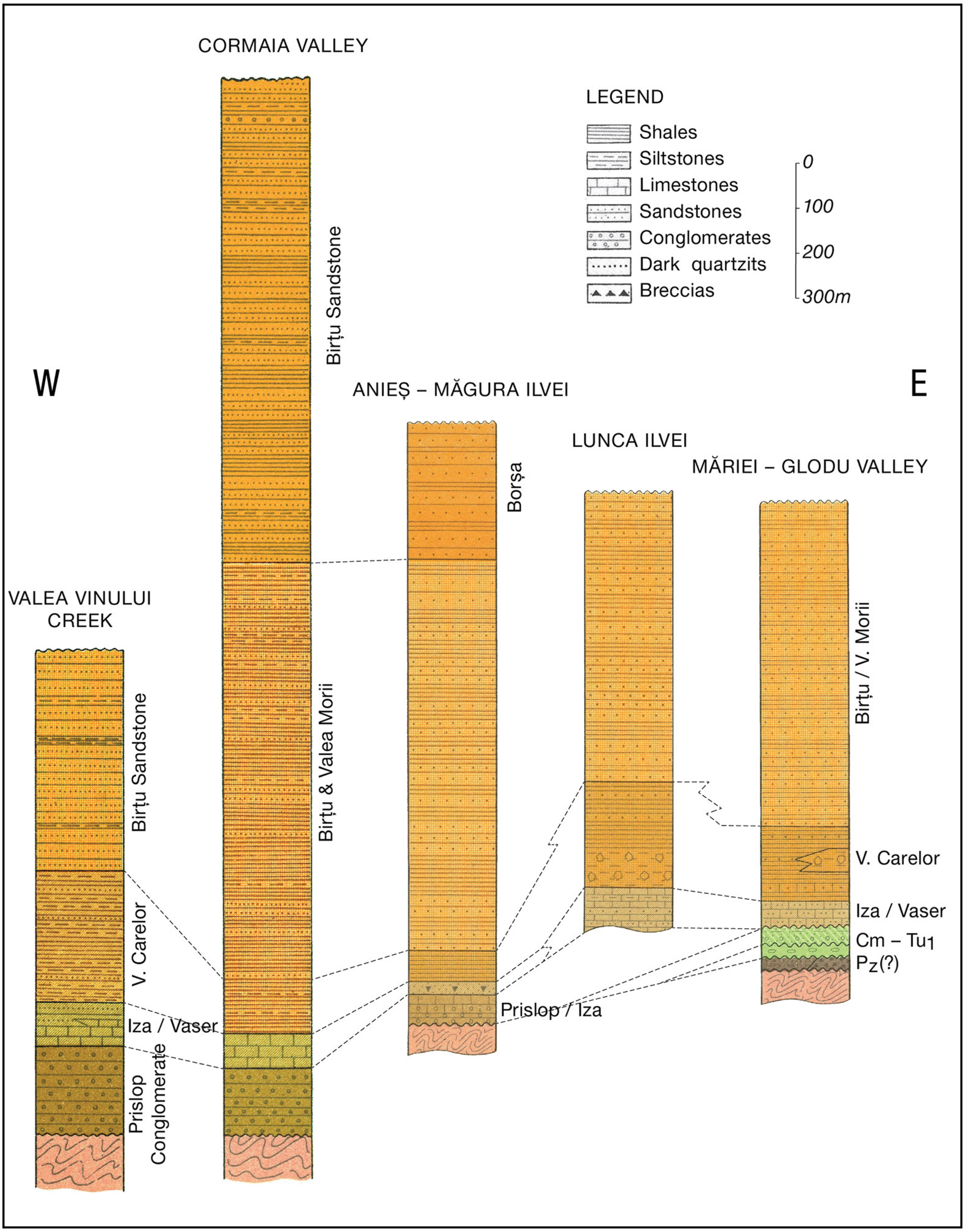

Fig. 11. Lithostratigraphic columns in the Botiza Foreland (adapted after IGG maps 1: 50,000 Rebra (Kräutner *et al.*, 1989) and Rodna Veche (Kräutner *et al.*, 1978).

Shortly to the east, in the Sălăuţa Valley, the Valea Lăpuşului Formation is laterally replaced by the sandy molasse of the *Salva Formation* (up to 850m) of Chattian-Aquitanian (possibly up to Burdigalian) age, that belongs to the terminal foredeep deposition cycle. Vima, Valea Lăpuşului and Salva formations are local heteropic facies.

In northern Transylvania region, the Burdigalian age *Hida Formation* (2,250-300m thickness) wedge covers all distinct depozones of the foreland. This formation, very little deformed corresponds with the final section of the megasequence and represents the last stage of the basin -the overfilling (Fig. 12), and is associated with an overall WSW-ENE change of sedimentary basin direction (Tischler *et al.*, 2008). As overall accepted into the scientific community, the fast subsidence and burial of this formation might have placed the subsequent Valea Carelor source rocks into the early oil generation and expulsion window. The Hida Formation is mainly made-up of mudstones with rare sandstone and proximal conglomerate interbedding, capped by patches of lacustrine sediments. The formation is a shallowing-up inner and mid-shelf foredeep wedge with southwards progressively onlapping deltaic-to-turbiditic sediments, as confirmed by regional seismic data (Fig. 12) (*e.g.*, de Broucker *et al.*, 1998, Györfi *et al.*, 1999, Krézsek and Bally, 2006, Tischler *et al.*, 2008, Tiliţă *et al.*, 2013, 2015).

The Hida Formation extends roughly north of the 46º40' N parallel, mainly over the former Oligocene-earliest Miocene fore- and backbulge depozones and is constrained to the south by the existence of a Burdigalian dry land. Moreover, the southern edge of the former Hida shoreline follows a WSW-ENE line linking Turda and Reghin city areas and was traced with the help of the following stratigraphic wells: Sic 1,2, Bistriţa 4135, Lunca Bradului 1 and Gurghiu 1041 (Ciupagea *et al.*, 1970) The Hida wedge was found only 100m thick in the Sărmăşel 80 well drilled on top of the forebulge. Other wells drilled in the central-northern part of Transylvania penetrated just Hida Formation-equivalents (Ciupagea *et al.*, 1970), with reduced thickness. Elsewhere, excepting the Vlădeni Corridor interpreted as linked to the Transcarpathian Unit (*e.g.*, Dumitrescu *et al.*, 1962), the marine facies of the Burdigalian was identified only in the Alba Iulia-Sebeş region, which belongs to a different paleogeographic setting.

To the north of the Lăpuş Valley, in front of the Botiza nappes, the Hida Formation is replaced by sandy facies known as the *Minget Formation* (1,250-100m thickness) of a poorly constrained Lower Burdigalian age (Fig. 7, Dicea *et al.*, 1980a). The Minget Formation covers areas extending from the Şetrii Fault in the west up to the Tibleş Fault, to the east (see Fig.1) and underwent variable deformation across its coverage, from tight folds on Şetrii Valley, to moderate-amplitude folds on Roia Valley. Some authors (*e.g.*, Dicea *et al.*, 1980a, Bombiţă and Müller, 1999) interpret the Minget Formation as the terminal member of the Borşa Sandstone. It is important to mention the absence of the Hida facies in the Bârgău Embayment outcrops, fact related the late Miocene-Pliocene exhumation and erosion as proven by a preserved complete section below the Dej Tuff, reported from the Bistriţa well (Ciupagea *et al.*, 1970).

The extensive Lutetian-Burdigalian Megasequence ends the sedimentary cycle of both the Botiza and the Petrova forelands covering a large area of the northern part (approx. 25%) of Transylvania region. The southeasternmost Lutetian-Burdigalian Megasequence occurrences of the Botiza Basin were drilled in the upper Mureş Valley (*e.g.*, wells Bistriţa 1, Lunca Bradului 1, Ciupagea *et al.*, 1970), about 75 km SSE of the BDVF and Botiza nappes. In several places the described megasequence is unconformably covered by the Middle Miocene-Pliocene Megasequence of the Transylvanian Basin dominating the Transylvanian plain and Târnave plateau.

3.3. Mara-Solotvino Subbasin

The Mara-Solotvino Subbasin is part of the Transcarpathian Basin Mio-Pliocene post-kinematic cover of the folded Transcarpathian Zone. It exhibits up to 3,500m thick non-deformed deposits of a transgressive sedimentary fill described in some detail by Bombiţă and Muller (1999). Small patches of Mio-Pliocene age sediments are known from the so-called Baia Mare or Șomcuta Subbasin, overlaying the north western end of the Botiza Foreland or the Dragomireşti erosion remnant, east of the Petrova nappes front.

3.3.1. Middle Miocene (Badenian) to Quaternary Megasequence

This megasequence is constantly encountered across the Carpathian foldbelt structure or in post-tectonic covers of their foreland and hinterland. The Mara-Solotvino Subbasin is no exception, the presence of this megasequence and its hinterland position classifies it as the Carpathian upper post-tectonic cover. There is little recent information about the architecture and lithofacies of this subbasin in Romania, but it is implied that robustly shares important lithostratigraphic similarities with the Transylvanian Basin. The most recent literature able to complete informational gaps is coming from the Ukrainian side of the basin, and represents data derived from the exploration for oil and gas (Fig. 13).

First sequences are the unconformable Badenian (1,000-700m) conglomerates, breccias, tuffaceous sandstones, and mudstones with *Globigerina sp.* characteristic to the *Moravian* sub-stage. The basal conglomerates and breccia can be tentatively correlated with the Karpatian age Ciceu-Giurgeşti Formation from the Transylvanian Basin (de Leeuw *et al.*, 2013), but this needs additional confirmation from further biostratigraphic studies. Leitha-type calcarenites with sparse gypsum interbeds were described in the southern part of this subbasin, along with thick salt of the Wielician *Ocna Dej Formation.* Outcropping salt diapirs can be found in the areas of Solotvino (Fig. 5), Ocna Şugatag and Costiui from the left bank of the Mara Valley.

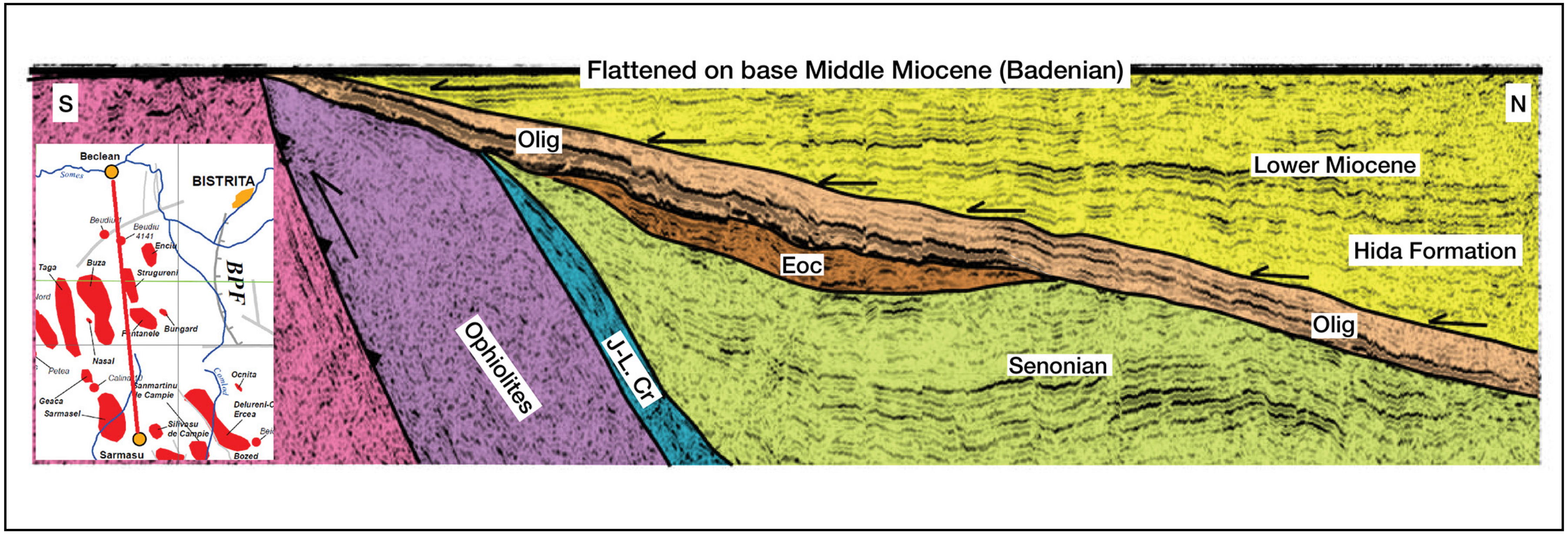

Fig. 12. Cross-section from Sărmașu (**S**) to Beclean (**N**) showing the onlaps of the Lower Miocene Hida wedge on the Botiza foreland. Note the northward significant thickening of the sequence (adapted after Krézsek and Bally, 2006).

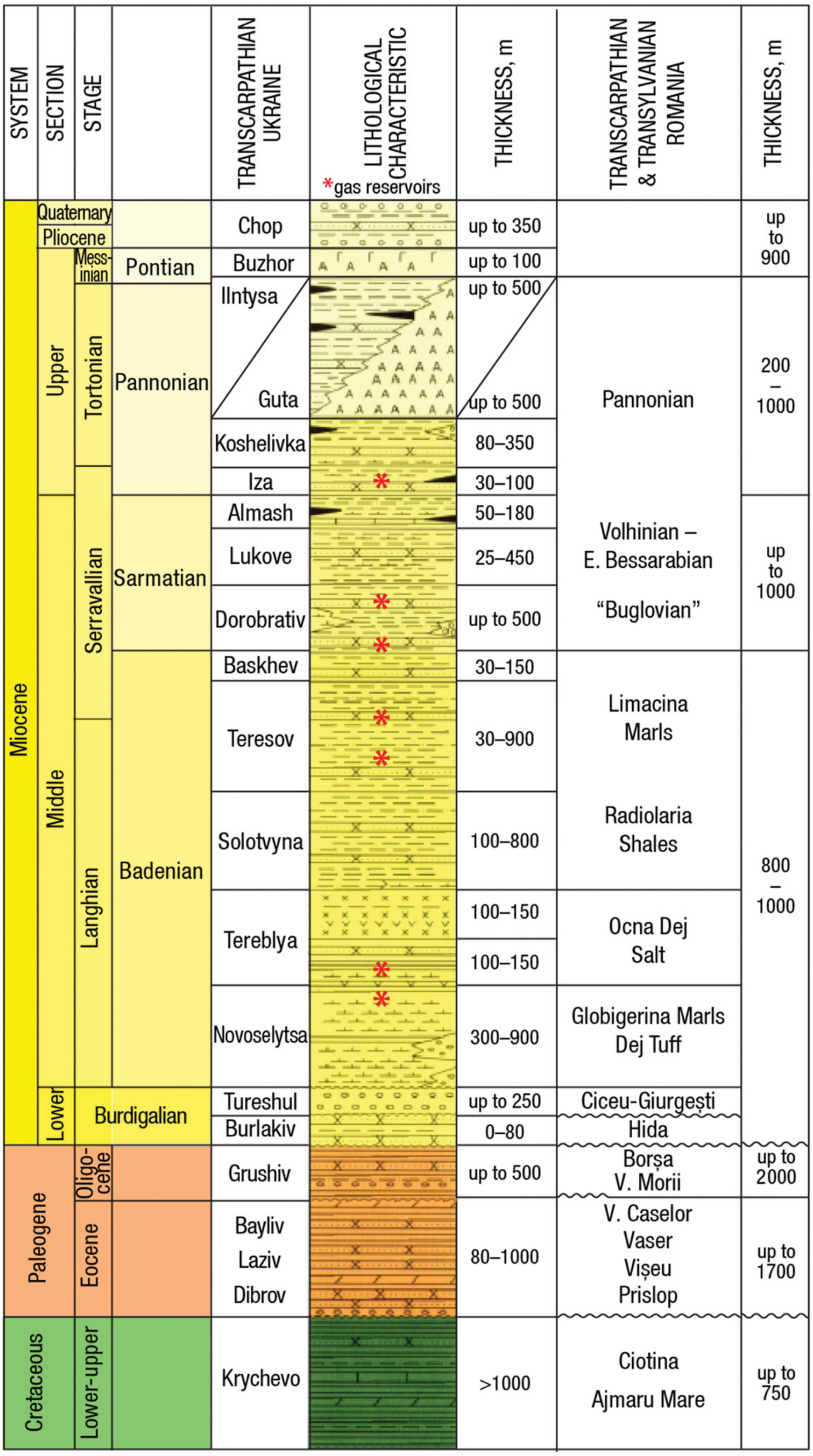

Fig. 13. Lithostratigraphy of the Transcarpathian Basin sub-divisions - Khust Subbasin and Mara-Solotvino Subbasin, without volcanics (modified after Hafych *et al.*, 2006).

The sediments corresponding to the *Radiolaria* shales (80-60m in the south) and *Limacina* marlstones bear a NP6-7 nannoplankton zone flora of the Kossovian sub-stage (Bombiță and Müller, 1999).

The sedimentary succession continues with Sarmatian (up to 1,000m) marlstones and sandstones sparsely interbedded by conglomerates, and with the *Pannonian* (300-200m) brackish marls and sands, usually assigned to typical molasse facies. The Pontian (up to 200m) marlstones, sandstones and andesitic volcano-sedimentary series covers large areas mainly south of the BDVF, while the Pliocene-Quaternary (900m) piedmont and alluvial coarse conglomerates cover 90% of the subbasin area north of the BDVF. Regardless of the paucity of recent lithostratigraphic information on the Mara-Solotvino Subbasin, correlations can be made with the Khust Subbasin (Fig. 13), studied in more detail in recent years (*e.g.*, Hafych *et al.*, 2006, Prikhodko *et al.*, 2019). A special remark should be given to the thick Middle Badenian salt largely present in both the Transylvanian and Transcarpathian basins, but almost absent in the Pannonian Basin.

In the whole Transcarpathian Basin, the mid-Miocene magmatic activity affected several areas in the Mio-Pliocene subbasins, the Pieniny nappes, their foreland and the Transylvanian Basin further towards SE. The volcanic activity developed mainly during several post-collisional episodes (Seghedi *et al.*, 2004). It worth mentioning that the volcanic rocks in the area were thoroughly studied and mined since the Middle Age due to their exceptional metallic ore richness.

4. PETROLEUM SYSTEMS

Two independent petroleum systems (PS) have been separated so far in the Transcarpathian Province: a proved thermogenic Paleogene system in the Magura/Pieniny forelands and another thermogenic Miocene system hosted by Miocene Mara-Solotvino Subbasin. At this point, due to lack of geochemical data, the Paleogene PS is rather divided in two subsystems by the BDVF, a proven northern one, and an inferred southern one, while the nappe system is considered barren since no hydrocarbons were found yet.

The habitat shows important surface oil seepages, but there are only a couple of commercial oilfields. The heat flow, temperature gradients and geochemical data from these PS is scarce. Gröger *et al.*, (2008), based on the zircon fission-track data excluded significant increase in heat-flow from the Paleogene to early Miocene burial load. Maturation kinetics and expulsion timing diagrams were not yet published, but based on subsidence patterns the migration of oil likely started in the Badenian, and of gas in the Sarmatian. The Petrova and Botiza nappe sediments apparently never achieved burial depths corresponding to the hydrocarbon generation window as shown by all the organic markers from the source-rock formations, excepting perhaps, the section underneath the Mara-Solotvino Subbasin. Nevertheless, there are not known similar producing oil fields from similar plays in the NW extension of the basin from Ukraine with a recent possible exception of the Dibrovski discovery from the Khust Subbasin.

4.1. The Valea Carelor-Birțu and Borșa petroleum system

This PS contains the small Săcel-Săliște oilfields known since the 19th century (Fig.1) on the Petrova foreland. It was proposed by Popescu (1995) that these fields belong to the Transcarpathian PS, including the thermogenic/biogenic gas systems of the Mara-Solotvino Subbasin as well.

In this contribution, this PS includes a separate subsystem that comprises the Bârsa field (also called Jibou, (Fig. 1) and Coşbuc oil and gas sub-commercial discovery from the Botiza Foreland. This field was initially assigned to the NW Transylvanian PS sourced by questionably mature Ileanda shales (Popescu 1995). However, comparable Cenozoic basin-forming mechanisms and geometry of foredeeps described in the above chapters, favours the interpretation of the Bârsa (Jibou) accumulation located in the Botiza foreland (Fig. 2) and that as such, it belongs to this Transcarpathian Zone PS although the hydrocarbon migration paths are still obscure and critical moment could not be established with the available data.

In the Petrova Foreland, the proved PS (independent or a subsystem) covers approx. 350 km^2 and includes Săcel and Săliște accumulations. Elsewhere, non-commercial oil shows were reported in the Ieud wells and in in the westernmost unit of the Transcarpathian Zone, at the Băbeşti 2805 well (Fig. 1). Present-day thermal gradient reported from the Săcel wells is 4-5°C/100m, reflecting the influence of the recent, Neogene volcanism.

In the Botiza Foreland, the speculative PS (independent or as subsystem) would cover approx. 2,000 km^2 and contains the shallow Bârsa oil accumulation abandoned since 19th century and several hydrocarbon shows found cropping-out or in a couple of wells. Its presence is further confirmed by oil seeps in the banks of the Someș River, north of Jibou, as well as by oil and gas shows at Dănești or Vima areas, and by a non-commercial discovery in Telciu (Coşbuc) 2 well. The eastern extension (*e.g.*, in the Bârgău Embayment) of this PS is difficult to establish a hydrocarbon potential as it is less studied. The southern basin extension is unclear because of probable less significant sedimentary load and an unlike long-distance migration pathways.

Source rocks – The Oligocene-early Miocene thick bituminous shales represents the potential source rocks for both northern and southern basins, with a possible contribution from the thinner Eocene dark shales intervals.

In the Petrova Foreland, the source rocks candidates feeding the Oligo-Miocene plays are the Rupelian *Valea Carelor* and *Valea Morii* formations, possibly the Priabonian *Vaser Formation* and the deep-water shales of the *Pârâul Mocilnei Formation*, which may become main system hydrocarbon source rock when optimally buried. The Oligocene organic shale section has a C_{org} up to 6%, average R_o 0.86% and dissolved hydrocarbons of 5,000ppm (Popescu, 1995). Krézsek *et al.*, (2012) disclose the *Valea Carelor* and *Valea Morii* bituminous shales, together are up to 750 m thick, and have a shale N/G ratio ranging from 60 to 90%. They have a kerogen II/III type, an average $TOC_{wt\%}$ of 2-3% with sweet spots of $TOC_{wt\%}$, up to 10%, reaching the oil window at less than 3,000m burial depth (Krézsek *et al.*, 2012). There is no rock-eval or isotope information available in the public domain, on the source rocks from the Petrova Foreland.

In addition, due to recent interest in unconventional hydrocarbons, the Oligocene organic-rich shales, might represent a prospective unconventional play (Fig. 14), especially at shallow depths beneath the Petrova-Leordina nappes (*e.g.*, Krézsek *et al.*, 2012) and possibly west of the Mara-Solotvino fault.

In the Botiza Foreland foredeep section, the organic-rich marls of Priabonian *Vaser* mudstones represent a good potential source rock. The main PS contributor candidate the Rupelian *Valea Carelor Formation*, with 100-400m gross thickness has in average good TOC_{wt} of 2-3.5% and the R_o is 0.8-1.2% showing that they are thermally mature. In the basinal sector, the dysodiles and menilites of *Valea Morii* implying a similar good source rock potential. Overall, these source rocks seem to match the geochemical characteristics of the coeval sections form the Eastern Carpathian Outer Moldavides (*e.g.*, Ştefănescu *et al.*, 2006).

In the backbulge depozone, the *Ileanda* organic-rich black shales were considered, for many years, the first source-rock candidate of this habitat (*e.g.*, Popescu 1995, Stefanescu *et al.*, 2006). An outcrop sample from the Ileanda Formation shown fair pyrolysis yields: HI 347mgHC/gTOC, S_2 3.72mgHC/g rock, in immature stage (T_{max} of 420°C), for a TOC_{wt} of 1.07% (Popescu, 1995). Furthermore, a regional subsurface study revealed that the Ileanda shales have $TOC_{wt\%}$ values between 1 and 3.5% and a R_o of 0.55, pointing that they are immature on all area of formation extension (de Broucker *et al.*, 1998), and that they never achieved maturity and generation stage because of improper burial of the Botiza backbulge deposits. Petroleum produced by pyrolysis from Ileanda shales TOC_{wt} values between 0.3 to 8.6%, varies between 3.2 and 77 l/ton (Clichici *et al.*, 1989).

Reservoirs – In the Petrova Foreland the main reservoirs are associated with the early Oligocene *Birţu Sandstones*, a micaceous litharenite with porosity reduced by compaction and cementation in its proximal facies. This relatively tight sandstone has 0.78-5.6% porosity and 10mD permeability (Paraschiv 1979) has been producing from the fracture porosity developed in the area close to BDVF zone, and it is expected to have an improved reservoir quality at a distance of the BDVF and in deep-water lobes. Good reservoirs parameters probably occur locally in the *Vişeu, Valea Carelor, Valea Morii* sandstone packages and in the *Borşa* Sandstone (Fig. 7). The above-mentioned reservoirs were not explored below the nappe-stack yet.

Reservoirs of the Săcel field are ranging between 50 and 200m gross thickness each and are labelled Ol_1 and Ol_2 starting top to bottom (Paraschiv, 1979). These reservoirs are separate hydrodynamic units and only Ol_1 had a just good enough commercial production of oil. The underlying Ol_2 tested oil in the well no. 21 and 20, but evaluations resulted in much smaller recoverable reserves. In the so-called clayey-marly upper horizon (of probably Valea Morii Formation) were recognised two reservoirs R_1 and R_2. The latter reservoir is marginally productive, while the R_1 is not yet fully appraised. The porosity in this area is under 10%, being either matrix and/or fractural type (fig 15).

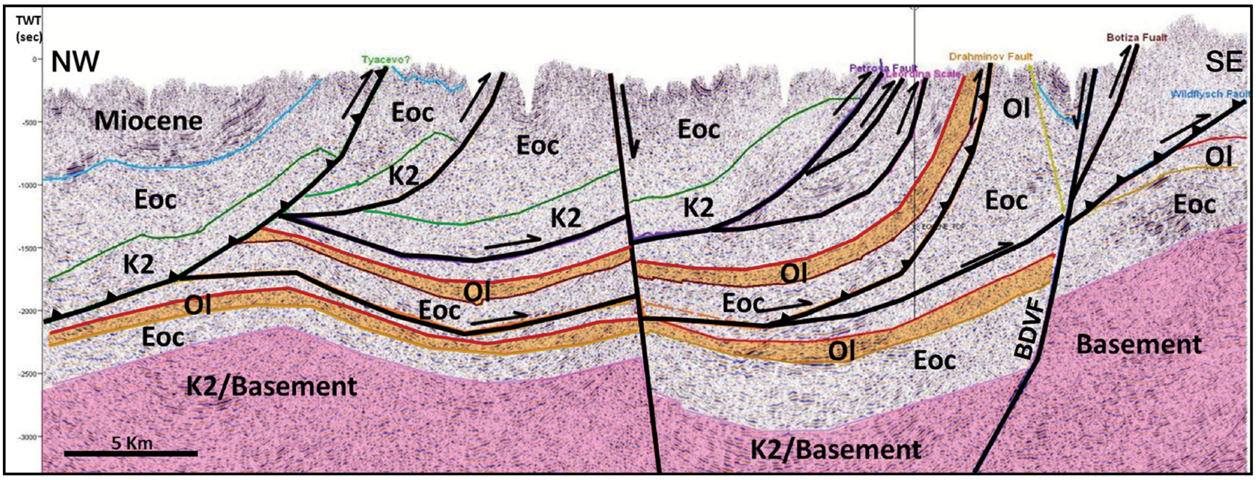

Fig. 14. NV-SE cross-section in the Petrova Foreland and nappes north of BDVF. The prospective non-conventional oil shales from the Oligocene highlighted (adapted and supplemented after Krézsek *et al.*, 2012).

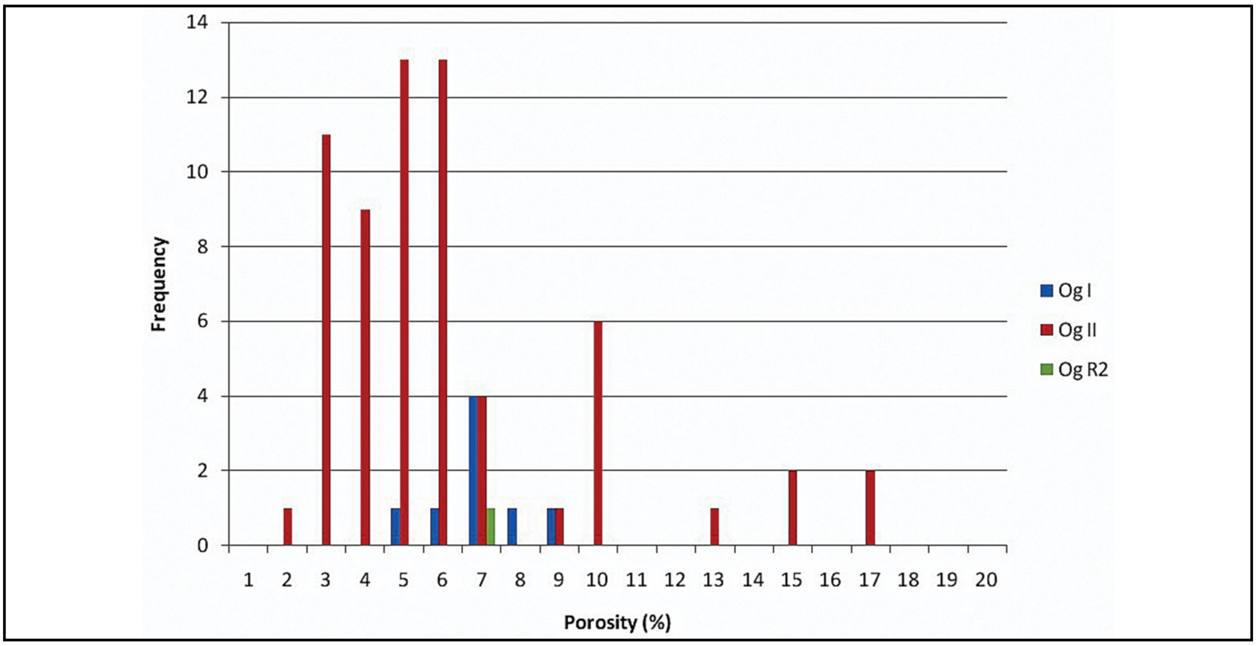

Fig. 15. Porosity distribution in the Oligo-Miocene reservoirs of the Petrova Foreland (by courtesy of Zeta Petroleum).

The regional fracture system of the BDVF is interpreted to have generated 0.01-0.1% rock volume porosity in this play. In the strongly folded and faulted anticlines (Săcel oilfield), the micro-fracture width varies between 0.1 to 0.5 mm generating porosity on the fold crests and less on flanks. The matrix porosity is however the main effective porosity, and it should be present elsewhere in both the unfolded and the slightly folded foreland.

In the Botiza Foreland, several reservoirs lenses have been reported with oil and gas shows. The only producing are the *Jibou Formation* un-compacted piedmont sand reservoirs encased in red mudstones. At Bârsa there were opened by hand-dug pits in the early(?) 19th century. Throughout the rest of the basin, just oil and gas shows were reported, such as in the Eocene *Cozla Limestone* (probably fracture-type or subaerial leaching) or the coeval *Iza Limestone*, which exhibits impregnations of petroleum on the Teilor Valley (*e.g.*, Dicea *et al.*, 1980a).

In addition to gas shows from the shallow wells of Vima Mare area (Ciupagea *et al.*, 1970) but the best gas shows were tested in the Telciu (Coșbuc) 2 well (Oltean, 1970), without any final commercial significance. Here, the main reservoir appears to be the Oligocene-Lower Miocene *Borşa Sandstone*, with rather good reservoir characteristics (above 2,500m depth): 5-12% porosity and 0.1-1mD permeability.

Traps are mostly represented by stratigraphic pinchouts and permeability barriers or by large post-Burdigalian low-relief anticlines. Main risk is represented by breaching, especially in the area close to BDVF due to repeated phases of transpression and transtension. The late Miocene uplift and subsequent erosion (*e.g.*, Gröger *et al.*, 2008) affected the existing accumulations as suggested by outcrop impregnations and seeps. Another example of a breached trap, due to the early Miocene shortening is the Jibou-Someș Odorhei anticline where several active seeps can be observed.

Seals usually are represented by intraformational shales, particularly in the Oligocene flysch sequences and by Eocene redbed claystones. The common risk is the seal-integrity often broken by the subsequent brittle tectonics in the proximity of tectonically-active areas..

Migration and accumulation of the hydrocarbons in the Petrova Foreland PS subsystem was mainly vertical, along numerous sub-vertical normal faults and strike-slips adjacent to BDVF zone. To certain extent, the migration could be also lateral as in the Săcel and Sălişte fields. Locally, effective source rocks situated below or lateral directly connects with the pay zones, while a long-distance (up to 10km) migration from sub-thrust mature source pods is also possible. After the post-Burdigalian trap formation, the migration of hydrocarbons took place during the period of the relative tectonic quiescence, between 15 and 5Ma.

The oil stains from the weathered basement in the Băbeşti 2805, point to an independent, speculative termogenic PS, however due to unclear structural unit affinity, little can be argued about its attributes and architecture.

The above-mentioned unconventional play (Fig. 14) is in the oil window at around 3,000m depth in an area covering some 500 km^2 (Krézsek *et al.*, 2012) making it one the best exploration unconventional target in the country despite the intricate structural setting.

In the Botiza Foreland, a still unclear migration fairway is under debate for the Bârsa (Jibou) anticlinal field as the source rock and the kitchen location is yet inferred. A possible model involves a pod of mature Oligocene source rocks located below the Botiza nappes, east of the Baia Mare where the high geothermal gradient and nappes overburden created possibility of oil generation and expulsion below 2,500-3,000m depth. A short distance migration is acknowledged by the hydrocarbon and helium shows reported in the wells from Dănești-Surdești-Coaș area, along the possible Bârsa fairway. A possible, 30-35km stretched, lateral updip migration of oil along the arenite pathways to the Jibou Formation stratigraphic traps could be an alternative play. This mechanism again assumes that the Ileanda shales from the backbulge of the Botiza Foreland were never effective.

Another possible pod of mature source rocks of this PS subsystem would have been located below the Sălăuța scales. The short-lateral migration might have occurred from Sălăuța imbricates to the location of the Telciu (Coşbuc) 2 well. The content of high-rank gaseous and liquid hydrocarbons (93.8-97.2% CH_4, 1.51- 5.35% ethane, propane, isobutane and butane), along traces of N_2 and CO_2 (Oltean, 1970), is pointing to the thermogenic origin of the Coşbuc gas.

4.2. The Maramureș Miocene gas system

Little is known about this petroleum system in this part of Romania. The PS was sporadically identified by gas shows from Badenian clastics in wells drilled in the in Mara-Solotvino Subbasin and in the Băbeşti 2805 wildcat. The gas found so far is termogenic although the existence of biogenic gas accumulation in the basin is likely.

Miocene reservoirs potential of this PS was investigated in Romania by wells drilled in the Sarasău area, which yielded only gas shows. The possible post-salt Badenian and Sarmatian reservoirs were found dry in the Mara-Solotvino Subbasin. However, in other Transcarpathian Basin subunits, *e.g.*, the Chop-Mukachivsk Subbasin, they are producing gas from the Sarmatian. Just a few hundred meters north, in the Ukrainian part of the Mara-Solotvino Subbasin, in 1982 at 1,400 m depth, gas was discovered in the Solotvino salt-related structure. A not-so-distant accumulation is the Dibrovski gas field, found in 2004, but apparently located in the top of the Paleogene basement. Additional plays may include weathered relief of the Mesozoic carbonates, secondary porosity in Paleogene basement sandstones, rollover fault reservoirs, stratigraphic traps in deltaic or near-shore Miocene clastic rocks.

One main difference to the nearby Transylvanian Basin is the higher geothermal gradient, reaching 3.7-4.24^{o}C/100m in the gas field areas (Hafych *et al.*, 2006) and even higher in the south-eastern and western parts, due to the close vicinity of Pannonian basin extension or the Neogene volcanic arc.

Source rocks are Badenian shales and possibly the Oligocene dark shales from the basin's basement that would hybridise this petroleum system. In the Transcarpathian Basin source rock geochemical characteristics were studied in more detail in the Trebišov Subbasin in East Slovakia founding a good genetic match between source rocks and hydrocarbons. The kerogen from the Karpatian to Sarmatian shales is humic and average TOC_{wt} 1.0 to 1.3% (Blizkovsky *et al.*, 1994). There, some biogenic gas was encountered in shallow reservoirs.

Reservoirs are located in the pre-Badenian evaporites (Fig. 5), fractured tuffs and thin sandstones of the Lower Badenian *Novoselytsa Formation*. In the contiguous Khust Subbasin, the Badenian reservoir formations have a porosity of 5-13%, a permeability of 1-100mD, while the formation pressure is close to hydrostatic, rarely exceeding it by 5-20% (Hafych *et al.*, 2006). Other minor reservoirs occur in the sparse arenites from *Limacina,* the *"Buglovian*" and *Iza* formations. In the Chop-Mukachivsk and Trebišov subbasins, deeper reservoirs are mainly in the Sarmatian or related to the post-salt Badenian sands, holding the bulk of gas and condensate reserves of the subbasin.

Traps are of great variety, from structural to combination. The main risk is related to their integrity, traps could be breached by the intense Neogene extensional and wrenching activity that affected the Transcarpathian Basin.

Seals are represented by mudstones or evaporites of the *Tereblya Formation* or *Ocna Dej Formation*. Other reservoirs are protected by intraformational mudstones of the *Tereshiv/ Radiolaria, Limacina, Dorobrativ/" the Buglovian"* or *Iza* formations (Fig.13).

Migration and accumulation – In the Mara-Solotvino Subbasin the geothermal gradient can be quite high near volcanic rocks, reaching probably 4.0-5.0^{0}C/100m as in eastern Transylvanian Basin (Paraschiv, 1979), confirmed by the relatively-high surface heatflow of 70-80mW/m^2 (Veliciu and Visarion 1984). It may be expected that higher heat-flow have generated thermogenic gas. Future gas finds are anticipated to be thermogenic, containing condensate, with higher percentages of CO_2 and N_2. It is possible that expulsion of gas to post Badenian to stratigraphic and combination traps started from shales buried below 2,500m.

The petroleum system and the exploration potential of the Mara-Solotvino subbasin area could be evaluated comparing it with successful plays from the Khust, Chop-Mukachivsk or from the Trebišov areas (Blizkovsky *et al.*, 1994). In the East Slovak Subbasin, the geothermal gradient in the upper 3 km section attains 3.7 to 5.0^{0}C/100 m. The expulsion of hydrocarbons occurred below 2 km burial depth for oil, 2.8 km for wet gas and 3.4 km for dry gas. Biogenic gas occurs below 1,2 km depth (Blizkovsky *et al.*, 1994).

5. EXPLORATION AND PRODUCTION HISTORY

The Transcarpathian province was explored for petroleum since the late 19th century. In 1870 oil was produced from hand-dug wells in Săcel area, totalling up to 300liters/day or approx. ~2bopd (*e.g.*, Batistatu 2015). Another accumulation that could belong to this habitat was on stream at Bârsa (a few km north of the Jibou town) where, between 1886-1897, half a dozen of hand dug pits produced 15-20 liters/day or 0.1-0.15bopd (Ciupagea *et al.*, 1970).

Modern exploration works, such as gravimetry, land- and aeromagnetic recordings started in 1950 (Paraschiv, 1979) and continued the next decade. Starting from 1979, a total of 475km of 2D seismic lines were recorded until present, while the non-seismic methods culminated with a large surface geochemical survey performed by OMV Petrom in 2008 (OMV Petrom 2009).

A more modern drilling activity have begun in the 1900 period when shallow, 155-655m deep wells were drilled using mining rigs at Săcel field (Paraschiv, 1979, Batistatu, 2015). In the mid-20th century, a wildcat was abandoned in the field area by the Italo-Maghiara Co. in 1943. A total of 79 wells (32 in the Petrova Foreland, 39 in the Botiza Foreland and 8 in the Mara-Solotvino Subbasin were drilled in this habitat, mostly after 1950. The deepest well is the Sarasău 4201 drilled to some 4550m through the Mara-Solotvino Subbasin, targeting the Pienine units below 850m of the Miocene base.

In the Petrova Foreland, a detailed appraisal and development drilling work in the conventional hydrocarbons plays was initiated in the southern sector by Sovrompetrol in 1951 to 1956, but without noticeable results. Intermittent exploratory and appraisal drilling-works were carried out later by the Ministry of Petroleum, in several drilling campaigns: in the late fifties, mid-sixties, early eighties and nineties of the last century. Some workover was reportedly performed with poor results by private companies in the early years of this century.

6. RESOURCES

This habitat has been poor in commercial hydrocarbon discovery so far. Only a couple of accumulations were discovered and produced for a while: one in the Petrova Foreland at Săcel and another one in the Botiza Foreland, at Bârsa. The total in place resources is estimated at 2,000,000 tonnes of oil and 150,000,000 m^3 of associated gas. There is not enough basic information available about the areal extension and physical characteristics of the Oligocene oil shale play, for the evaluation of the risked and technically recoverable OIIP.

In the Petrova Foreland, Gilbert (2007) ascertained the reserves of oil discovered (in the Săcel field only?) amount to only 110,000 tonnes for a cumulative production of 100,000tonnes as of the end of 2006. The recovery factor is extremely low, 10-15% for oil and 30-35% for the associated gas. Fracturing and acidizing was used at intervals for field production resumptions.

In the Botiza Foreland basin, the Bârsa oil accumulation produced in the 19th century from half a dozen of hand-dug pits. A cumulative total of about 100,000 tonnes of paraffinic crude oil was the estimated output between 1886-1897 period (Nicolescu and Popescu, 1994). There is no basin modelling for understanding the Valea Carelor or Valea Morii shale maturation and thus their nonconventional oil or gas prospectivity remained unknown until today.

If the Ukrainian gas and condensate resources of the Mara-Solotvino Subbasin are added to these estimations it would add 7.5-to-8,500,000 tonnes oil equivalent, (Hafych *et al.*, 2006) to the subbasin.

7. DISCUSSION AND CONCLUSIONS

The Transcarpathian Zone, Unit, Trough or Depression situated in the Inner Carpathians of the northern Romania has a complex structure that is not yet fully understood due to incertitudes of the stratigraphic dating and therefore, the equivocal large-scale correlation performed after the fifties of the last century and lack of modern exploration. Above the folded and thrusted Transcarpathian Zone lies the post-kinematic Transcarpathian Basin with a fairly well-known structure. Both units are bounded to the NE by the transcurrent deep-crustal Transcarpathian Line, not identified in Romania and to the SW by the Peri-Pannonian Line, identified in Romania as the Preluca Fault. These major fault lines are often hidden by the Neogene sedimentary sequence of the Transcarpathian Basin (*e.g.*, Figs. 2, 6).

The precedent sections set the emphasis on a detailed structural and sedimentary history of foreland sections of two sectors of the Transcarpathian Zone: *Petrova* and *Botiza* forelands and of the overlying Transcarpathian Basin's *Mara-Solotvino* Subbasin for the understanding their hydrocarbon habitat, the main goal of this paper. In this final section it shall be discussed: a) pre- and post-collisional events that conducted to basin forming; b) local impact of nappes emplacement and sediment geochemical response to the petroleum expulsion and accumulation in each foreland basins. This discussion is based mainly on Paraschiv 1979, Dicea *et al.*, 1980a, Săndulescu *et al.*, 1980, 1993, Soták *et al.*, 1993, Bombiță and Muller 1999, Aroldi 2001, Tischler *et al.*, 2007, 2008, Plašienka 2012, Oszczypko *et al.*, 2015, Jurewicz, 2018, IGG maps 1:200,000 and 1: 50,000 scales, Ukraine 1:200,000 maps and partly, on other contributions mentioned in the precedent chapters.

The Transcarpathian Zone fold-and-thrust belt includes *three main units* that are in overthrust contact from west to east: 1) Iňačovce-Kričevo Unit (called Băbesti-Tiacovo and Kričevo Nappe in Romania), 2) Pieniny Klippen Belt (PKB) finds its equivalent in Botiza and Poiana Botizii Nappe, 3) Magura Nappe with two subunits: inner one (called Petrova and Wildflysch in Romania) belonging to the Monastyrets or Rača Subunit and outer one (called Leordina in Romania) belonging to Fore-Magura's Vezhany Unit.

Associated with Petrova and Botiza nappes stack are *two foreland basins*, both having the Dacia-Mega Unit as basement. At the present they are separated by the east-west oriented Bogdan Dragoș Vodă (BDVF) strike-slip fault that dissects in outcrop sedimentary and volcanic series from the Transcarpathian Zone, along with Median Dacides mainly crystalline formations (Figs. 2, 3, 9).

Most of researchers believe that the Pieniny Klippen Belt units originate from the southern Vahic Ocean and represent the Upper-Cretaceous accretionary wedge of the Central Carpathians standing as the separation boundary with the Outer Carpathians Flysch nappes including the Magura one. It is also generally accepted that there was a CCW rotation in the late Oligocene-Miocene including Pienide units with their former, lower plate ALCAPA basement, that occurred in the Carpathian Embayment (or Magura Ocean) followed by the soft collision with the Dacia Mega-Unit.

The Burdigalian latest shortening phases deformed, exhumed and fragmented, mostly in the east, the PKB accretionary wedge and generated gravitational sliding and thrusting. In the eastern part of the Western Carpathians, during the Maastrichtian up to early Eocene, the PKB overthrust/gravitational slide onto the transitional Šariš/Grajcarek Unit resulted in an olistostromes with chaotic blocks named the Grajcarek-type lithostratigraphic succession in Poland. According to various authors the Šariš Unit, in Slovakia-Ukraine is either the lowermost PKB unit, either the uppermost Magura unit. The PKB disappears from outcrop at Novoselytsa in the Ukrainian Transcarpathian Zone but it is believed present in the subsurface up to northern Romania.

The continuation of the PKB/Magura units in Romania has been long debated. Lastly, Romanian geologists, except Bombiţă (see in the bibliography list) have seen in the Poiana Botizii basal scales the continuation of PKB. The updated correlations are: 1) north of BVDF, the Petrova Nappe with the Raca Unit of the Magura Nappe and the Leordina Nappe with the Vezhany Nappe of the Fore-Magura; 2) south of the BDVF, the Botiza and Poiana Botizii nappes with the PKB s.l. and the Wildflysch Nappe with to Magura Nappe. Up to the Cenomanian-Senonian Redbed Formation, both Botiza and Poiana Botizii nappes had a very similar stratigraphic succession with the Grajcarek Unit.

An additional hypothesis is klippen of PKB are elements of an olistostrome originating from the Šariš Unit, in the Magura Ocean southern margin, that preceded the gravitational emplacement of all Botiza nappe units. Then, probably in the early Paleocene, the lobed Botiza/Poiana Botizii gravitational units have selectively scrapped off olistostrome blocks and frontally transported them, on short distance gliding, during the Eocene. It is possible that the Botiza Nappe together with the Poiana Botizii "rabotage" slices (preferred term in this paper) were further progressively piggy-backed during the slow advancement of the Wildflysch Nappe (Šariš Unit?) over the Dacia basement, from the Oligocene until the pre-Badenian.

Correlations with the Marmarosh Klippen are not practicable because they are tectonically covered by the Vezhany (Fore-Magura) Unit, overthrusted in the Burdigalian, over the Rachiv and Burkut nappes equivalents of the late Cretaceous Ceahlău Nappe from the eastern flank of the Maramureș Massif. The Marmarosh Klippen represent deposits of the Ceahlău Ocean space and not of the Vahic one. It remains for the future to have a more precise paleogeography of nappes before their folding and gravitational/thrust episodes, better timing of the olistostrome gravitational advancement(s), as well as directions of their tectonic transport in both northern and southern nappe stacks, the latter, at present being in a perpendicular position due to rotation. However, these topics are beyond the scope of this paper.

There were no critical syntectonic sedimentary events associated to nappe emplacement, both nappe system being cover nappes except perhaps to Rupelian olistoliths from both forelands. These related foreland basins nevertheless recorded the convergence events of the mega-units from the Carpathian Embayment (ALCAPA and Tisza-Dacia) with the rigid Median Dacides and their exhumation history and increased burial in the fore tectonic wedges.

Significant for hydrocarbon maturation and accumulation is the contribution to basin flexural response to the emplacement of some 4,000m nappe stack over the Petrova Foreland and of some 5,000m nappe load over the Botiza Foreland with so far, very modest contribution to hydrocarbon expulsion. The sedimentary evolution of the Botiza Basin ends with the undisturbed deposits of the Hida clastic wedge in the late Burdigalian. In the Petrova Basin, the evolution ended with the slightly disturbed Borsa Formation in the early Burdigalian. Finally, the 3,500m thick post-tectonic Mara-Solotvino Subbasin contains Middle Miocene-Pliocene almost undisturbed clastic sediments and evaporites corelatable with the Transylvanian and Transcarpathian basins, but not with the Pannonian one.

The almost similar basin-fill sequences of these foreland basins (Fig. 7) include Oligocene organic-rich mudstones resembling the Maikopian facies "paper" shales (dysodiles) and silicolites (menilites), that are present elsewhere in the Outer Carpathian orogen and considered world class source rocks. In addition the Badenian-Sarmatian black mudstones are the presumable source rocks of the postectonic cover petroleum habitat. The reservoirs of the Transcarpathian petroleum province hosting small hydrocarbon accumulations are represented by Oligocene clastics of the Petrova and Botiza forelands proved by the presence of small oil accumulations, seeps and shows, Paleocene-Early Eocene sands of the Botiza Foreland with a minor accumulation, or Mid-Miocene arenites of the Mara-Solotvino Subbasin.

The source rocks and reservoirs were compressed at various degrees in the late Oligocene-early Miocene interval favouring trap formation and early hydrocarbon expulsion. On a background provided by an increased geothermal gradient induced by the mid-Miocene-Pliocene volcanic episodes, the optimal burial in this compact Petroleum System occurs as shallow as below 2,500m.

More information is required to establish both forelands source rocks history, the source rock-hydrocarbons relationship, especially for the Bârsa abandoned oilfield or Budeşti gas shows situated at fairly long distance of the supposed pods of mature source rocks.

The thermogenic gas system from the Mara-Solotvino Subbasin occurs only marginally in Romania. It appears to be generated by the Badenian dark mudstones and/or by the basement equivalents of the Valea Carelor and Valea Morii bituminous formations.

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