



The legacy of the Tethys Ocean: Anoxic seas, evaporitic basins, and megalakes in the Cenozoic of Central Europe

Dan V. Palcu^{a,b,c,*}, Izabela Mariş^d, Arjan de Leeuw^e, Mihaela Melinte-Dobrinescu^b, Eliza Anton^b, Dumitru Frunzescu^f, Sergey Popov^g, Marius Stoica^d, Luigi Jovane^c, Wout Krijgsman^{a,*}

^a Utrecht University, Fort Hoofddijk Paleomagnetic Lab, Department of Earth Sciences, the Netherlands

^b National Institute of Marine Geology and Geo-ecology, GeoEcoMar, Bucharest, Romania

^c University of Sao Paulo, Brazil

^d University of Bucharest, Romania

^e University of Grenoble, Romania

^f University of Oil and Gas Ploiesti, Romania

^g Borissiak Paleontological Institute of the Russian Academy of Science, Russia

ARTICLE INFO

Keywords:

Carbon sink
Paleogeography
Stratigraphy
Endemism
Strait

ABSTRACT

At the end of the Eocene, the demise of the Tethys Ocean led to the formation of one of the largest anoxic seas in the last 50 million years of Earth history. This long-lived anoxic water body, named *Paratethys*, covered large parts of central Eurasia and functioned as a major carbon sink for 15–20 million years, characterised by the deposition of cherts, anoxic turbidites and black shales. The anoxic episode was followed by a phase of instable connectivity where full marine episodes alternated with evaporitic crises and lacustrine episodes, resulting in the deposition of marine molasses, evaporites and continental-lacustrine sediments. Finally, *Paratethys* transformed into a megalake that progressively filled with clastic sediments from the neighbouring mountain ranges.

Paratethys was tectonically fragmented in numerous sub-basins that spread W–E from the Alpine and Carpathian orogens to the East European Platform. Most *Paratethyan* stratigraphic records from Central and Eastern European tectonically-active regions are not complete and thus hamper paleogeographic and paleoenvironmental reconstructions. The only exception is the *Outer Carpathian Basin*, located in the external part of the Carpathian arc in Central Europe, that preserved a complete record of Tethys demise and the rise and fall of *Paratethys*. The *Outer Carpathians* sedimentary successions show various lithologies that reflect an interplay of interbasinal connectivity and water exchange with the global ocean.

Here we review the stratigraphic schemes of the different tectonic domains of the *Outer Carpathians* and describe the most complete records to produce a Carpathian-wide framework for the Eocene to Miocene evolution of *Paratethys*, the *lost sea of Eurasia*. Finally, we focus on the paleogeographic reconstructions of the interbasinal *Paratethys* connections and discuss how marine connectivity influenced anoxia and hypersalinity and impacted the Cenozoic depositional environments in central Europe.

1. Introduction

The western branch of the *Tethys Ocean* ceased to exist during the Cenozoic, related to Africa–Arabia–Eurasia continental collision (Jovane et al., 2009; Khain et al., 2010; Rögl, 1998). Combined with a global sea-level drop that occurred during the Eocene–Oligocene transition, the *Western Tethys realm* fragmented into two large epicontinental seas (Popov et al., 2004; Rasser et al., 2008) – *Paratethys* and *Mediterranean*

(Fig. 1). In the north, *Paratethys* stretched from Germany to China and was separated from the Mediterranean Sea in the south by the Alpine–Carpathian–Himalayan continental collision zone, a tectonically active region characterised by subduction, obduction, back-arc rifting, and shear zone processes (Schmid et al., 2019). The *Paratethys* realm consisted of a tectonically stable region, the *Eastern Paratethys* (Harzhauser et al., 2002; Jones and Simmons, 1997; Popov et al., 2019; Steininger and Godfrid, 1999), centred around the Black Sea – Caspian basins, and

* Corresponding authors at: Utrecht University, Fort Hoofddijk Paleomagnetic Lab, Department of Earth Sciences, the Netherlands.

E-mail address: dan.palcu@gmail.com (D.V. Palcu).

<https://doi.org/10.1016/j.earscirev.2023.104594>

Received 16 December 2022; Received in revised form 3 October 2023; Accepted 9 October 2023

Available online 13 October 2023

0012-8252/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

a tectonically active region with smaller and shorter-lived marine basins, the *Western Paratethys* and *Central Paratethys* (Kováč et al., 2017b; Popov et al., 2004; Sant et al., 2017). Paratethyan connections with the global ocean, via the Mediterranean and North Sea, controlled circulation patterns and shaped the particular Paratethys environments (Fig. 2; Palcu and Krijgsman, 2021).

1.1. The changing paleogeography of Paratethys: anoxic sea, salt giant and megalake configurations

The exceptionally well-preserved and diverse Paratethyan sedimentary records represent some of the most complete archives documenting the closing of an ocean realm (Fig. 2). These records provide temporal and spatial stratigraphic challenges due to poor connectivity with the global ocean, that greatly reduced the diversity of oceanic taxa and hampers correlations with the standard geological time scale. Consequently, regional stratigraphic schemes have been developed, using cosmopolitan and endemic species and local faunal assemblages as chronostratigraphic markers (Piller et al., 2007b; Rasser et al., 2008, 2016; Raffi et al., 2020). The rise and fall of endemic species were often not centred in one unified basin, so various regional stratigraphic schemes were developed in parallel (Fig. 1) for the major Paratethyan

sub-domains.

The Paratethys realm was subdivided in three or two major sub-domains (Fig. 1). Some favour two subdomains: Central Paratethys - covering west and central Europe; and Eastern Paratethys - covering Eastern Europe and Asia, (Papp et al., 1974; Piller et al., 2007a; Popov et al., 2004). Others use three sub-domains (West, Central and East) different in size and life-span: *Western Paratethys* (Fig. 1) roughly matched the North-Alpine Foredeep; *Central Paratethys* (Fig. 1) enclosed (from W to E) the Vienna Basin, Styrian Basin, the Pannonian Basin and the Transylvanian Basin; and *Eastern Paratethys* (Fig. 1), comprising the Scythian Basin, Indol-Kuban Basin, Terek- Mangyshlak Basin, Caspian Basin and the Black Sea Basin (Nevesskaya et al., 1984; Rögl, 1999; Steininger and Rögl, 1984; Vető, 1987). The Outer Carpathian Basin (OCB), situated between the Central and Eastern Paratethys, initially belonged to Central Paratethys until the Middle Miocene and afterwards became part of the Eastern Paratethys.

The *Outer Carpathian Basin (OCB)* was the largest and longest-lasting tectonically active basin, containing crucial information about connectivity and environmental change during and after the Tethys demise. The sediments of the OCB are intrinsically connected with Carpathian tectonics, older in the Polish sector (Western Carpathians) where thrusting and infilling with sediments was completed by the Miocene,

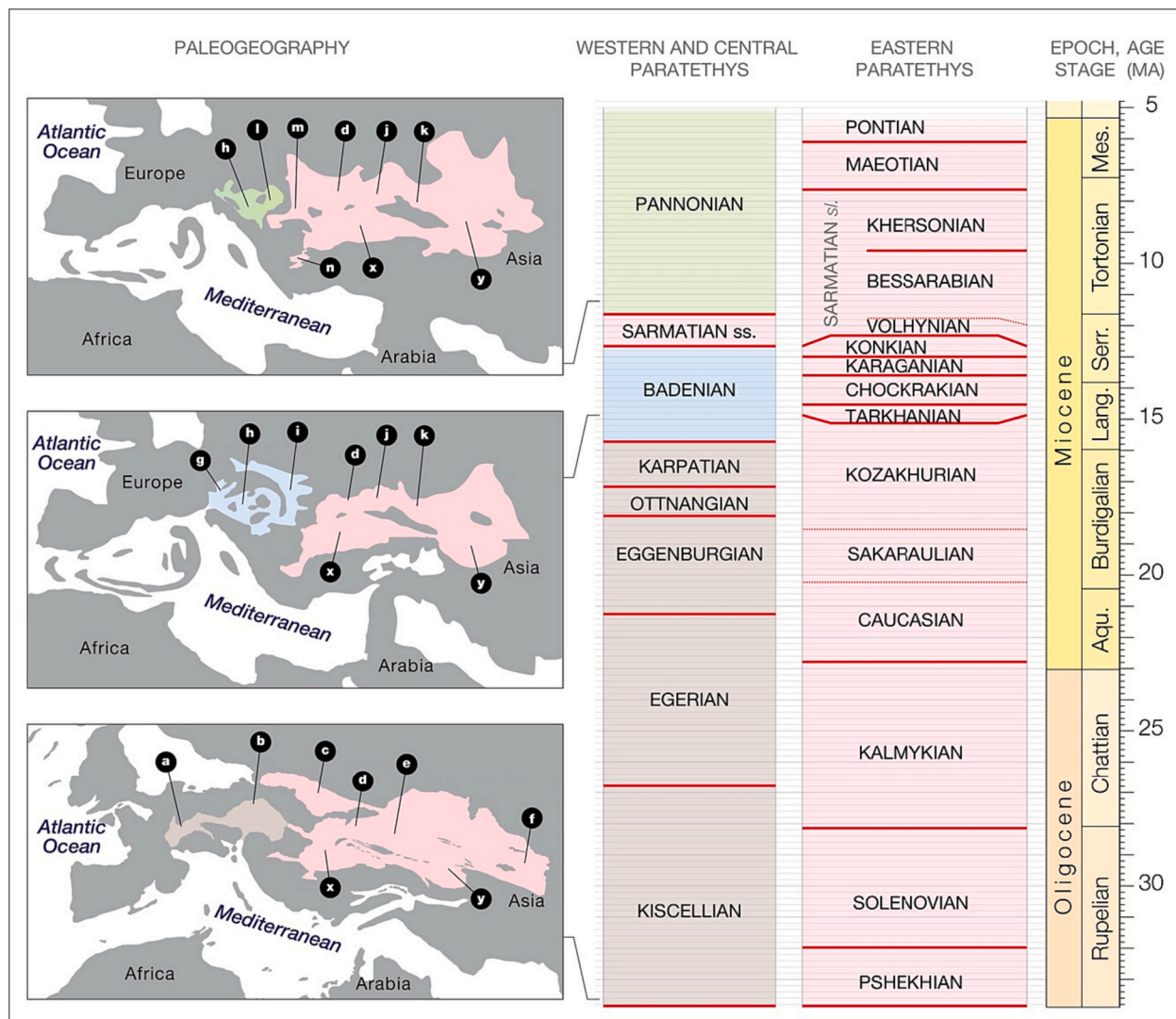


Fig. 1. Paleogeography and stratigraphy of the Paratethyan Realm (Popov et al., 2004; Raffi et al., 2020). The sub-basins of Paratethys during the Paleogene and Neogene: a. North-Alpine Foredeep, b. Outer Carpathian, c. Pripyat, d. Scythian, e. Fore-Caucasus, f. Turan, g. Vienna, h. Pannonian, i. Carpathian Foredeep, j. Indol-Kuban, k. Terek-Mangyshlak, l. Transylvanian, m. Dacian, n. North-Aegean; x. The Black Sea, y. Caspian.

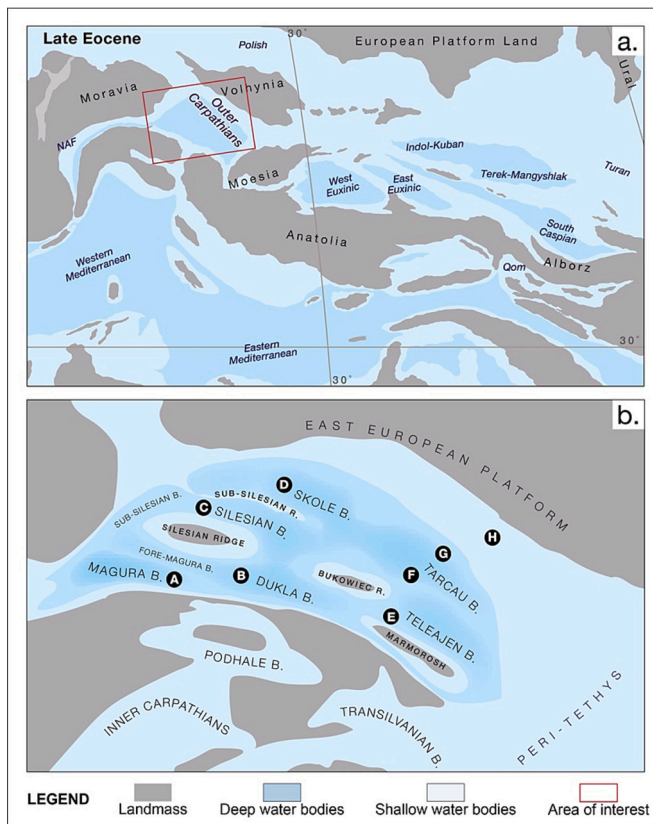


Fig. 2. The northern Tethys Realm sub-basins and ocean connections before the formation of Paratethys. The sediment infill history of each of these basins is influenced by basin connectivity and reflects sediment sources from the European Foreland, nearby landmasses (after Ciurej and Haczewski, 2016; Dziadzio et al., 2016; Garecka, 2012; Golonka, 2011; Golonka et al., 2007; Kotlarczyk and Uchman, 2012; Kováč et al., 2016; Książkiewicz, 1977; Leszczyński and Malata, 2002; Oszczytko-Clowes and Zydek, 2012; Palcu and Krijgsman, 2021; Ślăczka et al., 2006; Starzec et al., 2018; Teřák et al., 2019). (a.) General map of the Tethys realm during the Late Eocene, highlighting the fragmented character of the northern region of Tethys (Peri-Tethys). Note the weak connections with the global ocean via restricted seaways. (b.) The Outer Carpathian basin is characterised by fragmented sub-basins, shaped by regional tectonics: A-Magura b., B-Dukla b., C-Silesian b., D-Skole b., E-Teleajen b., F-Tarcău b., G-Vrancea b., H-East

and younger in the Ukrainian and Romanian sectors (Eastern and South-Eastern Carpathians), where the thrust front continued propagating eastwards marking the post collisional stage in the Outer Carpathians (Golonka, 2011). The youngest tectonics occurred in the East Carpathians, namely the Wallachian phase, between Pliocene and Quaternary times (Săndulescu, 1984). Later stratigraphic dating of structures, and thereby paleostresses, argued that the Wallachian phase was not a brief event at the Pliocene-Quaternary boundary, but lasted from middle Tortonian to early Pleistocene (Hippolyte and Săndulescu, 1996).

The Romanian sector of the OCB (South-Eastern Carpathians) contains one of the most complete sedimentary records of Paratethys history, revealing its paleogeographic and paleoenvironmental evolution from the Eocene till Recent. A large part of its literature, however, is found in local Romanian publications, poorly accessible and lacking stratigraphic and geochronological updates. Here, we review the Eocene, Oligocene, and Miocene stratigraphic subdivisions of the Romanian Sector of the OCB. We create a detailed timeline for the lithological and environmental changes and discuss how these reflect the restructuring of the marine Paratethys gateways. This results in revised stratigraphic and paleogeographic reconstructions and reveals how the formation of the main Paratethyan rock units are related to

variations in external and internal basin connectivity.

2. The Outer Carpathian Basin

The Outer Carpathian Basin evolution is related to the opening of the Alpine Tethys, in Jurassic - Early Cretaceous times. During the northward movement of the Inner Carpathian ALCAPA block toward the North European plate, an accretionary wedge, marked by the development of thick flysch sequences with olistostromes, triggered the partial closure of the Outer Carpathian basins (Schulz et al., 2005). At the beginning of the Oligocene the Outer Carpathian Basin became stratified and developed anoxic environments, due to poor connectivity with the global ocean. It was affected by changes in ocean connectivity as well as connectivity with the neighbouring *Eastern Paratethys* subbasin (Palcu et al., 2019b). The OCB basin gradually filled with sediments, that are outcropping mainly in Poland, Ukraine, and Romania and to a lesser extent in Slovakia, Czechia.

2.1. Tectonic background

The Carpathians are a range of mountains that stretch in an ~1,500 km long arc across Central and Eastern Europe. Mountain formation was linked to the emplacement of continental blocks during Africa Eurasia collision (e.g., Jolivet and Faccenna, 2000). The *Alpine-Carpathian-Pannonian mega-unit (ALCAPA)* and the *Tisza-Dacia blocks* moved north-eastwards and eastwards and occupied a concave embayment on the *Eastern European-Scythian-Moesian Platforms* of the European foreland (Schmid et al., 2008; Tischler et al., 2008). The resulting accretionary prism comprises various turbiditic successions of Late Jurassic to Miocene age. These accumulated on a thin-stretched continental crust of the European Platform's original passive margin in an array of narrow deep-water basins separated by sub-aqueous to sub-aerial ridges, referred to as "cordilleras" (Fig 1b).

From a geotectonic perspective, the Carpathians are traditionally subdivided into an older range, known as the Inner Carpathians, and a younger range known as the Outer Carpathians (Ślăczka et al., 2006). The Outer Carpathians are made up of a stack of nappes, each associated with a sub-basin. Due to intense folding and overthrusting, only sediments from the central parts of these sub-basins are generally preserved (Ślăczka et al., 2006). Three main depositional stages are observed: an early anoxic stage characterised by the development of black shales (Jurassic to Albian); a second oxic stage marked by the formation of red and variegated shales (Cenomanian-Eocene) and a third and final stage characterised by brown bituminous shales (Oligocene-Early Miocene) (Băncilă, 1958; Dumitrescu, 1952a; Dziadzio et al., 2016; Leszczyński, 1997; Oszczytko-Clowes and Zydek, 2012; Rauball, 2020; Rauball et al., 2019; Săndulescu, 1984; Ștefănescu, 1978). The thin-skinned nappes and intra-nappe imbricate thrust-sheets of the OCB were tectonically stacked in the Late Oligocene to Early Miocene and piled up northwards and eastwards onto the Miocene foreland basin at the flexural margin of the European Platform (Leszczyński et al., 2015; Leszczyński and Malata, 2002).

In the western *Outer Carpathians* (Poland and Czechia), these nappes consist of the Magura Nappe, the Fore-Magura Group of nappes, and the Dukla, Silesian, Subsilesian, and Skole nappes (Fig. 2).

In the eastern *Outer Carpathians*, the nappes are known as Skole, Skyba, and Boryslav-Pokuttya nappes in the Ukrainian sector (Ślăczka, 1996; Ślăczka et al., 2006) and correspond (Fig. 3) to the Tarcău, Vrancea and the Subcarpathian nappes in the Romanian sector (Băncilă, 1958; Dumitrescu, 1952b; Mrazec and Popescu-Voitești, 1914; Săndulescu, 1984, 1994). The Romanian terminology employs the *Dacides* and *Moldavides* names to describe tectonic units of the Eastern Carpathians. The *Dacides* represent nappes and thrusts of Cretaceous and Miocene ages, while the *Moldavides* correspond to Cenozoic nappes and thrusts (Săndulescu, 1984). The Carpathian Foredeep represents the youngest depocenter where molasse deposits accumulated. It consists of

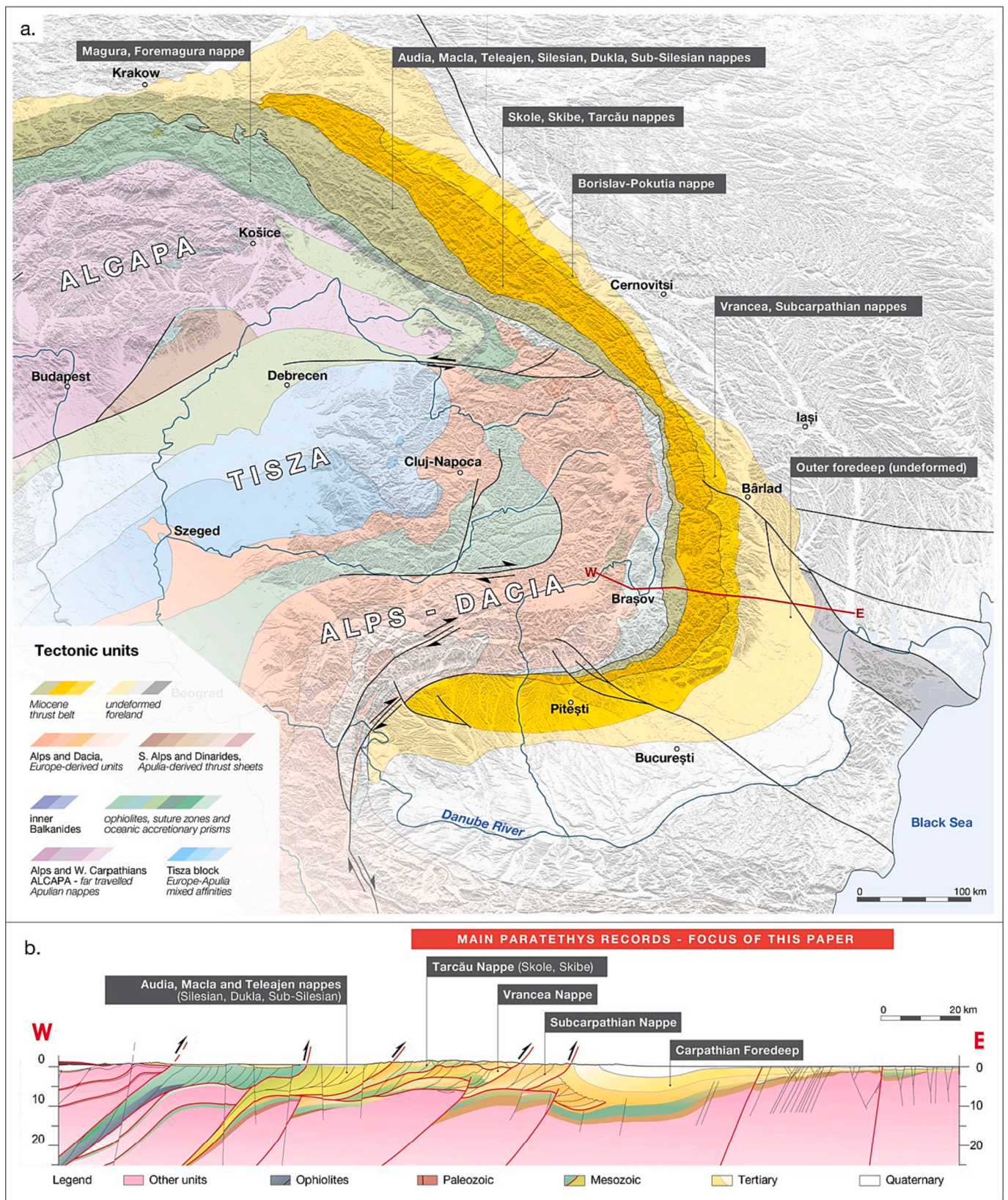


Fig. 3. The Carpathian structural domains linked with Paratethys (after Matenco et al., 2010) a. The Outer Carpathian nappes, b. The cross-section in the Carpathian bend region (no vertical exaggeration) highlights the tertiary deposits of interest.

two distinct zones; a folded internal zone of the Carpathian Foredeep, in contact with the Carpathian nappes (e.g., the Diapir Folds zone) and an external zone characterised by undeformed foreland deposits.

The complete Paratethys record of the OCB, covering the Oligocene – Pliocene interval, is present in the Eastern Carpathians of Romania, preserved in several successions exposing sediments of the Tarcău, Vrancea and Subcarpathian nappes and the Carpathian Foredeep.

The Tarcău Nappe (Săndulescu, 1994) is a polyfacial unit with sedimentary formations of the Lower Cretaceous to the Lower Miocene. During the Paleogene, the geometry of the Tarcău basin was extremely complicated, with many supply sources (internal and external) being active at different degrees, at different times (Bădescu, 2005). This complexity was gradually reduced throughout the Eocene. Starting with the Oligocene, the sedimentary facies became largely uniform, supplied by external sedimentary sources from the platform regions in the east and northeast and internal sources from the Carpathian orogen (Roban et al., 2022). In Miocene times, the Tarcău nappe is significantly reduced due to post-Miocene erosion and non-deposition (Bădescu, 2005). Complete Miocene successions are found only in the Romanian Carpathian Bend, where evaporitic sedimentation (gypsum of the *Cornu unit*, along with conglomerates of the *Brebu Fm.*) occurred in the Early Miocene, followed by molasse deposits (*Doftana Fm.* – Lower Miocene) the first molasse appearance in the Tarcău basin. Salt, stromatolites, tuffs, and breccia levels also occur (Ștefănescu et al., 1981).

The Vrancea Nappe (Marginal Folds Nappe) (Dumitrescu, 1952a; Ionesi, 1971; Săndulescu, 1994) emerges in a series of tectonic semi-windows (Vrancea, Slănic-Oituz, Bistrița, Putna) or tectonic windows (Dumesnic, Mitocu lui Bălan) and has been intercepted under the Tarcău nappe by a series of drillings (Bădescu, 2005). This unit is present in the Polish Ukrainian sector, known as *Boryslav-Pokuttya Nappe*. Lower Cretaceous shales represent the main tectonic decollement of the nappe that consists of sediments of Lower Cretaceous-Miocene age. Like the Tarcău basin, the Vrancea Nappe basin is characterised by diverse sedimentary facies, with limited flysch deposition, occurring mainly in the Paleocene–Eocene interval.

The Subcarpathian Nappe is the outermost unit of the Moldavides (Săndulescu, 1984). It was initially separated (Mrazec and Popescu-Voitești, 1914) as an incipient nappe, overthrust above the salt formation, and later confirmed by drilling and also named *Pericarpathian unit* (Băncilă, 1958). The Subcarpathian nappe contains Upper Eocene and Oligocene deposits and Lower Miocene molasse within the Carpathian bend zone.

The Carpathian Foredeep consists of a folded internal flank and an external unfolded flank, separated by a flexure. The sedimentary successions are predominantly represented by Upper Miocene–Pliocene molasses with components exclusively of Carpathian origin. The internal flank of the Foredeep, also known as *Diapir Folds Zone* represents the youngest Alpine structure in the foredeep area of the Eastern Carpathians (Ștefănescu et al., 1981). This zone also comprises the Wallachian folds that affected the Carpathian foreland along the *Intramoesic* and *Peceneaga-Camena* faults (Hippolyte et al., 1999).

2.2. The Stratigraphy of the Romanian sector of the Outer Carpathian Basin (OCB)

A long history of research (initiated in the late 19th Century), different schools studying Paratethys geology (e.g., Moscow, Vienna), and the 20th Century geopolitical isolation during the cold war led to the development of parallel terminologies and the attribution of different meanings to the same rock units. In the southern sector of the OCB, Romanian-specific stratigraphic and lithologic terminologies have been employed. Here we provide a simplified framework to describe key paleoenvironmental and palaeogeographic changes in the southern sector of OCB.

2.2.1. Eocene Tethys: turbidite deposits

The Eocene OCB deposits mainly represent expressions of the Tethys realm, with complex geometry, characterised by flysch deposition in well-ventilated environments connected with the global ocean (Tab. 1). During the Eocene, the *Tarcău-Krosno basin* (Fig. 2b) was characterised by three lithofacies areas with different sediment supply and environmental characteristics. In the western (inner) part of the Tarcău basin,

Table 1

Eocene – lowermost Oligocene Tethyan flysch and hemipelagic formations in the SE Outer Carpathian Basin.

TARCĂU NAPPE
TARCĂU LITHOFACIES. Internal (western facies) supplied with sandy, mica-rich sediments from the emerging ridges and the submerged cordilleras of the Carpathian orogen. Main sub-units: Tarcău Fm. Sandstones with small intercalations of red or green clays (~2000 m thick) contain bioturbations at their base (10 m thick) and frequent intercalations of clays, marls, limestones, and conglomerates with schist clasts. Sediments with rich ichnofaunas indicative for an oxic depositional regime (Brustur, 1997). The oxic regime is indicated also by the presence of variegated (mainly red) shales (Giurgiu-Ghelința beds – Săndulescu, 1984). Age: <i>Middle-Upper Eocene</i>. Podu Secu Fm. Flysch composed of a rhythmic alternation of calcareous sandstones with clays rich in bioglyphs, informally named 'hieroglyphic beds' (Waśkowska, 2015). Towards the top, variegated shales (mainly red) occur. The top of this unit is marked by a dm-thick level rich in globigerina, named the "globigerina marl". Age: <i>Upper Eocene</i>. DOAMNA LITHOFACIES. External (eastern facies) supplied with clay, marl, and limestone material from the platform units in the eastern part of the basin. Main lithological units: Straja Fm. Silica-rich unit consisting of clays and silts with glauconitic quartz-rich sandstones, limestones, and silicolithic sponge-rich beds. Coloured in brick-red with thin green and striped intervals, with interbeds of glauconitic sandstones and silicolites (gaize, spongolites, radiolarites). Locally, contains grey to blackish shales; Dysoxic. Sucevița Fm. A rhythmic alternation of green or grey calcareous sandstones, variegated shales, in cm-dm thick banks and greenish-grey clays, locally grading into white quartz sandstones (Scorbura sandstone). It is the lateral equivalent of the Leșunt fm. of the Vrancea nappe. Oxic depositional regime. Doamna limestone Fm. A mainly pelagic unit - fine-grained limestones, white-yellowish, greenish or brown, with siliceous concretions (Bădescu, 2005); Oxic regime. Bisericani Fm. A succession of clays, marls, grey or green siltites with occasional sideritic concretions. The beds also contain lenticular intercalations of breccias and conglomerates with green schists (sourced from the foreland) in a clayey matrix. Oxic depositional regime based on ichnofaunas (Brustur, 1997). Lucăcești Fm. Variable thickness (5–30 m) composed of intercalations of conglomerates, sandstones, and silt-clay layers. It is synchronous with the Ardeluța Fm. and similar to the Oligocene Kliwa Fm., but unlike the Kliwa Fm., the Lucăcești is associated with oxic environments (Amadori et al., 2012, Belayouni et al., 2009). TAZLĂU LITHOFACIES. Intermediate facies in the Tarcău basin, an interference of the western, mica-rich Carpathian orogen and eastern, marl and limestone-rich platform sediment sources. Main sub-units: Straja Fm. Alternating clays and silts with glauconitic quartzite sandstones, limestones, and red-brick coloured sponge-rich beds. Predominantly arenitic towards western areas. Oxic (Amadori et al., 2012). Tazlău Fm. Flysch-type sandstones and variegated shales (hieroglyphic beds) rich in micaceous content and greenschist detritus with very rare intercalations of Tarcău sandstone. Typically developed in the central areas of the Eastern Carpathians, it correlates laterally with the Ciunget fm. and the Leșunt fm. To the south, it merges with the Colți-Valea Rea Fm. (Micu, 1982). Plopu Fm. (synchronous with Podu Secu and Bisericani fm.) Consist of clay-sandstone flysch similar to the variegated flysch, but more clayey, with thinner sandstones and intercalations of red clays in the lower part (Bartonian). It appears to have anoxic levels in the top part (Belayouni et al., 2007). Lupoia Fm. (synchronous and similar to Ardeluța Fm. and the Lucăcești Fm.). Vrancea Nappe Lithological units similar to Tarcău nappe. These units occur in tectonic windows and half-windows with deposits of Eocene and younger ages in the north and Paleocene and younger ages in the south. Main sub-units: Piatra Uscată Fm. (= Straja fm.) located in the Vrancea half-window. Jgheabu Mare Fm. (= Sucevița fm.) outcropping in the Bistrița half-window; Oxic (Amadori et al., 2012). Greșu Fm. and Buciaș Fm. (= Sucevița Fm.), located in the Vrancea half-window; The upper third of the formation contains a series of intercalations of limestone beds with siliceous accidents equivalent to the Doamna limestones (Săndulescu, 1990). Bisericani Fm. and the Lucăcești Fm., described above.

the lithofacies consists of deposits rich in sands with high content of micas. This was related to an active supply from the emerging ridges of the Carpathian orogen or emerged cordilleras (Fig. 2b). To the east, the *Doamna lithofacies* consists of very diverse deposits, rich in limestones and marls supplied from the foreland. A third area, the *Tazlău lithofacies*

formed in between the Tarcău and Doamna basins (Ștefănescu et al., 1981), represents a transition with alternations of western and eastern supply. The Vrancea Nappe contains deposits similar to the Tarcău basin (Table 1).

The Early to Middle Eocene (Ypresian-Lutetian) stratigraphic record

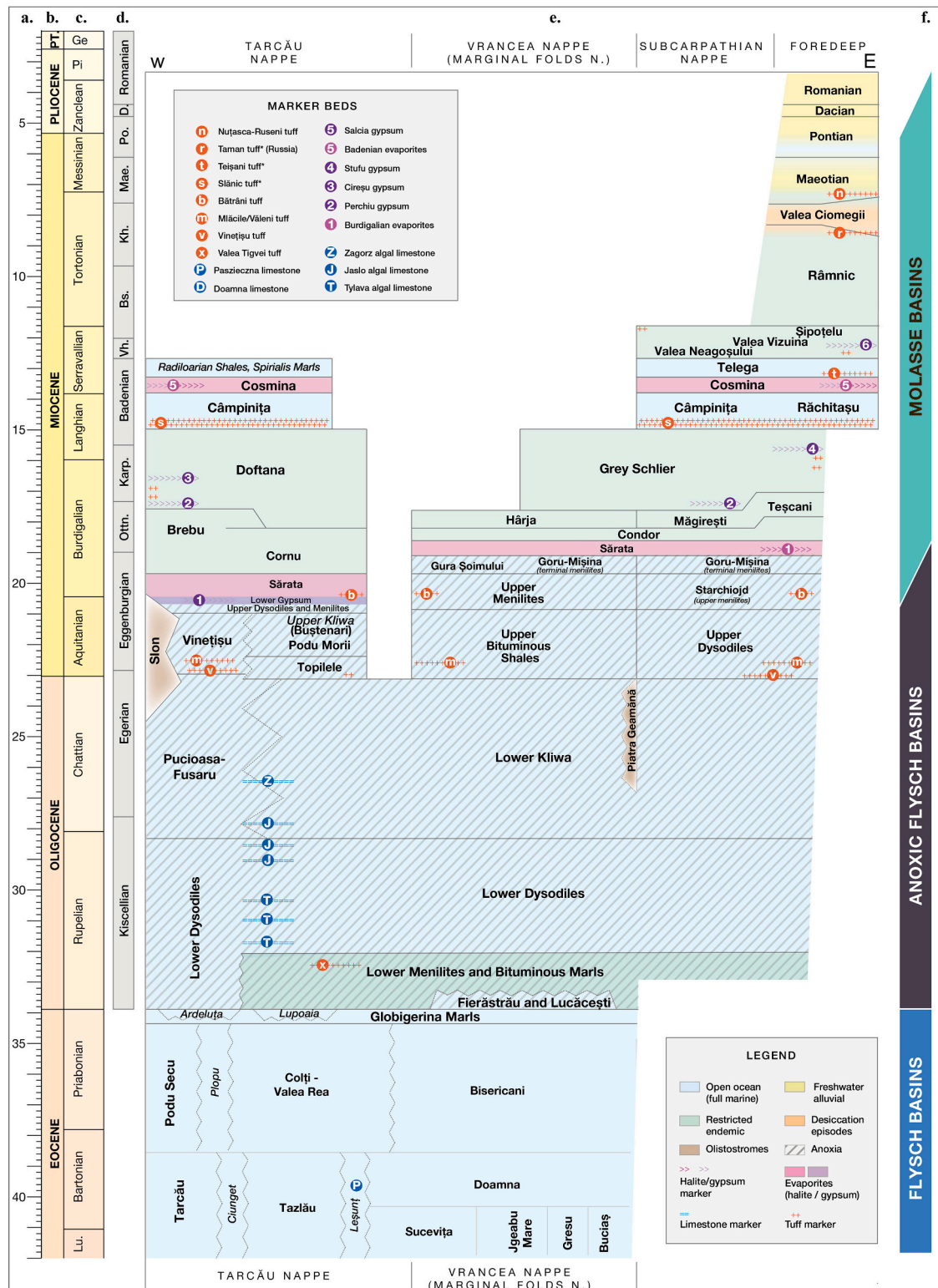


Fig. 4. Stratigraphic chart (simplified) of the Eocene-Pliocene formations from the Romanian Carpathians (references in the text and tables) : a. ages; b. c. global epochs and stages; d. regional stratigraphic units; e. key stratigraphic units and paleo-salinity estimations; f. simplified depositional environments. Acronyms: Lu – Lutetian, Pi – Piacenzian, Ge – Gelasian, Vh – Volhynian, Bs – Bessarabian, Kh – Khersonian, Mae – Maeotian, Po – Pontian, D – Dacian.

of the OCB is characterised by numerous sedimentary formations (Fig. 3). From the inner to the outer parts of the basin, the main lithofacial units and/or formations are: *Tarcău*, *Straja*, *Ciunget*, *Tazlău*, *Sucevița*, *Leșunt*, *Jgheabu Mare*, *Colți*, *Greșu* and *Buciaș* (Fig. 3; Table 1). Most facies comprise massive flysch-type sandstone that contains thin intercalations of red or green clay, variegated shale occasionally rich in siderites, conglomeratic lenses, limestone intercalations and siliceous concretions (Fig. 4).

The most common Middle-Upper Eocene (Bartonian-Priabonian) deposits of the OCB are termed *Podu Secu*, *Plopu*, *Paszieczna*, *Doamna*, *Lucăcești*, *Colți*, *Biserican* facies/formation (Fig. 5; Table 1). In the *Tarcău* domain, they mainly comprise clay-sandstone flysch or variegated flysch composed of a rhythmic alternation of calcareous sandstone

and red and/or green marls (Fig. 5).

In the Vrancea and Marginal Folds domain, monotonous successions of clays, clayey marls, grey or green silts are present in which, locally sideritic concretions appear. All flysch units are generally overlain by an uppermost Eocene marker bed, a calcareous unit known as “*globigerina marl*” that frequently contains sandstone intercalations. In some cases, it is even completely replaced by thick sandstone. The marls develop when a pelagic sedimentation regime is installed and deposits rich in planktonic foraminifera, especially *Globigerina* sp., accumulated (Książkiewicz, 1975).

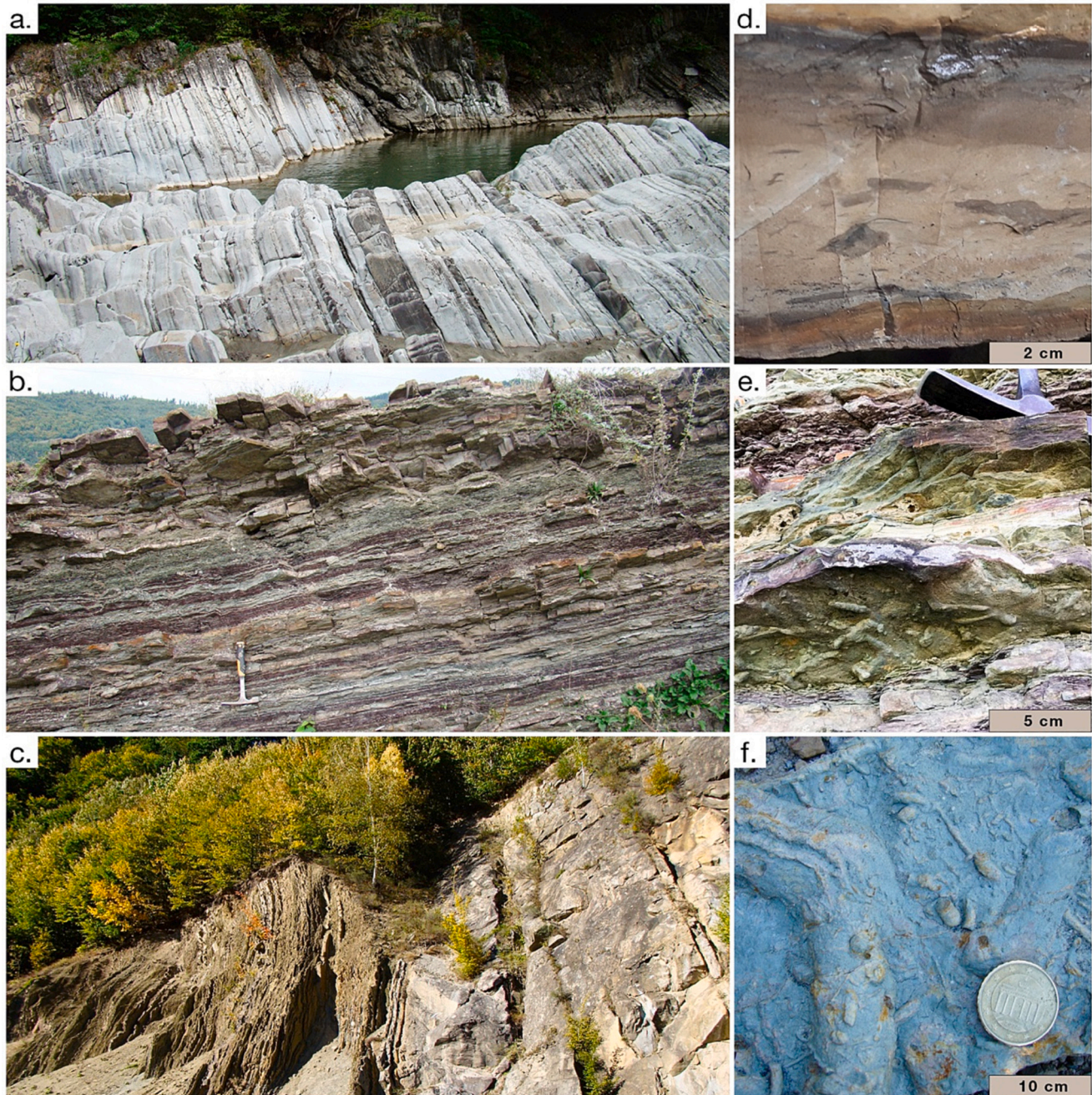


Fig. 5. Eocene facies of the Tethyan flysch formations. b. Doamna limestone Fm., b. Podu Secu Fm., c. Plopu Fm., d. Doamna Fm. - limestones with siliceous nodules (detail), e. The variegated aspect of the flysch from Podu Secu Fm. (detail), f. Bioturbations are very common in the flysch of the Plopu Fm (detail). (Photos: A. De Leeuw, I. Maris)

2.2.2. The Oligocene – Early Miocene Paratethys: bituminous flysch formations

After the Eocene-Oligocene transition, the Paratethyan environments show large-scale *anoxic conditions*. The Oligocene and earliest Miocene deposits represent a dysfunctional marine realm, characterised by flysch deposition in stratified and poorly ventilated environments (Fig. 6). As a result, successive sequences of *bituminous clays* (dysodilic shale - see supplementary materials) and *bituminous cherts* (menilites - see supplementary materials) developed in the external part of the OCB (Pătruț, 1955; Popescu, 1952). The lower menilites and dysodiles units represent a peak in anoxia during the Rupelian. These anoxic deposits are overlain by the massive Kliwa and Fusaru sandstone units (Săndulescu, 2011; Pătruț, 1955; Popescu, 1952), the main reservoir rocks of the OCB (see section 2.2.2). The main stratigraphic units of the bituminous formation are concisely presented in Table 2.

The overall aspect of bituminous turbidites is the occurrence of fine-grained anoxic sediments, interrupted from time to time (in different areas) by masses of clastic sediments. These clastics have two source areas: an internal source provided Carpathian-type material for the

Fusaru clastic units, and an external source provided the Kliwa-type orthoquartzite material from the foreland edge (currently subducted under the Moldavide nappes) (Frunzescu, 2013).

Unlike the Eastern Paratethys anoxia, where micropaleontological markers discontinuous or absent (Sachsenhofer et al., 2018), in the Central Paratethys, i.e., the OCB deposits preserved in the Oligocene foraminifers (mainly benthonic) and nannofossils. The identification of calcareous nannofossil zones provided age estimates in most formations and, together with carbonatic and tuff marker beds, have resulted in a geochronologic reference frame (Supp. fig. 1). The intercalated carbonatic marker beds (e.g., Tylawa, Jaslo and Zagórz - see supplementary materials for more information) are thin layers (mm to dm-thick) of pelagic coccolith limestone (Alexandrescu and Brustur, 1985; Ciurej and Haczewski, 2012, 2016; Grasu et al., 2018; Haczewski, 1984; Ionesi, 1986; Melinte-Dobrinescu and Brustur, 2008; Melinte, 2005; Nowak, 1965; Stefanescu et al., 1993). The Tylawa, Jaslo and Zagórz limestones have been correlated across major tectonic units and facies zones of the Outer Carpathians over distances up to 550 km and have been accepted as chronohorizons (Bojanowski et al., 2018; Racki and Narkiewicz,

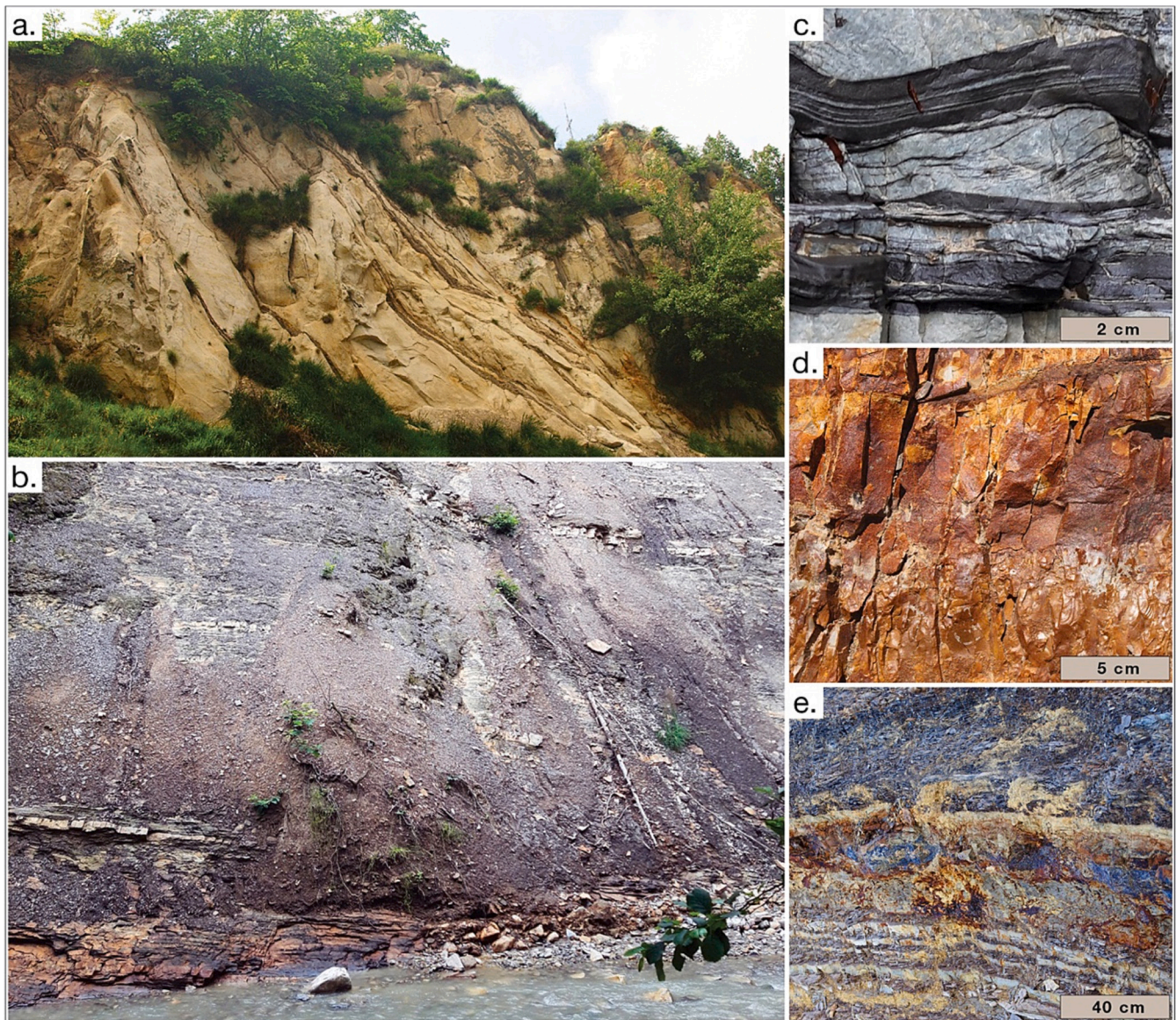


Fig. 6. Oligocene facies of Paratethyan anoxic flysch formations: a. Upper Kliwa Fm.; b. Lower Dysodiles, with concretion levels, c. Bituminous Marls – alternations of carbonatic (white) and organic rich (black) levels (*detail*); d. Menilite surface with glassy appearance and an iron oxidation crust (*detail*), e. Dysodiles with sulphur-rich levels (jarosite) and oxidation crusts (*detail*).

Table 2

Bituminous flysch formations (Lower Oligocene – Lower Miocene) in the SE Outer Carpathian Basin of Paratethys.

FUSARU-PUCIOASA FACIES. Internal (Carpathian) bituminous lithofacies
Bituminous marls with a specific bluish-white alteration. Age: earliest Rupelian, upper part of NP21 nannofossil zone (Melinte, 2005). Lower Menilites are organic-rich sediments rich in silica; Age: early Rupelian, lower part nannofossil zones NP22-NP23 (Melinte, 2005). Lower dysodiles Fm. The sequence begins with black to brownish menilites; cherts or dark red siliceous rocks (widespread marker horizon), interbedded with anoxic shales. They frequently contain fish scales. Peak Anoxia (Amadori et al., 2012; Belayouni et al., 2009). Pucioasa Fusaru Fm. Part of the Krosno-Fusaru lithofacies, similar to the Eocene Tarcău sandstone, a mica-rich greywacke (Săndulescu et al., 1995), characteristic of proximal flysch with occurrences of conglomerates containing mainly rolled clasts of Carpathian origin. The external occurrences of the Fusaru sandstone contain levels of Kliwa sandstone, leading to an alternation of sandstones with Carpathian clasts and Kliwa-type quartz sandstones; Age: late Oligocene (Chattian) - early Miocene (Aquitania) interval (Roban et al., 2022). Vinețușu Fm. (Grigoraș, 1955) Izvoarele beds (Pătruț, 1955). Thick “hieroglyphic” turbidites (1000–2000m) consisting of alternating grey sandstones and marls (Rusu et al., 1996). The lower part of the formation has two tuff marker beds (Stefanescu et al., 1993): the Vinețușu tuff (green-blackish with biotite, NN1 biozone) and the Mlăcile tuff (white, strongly bentonised, NN2 biozone). Starchiojd Fm. (Popescu and Popescu, 2002); Upper dysodiles and menilites (Coquand, 1867; Dumitrescu, 1948). Black-grey dysodilic shales alternating with cherts (menilites), brown diatomites (white when altered), and rare poorly-cemented Kliwa type-sandstone. The base of the formation contains tuffs (Bătrâni tuff). Thick diatomite packages (20–45m) occur in the Buzău River area; Age: late Aquitania-early Burdigalian, nannofossil zone NN2 (Melinte, 2005). Slon Fm. (Săndulescu et al., 1995). Lateral facies characterised by olistostromes with wildflysch character (olistoplaques) occurring in the innermost parts of the basin at various levels (particularly common in the interval corresponding to Vinețușu Fm.). Gura Șoimului Fm. (Stoica, 1953); Goru-Mișina beds (Dumitrescu, 1952a, 1952b). Grey marls alternating with sandstones containing large olistolith bodies from older anoxic formations. Facies restricted to the Vrancea Nappe (corresponding to the Vinețușu Fm.). Sub-Oxic (Amadori et al., 2012).
KLIWA SANDSTONE FACIES. External (foreland) bituminous lithofacies
Lower Menilites with bituminous marls Fm. (Săndulescu et al., 1995). Similar to the external facies (see above). Lower Dysodiles Fm. Bituminous clay rocks extremely poor in microfauna but relatively rich in fossil fish species (Rupelian). Intermittently interbedded with frequent sideritic limestone levels. Peak anoxia (Amadori et al., 2012; Belayouni et al., 2009). AGE: upper Rupelian-lower Chattian, NP23 and lower part of NP24 nannofossil biozone (Stefanescu and Melinte, 1994). Contains the Tylawa coccolithic limestones; Age: early Rupelian, NP23 biozone (Melinte, 2005). Kliwa Sandstone Fm. (Lower Kliwa) (Pătruț, 1955; Popescu, 1952). Sandstone rich in reworked quartz sands and greenschist elements from the foreland. Clayey intercalations, with variable thickness (centimetres to metres), are represented by bituminous clays with sulphur efflorescences such as dysodilic shales, anoxic. AGE: late Oligocene - earliest Miocene, NP24-NN1 biozones (Melinte, 2005; Roban et al., 2022). Podu Morii Fm. (Teisseyre, 1911). Alternating clays, thin arenites associated with Jaslo limestones. The lower and middle parts resemble the Pucioasa Beds, the upper part (Izvoarele Beds) contains an alternation of grey, grey-greenish clays, and convolute calcareous sandstones exhibiting biogenic sedimentary structures (e.g., Sabularia & Mammilichriis) at the base as well as pyroclastic interbeds (Văleni tuff); Jaslo coccolithic limestones age: Chattian, NP24 biozone (Melinte, 2005). Topilele Fm. (Stefanescu et al., 1993). Sandy flysch consists of alternating dysodiles and grey sandstones. Locally present in the Carpathian bend area as a transition between the Lower Kliwa and Podu Morii units; Age: upper Chattian–Aquitania, the Oligocene-Miocene boundary in the lower part of the formation. Buștenari Fm. (partly equivalent with Upper Kliwa Sandstone) (Stefanescu et al., 1993). An alternation of sands (Kliwa sandstone and sands, carbonatic sandstone with mica and convolute structures), silts (silty marls and coal-rich silts) and clays (marls, marls with siderites, dysodiles and bentonitic clays). The lower third is dominated by clays, while the remainder is sandy (coarsening-upwards trends, Frunzescu, 1989). Microbreccias with greenschist elements, volcanic tuffs and diatomites can occur in thin layers; Age: early Miocene (Burdigalian), NN2 biozone (Melinte, 2005; Roban et al., 2022). Starchiojd Fm. (Popescu and Popescu, 2002); Upper Menilites (Stoica, 1944), similar to the internal facies (see above); Age: late Aquitania - early Burdigalian, nannofossil zone NN2 (Melinte, 2005).

2006).

The anoxic sediments of the OCB are generally characterised by lack or scarcity of limestones and dolomites; thus, the exceptional occurrence of widespread limestone marker beds is very important for stratigraphic correlations. In most sections, the limestones are split by clastic deposits that are usually much thicker than the limestones. Investigations of the *Jaslo Limestone* has shown that the clastic rocks represent event deposits (Haczewski, 1989; Korab and Kotlarczyk, 1977) and the laminated limestone represents the bulk of the geological time (Ciurej and Haczewski, 2012; Jucha and Kotlarczyk, 1959; Jucha and Krach, 1962; Melinte-Dobrinescu and Brustur, 2008). Several tuff beds have been identified throughout the south-eastern OCB (e.g., Văleni, Bătrâni, Vinețușu and Mlăcile tuffs – (Alexandrescu, 1994; Alexandrescu et al., 1981, 1991, 1992; Alexandrescu and Brustur, 1985; Ștefănescu et al., 1989). They represent good stratigraphic markers, mostly regional, but their ages remain poorly constrained, based only on biostratigraphic data.

In the innermost zone of the *Tarcău nappe*, the *Slon Formation* is interfingering with the *Fusaru Sandstone* and part of the *Vinețușu Formation*, being Upper Oligocene-lowermost Miocene (lower Burdigalian) in age (Melinte and Băceanu, 1996). It contains olistoliths of internal origin, mostly Upper Cretaceous variegated shales. The origin of *Slon Fm.* was likely related to the rising of the neighbouring Inner Moldavides nappes (*Audia and Macla*) during the *Savian tectogenesis* in the Late Oligocene (Stefanescu et al., 2007).

2.2.3. Lower and Middle Miocene Carpathian foredeep: evaporites and molasse formations

The Lower-Middle Miocene deposits of the OCB represent expressions of a molasse basin (Fig. 7), a trapped sea characterised by clastic deposition in anomalohaline environments having fluctuating, generally poor connections with the global ocean (Table 3). During the Early Miocene, tectonic activity triggered significant changes in the depositional regime of the OCB sub-basins (Săndulescu, 1984; Săndulescu et al., 1995) and anoxic turbidites are progressively replaced by molasse deposits and evaporites.

In the Burdigalian, a first stage of folding and detachment occurred associated with NE-ward thrusting (Mațenco et al., 1997; Mațenco and Bertotti, 2000; Ștefănescu et al., 1980), known in the classic Paratethys literature as the *Old Styrian tectonic phases* (e.g., Ștefanescu et al., 2007). During this tectonic episode, the Tarcău Nappe was largely emerged, and the sedimentary basins receded to the southeast, where molassic and evaporitic formations of late Burdigalian to Langhian age were deposited.

Molasse deposition in shallow facies and under limited/absent marine connectivity continued throughout the Early Miocene, punctuated by several local gypsum evaporitic episodes. The oldest (Burdigalian) evaporitic episode, characterised by salt and gypsum precipitation, is recorded in the OCB basins at ~19 Ma (Roban et al., 2022), although other studies place it at around 17 Ma (Măruțeanu, 1999).

The Lower Miocene anoxic flysch is replaced by predominantly evaporitic formations and molasses (*Brebu, Doftana, Grey Schlier*) throughout the entire OCB domain. The molasse deposits are supplied from two clastic sources: an external source with greenschist clasts from the foreland (in the Subcarpathian and Vrancea nappes) and an internal source supplied by the Carpathians (Tarcău Nappe). The OCB molasse predominantly consists of rhythmic alternations of reddish conglomerate (gravel and sand) at the base and greyish silt and clay at the top (Măruțeanu, 1999; Săndulescu et al., 1995).

The Burdigalian succession contains several lithostratigraphic markers (Grasu et al., 1999; Olteanu, 1953): the *Perchiu Gypsum* and the *Valea Calului Marls* (represented by reddish clays) are found at the base, while the *Stufu Gypsum* is located in the upper part (Fig. 4; Table 3). The interval between the *Perchiu Gypsum* and the *Valea Calului marls* consists of grey marls and sandstones, called the “*Grey Formation*” (Grasu et al., 1999).



Fig. 7. Key Lower Miocene molasse formations: a, b. Brebu conglomerates (red horizons); c. Gypsum layers from the Grey Schlier unit Fm.; d-e Carpathian-type (internal) conglomerates (detail), f. Dobruja-type, greenschist-rich (foreland-derived) conglomerates (detail), g. Gypsum fold (detail) in Sărata Fm.

Middle Miocene tectonic activity (Bartol et al., 2012; Matenco et al., 2003; Matenco and Bertotti, 2000; Tărăpoancă et al., 2003), known in the classic literature as the *Young Styrian tectogenesis* (Săndulescu, 1988) and a profound marine transgression (Ćorić et al., 2009; Harzhauser and Piller, 2004; Hohenegger et al., 2009; Holcová et al., 2018; Kováč et al., 2004; Rögl, 1999; Rögl et al., 2002; Rundic et al., 2014; Sant et al., 2019a; Schreilechner and Sachsenhofer, 2007) increased the size and depth-domain of the Carpathian Foredeep, which became the main depositional area in the Outer Carpathian region. The Middle Miocene deposits of the Carpathian Foredeep consist of fine-grained sediments rich in marine fauna (Fig. 8), linked to the mid Langhian or Badenian

transgression, which is recognized throughout the entire Carpathian region (Mandic et al., 2019; Sant et al., 2019b; Studencka, 1999), at ~15 Ma (Sant et al., 2019a). The marine episode was followed by a second evaporitic succession linked to the so-called *Badenian Salinity Crisis* of the Central Paratethys, which spanned between 13.8 and 13.4 Ma (de Leeuw et al., 2010, 2013, 2018; Peryt, 2006). In the OCB, the evaporitic succession (Cosmina Fm.) generally started with a relatively monotonous salt breccia with clay matrix and many clasts, both in terms of size and petrography (Crihan, 1999a; Krézsek et al., 2023; Olteanu, 1951a; Popescu, 1951; Săndulescu et al., 1995; Schleder et al., 2019; Tamaş et al., 2018)

Table 3

Early-Middle Miocene Paratethys molasse formations in the Carpathian Foredeep with nannoplankton age estimations from (Mărunțeanu, 1999).

CENTRAL PARATETHYS. CARPATHIAN FOREDEEP. Middle Miocene molasse deposits
Sărata Fm. Rhythmic alternation of layers of gypsum and clayey – silty granofacies rocks (Frunzescu, 1996; Frunzescu and Anastasiu, 1995; Frunzescu et al., 1995). The clastic material consists of black shaley clays, grading into grey-whitish clays with high bituminous content, similar to dysodiles, and grey-purple marls, located at the top of the evaporitic sequence. In the Subcarpathian and Vrancea nappes, the Salt Formation developed as discontinuous salt bodies and intercalations of sedimentary breccias, conglomerates, clays, or saliferous marls and gypsum. Maximum thickness reaches 350–400 m, but its geographical distribution is discontinuous (Frunzescu, 2013). Evaporitic basin (Mărunțeanu, 1999) of Burdigalian age (nannofossil zone NN2b). Condor Fm. A sequence containing marls, clays, sandstones, and coarse granular arkose sandstone. Shallow basin (Frunzescu, 2000), Burdigalian age (nannofossil zone NN2b). Cornu Fm. Breccia with clay matrix representing the post evaporitic phase. It is unstratified and with heterogeneous clastic compositions. The upper part contains a grey-yellowish gypsum level (0.50–4m) and a rhythmic flysch sequence with red marls representing the subaerial exposure of older deposits—shallow basin (Filipescu et al., 2020) of Burdigalian age (nannofossil zone NN3). Brebu Fm. A rhythmic alternation of conglomerate and clayey sandstones with sandy marls, fining upwards. The sandstones are characterised by vertical grain sorting structures, oblique lamination, current structures and ichnologic casts. Shallow basin (Frunzescu, 2000), Burdigalian age (nannofossil zones NN3–NN4a). Măgirești Fm. and Pietricica Hârja, Pleșu, Bârsești conglomerates. Massive conglomerates generally rich in “greenschist” elements and diverse clastic material of Jurassic and Eocene limestones, Permo-Triassic sandstones and Jurassic marls (Săndulescu et al., 1995) located in the external part of Subcarpathian Nappe, on the basin margins. Shallow basin margin (Frunzescu, 2000), Burdigalian age (nannofossil zone). Măgirești Fm. (Hârja Fm.) Sandy-marly molasse (Săndulescu et al., 1995) corresponding to the Early Miocene conglomerates and the sandy or sandy-marly molasses that overlay the conglomerates. Shallow basin (Frunzescu, 2000), Burdigalian age (nannofossil zone NN3). Teșcani Fm. A marly-sandy molasse, rich in “greenschist” clastic material (Mărunțeanu, 1999). Shallow Marginal basin margin (Frunzescu, 2000) of Burdigalian age (nannofossil zone NN4a). Grey Schlier unit. Marly-sandy molasse, rich in “greenschist” clastic material (Mărunțeanu, 1999). Shallow basin (Filipescu et al., 2020; Ștefănescu, 1984; Ștefănescu et al., 1980) of Burdigalian/Langhian age (nannofossil zone NN4). Doftana Fm. Molasse consisting of silty clay layers, often red or grey, containing current structures at the bottom. In the terminal part, yellow-rusty bituminous calcareous shales (stromatolites) occur, followed by brown-rusty, slightly bituminous, compact gypsum. At the top, widespread ichnologic markers indicate intertidal conditions of deposition. Gypsum appears as thin and rare intercalations or as the Perchiu and Cireșu gypsum, two thick, widespread gypsum marker beds. Shallow basin (Filipescu et al., 2020; Ștefănescu, 1984; Ștefănescu et al., 1980) of Burdigalian/Langhian age (nannofossil zone NN4). Cămpinița Fm. (Slănic tuff). Marine succession starts with “<i>globigerina horizon</i>” (Popescu, 1951), a marly unit (Crihan, 1999a) marked by major intercalations of volcanic deposits called Slănic tuff in the South Carpathians (Murgeanu et al., 1968), similar to the Dej tuff in Transylvania (Meruțiu, 1912; Popescu-Voitești, 1915). The external part of Subcarpathian Nappe is characterised by calcareous sandstones (Răchitașu Fm). Middle Miocene (15 – 13.8 Ma) age (Crihan, 1999b; Sant et al., 2019a, 2019b). Cosmina Fm. (Slănic evaporites). Evaporitic succession, linked to the so-called Badenian Salinity Crisis (de Leeuw et al., 2010, 2013, 2018; Peryt, 2006). It generally consists of a monotonous salt breccia with clay matrix and a large variety of clasts, both in size and petrography (Crihan, 1999b; Olteanu, 1951a; Popescu, 1951; Săndulescu et al., 1995). The Badenian evaporitic formation is represented by gypsum and/or halite and can be distinguished from the Burdigalian salt formations by the different detrital material of the matrix (the Badenian evaporites lack “greenschist” components). Selenite gypsum occurs locally (Micu, 1982), similar to the selenites of the external flank of the Foredeep in south Poland and the Sub-Carpathian Ukraine (Frunzescu, 2000). Middle Miocene age (13.8 – 13.4 Ma) Telega Fm. (Radiolarian shales & <i>Spiralis</i> marls) (Olteanu, 1951b; Popescu, 1951; Crihan, 1999a, 1999b). Deposits with normal marine character (de Leeuw et al., 2018; Popescu, 1995). Depositional environments of the radiolarian shale are favourable to the accumulation of clayey deposits rich in siliceous organisms, radiolarian, ebruids, dinoflagellates, and rarely, foraminifera and nannoplankton. The <i>Spiralis</i> (planktonic gastropods) marls consist of clayey granofacies represented by compact grey calcareous limestones, with rare intercalations of sand/sandstone. Middle Miocene age (13.4 – 12.8 Ma).

The Badenian evaporitic formation (early Serravallian) is represented by gypsum and/or halite (Fig. 8) and can be distinguished from the evaporitic formations of the *Early Burdigalian Salinity Crisis* by the different detrital material of the matrix (the Badenian evaporites lack “greenschist” components). Wide crystallized “selenite” gypsum occurs locally (e.g., Valea Rea, Micu, 1982) and is similar to the selenite gypsum of the external flank of the foredeep in south Poland and the Sub-Carpathian Ukraine (Frunzescu, 2000).

The Middle Miocene evaporitic succession is overlain by deposits with a normal marine character correlated throughout the basin (Popescu, 1995). These marine environments, such as *Radiolarian shales* and *Spiralis marls* units (Crihan, 1999a, 1999b; de Leeuw et al., 2018; Olteanu, 1951b; Popescu, 1951) are characterised by radiolarian-rich clays, favourable to the accumulation of siliceous organisms, radiolarian, ebruids, dinoflagellates, and rarely, ostracods, foraminifera and nannofossils, along with marls, rich in planktonic gastropods (*Spiralis* sp.), probably indicating a stratified sea. After the Badenian stage, the deposition shifted from open marine to restricted brackish environments (Liu et al., 2017). This change triggered the *Badenian-Sarmatian Extinction Event* (BSEE), dated at 12.65 Ma (Palcu et al., 2015), when most marine fauna of the OCB basin became extinct (Crihan and Mărunțeanu, 2006; Filipescu and Silye, 2008; Harzhauser and Piller, 2007; Studencka, 2016; Studencka and Jasionowski, 2011), a feature also observed as well at the Konkian-Volhynian boundary in the Eastern Paratethys (Palcu et al., 2017).

2.2.4. Late Miocene Dacian basin: lacustrine deposits of the Paratethys megalake and Pliocene-Quaternary basin fill

The deposits of the early *Sarmatian regional stage* indicate a joint Eastern and Central Paratethys domain. During the middle Sarmatian, the Tarcău, Vrancea and Subcarpathian nappes were thrust over the foreland units. The Vrancea nappe became covered by the Tarcău nappe (Kręzek et al., 2023; Ștefănescu et al., 2007), except for several tectonic windows (Dumesnic and Mitocul lui Bălan) and half-windows (Vrancea, Oituz, Bistrița, and Putna). At the beginning of the *Sarmatian regional stage*, the Outer Carpathian region became incorporated in the Eastern Paratethys (Jipa and Olariu, 2009). To distinguish it from the active foredeep, part of the Central Paratethys those times, the name *Dacian basin* is used for the Sarmatian and post-Sarmatian basin. The sediments of the Dacian basin represent the filling of this last relict of Outer Carpathian basins (See Table 4).

The *Sarmatian* succession consists in the monotonous clay-silt formations corresponding to the *Volhynian and lower Bessarabian substages*, often rich in pyrite and pyritized fossils (e.g., insects) – indicating anoxic/suboxic depositional environments (Munteanu, 1998). The clays are covered by intervals richer in sands, which increase in thickness and eventually grade into the sandy sediments, corresponding to the *upper Bessarabian substage* characterised by the predominance of coarse siliciclastic sequences (sands, sandstones, silts, conglomerates) of early Tortonian age (Fig. 9). These sandy units are the expression of extensive alluvial systems that discharged in the Dacian Basin. The largest of these deltaic systems, dubbed Balta Formation (de Leeuw et al., 2020; Matoshko et al., 2016) formed the southern limit of the axial drainage system of the Carpathian foreland basin and developed in vast areas of eastern Romania, western Ukraine and most of the area of the Republic of Moldova.

During the *Khersonian substage* (corresponding to the late Tortonian Stage, global chronostratigraphy), the lithology becomes predominantly characterised by continental deposits alternating with lacustrine/brackish sequences (Fig. 9). In the southeast, the Khersonian succession covers a reduced area and corresponds to a large erosional gap in the former marginal areas of the basin (Munteanu, 1998).

The deposits of the Maeotian regional stage (lower Messinian) (Fig. 9) lay either concordantly over Khersonian limestones and continental deposits or transgressively with frequent angular unconformities over older deposits (Lazarev et al., 2020; Palcu et al., 2019b). The



Fig. 8. Middle Miocene molasse formations. a. Thick green tuffs (Slănic tuff) from the Câmpinița Fm., b. Salt diapir from Cosmina Fm., c. Gypsum from the Cosmina Fm. overlain by clays of the Teleaga Fm.; d. White tuff in the Răchitașu Fm., e. Slănic Prahova Salt Mine in the Cosmina Fm., f. Algal gypsum from Cosmina Fm., g. Gypsum nodules in Cosmina Fm.

deposits of the Pontian, Dacian and the Romanian regional stages (latest Miocene-Pliocene) have a widespread development and represent the final stage of deposition in aquatic environments, followed by coarse alluvial deposits, terraces and landslides of Quaternary ages (Andreescu et al., 2011). The present-day structural configuration was finished during the Lower Pleistocene tectonic movements (*Wallachian tectogenesis*), when the youngest deposits were also involved in folding and faulting processes (Dicea, 1995; Stefanescu et al., 2007).

3. Paleogeographic and paleoenvironmental reconstructions of the Outer Carpathian Basin

Tectonic rearrangements of the internal seaways and straits, as well as sediment infill have produced many configurations of the Paratethyan realm (Allen and Armstrong, 2008; Dercourt, 2000; Haq, 1981; Harzhauser et al., 2002; Jovane et al., 2009; Oberhänsli and Hsü, 1986), but the evolution of Paratethys after the separation from the Tethys realm (Fig. 1) can be summarized in three key paleogeographic snapshots: “*Anoxic Giant*”, (*Oligocene - early Miocene*) was a phase when large

Table 4
Middle Miocene Paratethys molasse formations in the Carpathian Foredeep.

PARATETHYS, DACIAN BASIN. Miocene (Middle to Upper) to Pliocene molasse deposits
Valea Neagoşului Fm. Clays and blue-grey silty clays, tuffs, sandstone concretions, and conglomerates (Papaianopol, 1992; Munteanu, 1998). Brackish anoxic/dysoxic facies of Middle Miocene age (12.8 – 12.3 Ma; Crihan, 1999a, 1999b; Liu et al., 2017).
Valea Vizuinei Fm. (Munteanu, 1998), also known as Dara beds (Papaianopol, 1992). Clayey formation with gypsum intercalations, deposited between two regressive phases, characterised by coarse clastics and gypsum precipitation (end Kossovian and lower Volhynian). The upper gypsum level (Salcia gypsum) is the most developed. Brackish anoxic/dysoxic facies of Middle Miocene age (12.3 – 11.6 Ma; Crihan, 1999a).
Şipoşelu Fm. Marls and silty clays with levels of fossil-rich sandstones (Andreescu, 1972). It marks a broad development of the Paratethyan endemic faunas of the Sarmatian and corresponds to the local Volhynian and Bessarabian regional stages (Papaianopol, 1992; Munteanu, 1998). Brackish anoxic/dysoxic deposits, Late Miocene in age (11.6 – 9.7 Ma; Crihan, 1999a, 1999b).
Râmnic Fm. Sands with sandstone concretions, sandstones, and clays (Andreescu, 1972), with oolitic intervals, partly corresponding to the “marly-sandy-oolitic levels” (Iorgulescu, 1953), lower part of the Istrița limestone (Papaianopol, 1992).
Milcov Fm (= beds, Motaş et al., 1976). A brackish shallowing oxic basin of Late Miocene age (9.7 – 7.65 Ma; Crihan, 1999a, 1999b; Palcu et al., 2019b).
Valea Ciomegii Fm (=beds, Munteanu, 1998). Continental deposits alternating with freshwater and brackish levels known as “variegated complex,” “striped complex,” “package of the purple-green clays,” “purple-green marl series,” “brackish-freshwater complex” (Andreescu, 1972; Ciocârdel, 1952; Ciocârdel and Patrulea, 1950; Macarovic et al., 1967; Motaş et al., 1976; Munteanu, 1998; Pana, 1966). Partially desiccated basin with freshwater and continental deposits of Late Miocene age (8.7 – 7.65 Ma; Crihan, 1999a; Lazarev et al., 2020; Palcu et al., 2021).
Maeotian regional stage deposits. Consist in a lower Maeotian depositional interval, with clays and marls, sandy in the peripheric zones and an upper Maeotian depositional interval dominated by sandy marls, micaceous sands, and diverse sandstones. At the top of the lower Maeotian, the sediments are disturbed by slumps and erosional episodes, followed by the redeposition of reworked lower Maeotian sediments and fauna (Pana, 1966). Brackish early Maeotian and freshwater environments with marine influxes during late Maeotian; Late Miocene age (7.65 – 6.1Ma; Lazarev et al., 2020; Palcu et al., 2019b; Stoica et al., 2013; Vasiliev et al., 2021).
Pontian regional stage deposits. Consist of a lower Pontian clayey granofacies, a middle Pontian of predominantly sandy granofacies and an upper Pontian marly-sandy facies. The base of the Pontian contains a short influx of mesohaline to polyhaline microfauna, including benthic and planktonic foraminifera from the Aegean, defined as the “Pontian Salinity Incursion.” Restricted marine - freshening (Krijgsman et al., 2010; Stoica et al., 2007; Vasiliev et al., 2010) Late Miocene-Pliocene age, i.e., 6.1 – 4.8 Ma, Jorissen et al., 2018).
Dacian regional stage deposits. An alternation of yellowish-white, fine to medium-grained sands, with intercalations of grey-purple-brown marls, silty marls, coarse granular rusty sandstones, and small gravels in thin layers. To the top, the fine-grained facies is dominant in the form of marls and blackish-brown clays and layers of coal. Brackish-freshwater deposits of Pliocene age (4.8 – 4.4 Ma; Jorissen et al., 2018)
Romanian regional stage deposits. Consist of a lower clayey-sandy subdivision (including brown compact sandy clays, alternating with grey-yellowish sands with low cross-stratification, fine-medium or coarse granular, with grey, brown marls, sometimes with calcareous concretions) and a higher subdivision (mainly gravels, including medium and fine granular gravels with polygenic subrounded and rounded clasts. Freshwater deposits of Pliocene-Pleistocene age (4.4 – 2.2 Ma; Van Baak et al., 2015).
Quaternary deposits. Alluvial deposits, terraces and landslides (Andreescu et al., 2011; Necea et al., 2005). Pleistocene gravels frequently occur deformed, highlighting the recent appearance of the Wallachian tectonic phase (Hippolyte and Sandulescu, 1996).

anoxic seas experiencing various degrees of anoxia, developed throughout Paratethys; “*Changing Seas*” (early and middle Miocene) was an episode when the sub-basins of Paratethys experienced alternations between fully marine and anomalohaline environments (hypersaline or hyposaline); “*Megalakes*” (Late Miocene) was the last stage of Paratethys, characterised by poor connectivity with- or complete disconnections from- the global ocean and brief incursions of marine water masses from the Mediterranean Sea. The lithological successions from the southern sector of the Outer Carpathian basin represent the only complete record of these paleogeographic and paleoenvironmental changes from the

tectonically active region of Paratethys.

3.1. Eocene open ocean environments with short-term local anoxia

The Eocene stratigraphic units of Central Europe mostly reflect deep, tectonically-dynamic, open-ocean environments. Paleogeographic reconstructions (Fig. 10a) point to a particular morphology, characterised by deep narrow basins, and abundant clastic fill. The clastic Kliwa, and Fusaru (Krosno) sandstones reflect the proximity to *cordilleras* that were emerging and undergoing erosional processes, but their occurrences are mainly related to the regional tectonic setting and are not linked with paleoenvironmental changes. Throughout the Eocene, multiple gateways existed in the western Tethys region, allowing a good connection between the Tethyan sub-basins and between Tethys and the global ocean (Palcu and Krijgsman, 2021). The Eocene is generally perceived as the time when the northern Tethys region was characterised by well-connected and well-oxygenated basins, with short-lived local occurrences of anoxic sediments described in the OCB: e.g., the “black shale” of the Silesian (Tarcău) Nappe of the Ukrainian Carpathians (Hnylko and Hnylko, 2019), the “black Eocene” of the Polish Carpathians (Waśkowska et al., 2015). In the Eocene of the Eastern Paratethys a period of more significant restriction occurred, leading to the Kuma anoxic event (Beniamovski et al., 2003; Cramwinckel et al., 2022; van der Boon et al., 2019; Zastrozhnov et al., 2019). Limited age control exists and palaeogeographical constraints are too poor to establish if and how these restrictions are related to the Middle Eocene Climatic Optimum or its aftermath (Bohaty et al., 2009; Cramwinckel et al., 2022; Giorgioni et al., 2019; Sluijs et al., 2013; van der Boon et al., 2021; Zhang et al., 2013). While the geography and chronology of Eocene anoxia remains poorly constrained, it is important to note that open marine oxic environments prevailed in most of the Central Paratethys basins up to the Eocene-Oligocene Transition.

The Eocene paleogeographic episode was furthermore dominated by the deposition of *marine turbidites* in the central European basins. The OCB domain was characterised by good connections with the oceans, albeit a decline during the Middle Eocene (Bartonian) took place, when a deficiency in connectivity led to the formation of deep-water stratification and anoxia. This restriction may be linked with connectivity changes in the Eastern Paratethys region. After the Middle Eocene connectivity restriction, the basins recover their ventilation until the Early Oligocene. The late Eocene OCB turbidites are generally replaced by “*globigerina marl*” at the Eocene-Oligocene Transition. These marls appear to develop throughout Paratethys during the uppermost Eocene and may represent foraminiferal blooms due to increased nutrient-rich superficial waters flowing out from the anoxic basins.

3.2. Oligocene restriction and anoxia

During the latest Eocene (Terminal Eocene Cooling Event) and throughout the Eocene-Oligocene transition (Priabonian – early Rupelian), the OCB transformed from a carbonate factory into a poorly ventilated basin (bituminous marls) and ultimately switched into an anoxic basin (Fig. 10b). The *de facto* transition to anoxia occurred in the Oligocene – in the early Rupelian – corresponding to the calcareous nannofossil zone NP21, upper part (Melinte-Dobrinescu and Brustur, 2008), when the basin experienced severe restrictions. This Early Oligocene restriction correlates with the Solenovian “isolation” of the Eastern Paratethys (Rusu, 1977, 1999; Báldi and Báldi-Beke, 1985; Merklin, 1974;; Sachsenhofer et al., 2018). Similar restrictions have been documented in events throughout the West-Central Paratethys region (Soták, 2010). Restriction of the connections to the proto-Mediterranean region via the Slovenian basin was particularly important for the internal connections in Paratethys, given that the faunal assemblages in the OCB became dominated by boreal fauna elements (Soták, 2010), an event described as the abrupt and synchronous occurrence of the *Spiratella Sea* (Báldi, 1984).



Fig. 9. Upper Miocene facies of the foredeep fill and molasse formations. A. Sands and sandstones of the Șipoțelu fm.; b. Continental sands and paleosols of the Râmnic fm.; c. Maeotian lacustrine sediments; d. Selenite from Valea Vizuinei fm.; e. Sandstone concretions in the Râmnic fm.; f. Istria limestone beds with limestones and oolitic sands; g. Intra-Maeotian slump with clay debris fill, capped by coarse bioclastic debris.

The restrictions in circulation and the increased stratification in the OCB were not constant throughout the Oligocene (Table 2). The initial restriction comprises three episodes, all of them in the Rupelian, with deposition of typical lithologies: (1) *Bituminous Marls* corresponding to the onset of anoxia, followed by (2) *Lower Menilites* – peaking in anoxia (Amadori et al., 2012; Belayouni et al., 2009; Puglisi et al., 2006), and (3) *Lower Dysodiles*, when the basin connectivity improved while the basin remained poorly ventilated. These anoxic deposits formed in the OCB consecutive with a freshening in Eastern Paratethys suggesting they might represent lithological expressions of exchange between the two

basins in a context of limited connections with the ocean. As marine connectivity slightly improved, anoxic turbidites became the dominant lithology in the OCB. The Central European basins remained poorly ventilated until the Early Miocene (Fig. 11a), when sub-oxic episodes such as those found in the *Gura Șoimului Formation* (Amadori et al., 2012) indicate a new phase of vertical basin circulation.

3.3. Miocene restricted anomalous environments and evaporites

Miocene paleogeographic reorganizations created diverse

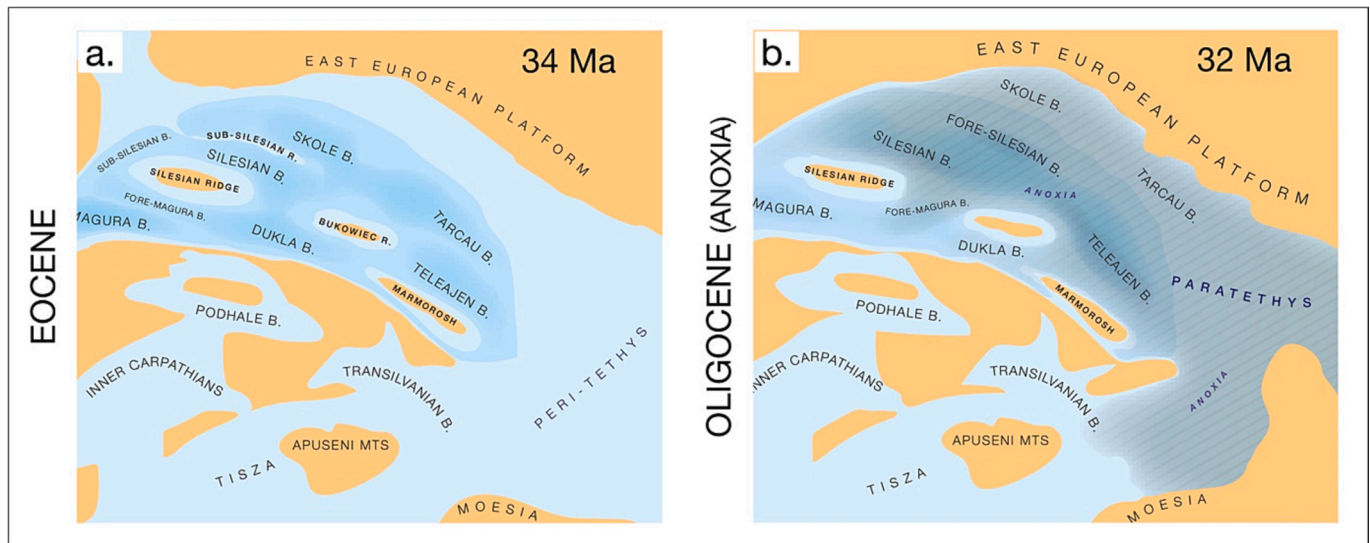


Fig. 10. Simplified paleogeographic sketches highlighting the evolution of the Outer Carpathian Basin during the Late Eocene (a) and Early Oligocene (b) (after Golonka, 2011; Golonka et al., 2007; Palcu and Krijgsman, 2021). Reconstructions indicating the main sub-basins and connections with nearby basins. Orange areas represent landmasses, blue areas represent marine basins (darker blue – deep basins). The brown shades indicate anoxic domains.

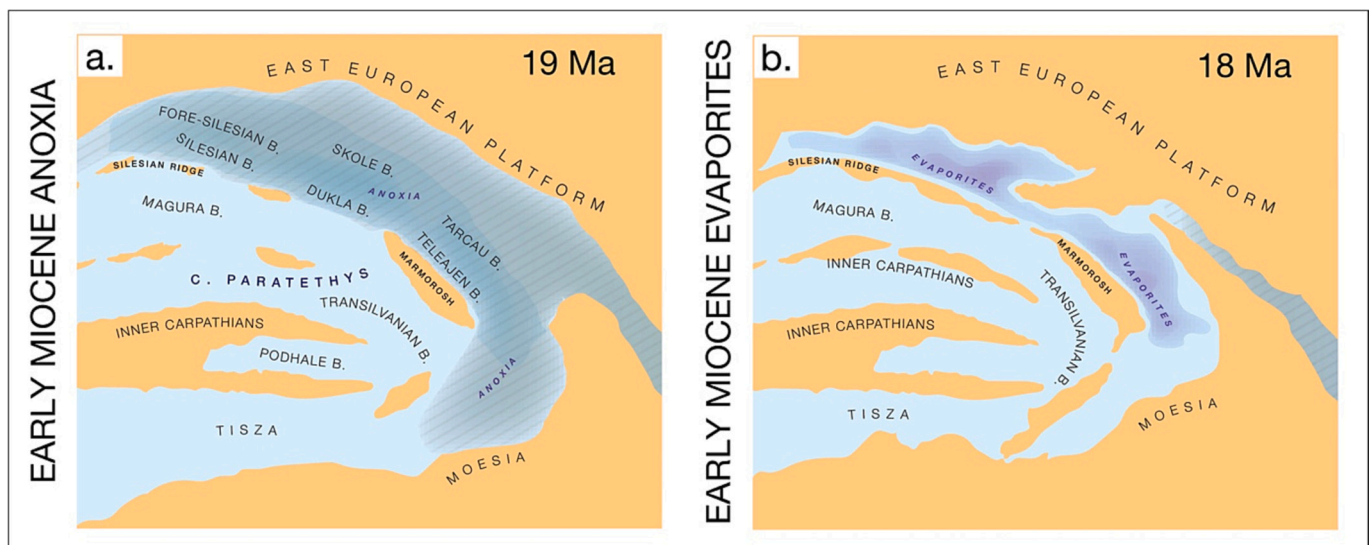


Fig. 11. Simplified paleogeographic sketches highlighting the evolution of the Outer Carpathian Basin during the Early Miocene (after Golonka, 2011; Golonka et al., 2007; Palcu and Krijgsman, 2021). Reconstructions indicating the main sub-basins and connections with nearby basins. Orange areas represent landmasses, blue areas represent marine basins. The brown shades indicate anoxic domains, and the purple shade shows the evaporitic domains.

environments dominated by *brackish and marine molasse, evaporites and carbonatic sediments*. Molasse deposits formed in the OCB at the beginning of the Early Miocene when marine connectivity deteriorated further. During the Burdigalian stage, the connectivity within the OCB was affected by the Old Styrian tectonic phase (Săndulescu, 1988). Intense eastward thrusting of the Outer Carpathian nappes led to uplift and the formation of thick olistoplaques at the front of the nappe thrusts, which likely affected intra-Paratethyan connectivity in the Polish-Ukrainian region. This tectonic episode led to restrictions in marine connectivity and the formation of evaporites in the Ukrainian and Romanian sectors of the OCB (Fig. 11b). Halite and gypsum precipitated in restricted pools during the earliest Burdigalian and late Burdigalian, as the basin became further isolated. During and after the evaporitic episodes, the western connections with the global ocean re-opened and a relatively well-distributed presence of marine faunistic and floristic elements was found and described from most of the Lower Miocene

sedimentary record (Mărunțeanu, 1999).

Following the Burdigalian evaporitic episodes and the Old Styrian tectonic phase, the OCB was greatly reduced in size (Cheremisska and Cheremissky, 2019; Kováč et al., 2017a; Popov et al., 2006; Saulea et al., 1969) and characterised by shallow aquatic environments. In the Subcarpathian area, sediments indicate a major continental contribution, while scarcity in fossils suggests that the environment was unfavourable to marine life (Mărunțeanu, 1999). Regional gypsum deposits indicate partial desiccation episodes. Frequent ichnologic evidence, traces of land mammals and birds (Brustur, 1997), suggest that large basin areas were covered by shallow to tidal aquatic environments.

Middle Miocene Tectonic activity in Central Europe (Fodor et al., 1999; Huismans et al., 2001; Kováč et al., 2004; Vakarcis et al., 1998), also known as the *Young Styrian tectonic phase* in the classical literature (e.g., Săndulescu, 1988), combined with a global sea-level high-stand led to the transgression of marine environments (Fig. 12a) on large

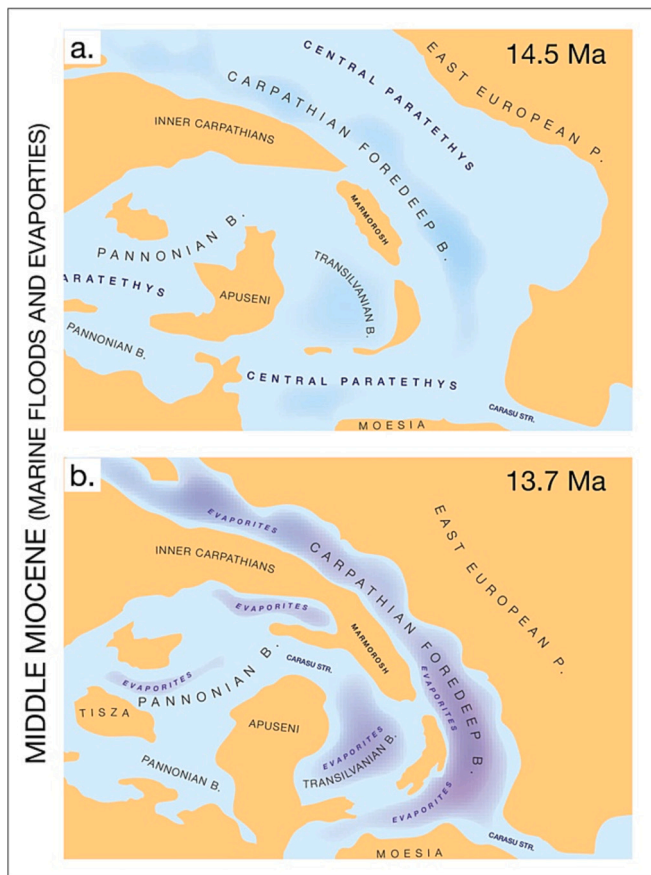


Fig. 12. Simplified paleogeographic sketches highlighting the evolution of the Outer Carpathian Basin during the middle Miocene (after Golonka, 2011; Golonka et al., 2007; Palcu and Krijgsman, 2021). Reconstructions indicating the main sub-basins and connections with nearby basins. Orange areas represent landmasses, blue areas represent marine basins and purple shades show the evaporitic domains.

swathes of Central Europe. This drastic paleoenvironmental change, that occurred at ~15 Ma (Sant et al., 2019b, 2020), during the Langhian (Badenian regional stage) is known as the Badenian flooding event (Harzhauser and Piller, 2007; Holcová et al., 2018; Kováč et al., 2007; Piller et al., 2007b) and has been documented throughout Central Paratethys, in Poland (Oszczypko and Oszczypko-Clowes, 2012), Ukraine (Nevesskaja et al., 2003), Czechia (Brzobohatý and Stráňk, 2012; Hladilová et al., 2014; Rybář et al., 2016; Svábenická, 2002), Slovakia (Csibí et al., 2022), Hungary (Báldi et al., 2002), Romania (Beldean et al., 2013; Chira et al., 2000; Filipescu and Silye, 2008; Sant et al., 2019b, 2020), Croatia (Brlek et al., 2016; Ćorić et al., 2009; Sremac et al., 2016), Bosnia-Herzegovina (Mandic et al., 2019), Serbia (Rundic et al., 2014) and Bulgaria (Popov et al., 2006).

Before the transgression, a limited area of Central Europe was covered by the Karpatian Sea, a basin characterised by brackish-marine environments, spanning from Slovakia, Czechia, and Austria to Slovenia via rifts in the central Hungarian region (Kováč et al., 2016; Piller et al., 2007b; Sant et al., 2017). Thus, during the high stands that accompanied the Middle Miocene climatic optimum, the basins of Central Europe became better connected with each other and with the global ocean.

In the OCB, this transgressive event led to the expansion of the basin and increases in bathymetric regimes (Beldean et al., 2013). Former tidal zones turned to deep offshore areas (Bicchi et al., 2003; Sztanó, 1995) and the new marine realm transgressed on nearby lands (Holcová et al., 2018; Sant et al., 2019a). After the Middle Miocene transgressive and tectonic episode, the basin depocenters shifted eastwards (Popov et al., 2004) but also expanded on top of older nappes that were

previously emerged (Bădescu, 2005). That is why Badenian and post-Badenian deposits are often referred to as “post-tectogenetic cover” (Haas, 2012). The Badenian flooding opened connections between the OCB and the Vienna Basin via a Polish-Czech strait (Palcu and Krijgsman, 2021), but the OCB was also connected with the Pannonian and Transylvanian basins via a system of straits fragmenting the Eastern Carpathians (Kováč et al., 2017a). A key connection to the east (Carasu Strait) allowed passage of marine waters to Eastern Paratethys. This triggered water exchanges between the “open marine” Central Paratethys and the “anoxic, anomalous” Eastern Paratethys, followed by the shutdown of the anoxic condition in the Eastern Paratethys sea (Palcu et al., 2019b).

Global eustatic changes led to a deterioration of marine conditions at the beginning of the Serravallian at ~13.8 Ma (de Leeuw et al., 2010), when the OCB experienced a second evaporitic crisis (Fig. 12b). This Middle Miocene event, known as the “Badenian Salinity Crisis” (de Leeuw et al., 2013; Harzhauser et al., 2018; Peryt, 2006) is spread throughout the OCB and beyond in the nearby Transylvanian, Marmureş and Pannonian basins to the west. The evaporitic facies did not spread in the regions west than of the Pannonian basin, e.g., Vienna basin (Harzhauser et al., 2018), suggesting that the chokepoint in marine connectivity must have been in the Pannonian region. Tectonic changes in the Pannonian basin ended the connectivity restrictions and terminated the evaporitic phase at ~13.4 Ma (de Leeuw et al., 2018; Peryt, 2006). After the evaporitic phase ceased, the basin recovered, becoming initially stratified and then fully marine during the middle Serravallian (Melinte-Dobrinescu and Stoica, 2014). During the Middle Miocene, the Eastern Paratethys region alternated between a sea poorly connected with the ocean via the OCB and a lake that discharged waters to the OCB (Palcu et al., 2017; Simon et al., 2019).

3.4. Late Miocene megalake environments

At 12.65 Ma the paleogeography of the entire Paratethys realm changed again due to reorganizations in the internal connectivity that allowed a mixing of the Eastern and Central Paratethys water masses while the connectivity with the global ocean decreased (Palcu et al., 2015, 2017). The improved connectivity between the Central and Eastern Paratethys was triggered by progressive down-flexing of the lithosphere in the area of southern Moldavia and SW Ukraine due to eastward subduction roll-back and coincident advance of the Carpathian wedge, which brought this formerly exposed area below sea-level (de Leeuw et al., 2020). This “unification” of the Paratethyan basins led to two simultaneous faunal crises in the region: (1) the Badenian-Sarmatian Extinction (Harzhauser and Piller, 2007; Palcu et al., 2015) event corresponding to the extinction of marine fauna in Central Paratethys while (2) the Konkian-Volhynian event (Palcu et al., 2017) led to significant faunal changes in Eastern Paratethys. In the aftermath of these two events, the unification of the Paratethys realm marks the beginning of the Sarmatian regional stage (Piller et al., 2007b), characterised by a thriving endemic fauna.

After almost a million years of effective internal connectivity (Fig. 13a), at the Serravallian-Tortonian boundary (11.6 Ma), Paratethys broke into a collage of basins again (ter Borgh et al., 2013) along the alignment of the East and South Carpathian Mountains. The smaller lake Pannon broke apart from Paratethys in the west of the Carpathians (Magyar et al., 2013; 2021) developing a rich “Pannonian” endemic fauna that evolved from the Sarmatian endemic faunas of Paratethys (Fig. 13b). After the fragmentation, Eastern Paratethys continued to function as a large unified aquatic realm characterised by endemic Sarmatian environments and faunas (Popov et al., 2004). Eastern Paratethys stretched from the Carpathian Mountains in the west to modern Kazakhstan in the east, incorporating the OCB (Popov et al., 2006, 2010). Both the Pannonian and Eastern Paratethys basins were deprived of significant connections with the global ocean, although short-lived, weak marine connections cannot be completely excluded. The rise of

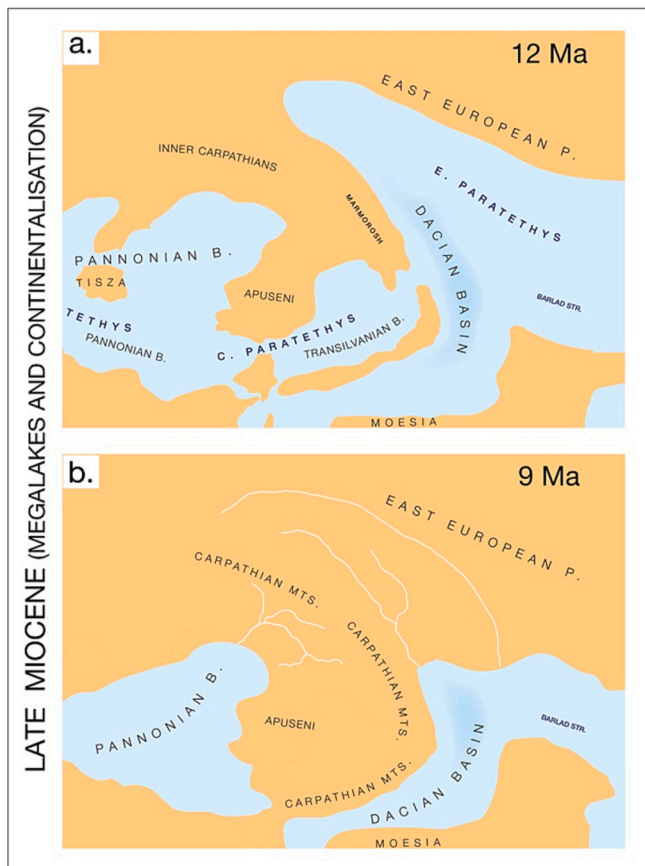


Fig. 13. Simplified paleogeographic sketches highlighting the evolution of the Outer Carpathian Basin during the late Miocene (after Golonka, 2011; Golonka et al., 2007; Palcu and Krijgsman, 2021). Reconstructions indicating the main sub-basins and connections with nearby basins. Orange areas represent landmasses, blue areas represent marine basins.

the Carpathian thrust-fold belt not only affected the western connection of the OCB with the Transylvanian and Pannonian basins but also provided large amounts of sediments that began to fill the depressions (Jipa, 2018; Matoshko et al., 2016). Gradually the sea retreated, initially from the Polish-Ukrainian sector in the NW and then along the Carpathians towards the SSE (de Leeuw et al., 2020).

Brackish and freshwater molasse developed in the OCB during the Late Miocene, when the western connections faded, and the Dacian Basin became a marginal basin of Eastern Paratethys. During the Tortonian-early Messinian, the remaining Paratethys realm experienced significant base-level fluctuations, expressing the climatic forcing of their watershed. In the second half of the Tortonian, it suffered several desiccation crises (Buttiseacă et al., 2021). In the maximum desiccation episodes, such as the Great Khersonian Drying (Lazarev et al., 2020; Palcu et al., 2019b), the connectivity between Eastern Paratethys and the OCB was greatly reduced, and the latter experienced episodes of freshening possibly as a result of restriction of its connection with the Eastern Paratethys by the Balta Delta (Matoshko et al., 2016). This regressive trend was reversed in the late Tortonian due to a global cooling episode that changed the water balance of Paratethys to positive values. This change, in turn, triggered a gradual refill of Eastern Paratethys (7.65–7.4 Ma), known as the Maeotian transgression (Lazarev et al., 2020; Palcu et al., 2019b). During the early Messinian (6.9–6.7 Ma, Golovina et al., 2019), a discharge towards the nearby Mediterranean basin reinstalled a new connection with the global ocean through the Aegean region (Krijgsman et al., 2020). The Black Sea basin became linked with the Mediterranean realm, although the connection remained weak (van Baak et al., 2017; Floroiu et al., 2011; Grothe et al., 2016;

Krijgsman et al., 2010; Stoica et al., 2013; Vasiliev et al., 2005, 2021). In Messinian and later stages, the Dacian Basin continued filling up with sediments while gradually losing its marine and brackish character (Van Baak et al., 2015; Olariu et al., 2018; Vasiliev et al., 2021).

4. Outlook, future perspectives & concluding remarks

This review shows that a restricted aquatic basin can develop heterogeneous aquatic environments due to changes in marine connectivity. This raises the exciting opportunity of a combined approach to investigate these anomalohaline waterbodies in more detail and to better understand their past, present and future behaviour. Despite their broad occurrence (Fig. 14), bituminous marls are still poorly understood and often confused with anoxic, carbon-free black shales (bituminous shales). These marls can be markers of a particular connectivity window between marine basins and their anoxic neighbours. The mechanisms of marine connectivity associated with the formation of carbonate factories remain poorly understood but might be similar to changes in the connectivity of the modern Black Sea with the Mediterranean Sea via the Sea of Marmara. The Black Sea can become supplier of nutrient-rich waters to the nearby marine basins due to the onset of natural density pumps as a result of marine connectivity increases due to sea-level rise and anthropogenic activities. Similar density pumps are considered responsible for major paleoenvironmental cataclysms in the Paratethys realm such as the Badenian-Sarmatian Extinction Event (Palcu et al., 2015) or the demise of the Paratethys Anoxic Giant (Palcu et al., 2019a).

Large anoxic seas are important natural carbon sinks and in the case of long-lived anoxic giants the amount of carbon trapped in the anoxic sediments can be considerable. However, the impact of anoxic carbon sinks on global climate is still poorly understood. It is estimated that the anoxic sediments of the Eurasian Epicontinental Sea of Tethys captured between 0.72×10^{12} T and 1.3×10^{12} T (720–1300 GT) of organic sedimentary carbon released during the Paleocene-Eocene Thermal Maximum (PETM) (Kaya et al., 2022). A significantly larger amount of organic sedimentary carbon, around 60×10^{12} T (60,000 GT), is estimated to have been captured by the Paratethys anoxic giant during the latest Eocene-Oligocene, at a rate of $\sim 6 \times 10^{12}$ T (6,000 GT) per Ma (Allen and Armstrong, 2008), that would correspond to $\sim 12\%$ of the estimated global organic carbon flux in the late Paleogene (Raymo, 1994). This flux, even though just a crude estimation, shows that the overall effect of the carbon drawdown of Paratethys would have suppressed atmospheric CO_2 levels during the EOT and in the Oligocene (Fig. 14). Further investigations are required to confirm these estimations and clarify the role of Paratethys in the Eocene-Oligocene Transition (EOT) greenhouse-icehouse transition.

The sediments of the Paratethys anoxic giant represent an important hydrocarbon source rock associated with some of the largest natural gas and oil reservoirs on the planet. The sea bottom of these anoxic seas can be rich reservoirs of methane, trapped under the seafloor in solid form as methane clathrates (gas hydrates). The modern Black Sea is the largest anoxic sea on Earth and contains a large reservoir of gas hydrates (Kruglyakova et al., 2004; Riboulot et al., 2018; Vassilev and Dimitrov, 2002) that might be at risk of being released from the sea-bottom due to global warming, sea-level rise and improved connectivity. Remarkably, the mechanism of this natural process remains poorly understood and awaits future modeling studies.

In the case of Paratethys evaporites, its Lower Miocene gypsum and halite deposits are relatively poorly studied and depositional models for the Middle Miocene evaporites differs from the well-known Mediterranean Messinian models (Andreetto et al., 2021; Cita, 1982; Flecker et al., 2015; Hernández-Molina et al., 2014; Hsü et al., 1973; Krijgsman and Meijer, 2008; Lugli et al., 2010; Müller and Mueller, 1991; Roveri et al., 2014, 2016; Selli, 1954). More studies are required to clarify and improve the understanding of Paratethyan evaporite deposits and their chronological models to allow direct comparison with the other evaporitic basins of the world.

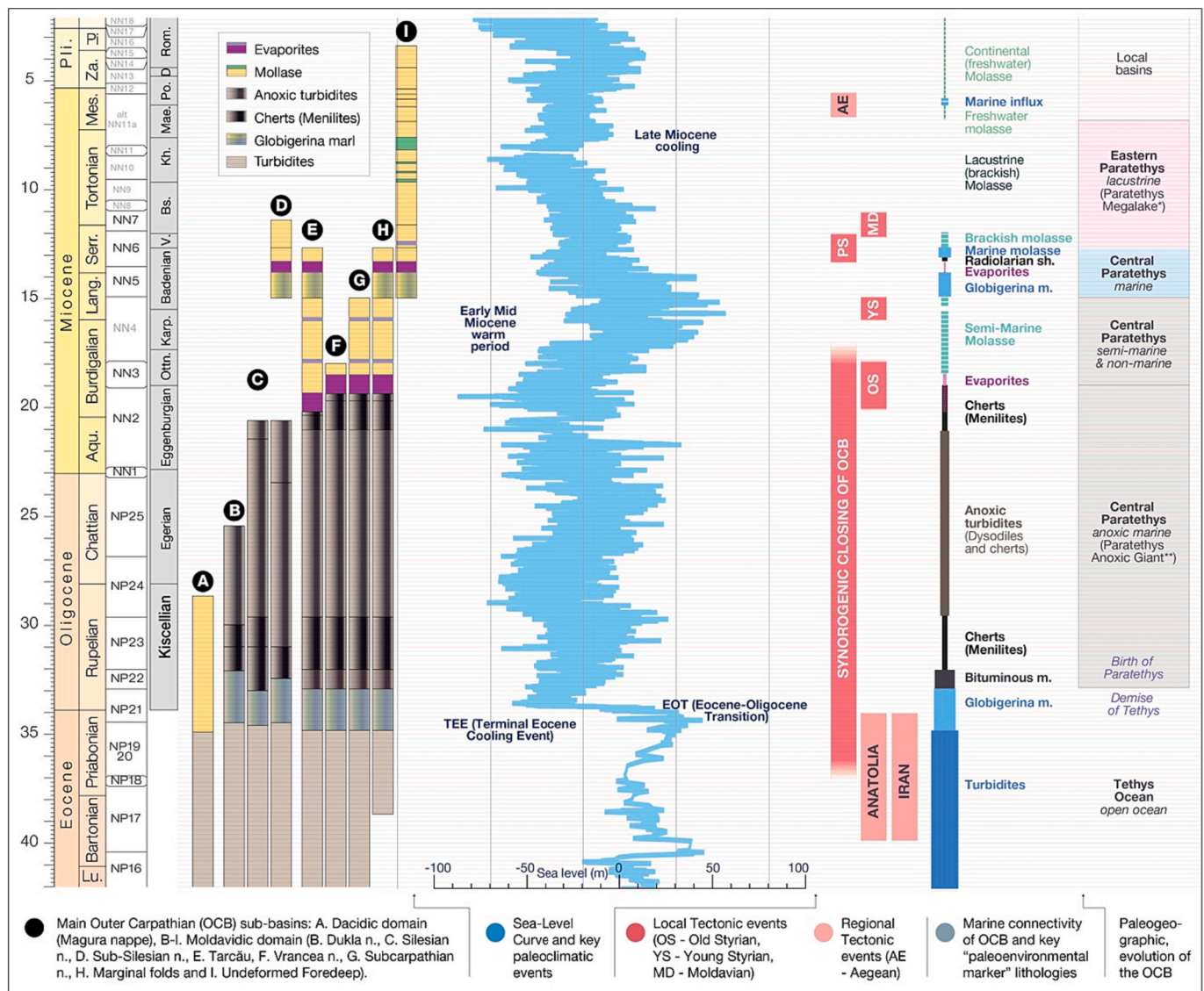


Fig. 14. Sedimentary records of the OCB sub-domains correlated with the eustatic curve (Miller et al., 2020), tectonic events, specific lithological features and qualitative estimations of marine connectivity trends based on the biostratigraphic data reviewed in this study. The paleogeographic evolution of the OCB can be resumed to several episodes, determined by the connectivity of the basin with the global ocean.

The paleoenvironmental change towards the endorheic Paratethys megalake resulted in the development of rich endemic floras and faunas, such as nannoplankton, malacofauna, microfauna (e.g., ostracods), vertebrate fauna (e.g., fish or marine mammals) (Čorić, 2005; Lukeneder et al., 2011). Part of this fauna survived and currently thrives in the Caspian Sea, the largest modern endorheic megalake (e.g., Krijgsman et al., 2019). The special faunas of these megalakes have been studied over more than a century but the exact mechanisms and the required conditions for the development and spread of the endemic species between isolated basins or after the basin isolation ceases.

Our review of Cenozoic paleoenvironmental change in the Central European basins highlights several key research directions and research questions to better understand what happens during and after the demise of oceans and seas. After the demise of the Tethys Ocean, long transition phases, in the order of tens of millions of years (more than 30 million years in the case of Paratethys), are required to shift the once marine realms to continental environments. These paleoenvironmental changes were mainly governed by the degree of marine connectivity with the global ocean. During episodes of increased marine connectivity, the basins were influenced by the global ocean reflecting global climate

trends. As connectivity with the ocean dwindled, however, the environments became more influenced by the surrounding continental landmasses reflecting local climate trends. The transition from ocean to continental environments was characterised by a dominant regressive trend in the marine connectivity: alternating between gradual and sharp connectivity decrease episodes and short-lived connectivity increase trends. These changes were in turn governed by the interplay between tectonic processes and eustatic fluctuations.

Tectonic processes provided a direct influence on the basins by means of geometric deformations (subduction, nappe thrusting and back-arc extension) but also contributed indirectly to the increase of sediment supply that filled the basins. The main impact of tectonics, however, relates to marine connectivity, as uplift and sediment supplied by nearby orogens effectively choked the sea-straits. Tectonic activity also triggered “gateway opening” episodes, associated with shear zones, back-arc extension, or the flexure of foreland basin. Tectonic activity also triggered episodes of basin expansion, due to basin subsidence processes, opening of piggy-back basins and back-arc basins. Also, it influenced the formation and relocation of fore-bulge, back-bulge and foredeep zones affecting internal connectivity and inducing more

complexity in reconstructing the evolution of former oceanic basins.

Detailed stratigraphic correlations show a resonance relation between eustatic fluctuations and tectonic events: sea-level drops occurring during the tectonic closure of basins and of marine gateways were associated with regional evaporitic crises while global sea-level rise episodes that correlated with the opening of back-arc basins and gateways triggered large “marine flood” events. During and after the demise of the Tethys Ocean, its former oceanic basins underwent exotic paleo-environmental configurations that reflect specific degrees of connectivity with the ocean such as the carbonate factories, anoxic seas, evaporite basins and megalakes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

Funding: This publication is part of the project “Impact of sea-level rise on anoxic basins: Paratethys vs. Black Sea” [grant Veni.212.136] of the research Talent programmed – Veni which is financed by the Dutch Research Council (NWO) of DVP. DVP also acknowledges the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for financial support through grant 2018/20733-6. DVP, MMD, EA and MS also acknowledge Project PNR C9 - 18 “Multiproxy reconstruction of Eurasian Megalakes, connectivity and isolation patterns during Neogene-Quaternary times”, code 97/15.11.2022, Contract No. 760115/23.05.2023. WK acknowledges the Dutch Research Council (NWO) [grant 865.10.011].

Photo credits to Arjan de Leeuw (Figs.: 1a, 1e, 6a, 7b, 7c, 7d, 7e, 7f, Supp. 1a, Supp. 1b, Supp. 1c, Supp. 1e, 2 Supp. 1f.); Isabela Maris (Figs.: 1d, 6b, 6c, 9e, Supp. 1d.); Dan V. Palcu (Figs.: 1b, 1c, 1f, 6d, 6e, 7a, 7g, 8a, 8b, 8c, 8d, 8f, 8g, 9a, 9b, 9c, 9d, 9f, 9g); Wikimedia commons (Fig.: 8e).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.earscirev.2023.104594>.

References

- Alexandrescu, G., 1994. Sur quelques restes de rhinocéros d'âge Sarmatien du Bassin de Comănești. *Carpates Orientales, Roumanie*.
- Alexandrescu, G., Brustur, T., 1985. Structures sédimentaires biogènes (traces fossiles) du flysch des Carpathes Orientales (III-ème partie). *Dări seamă ale Sedint. Institutul Geol. si Geofiz. 3. Paleontol*, 72, pp. 5–20.
- Alexandrescu, G.R., Brustur, T., Matei, V., Antonescu, A.L., 1981. Asupra unor cinerite din partea centrală și nordică a Carpaților Orientali, D.S. *Inst. Geol. Geof LXVII*, 69–90.
- Alexandrescu, G., Brustur, T., Nica, M., Urcan, T., Enache, G., 1991. Bentonitic clays from the lower Oligocene at Târgu-Ocna (East Carpathians). In: Petrescu, I. (Ed.), *The Oligocene from the Transylvanian Basin, Romania*. University of Cluj-Napoca, Geology-Mineralogy Department, Special Issue, Cluj-Napoca, Romania, pp. 331–341.
- Alexandrescu, G.R., Frunzescu, D., Cehlarov, A., 1992. Recurrence de l'olistostrome de type Slon. *Stud. și Cercet. Geol. Geofiz. Geogr. Ser. Geol.* 37, 71.
- Allen, M.B., Armstrong, H.A., 2008. Arabia-Eurasia collision and the forcing of mid-Cenozoic global cooling. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 265, 52–58. <https://doi.org/10.1016/j.palaeo.2008.04.021>.
- Amadori, M.L., Belayouni, H., Guerrero, F., Martín-Martín, M., Martín-Rojas, I., Miclăuș, C., Raffaelli, G., Miclăuș, C., Raffaelli, G., 2012. New data on the Vrancea Nappe (Moldavidian Basin, Outer Carpathian Domain, Romania): Paleogeographic and geodynamic reconstructions. *Int. J. Earth Sci.* 101, 1599–1623. <https://doi.org/10.1007/s00531-011-0744-1>.
- Andreescu, I., 1972. Faciostratotipul Malvensianului din zona de curbură a Carpaților Orientali, D.S. *Inst. Geol LVIII*, 157–176.
- Andreescu, I., Codrea, V., Enache, C., Lubenescu, V., Munteanu, T., Petculescu, A., Stiuca, E., Terzea, E., Știucă, E., Terzea, E., 2011. Reassessment of the Pliocene/Pleistocene (Neogene/Quaternary) boundary in the Dacian Basin (Eastern Paratethys), Romania. *Oltenia. Stud. și comunicări. Științele Nat.* 27, 197–220.
- Andreetto, F., Aloisi, G., Raad, F., Heida, H., Flecker, R., Agiadi, K., Lofi, J., Blondel, S., Bulian, F., Camerlenghi, A., Caruso, A., Ebner, R., Garcia-Castellanos, D., Gaullier, V., Guibourdenche, L., Gvirtzman, Z., Hoyle, T.M., Meijer, P.T., Moneron, J., Sierro, F.J., Travan, G., Tzevahirtzian, A., Vasiliev, I., Krijgsman, W., 2021. Freshening of the Mediterranean Salt Giant: controversies and certainties around the terminal (Upper Gypsum and Lago-Mare) phases of the Messinian Salinity Crisis. *Earth-Sci. Rev.* 216, 103577. <https://doi.org/10.1016/j.earscirev.2021.103577>.
- Bădescu, D., 2005. Evoluția tectono-stratigrafică (Mezozoică și Neozoică) a Carpaților Orientali. University of Bucharest.
- Báldi, T., 1984. The terminal Eocene and Early Oligocene events in Hungary and the separation of anoxic, cold Paratethys. *Eclogae Geol. Helv.* 77, 1–27.
- Báldi, T., Báldi-Beke, M., 1985. The evolution of the Hungarian Paleogene basins. *Acta Geol. Hung.* 28, 5–28.
- Báldi, K., Benkovics, L., Sztanó, O., 2002. Badenian (Middle Miocene) basin development in SW Hungary: subsidence history based on quantitative paleobathymetry of foraminifera. *Int. J. Earth Sci.* 91, 490–504. <https://doi.org/10.1007/s005310100226>.
- Băncilă, I., 1958. Geologia Carpaților Orientali. In: Editura Științifică, București (Eds.), . Ed. Did. Pedag., București, 369 p.
- Bartol, J., Matenco, L., Garcia-Castellanos, D., Leever, K., 2012. Modelling depositional shifts between sedimentary basins: Sediment pathways in Paratethys basins during the Messinian Salinity Crisis. *Tectonophysics* 536–537, 110–121. <https://doi.org/10.1016/j.tecto.2012.03.007>.
- Belayouni, H., Di Staso, A., Guerrero, F., Martín Martín, M., Miclăuș, C., Serrano, F., Tramontana, M., Miclăuș, C., Serrano, F., Tramontana, M., 2009. Stratigraphic and geochemical study of the organic-rich black shales in the Tarcău Nappe of the Moldavidian Domain (Carpathian Chain, Romania). *Int. J. Earth Sci.* 98, 157–176. <https://doi.org/10.1007/s00531-007-0226-7>.
- Beldean, C., Bercea, R., Filipescu, S., 2013. Sedimentology and biostratigraphy of the Early-Middle Miocene transition in NW Transylvanian Basin (Păgășa and Dej sections). *Stud. UBB Geol.* 58, 57–70. <https://doi.org/10.5038/1937-8602.58.1.5>.
- Beniamovski, V., Alekseev, A., Ovechkin, M.N., Oberhansli, H., 2003. Middle to upper Eocene dysoxic/anoxic Kuma Formation (northeast Peri-Tethys): Biostratigraphy and Paleoenvironments. In: Wing, S.L., Gingerich, P.D., Schmitz, B., Thomas, E. (Eds.), *Causes and Consequences of Globally Warm Climates in the Early Paleogene*. Boulder, Colorado, pp. 95–112.
- Bicchi, E., Ferrero, E., Gonera, M., 2003. Palaeoclimatic interpretation based on Middle Miocene planktonic foraminifera: the Silesia Basin (Paratethys) and Monferrato (Tethys) records. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 196, 265–303. [https://doi.org/10.1016/S0031-0182\(03\)00368-7](https://doi.org/10.1016/S0031-0182(03)00368-7).
- Bohaty, S.M., Zachos, J.C., Florindo, F., Delaney, M.L., 2009. Coupled greenhouse warming and deep-sea acidification in the middle Eocene. *Paleoceanography* 24, 1–16. <https://doi.org/10.1029/2008PA001676>.
- Bojanowski, M.J., Ciurej, A., Haczewski, G., Jokubauskas, P., Schouten, S., Tyszka, J., Bijl, P.K., 2018. The Central Paratethys during Oligocene as an ancient counterpart of the present-day Black Sea: Unique records from the coccolith limestones. *Mar. Geol.* 403, 301–328. <https://doi.org/10.1016/j.margeo.2018.06.011>.
- Brlek, M., Špišić, M., Brčić, V., Mišur, I., Kurečić, T., Miknić, M., Avanić, R., Vrsaljko, D., Slovenec, D., 2016. Mid-Miocene (Badenian) transgression on Mesozoic basement rocks in the Mt. Medvednica area of northern Croatia. *Facies* 62, 1–21.
- Brustur, T., 1997. The stages of the paleoichnological studies in Romania. In: *Proceedings of the International Workshop on “Fluvial-Marine Interactions”*, pp. 205–216.
- Brzobohatý, R., Stránik, Z., 2012. Paleogeography of the Early Badenian connection between the Vienna Basin and the Carpathian Foredeep. *Cent. Eur. J. Geosci.* 4, 126–137. <https://doi.org/10.2478/s13533-011-0045-z>.
- Butisecă, G.A., Vasiliev, I., van der Meer, M.T.J., Krijgsman, W., Palcu, D.V., Feurdean, A., Niedermeyer, E.M., Mulch, A., 2021. Severe late Miocene droughts affected western Eurasia. *Glob. Planet. Chang.* 206. <https://doi.org/10.1016/j.gloplacha.2021.103644>.
- Cheremisska, O.M., Cheremissky, Y.V., 2019. Lithofacial and paleogeographic analysis of the Burdigallian-Langhian formations of the Ukrainian Carpathian Foredeep. *J. Geol. Geogr. Geocool.* 28, 19–28. <https://doi.org/10.15421/111903>.
- Chira, C., Filipescu, S., Codrea, V., 2000. Palaeoclimatic evolution in the Miocene from the Transylvanian Depression reflected in the fossil record. *Geol. Soc. London Spec. Publ.* 181, 55–64. <https://doi.org/10.1144/gsl.sp.2000.181.01.06>.
- Ciocărdel, R., 1952. Geologia regiunii Gornetului Cuib-Matița-Apostolache și considerații generale asupra rocilor-mame ale petrolului din Subcarpați. *Dări Seamă ale Institutului Geol. al României XXXVI*, 87–95.
- Ciocărdel, R., Patrulea, D., 1950. Contribuția la cunoașterea geologiei regiunii Canara-Năvodari (jud. Constanța). *Bul. st. Acad. RPR, Geol.-geogr., biol., st. agr., II*, 1, pp. 51–57.
- Cita, M.B., 1982. The Messinian salinity crisis in the Mediterranean: a review. *Alpine-Mediterranean Geodyn.* 7, 113–140.
- Ciurej, A., Haczewski, G., 2012. The Tylawa Limestones—a regional marker horizon in the Lower Oligocene of the Paratethys: diagnostic characteristics from the type area. *Geol. Q.* 56, 833–844. <https://doi.org/10.7306/gq.1058>.
- Ciurej, A., Haczewski, G., 2016. The sokolska limestone, a new regional marker horizon of coccolith laminites in the oligocene of the outer carpathians: Diagnostic features

- and stratigraphic position. *Ann. Soc. Geol. Pol.* 86, 415–427. <https://doi.org/10.14241/asgp.2016.018>.
- Coquand, H., 1867. Sur les gîtes de pétrole de la Valachie et de la Moldavie et sur l'âge des terrains qui les contiennent.
- Čorić, S., 2005. Endemic Sarmatian and Pannonian calcareous nannoplankton from the Central Paratethys. In: 12th Congress RCMNS, 6–11, September 2005, Vienna, Abstract Volume, pp. 53–54.
- Čorić, S., Pavelić, D., Rögl, F., Mandić, O., Vrabac, S., Avanić, R., Jerković, L., Vranjković, A., 2009. Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys). *Geol. Croat.* 62, 31–43. <https://doi.org/10.4154/gc.2013.05>.
- Cramwinckel, M.J., van der Ploeg, R., van Helmond, N.A.G.M., Waarlo, N., Agnini, C., Bijl, P.K., van der Boon, A., Brinkhuis, H., Frieling, J., Krijgsman, W., Mather, T.A., Middelburg, J.J., Peterse, F., Slomp, C.P., Sluijs, A., 2022. Deoxygenation and organic carbon sequestration in the Tethyan realm associated with the middle Eocene climatic optimum. *GSA Bull.* 1–17. <https://doi.org/10.1130/b36280.1>.
- Crihan, I.M., 1999a. Litobiostratigrafia Miocenului mediu dintre valea Prahovei și valea Teleajenului la sud de sinclinalul Slănic (in Romanian).
- Crihan, I.M., 1999b. The stratigraphy of the Middle Miocene deposits from the Subcarpathians of Muntenia (Romania). *Biul. Państwowe Inst. Geol.*
- Crihan, I.M., Marunteanu, M., 2006. The Badenian-Sarmatian transition in the Melicesti syncline (sub-Carpathians of Muntenia, Romania). In: XVIII Congress of the Carpathian-Balkan Geological Association, Belgrade, Belgrade, Serbia, pp. 83–86.
- Csibri, T., Ruman, A., Hudáková, N.H., Jamrich, M., Sliva, L., Šarinová, K., Kováč, M., 2022. Deltaic systems of the northern Vienna Basin: The lower-middle Miocene conglomerate bodies. *Geol. Carpath.* 73, 245–269.
- de Leeuw, A., Bukowski, K., Krijgsman, W., Kuiper, K.F., 2010. Age of the Badenian salinity crisis: Impact of Miocene climate variability on the circum-mediterranean region. *Geology* 38, 715–718. <https://doi.org/10.1130/G30982.1>.
- de Leeuw, A., Filipescu, S., Mațenco, L., Krijgsman, W., Kuiper, K., Stoica, M., 2013. Paleomagnetic and chronostratigraphic constraints on the middle to late miocene evolution of the transylvanian basin (Romania): Implications for central paratethys stratigraphy and emplacement of the tisa-dacia plate. *Glob. Planet. Chang.* 103, 82–98. <https://doi.org/10.1016/j.gloplacha.2012.04.008>.
- de Leeuw, A., Tulbure, M., Kuiper, K.F., Melinte-Dobrinescu, M.C., Stoica, M., Krijgsman, W., 2018. New 40Ar/39Ar, magnetostratigraphic and biostratigraphic constraints on the termination of the Badenian Salinity Crisis: Indications for tectonic improvement of basin interconnectivity in Southern Europe. *Glob. Planet. Chang.* 169, 1–15. <https://doi.org/10.1016/j.gloplacha.2018.07.001>.
- de Leeuw, A., Vincent, S.J., Matoshko, A.A., Matoshko, A.A., Stoica, M., Nicoara, I., 2020. Late Miocene sediment delivery from the axial drainage system of the East Carpathian foreland basin to the Black Sea. *Geology* 48, 761–765. <https://doi.org/10.1130/G47318.1>.
- Dercourt, J., 2000. Peri-Tethys atlas: palaeogeographical maps. CCGM.
- Dicea, O., 1995. The structure and hydrocarbon geology of the Romanian East Carpathian border from seismic data. *Pet. Geosci.* 1, 135–143.
- Dumitrescu, I., 1948. La Nappe du Gres de Tarcău, la zone marginale et la zone néogène, entre Cașin et Putna. *D.S. Inst. Geol. Rom* 29, 84–105.
- Dumitrescu, I., 1952a. Cercetări geologice în Vrancea de Nord. *DS Inst. Geol. Rom* 36, 51–61.
- Dumitrescu, I., 1952b. Etude géologique de la région entre l'Oituz et la Coza. *Annu. la Com. Géologique* 14, 195–270.
- Dziedzic, P., Matyasik, I., Garecka, M., Szydio, A., 2016. Lower Oligocene Menilite Beds, Polish Outer Carpathians: supposed deep-sea flysch locally interpreted as shelfal, based on new sedimentological, micropaleontological and organic-geochemical data, Lower Oligocene Menilite Beds, Polish Outer Carpathians: supposed deep-sea flysch locally interpreted as shelfal, based on new sedimentological, micropaleontological and organic-geochemical data. *Kraków*. <https://doi.org/10.18668/pn2016.213>.
- Filipescu, S., Silye, L., 2008. New paratethyan biozones of planktonic foraminifera described from the Middle Miocene of the Transylvanian Basin (Romania). *Geol. Carpath.* 59, 537–544.
- Filipescu, S., Tămaș, D.M., Bercea, R.I., Tămaș, A., Bălc, R., Țabără, D., Bindu-Haitonic, R., Silye, L., Auer, A., Krézsek, C., Schlöder, Z., Săsăran, E., Țabără, D., Bindu-Haitonic, R., Silye, L., Auer, A., Krézsek, C., Schlöder, Z., Săsăran, E., 2020. Biostratigraphic re-evaluation of the lower to middle miocene succession in the eastern carpathians: A case study related to the oil fields of the diapir fold zone, Romania. *Geol. Q.* 64, 781–800. <https://doi.org/10.7306/gq.1554>.
- Flecker, R., Krijgsman, W., Capella, W., de Castro Martins, C., Dmitrieva, E., Mayser, J.P., Marzocchi, A., Modestu, S., Ochoa, D., Simon, D., Tulbure, M., van den Berg, B., van der Schee, M., de Lange, G., Ellam, R., Govers, R., Gutjahr, M., Hilgen, F., Kouwenhoven, T., Lofi, J., Meijer, P., Sierro, F.J., Bachiri, N., Barhoun, N., Alami, A. C., Chacon, B., Flores, J.A., Gregory, J., Howard, J., Lunt, D., Ochoa, M., Pancost, R., Vincent, S., Yousfi, M.Z., 2015. Evolution of the Late Miocene Mediterranean-Atlantic gateways and their impact on regional and global environmental change. *Earth-Sci. Rev.* <https://doi.org/10.1016/j.earscirev.2015.08.007>.
- Florou, A., Stoica, M., Munteanu, I., Dinu, C., 2011. Stratigraphical and paleontological data from Upper Miocene-Pliocene sediments, Romanian Black Sea shelf. *Geophys. Res. Abstr.* 13, 5861.
- Fodor, L., Csontos, L., Bada, G., Györfi, I., Benkovic, L., 1999. Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: a new synthesis of palaeostress data. *Spec. Publ. Soc. LONDON* 156, 295–334.
- Frunzescu, D., 1989. Analiza sedimentologică a evaporitelor miocene dintre Valea Buzăului și Valea Teleajenului. *Univ. Pet.* LIV 5, 1–8.
- Frunzescu, D., 1996. Analiza stratonomică a gipsurilor inferioare din Valea Teleajenului, Măneacu Ungureni (sinclinalul Slănic). *Rev. Rom. Petr* 3 (1), 7–12.
- Frunzescu, D., 2000. Evoluția sectorului sudic al bazinului avansat al Carpaților Orientali reflectată în evoluția evaporitelor miocene. *Bul. Univ. Pet. LII* 4, 145–150.
- Frunzescu, D., 2013. Miocenul din partea de sud a Carpaților Orientali. Megasecvente evaporitice sulfatice (in Romanian). Editura Universității Petrol-Gaze Ploiești.
- Frunzescu, D., Anastasiu, N.M.P., 1995. Clastic Evaporite events in the Lower Neogene of the Pericarpatian Unit. *Rom. J. Strat.* 76, 7.
- Frunzescu, D., Alexandrescu, G., Cehlarov, A., 1995. Aspects sedimentologiques des gypses inférieurs de la carrière de Cerașu (synclinal de Slănic). *Stud. Cerc. Geol.-Geogr* 40, 65–72.
- Garecka, M., 2012. Record of changes in the Oligocene-Miocene sediments of the Menilite-Krosno series of the Skole unit based on calcareous nannoplankton studies—biostratigraphy and palaeogeographical implications (Polish Outer Carpathians). *Biul. Państw. Inst. Geol.* 453, 1–22.
- Giorgioni, M., Jovane, L., Rego, E.S., Rodelli, D., Frontalini, F., Coccioni, R., Catanzariti, R., Özcan, E., 2019. Carbon cycle instability and orbital forcing during the Middle Eocene Climatic Optimum. *Sci. Rep.* 9, 1–10. <https://doi.org/10.1038/s41598-019-45763-2>.
- Golonka, J., 2011. Evolution of the Outer Carpathian Basins. *Integr. Microfossil Rec. from Ocean. Epic. Seas* 3–14.
- Golonka, J., Gahagan, L., Krobicki, M., Marko, F., Oszczypko, N., Ślaczka, A., 2007. Plate-tectonic Evolution and Paleogeography of the Circum-Carpathian Region. Carpathians Their Foreland Geology Hydrocarb. Resour. pp. 11–46. <https://doi.org/10.1306/985606m843066>.
- Golovina, L.A., Radionova, E.P., van Baak, C.G.C., Krijgsman, W., Palcu, D.V., 2019. A Late Maetian age (6.7–6.3 Ma) for the enigmatic “Pebble Breccia” unit in DSDP Hole 380A of the Black Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 533, 109269. <https://doi.org/10.1016/j.palaeo.2019.109269>.
- Grasu, C., Catană, C., Miclăuș, C., Boboș, I., 1999. The East Carpathian molasse. Petrography and sedimentogenesis (In Romanian). Editura Tehnică, București.
- Grasu, C., Alexandru, U., Cuza, I., 2018. Considerations petrogenetiques sur les Calcaires de Jaslo du flysch des Carpatés Orientales.
- Grigoraș, N., 1955. Studiul comparativ al faciesurilor Paleogenului dintre Putna și Buzău. *An. Com. Geol XXVIII* 99–220.
- Grothe, A., Sangiorgi, F., Brinkhuis, H., Stoica, M., Krijgsman, W., 2016. Migration of the dinoflagellate *Galeacysta etrusca* and its implications for the Messinian Salinity Crisis. *Newsl. Stratigr.* 51, 73–91. <https://doi.org/10.1127/nos/2016/0340>.
- Haas, J., 2012. Geological and tectonic setting. In: Recent Landform Evolution: The Carpatho-Balkan-Dinaric Region. Springer, pp. 3–18. https://doi.org/10.1007/978-94-007-2448-8_1.
- Haczewski, G., 1984. Korelacja lamin w chronohoryzontach wapienia jasielskiego i wapienia z Zagorza (Karpaty Zewnętrzne). *Kwartalnik Geol.* 28, 675–688.
- Haczewski, G., 1989. Poziomy wapieni kokkolitowych w serii menilitowo-krośnieńskie-rozróznianie, korelacja i geneza. In: *Annales Societatis Geologorum Poloniae*, pp. 435–523.
- Haq, B.U., 1981. Paleogene paleoceanography: Early Cenozoic oceans revisited. *Oceanol. Acta*, Spec. Issue.
- Harzhauser, M., Piller, W.E., 2004. The Early Sarmatian - Hidden seesaw changes. *CFS Cour. Forschungsinstitut Senckenb.*, pp. 89–111.
- Harzhauser, M., Piller, W.E., 2007. Benchmark data of a changing sea - Palaeogeography, Palaeobiogeography and events in the Central Paratethys during the Miocene. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 253, 8–31. <https://doi.org/10.1016/j.palaeo.2007.03.031>.
- Harzhauser, M., Piller, W.E., Steininger, F.F., 2002. Circum-Mediterranean Oligo-Miocene biogeographic evolution - The gastropods' point of view. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 183, 103–133. [https://doi.org/10.1016/S0031-0182\(01\)00464-3](https://doi.org/10.1016/S0031-0182(01)00464-3).
- Harzhauser, M., Grunert, P., Mandić, O., Lukeneder, P., Gallardo, Á.G., Neubauer, T.A., Carnevale, G., Landau, B.M., Sauer, R., Strauss, P., 2018. Middle and late Badenian palaeoenvironments in the northern Vienna Basin and their potential link to the Badenian Salinity Crisis. *Geol. Carpath.* 69, 149–168. <https://doi.org/10.1515/geoca-2018-0009>.
- Hernández-Molina, F.J., Stow, D.A.V., Alvarez-Zarikian, C.A., Acton, G., Bahr, A., Balestra, B., Ducassou, E., Flood, R., Flores, J.-A., Furota, S., Brunetti, P., Hodell, D., Jimenez-Espejo, F., Kim, J.K., Krissek, L., Kuroda, J., Li, B., Llave, E., Lofi, J., Lourens, L., Miller, M., Nanayama, F., Nishida, N., Richter, C., Roque, C., Pereira, H., Sanchez Goñi, M.F., Sierro, F.J., Singh, A.D., Sloss, C., Takashimizu, Y., Tzanova, A., Voelker, A., Williams, T., Xuan, C., 2014. Onset of Mediterranean outflow into the North Atlantic. *Science* (80-.) 344. <https://doi.org/10.1126/science.1251306>, 1244 LP – 1250.
- Hippolyte, J.C., Sandulescu, M., 1996. Paleostress characterization of the “Wallachian phase” in its type area (southeastern Carpathians, Romania). *Tectonophysics* 263, 235–248. [https://doi.org/10.1016/S0040-1951\(96\)00041-8](https://doi.org/10.1016/S0040-1951(96)00041-8).
- Hippolyte, J.C., Badescu, D., Constantin, P., 1999. Evolution of the transport direction of the Carpathian belt during its collision with the east European platform. *Tectonics* 18, 1120–1138. <https://doi.org/10.1029/1999TC900027>.
- Hladilová, Š., Nehyba, S., Žágoršek, K., Tomanová-Petrová, P., Bitner, M.A., Demy, A., 2014. Early Badenian transgression on the outer flank of Western Carpathian Foredeep, Hlučov area, Czech Republic. In: *Annales Societatis Geologorum Poloniae*.
- Hnylko, O., Hnylko, S., 2019. Geological Environments Forming the Eocene Black-Shale Formation of the Silesian Nappe (Ukrainian Carpathians). *GEODYNAMICS* 2(25) 2018, 5–14. <https://doi.org/10.23939/jgd2019.01.060>.
- Hohenegger, J., Hohenegger, J., Rögl, F., Čorić, S., Pervessler, P., Lirer, F., Roetzel, R., Scholger, R., Stingl, K., 2009. The Styrian Basin: A key to the Middle Miocene (Badenian / Langhian) Central Paratethys The Styrian Basin: A key to the Middle

- Miocene (Badenian/Langhian) Central Paratethys transgressions. *Austrian J. Earth Sci.* 102, 102–132.
- Holcová, K., Doláková, N., Nehyba, S., Vacek, F., 2018. Timing of langhian bioevents in the carpathian foredeep and northern Pannonian basin in relation to oceanographic, tectonic and climatic processes. *Geol. Q.* 62, 3–17. <https://doi.org/10.7306/gq.1399>.
- Hsü, K.J., Ryan, W.B.F.F., Cita, M.B., 1973. Late miocene desiccation of the mediterranean. *Nature* 242, 240–244. <https://doi.org/10.1038/242240a0>.
- Huisman, R.S., Podladchikov, Y.Y., Cloetingh, S., 2001. Dynamic modeling of the transition from passive to active rifting, application to the Pannonian basin. *Tectonics* 20, 1021–1039. <https://doi.org/10.1029/2001TC900010>.
- Ionesi, B., 1986. Asupra Sarmațianul și subdiviziunilor sale, An. Muz. Științ. Nat. Piatra Neamț (Geol.-Geogr. Piatra Neamț).
- Ionesi, L., 1971. Flisul paleogen din bazinul vâii Moldovei. Ed. Acad. RSR, 200 pp. (in Romanian).
- Iorgulescu, T., 1953. Notă preliminară asupra rezultatelor micropaleontologice obținute pe profile normale, urmărite în județele Prahova, Dâmbovița, Argeș, Vâlcea. Dări de Seamă ale Institutului de Geologie XXXVII, 93–106.
- Jipa, D.C., 2018. Large-scale along-arc sedimentary migration in the Carpathian Foredeep. A paleogeographic approach. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 505, 140–149. <https://doi.org/10.1016/j.palaeo.2018.05.037>.
- Jipa, D.C., Olariu, C., 2009. Dacian Basin. *Depos. Archit. Sediment. Hist. a Paratethys Sea. Geo-Eco-Marina, Spec. Publ.* p. 3.
- Jolivet, L., Faccenna, C., 2000. Mediterranean extension and the Africa-Eurasia collision AND FACENNA- CENOZOIC BASINS AND AFRICA-EURASIA, 19, pp. 1095–1106.
- Jones, R.W.W., Simmons, M.D., 1997. A review of the stratigraphy of eastern Paratethys (Oligocene-Holocene), with particular emphasis on the Black Sea. In: *Regional and Petroleum Geology of the Black Sea and Surrounding Region: AAPG Memoir*, 68, pp. 39–52.
- Jorissen, E.L., de Leeuw, A., van Baak, C.G.C., Mandic, O., Stoica, M., Abels, H.A., Krijgsman, W., 2018. Sedimentary architecture and depositional controls of a Pliocene river-dominated delta in the semi-isolated Dacian Basin, Black Sea. *Sediment. Geol.* 368, 1–23. <https://doi.org/10.1016/j.sedgeo.2018.03.001>.
- Jovane, L., Coccioni, R., Marsili, A., Acton, G., 2009. The late Eocene greenhouse-icehouse transition: observations from the Massignano global stratotype section and point (GSSP). *Geol. Soc. Am. Spec. Pap.* 452, 149–168.
- Jucha, S., Kotlarczyk, J., 1959. Próba ustalenia nowych poziomów korelacyjnych w warstwach krosieńskich Karpat Polskich. *Acta Geol. Pol.* 9, 55–112.
- Jucha, S., Krach, W., 1962. Nowe stanowiska fauny w serii menilitowej. *Acta Geol. Pol.* 12, 227–262.
- Kaya, M.Y., Dupont-Nivet, G., Frieling, J., Fioroni, C., Rohrmann, A., Altner, S.O., Vardar, E., Tanyaş, H., Mamtimin, M., Zhaojie, G., 2022. The Eurasian epicontinental sea was an important carbon sink during the Palaeocene-Eocene thermal maximum. *Commun. Earth Environ.* 3 <https://doi.org/10.1038/s43247-022-00451-4>.
- Khain, V.E., Popkov, V.I., Yudin, V.V., 2010. Paleodynamics of the southern margin of the East European craton. *Mosc. Univ. Geol. Bull.* 65, 59–65. <https://doi.org/10.3103/s0145875210020018>.
- Korab, T., Kotlarczyk, J., 1977. Młodszy paleogen jednostki dukielkiej w Karpatach Słowackich i próba jego powiązania z paleogenem polskim. In: *Annales Societatis Geologorum Poloniae*, pp. 93–114.
- Kotlarczyk, J., Uchman, A., 2012. Integrated ichnology and ichthyology of the Oligocene Menilit Formation, Skole and Subsilesian nappes, Polish Carpathians: A proxy to oxygenation history. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 331, 104–118.
- Kováč, M., Andreyeva-Grigorovich, A., Bajraktarević, Z., Brzobohatý, R., Filipescu, S., Fodor, L., Harzhauser, M., Oszczypko, N., Pavelić, D., Rögl, F., 2004. Paleogeography of the Central Paratethys during the Karpatian and Badenian. *Scr. Fac. Sci. Nat. Univ. Masaryk. Brun. Geol.* 31, 7–17.
- Kováč, M., Andreyeva-Grigorovich, A., Bajraktarević, Z., Brzobohatý, R., Filipescu, S., Fodor, L., Harzhauser, M., Nagymarosy, A., Oszczypko, N., Pavelić, D., Roegl, F., Saftic, B., Sliva, L., Studencka, B., 2007. Badenian evolution of the Central Paratethys Sea: paleogeography, climate and eustatic sea-level changes. *Geol. Carpath.* 58, 579–606.
- Kováč, M., Plašienka, D., Soták, J., Vojtko, R., Oszczypko, N., Less, G., Čosović, V., Fügenschuh, B., Králíková, S., 2016. Paleogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Glob. Planet. Chang.* 140, 9–27. <https://doi.org/10.1016/j.gloplacha.2016.03.007>.
- Kováč, M., Hudáková, N., Halášová, E., Kováčová, M., Holcová, K., Oszczypko-Clowes, M., Báldi, K., Less, G., Nagymarosy, A., Ruman, A., Klučiar, T., Jamrich, M., 2017a. The Central Paratethys palaeoceanography: A water circulation model based on microfossil proxies, climate, and changes of depositional environment. *Acta Geol. Slovaca* 9, 75–114.
- Kováč, M., Márton, E., Oszczypko, N., Vojtko, R., Hók, J., Králíková, S., Plašienka, D., Klučiar, T., Hudáková, N., Oszczypko-Clowes, M., 2017b. Neogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Glob. Planet. Chang.* 155, 133–154. <https://doi.org/10.1016/j.gloplacha.2017.07.004>.
- Krězsek, C., Schlöder, Z., Olaru-Florea, R., Tamas, A., Oteleanu, A., Stoicescu, A., Ungureanu, C., Dudus, R., Tari, G., 2023. Structure and petroleum systems of the Eastern Carpathians, Romania. *Mar. Pet. Geol.* 151 <https://doi.org/10.1016/j.marpetgeo.2023.106179>.
- Krijgsman, W., Meijer, P.T., 2008. Depositional environments of the Mediterranean “Lower Evaporites” of the Messinian salinity crisis: Constraints from quantitative analyses. *Mar. Geol.* 253, 73–81.
- Krijgsman, W., Stoica, M., Vasiliev, I., Popov, V.V., 2010. Rise and fall of the Paratethys Sea during the Messinian Salinity Crisis. *Earth Planet. Sci. Lett.* 290, 183–191. <https://doi.org/10.1016/j.epsl.2009.12.020>.
- Krijgsman, W., Tesakov, A., Yanina, T., Lazarev, S., Danukalova, G., Van Baak, C.G.C., Agustí, J., Alçiçek, M.C., Aliyeva, E., Bista, D., Bruch, A., Büyükeriç, Y., Bukhsianidze, M., Flecker, R., Frolov, P., Hoyle, T.M., Jorissen, E.L., Kirscher, U., Korić, S.A., Kroonenberg, S.B., Lordkipanidze, D., Oms, O., Rausch, L., Singarayer, J., Stoica, M., van de Velde, S., Titov, V.V., Wesselingh, F.P., 2019. Quaternary time scales for the Pontocaspian domain: Interbasinal connectivity and faunal evolution. *Earth-Sci. Rev.* 188, 1–40. <https://doi.org/10.1016/j.earscirev.2018.10.013>.
- Krijgsman, W., Palcu, D.V., Andreotto, F., Stoica, M., Mandic, O., 2020. Changing seas in the late Miocene Northern Aegean: A Paratethyan approach to Mediterranean basin evolution. *Earth-Sci. Rev.* 210, 103386 <https://doi.org/10.1016/j.earscirev.2020.103386>.
- Kruglyakova, R.P., Byakov, Y.A., Chalenko, L.A., Shevtsova, N.T., 2004. Natural oil and gas seeps on the Black Sea floor. *Geo-Marine Lett.* 24, 150–162. <https://doi.org/10.1007/s00367-004-0171-4>.
- Książkiewicz, M., 1975. Bathymetry of the Carpathian flysch basin. *Acta Geol. Pol.* 25, 309–368.
- Książkiewicz, M., 1977. Hipoteza ruchów kier lotosfery a powstanie Karpat. In: *Annales Societatis Geologorum Poloniae*, pp. 329–353.
- Lazarev, S., de Leeuw, A., Stoica, M., Mandic, O., van Baak, C.G.C., Vasiliev, I., Krijgsman, W., 2020. From Khersonian drying to Pontian “flooding”: late Miocene stratigraphy and palaeoenvironmental evolution of the Dacian Basin (Eastern Paratethys). *Glob. Planet. Chang.* 192, 103224 <https://doi.org/10.1016/j.gloplacha.2020.103224>.
- Leszczyński, S., 1997. Origin of the Sub-Menilit Globigerina Marl (Eocene-Oligocene Transition) in the Polish Outer Carpathians 67.
- Leszczyński, S., Malata, E., 2002. Sedimentary conditions in the Siary zone of the Magura basin (Carpathians) in the late Eocene-early Oligocene. *Ann. Soc. Geol. Pol.* 72, 201–239.
- Leszczyński, S., Dziadzio, P.S., Nemec, W., 2015. Some current sedimentological controversies in the Polish Carpathian flysch.
- Liu, S., Krijgsman, W., Dekkers, M.J., Palcu, D.V., 2017. Early diagenetic greigite as an indicator of paleosalinity changes in the middle Miocene Paratethys Sea of central Europe. *Geochemistry. Geophys. Geosystems* 18, 2634–2645. <https://doi.org/10.1002/2017GC006988>.
- Lugli, S., Manzi, V., Roveri, M., Schreiber, B.C., 2010. The Primary Lower Gypsum in the Mediterranean: A new facies interpretation for the first stage of the Messinian salinity crisis. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 297, 83–99. <https://doi.org/10.1016/j.palaeo.2010.07.017>.
- Lukeneder, S., Zuschin, M., Harzhauser, M., Mandic, O., 2011. Spatiotemporal signals and palaeoenvironments of endemic molluscan assemblages in the marine system of the sarmatian paratethys. *Acta Palaeontol. Pol.* 56, 767–784. <https://doi.org/10.4202/app.2010.0046>.
- Macarovič, N., Motas, C.I., Contescu, L., 1967. Caracteres stratigraphiques et sedimentologiques des depots sarmato-pliocenes de la courbe des Carpates Orientales. *Analele Stiintifice ale Univ. “Al. I. Cuza” din Iasi (serie noua)*. Secțiunea 2, 46–59.
- Magyar, Imre., 2021. Chronostratigraphy of clinothem-filled non-marine basins: Dating the Pannonian Stage. *Global and Planetary Change* 205, 103609.
- Magyar, I., Radivojević, D., Sztanó, O., Synak, R., Ujszászi, K., Pócsik, M., 2013. Progradation of the paleo-Danube shelf margin across the Pannonian Basin during the Late Miocene and Early Pliocene. *Glob. Planet. Chang.* 103, 168–173. <https://doi.org/10.1016/j.gloplacha.2012.06.007>.
- Mandic, O., Sant, K., Kallanxhi, M.E., Corić, S., Theobalt, D., Grunert, P., de Leeuw, A., Krijgsman, W., 2019. Integrated bio-magnetostratigraphy of the Badenian reference section Ugljevik in southern Pannonian Basin - implications for the Paratethys history (middle Miocene, Central Europe). *Glob. Planet. Chang.* 172, 374–395. <https://doi.org/10.1016/j.gloplacha.2018.10.010>.
- Măruțeanu, M., 1999. Litho- and biostratigraphy (calcareous nannoplankton) of the Miocene deposits from the outer Moldavides. *Geol. Carpath.* 50, 313–324.
- Matenco, L., Bertotti, G., 2000. Tertiary tectonic evolution of the external East Carpathians (Romania). *Tectonophysics* 316, 255–286. [https://doi.org/10.1016/S0040-1951\(99\)00261-9](https://doi.org/10.1016/S0040-1951(99)00261-9).
- Matenco, L., Bertotti, G., Dinu, C., Cloetingh, S., 1997. Tertiary tectonic evolution of the external South Carpathians and the adjacent Moesian platform (Romania). *Tectonics* 16, 896–911. <https://doi.org/10.1029/97TC01238>.
- Matenco, L., Bertotti, G., Cloetingh, S., Dinu, C., 2003. Subsidence analysis and tectonic evolution of the external Carpathian - Moesian Platform region during Neogene times. *Sediment. Geol.* 156, 71–94. [https://doi.org/10.1016/S0037-0738\(02\)00283-X](https://doi.org/10.1016/S0037-0738(02)00283-X).
- Matenco, L., Krězsek, C., Merten, S., Schmid, S., Cloetingh, S., Andriessen, P., Matenco, L., Kre, C., Andriessen, P., Krězsek, C., Merten, S., Cloetingh, S., Andriessen, P., Matenco, L., Kre, C., Andriessen, P., Krězsek, C., Merten, S., Schmid, S., Cloetingh, S., Andriessen, P., 2010. Characteristics of collisional orogens with low topographic build-up: An example from the Carpathians. *Terra Nova* 22, 155–165. <https://doi.org/10.1111/j.1365-3121.2010.00931.x>.
- Matoshko, A.A., Matoshko, A.A., de Leeuw, A., Stoica, M., 2016. Facies analysis of the Balta Formation: Evidence for a large late Miocene fluvio-deltaic system in the East Carpathian Foreland. *Sediment. Geol.* 343, 165–189. <https://doi.org/10.1016/j.sedgeo.2016.08.004>.
- Melinte, M.C., 2005. Oligocene palaeoenvironmental changes in the Romanian Carpathians, revealed by calcareous nannofossils. *Stud. Geol. Pol.* 124, 341.

- Melinte, M., Băceanu, 1996. Cretaceous and Tertiary arenites from the Bâsca Basin (Carpathians Flysch Bend). *Anu. Institutului Geol. al României* 69, 49–55.
- Melinte-Dobrinescu, M.C., Brustur, T., 2008. Oligocene–Lower Miocene events in Romania. *Acta Palaeontol. Rom.* 6, 203–215.
- Melinte-Dobrinescu, M.C., Stoica, M., 2014. Badenian calcareous nannofossil fluctuation in the Eastern Carpathians: palaeoenvironmental significance. *Acta Palaeontol. Rom.* 9, 47–57.
- Merklin, R.L., 1974. Handbook of Oligocene bivalvia of the south of the USSR. *Nauka*.
- Meruțiu, V., 1912. Contribuțiune la studiul masivelor de sare din România. *Stabilimentul de Arte Grafice Albert Baer*.
- Micu, M., 1982. Explanatory Notes to Lithotectonic Profiles of Miocene Molasses from Central Moldavia (Eastern Carpathians, România). *Veröff Zentralinst. Phys. Erde. Ad WDDR, Potsdam Comment to*.
- Miller, K.G., Browning, J.V., John Schmelz, W., Kopp, R.E., Mountain, G.S., Wright, J.D., 2020. Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. *Sci. Adv.* <https://doi.org/10.1126/sciadv.aaz1346>.
- Motaș, I.C., Marinescu, F., Popescu, G., 1976. Essai sur le Néogène de Roumanie. *An. Inst. Geol. Geof. I* 127–148.
- Mrazec, L., Popescu-Voitești, I., 1914. Contributions a la connaissance des nappes du Flysch Carpatique en Roumanie. *Annu. l'Institut Geol. Roum.* 5, 495–527.
- Müller, D.W., Mueller, P.A., 1991. Origin and age of the Mediterranean Messinian evaporites: implications from Sr isotopes. *Earth Planet. Sci. Lett.* 107, 1–12. [https://doi.org/10.1016/0012-821X\(91\)90039-K](https://doi.org/10.1016/0012-821X(91)90039-K).
- Munteanu, 1998. Geologia depozitelor miocene din zona v. Lopatna - v. Buzău. *Univ. "Al. I. Cuza" - Iași*.
- Murgeanu, G., Patrulius, D., Gherasi, N., Ghenea, A., Ghenea, C., 1968. Harta Geologică a României 1:200000. Scara 1.
- Necea, D., Fielitz, W., Matenco, L., 2005. Late Pliocene-Quaternary tectonics in the frontal part of the SE Carpathians: Insights from tectonic geomorphology. *Tectonophysics* 410, 137–156. <https://doi.org/10.1016/j.tecto.2005.05.047>.
- Neveskaja, L.A., Goncharova, I.A., Iljina, L.B., Paramonova, N.P., Khondkarian, S.O., 2003. a. [The Neogene stratigraphic scale of the Eastern Paratethys.] *Stratigrafiya. Geologicheskaya Korrelyatsiya*. 11 (2), 3026. See 105–127.
- Neveskaya, L.A., Goncharova, I.A., Il'ina, L.B., 1984. The regional stratigraphic scale of the Neogene of East Paratethys. *Soviet Geol.* 9, 37–49.
- Nowak, W., 1965. Sur l'origine organique des calcaires de Jaslo des couches ménilitiques et de Krosno dans les Carpates flyschueses (Oligocene). In: *Carpatho-Balkan Association, VII Congress, Sofia*, pp. 287–290.
- Oberhänsli, H., Hsü, K.J., 1986. Paleocene-Eocene Paleocyanography. *Mesozoic Cenozoic Ocean*, 15, pp. 85–100.
- Olariu, C., Krezsek, C., Jipa, D.C., 2018. The Danube River inception: Evidence for a 4 Ma continental-scale river born from segmented Paratethys basins. *Terra Nova* 30, 63–71. <https://doi.org/10.1111/ter.12308>.
- Olteanu, F., 1951a. Observații asupra "brecei sarii" la masivele de sare miocene cuprinse între valea Teleajenului și valea Bălăneasa, cu privire specială asupra regiunii Pietrari-Buzău (in Romanian). *Dări Seamă ale edinelor Institutului Geo-Log.* 32, 12–19.
- Olteanu, F., 1951b. Observatii asupra 'brecei sarii', cu masive de sare din regiunea mio-Pliocena dintre valea Teleajenului si pirul Balaneasa (cu privire speciala pentru regiunea Pietrari-Buzau). *Dari seama ale Sedint. Institutului Geol. al Rom.* 32, 12–18.
- Olteanu, F., 1953. Les facies et la tectonique du Miocene subcarpatique de la region de Berzunt. *DS Com. Geol. XXXVII*, 76–93.
- Oszczypko, N., Oszczypko-Clowes, M., 2012. Stages of development in the Polish Carpathian Foredeep basin. *Cent. Eur. J. Geosci.* <https://doi.org/10.2478/s13533-011-0044-0>.
- Oszczypko-Clowes, M., Zydek, B., 2012. Paleogeology of the Upper Eocene-Lower Oligocene Malcov Basin based on the calcareous nannofossils: A case study of the Leluchów section (Krynica Zone, Magura Nappe, Polish Outer Carpathians). *Geol. Carpath.* 63, 149–164. <https://doi.org/10.2478/v10096-012-0012-8>.
- Palcu, D.V., Krijgsman, W., 2021. The dire straits of Paratethys: Gateways to the anoxic giant of Eurasia. *Geol. Soc. London Spec. Publ.* 523 <https://doi.org/10.1144/SP523-2021-73>. SP523-2021–73.
- Palcu, D.V., Tulbure, M., Bartol, M., Kouwenhoven, T.J., Krijgsman, W., 2015. The Badenian – Sarmatian Extinction Event in the Carpathian foredeep basin of Romania: Paleogeographic changes in the Paratethys domain. *Glob. Planet. Chang.* 133, 346–358. <https://doi.org/10.1016/j.gloplacha.2015.08.014>.
- Palcu, D.V., Golovina, L.A., Vernyhorova, Y.V., Popov, S.V., Krijgsman, W., 2017. Middle Miocene paleoenvironmental crises in Central Eurasia caused by changes in marine gateway configuration. *Glob. Planet. Chang.* 158, 57–71. <https://doi.org/10.1016/j.gloplacha.2017.09.013>.
- Palcu, D.V., Vasiliev, I., Stoica, M., Krijgsman, W., 2019a. The end of the Great Khersonian Drying of Eurasia: Magnetostratigraphic dating of the Maeotian transgression in the Eastern Paratethys. *Basin Res.* 31, 33–58. <https://doi.org/10.1111/bre.12307>.
- Palcu, D.V., Popov, S.V., Golovina, L.A., Kuiper, K.F., Liu, S., Krijgsman, W., 2019b. The shutdown of an anoxic giant: Magnetostratigraphic dating of the end of the Maikop Sea. *Gondwana Res.* 67, 82–100. <https://doi.org/10.1016/j.jgr.2018.09.011>.
- Palcu, D.V., Patina, I.S., Șandric, I., Lazarev, S., Vasiliev, I., Stoica, M., Krijgsman, W., 2021. Late Miocene megaleak regressions in Eurasia. *Sci. Rep.* 11, 11471. <https://doi.org/10.1038/s41598-021-91001-z>.
- Pana, I., 1966. Studiul depozitelor pliocene din regiunea cuprinsa între valea Buzau si valea Balaneasa. *Stud. Teh. si Econ. J1-Stratigrafie*.
- Papaianopol, J., 1992. "Studiul stratigrafic al neogenului din molasa pericarpatica. Univ. "Al. I. Cuza, Iasi.
- Papp, A., Cicha, I., Rögl, F., Senes, J., Steininger, F.F., Baldi, T., 1974. Principes de la subdivision stratigraphique de la Paratéthys centrale. *Mem. BRGM* 78, 767–774.
- Pătruț, I., 1955. Geologia și tectonica regiunii Vălenii de Munte-Cosminel-Bușteni. *Anu. Institutului Geol. al României* 28, 5–98.
- Peryt, T.M., 2006. The beginning, development and termination of the Middle Miocene Badenian salinity crisis in Central Paratethys. *Sediment. Geol.* 188–189, 379–396. <https://doi.org/10.1016/j.sedgeo.2006.03.014>.
- Piller, W.E., Harzhauser, M., Mandić, O., 2007a. Miocene Central Paratethys stratigraphy. *Stratigraphy* 4, 151–168. <https://doi.org/10.1109/APPEEC.2009.4918425>.
- Piller, W.E., Harzhauser, M., Mandić, O., 2007b. Miocene Central Paratethys stratigraphy – current status and future directions. *Stratigraphy* 4, 151–168.
- Popescu, G., 1951. Observațiuni asupra "brecei sarii" și a unor masive de sare din zona paleogenă-miocenă a jud. Prahova (in Romanian). *Dări Seamă ale edinelor Institutului Geol.* 32, 3–12.
- Popescu, G., 1952. Zona Flișului paleogen între Valea Buzăului și Valea Vărbilăului (in Romanian). *Dări Seamă ale edinelor Institutului Geol.* 36, 113–125.
- Popescu, B.M., 1995. Romania's petroleum systems and their remaining potential. *Pet. Geosci.* 1, 337–350. <https://doi.org/10.1144/petgeo.1.4.337>.
- Popescu, L.G., Popescu, D.A., 2002. Studiul geologic al formațiunii de Gura Soimului din semiferastra Bistrita – Rasca (Panza de Vrancea – Carpatii Orientali) 2–6.
- Popescu-Voitești, I., 1915. "Panza conglomeratului de Bucegi în Valea Olteului cu date noi asupra structurii acestei văi în regiunea Carpaților Meridionali. Institutul de Arte Grafice" Carol Göbl.
- Popov, S.V., Rögl, F., Rozanov, A.Y., Steininger, F.F., Shcherba, I.G., Kováč, M., 2004. Lithological-paleogeographic maps of paratethys. *CFS Cour. Forschungsinstitut Senckenb.*
- Popov, S.V., Shcherba, I.G., Ilyina, L.B., Nevesskaya, L.A., Paramonova, N.P., Khondkarian, S.O., Magyar, I., 2006. Late Miocene to Pliocene paleogeography of the Paratethys and its relation to the Mediterranean. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 238, 91–106. <https://doi.org/10.1016/j.palaeo.2006.03.020>.
- Popov, S.V., Antipov, M.P., Zastrozhenov, A.S., Kurina, E.E., Pinchuk, T.N., 2010. Sea-level fluctuations on the northern shelf of the Eastern Paratethys in the Oligocene-Neogene. *Stratigr. Geol. Correl.* 18, 200–224. <https://doi.org/10.1134/s0869593810020073>.
- Popov, S.V., Rostovtseva, Y.V., Pinchuk, T.N., Patina, I.S., Goncharova, I.A., 2019. Oligocene to Neogene paleogeography and depositional environments of the Euxinian part of Paratethys in Crimean – Caucasian junction. *Mar. Pet. Geol.* 103, 163–175. <https://doi.org/10.1016/j.marpetgeo.2019.02.019>.
- Puglisi, D., Bădescu, D., Carbone, S., Corso, S., Franchi, R., Gigliuto, L.G.G., Loiacono, F., Miclăuș, C., Moretti, E., Bădescu, D., Carbone, S., Corso, S., Franchi, R., Gigliuto, L.G. G., Loiacono, F., Miclăuș, C., Moretti, E., 2006. Stratigraphy, petrography and paleogeographic significance of the Early Oligocene "menilitic facies" of the Tarcău Nappe (Eastern Carpathians, Romania). *Acta Geol. Pol.* 56, 105–120.
- Racki, G., Narkiewicz, M., 2006. Polskie zasady stratygrafii.
- Raffi, I., Wade, B.S., Pálke, H., Beu, A.G., Cooper, R., Crundwell, M.P., Krijgsman, W., Moore, T., Raine, I., Sardella, R., Vernyhorova, Y.V., 2020. Chapter 29 - The Neogene Period. In: *Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M.B.T.-G.T.S. 2020 (Eds.) Elsevier*, pp. 1141–1215. <https://doi.org/10.1016/B978-0-12-824360-2.00029-2>.
- Rasser, M.W., Harzhauser, M., Anistratenko, O.Y., Anistratenko, V.V., Bassi, D., Belak, M., Berger, J.P., Bianchini, G., Čičić, S., Čosović, V., Doláková, N., Drobne, K., Filipescu, S., Gürs, K., Hladilová, S., Hrvatović, H., Jelen, B., Kasiński, J.R., Kováč, M., Kralj, P., Marjanac, T., Márton, E., Mietto, P., Moro, A., Nagymarosy, A., Nebelsick, J.H., Nehyba, S., Ogorelec, B., Oszczypko, N., Pavelić, D., Pavlovic, R., Pavišić, J., Petrová, P., Piwocki, M., Poljak, M., Pogliase, N., Redžepović, R., Rifelj, H., Roetzler, R., Skaberne, D., Sliva, L., Standke, G., Tunis, G., Vass, D., Wägreich, M., Wesselingh, F., 2008. Palaeogene and Neogene. *Cent. Eur.* 6, 1031–1139. <https://doi.org/10.1144/cev2p.5>.
- Rasser, M.W., Harzhauser, M., Filipescu, S., Gu, K., Mietto, P., Moro, A., Standke, G., Tunis, G., 2016. Paleogene and Neogene of Central Europe.
- Rauball, J.F., 2020. Hydrocarbon potential of organic-rich sediments in the Ukrainian Outer Carpathians and its Foreland.
- Rauball, J.F., Sachsenhofer, R.F., Bechtel, A., Čorić, S., Gratzer, R., 2019. The oligocene-miocene menilitic formation in the Ukrainian Carpathians: a world-class source rock. *J. Pet. Geol.* 42, 393–415. <https://doi.org/10.1111/jpg.12743>.
- Raymo, M.E., 1994. The Himalayas, organic carbon burial, and climate in the Miocene. *Paleoceanography* 9, 399–404. <https://doi.org/10.1029/94PA00289>.
- Riboulot, V., Ker, S., Sultan, N., Thomas, Y., Marsset, B., Scalabrin, C., Ruffine, L., Boulart, C., Ion, G., 2018. Freshwater lake to salt-water sea causing widespread hydrate dissociation in the Black Sea. *Nat. Commun.* 9, 1–8. <https://doi.org/10.1038/s41467-017-02271-z>.
- Roban, R.D., Ducea, M.N., Mihalcea, V.I., Munteanu, I., Barbu, V., Melinte-Dobrinescu, M.C., Olariu, C., Vlăscanu, M., 2022. Provenance of Oligocene lithic and quartz arenites of the East Carpathians: Understanding sediment routing systems on compressional basin margins. *Basin Res.* 1–27 <https://doi.org/10.1111/bre.12711>.
- Rögl, F., 1998. Palaeogeographic Considerations for Mediterranean and Paratethys Seaways (Oligocene to Miocene). *Ann. des Naturhistorischen Museums Wien. Ser. A für Mineral. und Petrogr. Geol. und Paläontologie, Anthropol. und Prähistorie* 279–310. <https://doi.org/10.2307/4170219>.
- Rögl, F., 1999. Palaeogeographic considerations for Mediterranean and Paratethys seaways. *Ann. Naturhist. Mus. Wien* 99A, 279–310.
- Rögl, F., Spezzaferri, S., Čorić, S., 2002. Micropaleontology and biostratigraphy of the Karpatian-Badenian transition (Early-Middle Miocene boundary) in Austria (Central Paratethys). *CFS Cour. Forschungsinstitut Senckenb.* 237, 47–67.

- Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, S., Manzi, V., Sierro, F.J., Bertini, A., Camerlenghi, A., De Lange, G., Govers, R., Hilgen, F.J., Hübscher, C., Meijer, P.T., Stoica, M., 2014. The Messinian Salinity Crisis: Past and future of a great challenge for marine sciences. *Mar. Geol.* 352, 25–58. <https://doi.org/10.1016/j.margeo.2014.02.002>.
- Roveri, M., Gennari, R., Lugli, S., Manzi, V., Minelli, N., Reghizzi, M., Riva, A., Rossi, M. E., Schreiber, B.C., 2016. The Messinian salinity crisis: open problems and possible implications for Mediterranean petroleum systems. *Pet. Geosci.* 22, 283–290. <https://doi.org/10.1144/petgeo2015-089>.
- Rundic, L., Knezevic, S., Rakijas, M., 2014. Middle miocene badenian transgression: New evidences from the Vrdnik coal basin (Fruska Gora Mt., Northern Serbia). *Geol. Anal. Balk. poluostrvaAnnales g?ologiques la Penins. Balk.* 9–23. <https://doi.org/10.2298/gabp1374009r>.
- Rusu, A., 1977. La stratigraphie des depots oligocènes du nord-ouest de la Transylvanie (la region de Trăzneva-Hida-Poiana Blenchi). *Anu. Institutului Geol.* 69–223.
- Rusu, A., 1999. Rupelian mollusk fauna of Solenovian type found in Eastern Carpathians (Romania). *Acta Palaeontol. Rom.* 2, 449–452.
- Rusu, A., Popescu, G., Melinte, M., 1996. Oligocene-Miocene Transition and Main Geological Events in Romania. *Rom. J. Stratigr.* 76, 56.
- Rybár, S., Kováč, M., Šarinová, K., Halášová, E., Hudáčeková, N., Šujan, M., Kováčová, M., Ruman, A., Klučiar, T., 2016. Neogene changes in palaeogeography, palaeoenvironment and the provenance of sediment in the Northern Danube Basin. *Bull. Geosci.* 91, 367–398. <https://doi.org/10.3140/bull.geosci.1571>.
- Sachsenhofer, R.F., Popov, S.V., Čorić, S., Mayer, J., Misch, D., Morton, M.T., Pupp, M., Rauball, J., Tari, G., 2018. Paratethyan Petroleum Source Rocks: an Overview. *J. Pet. Geol.* 41, 219–245. <https://doi.org/10.1111/jpg.12702>.
- Săndulescu, M., 1984. *Geotectonica României* (translated title: Geotectonics of Romania). Ed. Tehnică, Bucharest.
- Săndulescu, M., 1988. Cenozoic Tectonic History of the Carpathians. In: *The Pannonian Basin: A Study in Basin Evolution*. AAPG Special Volumes, pp. 17–25.
- Săndulescu, M., 1990. Structure and tectonic history of the northern margin of Tethys between the Alps and the Caucasus. In: *Evolution of the Northern Margin of Tethys*, pp. 5–16. Vol II, *Memoires de La Societe Geologique de France*.
- Săndulescu, M., 1994. Overview on Romanian geology. *Rom. J. Tectonics Reg. Geol.* 3–15.
- Săndulescu, M., 2011. Structural and paleogeographic correlations of the Moldavides within the East Carpathian. *Rev. Roum. Géol.* 53, 54.
- Săndulescu, M., Popescu, G., Mărunteanu, M., 1995. Facies and stratigraphy of the Lower and Middle Miocene formations of the Slănic Syncline. *Rom. J. Stratigr.* 76, 3–11.
- Sant, K., Palcu, D.V., Mandic, O., Krijgsman, W., Palcu, D.V., Mandic, O., Krijgsman, W., Palcu, D.V., Mandic, O., Krijgsman, W., 2017. Changing seas in the Early–Middle Miocene of Central Europe: a Mediterranean approach to Paratethyan stratigraphy. *Terra Nova* 29, 273–281. <https://doi.org/10.1111/ter.12273>.
- Sant, K., Palcu, D.V., Turco, E., Di Stefano, A., Baldassini, N., Kouwenhoven, T., Kuiper, K.F., Krijgsman, W., 2019a. The mid-Langhian flooding in the eastern Central Paratethys: integrated stratigraphic data from the Transylvanian Basin and SE Carpathian Foredeep. *Int. J. Earth Sci.* 108, 2209–2232. <https://doi.org/10.1007/s00531-019-01757-z>.
- Sant, K., Palcu, D.V., Turco, E., Di Stefano, A., Baldassini, N., Kouwenhoven, T., Kuiper, K.F., Krijgsman, W., 2019b. Litho- and biostratigraphic data of lower-middle Miocene sections in the Transylvanian basin and SE Carpathian Foredeep (Romania). *Data Br.* 24, 103904. <https://doi.org/10.1016/j.dib.2019.103904>.
- Sant, K., Kuiper, K.F., Rybár, S., Grunert, P., Harzhauser, M., Mandic, O., Jamrich, M., Šarinová, K., Hudáčeková, N., Krijgsman, W., 2020. 40Ar/39Ar geochronology using high sensitivity mass spectrometry: Examples from middle Miocene horizons of the Central Paratethys. *Geol. Carpath.* 71, 166–182. <https://doi.org/10.31577/GeolCarp.71.2.5>.
- Saulea, E., Popescu, I., Săndulescu, J., 1969. *Lithofacies atlas*. Institutul Geol. si Geofiz, Bucharest.
- Schleder, Z., Tamas, D.M., Krézsek, C., Arnberger, K., Tulucan, A., 2019. Salt tectonics in the Bend Zone segment of the Carpathian fold and thrust belt, Romania. *Int. J. Earth Sci.* 108, 1595–1614. <https://doi.org/10.1007/s00531-019-01721-x>.
- Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M., Ustaszewski, K., 2008. The Alpine-Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss J. Geosci.* 101, 139–183. <https://doi.org/10.1007/s00015-008-1247-3>.
- Schmid, S.M., Fügenschuh, B., Kounov, A., Matenco, L., Nievergelt, P., Oberhänsli, R., Pleuger, J., Schefer, S., Schuster, R., Tomljenović, B., Ustaszewski, K., van Hinsbergen, D.J.J., 2019. Tectonic units of the Alpine collision zone between Eastern Alps and western Turkey. *Gondwana Res.* <https://doi.org/10.1016/j.gr.2019.07.005>.
- Schreilechner, M.G., Sachsenhofer, R.F., 2007. High resolution sequence stratigraphy in the eastern Styrian Basin (Miocene, Austria). *Austrian J. Earth Sci.* 100, 164–184.
- Schulz, H.M., Bechtel, A., Sachsenhofer, R.F., 2005. The birth of the Paratethys during the Early Oligocene: From Tethys to an ancient Black Sea analogue? *Glob. Planet. Chang.* 49, 163–176. <https://doi.org/10.1016/j.gloplacha.2005.07.001>.
- Selli, R., 1954. Il Bacino del Metauro. *G. di Geol.* 24, 1–294.
- Simon, D., Palcu, D.V., Meijer, P., Krijgsman, W., 2019. The sensitivity of middle Miocene paleoenvironments to changing marine gateways in Central Europe. *Geology* 47, 35–38. <https://doi.org/10.1130/G45698.1>.
- Ślaczka, A., 1996. Oil and gas in the Northern Carpathians.
- Ślaczka, A., Kruglov, S., Golonka, J., Oszczytko, N., Popadyuk, I., 2006. Geology and Hydrocarbon Resources of the Outer Carpathians, Poland, Slovakia, and Ukraine: General Geology. In: Golonka, J., Picha, F.J. (Eds.), *The Carpathians and their foreland: Geology and hydrocarbon resources*. AAPG Memoir 84, pp. 221–258.
- Ślaczka, A., Kruglov, S., Golonka, J., Oszczytko, N., Popadyuk, I., Kruglov, S., Golonka, J., Oszczytko, N., Popadyuk, I., 2006. Geology and hydrocarbon resources of the Outer Carpathians, Poland, Slovakia, and Ukraine: general geology. *Carpathians their Forel. Geol. Hydrocarb. Resour. AAPG Mem.* 84, 221–258. <https://doi.org/10.1306/985610m843070>.
- Sluijs, A., Zeebe, R.E., Bijl, P.K., Bohaty, S.M., 2013. A middle Eocene carbon cycle conundrum. *Nat. Geosci.* 6, 429–434. <https://doi.org/10.1038/ngeo1807>.
- Soták, J., 2010. Paleoenvironmental changes across the Eocene-Oligocene boundary: Insights from the Central-Carpathian Paleogene Basin. *Geol. Carpath.* 61, 393–418. <https://doi.org/10.2478/v10096-010-0024-1>.
- Sremac, J., Bošnjak Makovec, M., Vrsaljko, D., Karaica, B., Tripalo, K., Fio Firi, K., Majstorović Bušić, A., Marjanac, T., 2016. Reefs and Bioaccumulations in the Miocene Deposits of the North Croatian Basin – Amazing Diversity Yet To Be Described. *Rud. Zb.* 31, 19–29. <https://doi.org/10.17794/rgn.2016.1.2>.
- Starzec, K., Wendorff, M., Siemińska, A., Starzec, K., Godlewski Paweł Wendorff, M., 2018. Sedimentary response to tectonic uplift of the Dukla basin margin recorded at Skrzydlina – the Menilite Beds (Oligocene), Outer Carpathians, S Poland. *Geol. Geophys. Environ.* 44, 231. <https://doi.org/10.7494/geol.2018.44.2.231>.
- Ștefănescu, M., 1978. Stratigrafia și structura flisului cretacic și paleogen dintre valea Prahovei și valea Ialomiței. Teză de doctorat. Universitatea București. Gheța N., Dicea M.(1979) On the Oligocene-Miocene Boundary in tine Ex-ternal Flysch Zone of the Carpathian Bend. *Rev. Roum. géol., géoph., géogr., Géol.* 2, 89–94.
- Ștefănescu, M., 1984. The algal nature of certain calcareous rocks intercalated in the Doftana Molasse.
- Ștefănescu, M., Melinte, M., 1994. New data concerning the eocene/oligocene boundary in the outer flysch zone of the Buzău Valley Basin on the basis of the Nannoplankton Assemblages. *Rom. J. Stratigr.* 76, 61.
- Ștefănescu, M., Mărunteanu, M., Ștefănescu, M., Marunteanu, M., 1980. Age of the Doftana Molasse. *Dări Seamă ale Sediñelor Institutului Geol. si Geofiz.* 65, 169–182.
- Ștefănescu, M., Săndulescu, M., Butac, A., 1981. Genetical and Structural Relations Between Flysch and Molasse: The East Carpathian Model: Guide to Excursion A5. Institute of Geology and Geophysics.
- Ștefănescu, M., Popescu, I., Ștefănescu, M., Melinte, M., Ivan, V., Stănescu, V., 1989. Aspects of the possibilities of the lithological correlations of the Oligocene-Miocene boundary in the Buzău Valley. *Rom. J. Stratigr.* 75, 83–91.
- Ștefănescu, M., Popescu, I., Ștefănescu, M., Ivan, V., Melinte, M.C., Stănescu, V., 1993. Aspects of the possibilities of lithological correlation of the Oligocene - Lower Miocene deposits of the Buzau valley. *Rom. J. Stratigr.* 75, 83–90.
- Ștefănescu, M., Dicea, O., Butac, A., Ciulavru, D., 2007. Hydrocarbon Geology of the Romanian Carpathians, Their Foreland, and the Transylvanian Basin. *Carpathians their Foreland Geology Hydrocarb. Resour.* <https://doi.org/10.1306/985619m843077>.
- Steininger, F.F., Godfrid, W., 1999. From the Tethyan Ocean to the Paratethys Sea: Oligocene to Neogene Stratigraphy, Paleogeography and circum-Mediterranean region and the Oligocene to Neogene Basin evolution in Austria. *Mitteilungen Gesellschaft Geol. Bergbaustudenten Österreich* 92, 96–116.
- Steininger, F.F., Rögl, F., 1984. Paleogeography and palinspastic reconstruction of the Neogene of the Mediterranean and Paratethys. *Geol. Soc. Spec. Publ.* 17, 659–668. <https://doi.org/10.1144/GSL.SP.1984.017.01.52>.
- Stoica, C., 1944. Paleogenul din valea Sibiului (jud Buzău). *Rev. Muzeului Geol. Miniera. Univ. Cluj-Napoca* 8, 64–85.
- Stoica, C., 1953. Stratele de Gura Șoimului – Tazlău. *Rev. Univ."C.I.Parhon" și Polit. București*, St. Nat.: 171–176.
- Stoica, M., Lazăr, I., Vasiliev, I., Krijgsman, W., 2007. Mollusc assemblages of the Pontian and Dacian deposits from the Topolog-Argeș area (southern Carpathian foredeep - Romania). *Geobios* 40, 391–405. <https://doi.org/10.1016/j.geobios.2006.11.004>.
- Stoica, M., Lazăr, I., Krijgsman, W., Vasiliev, I., Jipa, D., Floroiu, A., 2013. Paleoenvironmental evolution of the East Carpathian foredeep during the late Miocene-early Pliocene (Dacian Basin; Romania). *Glob. Planet. Chang.* 103, 135–148. <https://doi.org/10.1016/j.gloplacha.2012.04.004>.
- Studencka, B., 1999. Remarks on Miocene bivalve zonation in the polish part of the Carpathian Foredeep. *Kwartalnik Geol.* 43, 467–477.
- Studencka, B., 2016. The Medobory Hills (Ukraine): Middle Miocene reef systems in the Paratethys , their biological diversity and lithofacies.
- Studencka, B., Jasionowski, M., 2011. Bivalves from the Middle Miocene reefs of Poland and Ukraine: A new approach to Badenian/Sarmatian boundary in the Paratethys. *Acta Geol. Pol.* 61, 79–114.
- Švábenická, L., 2002. Calcareous Nannofossils of the Upper Karpatian and Lower Badenian Deposits in the Carpathian Foredeep , Moravia (Czech Republic). *Geol. Carpath.* 53, 197–210.
- Sztanó, O., 1995. Paleogeographic significance of tidal deposits: an example from an early Miocene Paratethys embayment, Northern Hungary. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 113, 173–187. [https://doi.org/10.1016/0031-0182\(95\)00054-P](https://doi.org/10.1016/0031-0182(95)00054-P).
- Tamaş, D.M., Schleder, Z., Krézsek, C., Man, S., Filipescu, S., 2018. Understanding salt in orogenic settings: The evolution of ideas in the Romanian Carpathians. *Am. Assoc. Pet. Geol. Bull.* 102, 941–958. <https://doi.org/10.1306/0913171615517088>.
- Tărăpoancă, M., Bertotti, G., Mañenco, L., Dinu, C., Cloetingh, S.A.P.L., 2003. Architecture of the Focșani Depression: A 13 km deep basin in the Carpathians bend zone (Romania). *Tectonics* 22. <https://doi.org/10.1029/2002tc001486> n/a–n/a.
- Teisseyre, W., 1911. *Harta geologică. Văleni de Munte. Ediție provizorie*.
- ter Borgh, M., Vasiliev, I., Stoica, M., Knežević, S., Matenco, L., Krijgsman, W., Rundić, L., Cloetingh, S., 2013. The isolation of the Pannonian basin (Central Paratethys): New constraints from magnetostratigraphy and biostratigraphy. *Glob. Planet. Chang.* 103, 99–118. <https://doi.org/10.1016/j.gloplacha.2012.10.001>.

- Tet'ák, F., Pivko, D., Kováčik, M., 2019. Depositional systems and paleogeography of Upper Cretaceous-Paleogene deep-sea flysch deposits of the Magura Basin (Western Carpathians). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 533, 109250 <https://doi.org/10.1016/j.palaeo.2019.109250>.
- Tischler, M., Matenco, L., Filipescu, S., Gröger, H.R., Wetzel, A., Fügenschuh, B., 2008. Tectonics and sedimentation during convergence of the ALCAPA and Tisza-Dacia continental blocks: the Pienide nappe emplacement and its foredeep (N. Romania). *Geol. Soc. London Spec. Publ.* 298, 317–334. <https://doi.org/10.1144/SP298.15>.
- Vakarcs, G., Hardenbol, J., Abreu, V.S., Vail, P.R., Várnai, P., Tari, G., 1998. Oligocene-Middle Miocene depositional sequences of the central Paratethys and their correlation with regional stages.
- Van Baak, C.G.C.C., Mandic, O., Lazar, I., Stoica, M., Krijgsman, W., 2015. The Slanicul de Buzau section, a unit stratotype for the Romanian stage of the Dacian Basin (Plio-Pleistocene, Eastern Paratethys). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 440, 594–613. <https://doi.org/10.1016/j.palaeo.2015.09.022>.
- van Baak, C.G.C.C., Krijgsman, W., Magyar, I., Sztanó, O., Golovina, L.A., Grothe, A., Hoyle, T.M., Mandic, O., Patina, I.S., Popov, S.V., Radionova, E.P., Stoica, M., Vasiliev, I., 2017. Paratethys response to the Messinian salinity crisis. *Earth-Sci. Rev.* 172, 193–223. <https://doi.org/10.1016/j.earscirev.2017.07.015>.
- van der Boon, A., van der Ploeg, R., Cramwinckel, M.J., Kuiper, K.F., Popov, S.V., Tabachnikova, I.P., Palcu, D.V., Krijgsman, W., 2019. Integrated stratigraphy of the Eocene-Oligocene deposits of the northern Caucasus (Belaya River, Russia): Intermittent oxygen-depleted episodes in the Peri-Tethys and Paratethys. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 536, 109395 <https://doi.org/10.1016/j.palaeo.2019.109395>.
- van der Boon, A., Kuiper, K.F., van der Ploeg, R., Cramwinckel, M.J., Honarmand, M., Sluijs, A., Krijgsman, W., 2021. Exploring a link between the Middle Eocene Climatic Optimum and Neotethys continental arc flare-up. *Clim. Past* 17, 229–239. <https://doi.org/10.5194/cp-17-229-2021>.
- Vasiliev, I., Krijgsman, W., Stoica, M., Langereis, C.G., 2005. Mio-Pliocene magnetostratigraphy in the southern Carpathian foredeep and Mediterranean-Paratethys correlations. *Terra Nova* 17, 376–384. <https://doi.org/10.1111/j.1365-3121.2005.00624.x>.
- Vasiliev, I., Reichart, G.J., Davies, G.R., Krijgsman, W., Stoica, M., 2010. Strontium isotope ratios of the Eastern Paratethys during the Mio-Pliocene transition; Implications for interbasinal connectivity. *Earth Planet. Sci. Lett.* 292, 123–131. <https://doi.org/10.1016/j.epsl.2010.01.027>.
- Vasiliev, I., Stoica, M., Grothe, A., Lazarev, S., Palcu, D.V., Baak, C., Leeuw, A., Sangiorgi, F., Reichart, G., Davies, G.R., Krijgsman, W., 2021. Hydrological Changes in Restricted Basins: Insights From Strontium Isotopes on Late Miocene-Pliocene Connectivity of the Eastern Paratethys (Dacian Basin, Romania). *Geochemistry. Geophys. Geosystems* 22, 1–18. <https://doi.org/10.1029/2020gc009369>.
- Vassilev, A., Dimitrov, L., 2002. Spatial and quantitative evaluation of the Black Sea gas hydrates. *Geol. Geofiz.* 43, 672–684.
- Vetö, I., 1987. An oligocene sink for organic carbon: Upwelling in the paratethys? *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 60, 143–153. [https://doi.org/10.1016/0031-0182\(87\)90029-0](https://doi.org/10.1016/0031-0182(87)90029-0).
- Waskowska, A., 2015. The eocene hieroglyphic beds of the silesian nappe in the western polish carpathians - Their development and foraminiferal record. *Geol. Q.* 59, 271–299. <https://doi.org/10.7306/gq.1213>.
- Waskowska, A., Golonka, J., Machowski, G., 2015. Black Eocene in the Silesian Nappe 80–81.
- Zastrozhnov, A.S., Popov, S.V., Beniamovsky, V.N., Musatov, V.A., Akhmetiev, M.A., Zaporozhets, N.I., Bogachkin, A.B., Stolyarov, A.S., 2019. The Oligocene Reference Section in the South of the East European Platform (Northern Ergeni). *Stratigr. Geol. Correl.* 27, 442–474. <https://doi.org/10.1134/S0869593819040063>.
- Zhang, Y.G., Pagani, M., Liu, Z., Bohaty, S.M., Deconto, R., 2013. A 40-million-year history of atmospheric CO₂. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 371 <https://doi.org/10.1098/rsta.2013.0096>.