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Reshaping the Understanding of the Paratethys using Paleogeographic Reconstructions and Geochronology Studies

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Abstract. The history of the Paratethys and its inhabiting organisms was profoundly influenced by its connections with the Global Ocean. As the sea-straits linking Paratethys with the ocean expanded, they integrated the Paratethys with the global ocean, causing its water level to mirror the global eustatic fluctuations. These intervals of increased ocean connectivity existed during most part of the Oligocene–Early Miocene, in the Early Badenian–Tarkhanian, and in the Late Badenian–Konkian, when also fostered favourable environments for marine life to flourish in the Paratethys.

When the marine connections became unstable and the sea-straits closed (e.g., in the second half of Ruppelian–Solenovian time, late Ottnangian–Kotzakhurian, middle Badenian–Karaganian and from the onset of the Sarmatian up to the Pliocene), ransformed into vast lacustrine waterbodies where water levels and salinities were controlled by the balance between river runoff and precipitation versus evaporation.

Excess of water led to the basin expansion and brackish conditions, while deficits caused contraction and fragmentation. This resulted in hypersaline basins and lagoons co-existing with freshwater lakes, creating diverse environments and faunas that hindered effective biostratigraphic correlations. These fluctuations caused the decline of the marine biota, leaving behind only euribiontic organisms capable of enduring drastic shifts in salinity, ion composition, and oxygen levels. Over time, these survivors diversified and gave rise to endemic faunal communities adapted to the brackish environments.

The history of the faunistic and phytoplankton composition of the Carpathian part of the basin (Central Paratethys) became noticeably different from the Euxine-Caspian ones from the beginning of the Neogene, which led to different stratigraphic schemes of these parts of the Paratethys. In recent decades, our focus has centred on refining our understanding of the Eastern Paratethys paleogeography. While the periods of high base levels in the Eastern Paratethys are well-documented, the significant base-level drops during isolation phases have often been overlooked. This was primarily because, until recently, there

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were no effective methods for reconstructing the paleogeography and geochronology of Paratethys during these episodes of base-level drops. However, with the advancements in seismic stratigraphy and the utilization of integrated magneto-bio-stratigraphy, we now possess the means to explore the scale and spatial distribution of paleogeographic changes, particularly during the substantial basin reductions in partial desiccation periods. Large regressions (during second part of the Ruppelian, terminal Tarkhanian and Sarmatian in the Eastern Paratethys and during early Pliocene in the Caspian basin) erode parts of sedimentary layers, forming surfaces of inconsistency between geological bodies accumulated before and after the sea-level drop, which can be traced on seismic profiles as erosion boundaries. By deciphering such surfaces and the depth of river incisions flowing into the basin, it is now possible to reconstruct the relief picture resulting from these erosions and quantify the depth of base-level drops in the Paratethys during the largest regressions.

Key words:
Paleogene, Neogene, Sea level, Transgression, Regression.

Апстракт. На развој Паратетиса и његове фауне значајно је утицала његова веза са светским морем. Како су се морски мореузи који повезују Паратетис са океаном ширили, они су повезали Паратетис са светским океаном, узрокујући да ниво воде у басену одражава глобалне еустатичке флуктуације. Ови интервали интензивне повезаности са океаном постојали су током већег дела олигоцена–раног миоцена, у раном и касном бадену, када су условили повољно окружење за процват морског света у Паратетису.

Када је веза са океаном постала нестабилна и морски мореузи затворени (нпр. у другој половини рупелско–соленовског ката, касног отнанга–коцахурског ката, средњег бадена–караганског ката и од почетка сармата до плиоцена), формирана су велика језера у којима је ниво воде и салинитет контролисан равнотежом између речног отицања и количином падавина у односу на испаравање.

Већи прилив воде је условљавао проширење басена и стварање бочатих услова, док је недостатак воде проузроковао смањење и фрагментацију басена. Ово је довело до тога да хиперсалински басени и лагуне коегзистирају са слатководним језерима, стварајући разноврсна окружења и различит састав фауне што је отежавало адекватне биостратиграфске корелације. Ова колебања су изазвала смањење броја маринских организама, остављајући за собом само еврибиотичке организме способне да издрже драстичне промене у салинитету, саставу јона и нивоу кисеоника. Током времена, преживели организми су се диверзификовали и довели до стварања ендемских фаунских заједница прилагођених бракичним условима живота.

Развој фауне и фитопланктона у карпатском делу басена (Централни Паратетис) се значајно разликовао од еуксинског-каспијског са почетка неогена, што је довело до различитих стратиграфских шема ових делова Паратетиса. Последњих деценија, наш фокус је био усредсређен на унапређење разумевања палеогеографије Источног Паратетиса. Док су периоди високог нивоа воденог стуба у басену Источног Паратетиса добро документовани, значајно опадање нивоа током фаза изолације често је занемарено. Ово је првенствено последица тога што до недавно није било ефикасних метода за реконструкцију палеогеографије и геохронологије Паратетиса током оваквих периода. Међутим, са напретком сеизмичке стратиграфије и применом интегрисане магнето-биостратиграфије, сада имамо могућност да истражујемо обим и просторну дистрибуцију палеогеографских промена, посебно током значајног смањења басена за време периода његовог делимичног исушивања. Велике регресије (током другог дела рупелског, краја тархханског ката и сармата у источном Паратетису и током раног плиоцена у каспијском басену) условљавају ерозију седиментних слојева и формирање дискордатних површи између слојева акумулираних пре и након пада нивоа мора, који се на сеизмичким профилима могу пратити као ерозивне границе. Откривањем таквих површина и дубине речних корита који се уливају у басен, сада је могуће реконструисати изглед рељефа који је настао као резултат ерозије и квантификовати дубину воде Паратетиса током периода највећих регресија.

Кључне речи:
палеоген, неоген, ниво мора, трансгресија, регресија.

Introduction

During the Mesozoic and early Cenozoic, the southern and eastern margins of the East European Platform were submerged under shallow seas, connecting to the North Atlantic in the west with and the vast Tethys Ocean to the south, effectively blending the waters of the Indian and Atlantic Oceans (Fig. 1). Plate tectonics gradually closed this ocean due to the northward movement of the African and Indian continents. About 40 million years ago, during the Eocene, the collision of the African-Arabian and Indian continental plates with the Eurasian plate commenced, resulting in critical geological changes such as orogenesis and volcanic activity. As a result of this collision and deformations of the sedimentary cover, the Alpine folding belt was formed. This collision led to the formation of the Alpine folding belt, accompanied by a wide zone of depressions., A massive inland basin called Paratethys (LASKAREV, 1924) formed to the north of the Alpine uplift zone during the Eocene – Oligocene transition, about 34 million years ago (according to BALDI et al., 1984; POPOV et al., 2004; SCHULZ et al., 2005).

The tectonic processes occurring at the contact zone of the African and Eurasian continents, coupled with the loss of deep-sea connection between the oceans, significantly transformed global oceanic circulation. This resulted in a rapid thermal separation of waters, with heated near-surface layers and very cold deep waters descending towards the polar regions. Consequently, the global climate trend shifted towards a cold snap, accompanied by intermittent formation of polar ice caps. These changes played a crucial role in causing fluctuations in the level of the World Ocean.

Paleogeographic method

Studying the facial composition of deposits, fossilized remains of organisms, and their biogeographic structure, allows us to reconstruct the paleogeography of seas in the distant past, providing insights into coastal lines, the near-shore zone of the shelf, and deep-sea troughs, and the ecological conditions in

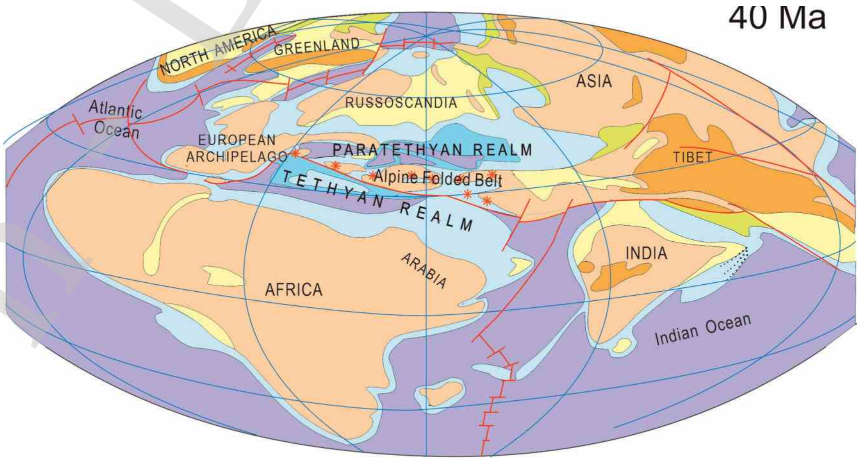

Fig. 1. *Map depicting the paleogeography of Eurasia and nearby territories in the second half of the Eocene epoch of the Paleogene period (40 Ma) (POPOV et al., 2004). Legend shown in Fig. 3.*

basins and their connections (Popov et al., 2001, 2004; Popov & Patina, 2023). In the beginning of the Oligocene, the waters of the Paratethys were teemed with diverse marine flora and fauna, akin to the contemporary North Atlantic fauna but adapted to warmer climates (Amitrov, 1993; Popov et al., 2002). This diverse biota included mollusks, foraminifera, ostracods, diatoms algae, nannoplankton, fish, and marine mammals with mineralized skeletons, which could be preserved as fossils in sedimentary layers. Analysis of terrestrial vegetation remains, spores and pollen aids in reconstructing past climatic changes of past epochs.

Throughout the Neogene period, the biota of the Paratethys was profoundly influenced by its connections with open marine basins. During time when wide and deep marine straits were present, the water level in the Paratethys mirrored that of the World Ocean, fostering rich marine fauna and plankton populations (Nevesskaya et al., 1986; Krasheninnikov et al., 2003). Conversely, when connections were limited, a significant portion of marine organisms faced extinction. The water level in the basin was then regulated by the balance between inflow, evaporation, and the potential discharge of excess water into neighbouring basins (Popov et al., 2010).

Fossils of animals and phytoplankton, preserved in ancient sea sediments serve as sensitive indicators of environmental changes (Nevesskaya et al., 2005). When a basin becomes isolated and marine fauna declines, only resilient organisms capable of withstanding oxygen-depleted environments and fluctuating levels of ions, pH and salinity can survive. These survivors play a crucial role in the emergence of new species, genera, and even families, particularly in the absence of competitors, leading to a significant acceleration in the rate of endemics evolution. Detailed stratigraphic research has facilitated precise dating of the major stages in the history of the Paratethys basins (Andrusov, 1961, 1963; Nevesskaya et al., 1986; Popov et al., 2022).

Paleomagnetic Methods for advancing Paleogeographic Reconstructions

A robust geochronological framework is crucial for advancing paleogeographic reconstructions. However, establishing the chronology of events in Paratethys presents notable challenges (Papp et al., 1974; Harzhauser & Piller, 2004; Palcu & Krijgsman, 2021). The presence of endemic faunas, alongside sparse marine elements in the Paratethys environments throughout its history, significantly complicates fossil utilization (Harzhauser & Piller, 1998). Furthermore, pervasive tectonic activity has obscured the tracing of ocean regression-transgression cycles across much of the basin (Mandic et al., 2019), except for brief intervals characterized by improved ocean connections and reduced tectonic disturbance. Additionally, the sensitivity of lithological records to local events and the instability of the Paratethyan water chemistry due to ever unstable marine connections (Lirer et al., 2009) have hindered the broad use of chemostratigraphy or cyclostratigraphy as a geochronological tool (Auer et al., 2015).

To answer these challenges, the primary methods for establishing geochronological markers have relied on a regional stratigraphic framework based on Paratethys' endemic fauna (Raffi et al., 2020; Popov et al., 2022; Palcu et al., 2023), combined with paleomagnetism (Vasiliev, 2006; van Baak et al., 2016; Palcu, 2018; Krijgsman et al., 2019), and, where feasible, isotopic tephrochronology (de Leeuw et al., 2010; Lukács et al., 2018; Sant et al., 2020). While isotopic tephrochronology is limited to volcanic tephra marker beds, magnetostratigraphic dating offers broader applicability. Magnetic stratigraphy, or magnetostratigraphy, serves as a potent tool for paleogeographic reconstructions by analysing the magnetic properties of sedimentary rocks to identify polarity reversals and establish precise chronological sequences (Langereiset al., 2010).

This approach not only aids in pinpointing the timing of significant geological events, such as sea-level fluctuations and basin reductions but also provides insights into their spatial distribution (e.g., Palcu et al., 2019a). Thus, magnetostratigraphy assumed a pivotal role in deepening our comprehension of the intricate interplay between tectonics, sea-level variations, and climate evolution throughout Paratethys history (Vasiliev et al., 2005; Krijgsman et al., 2010; Paulissen et al., 2011; Trubikhin & Pilipenko, 2011; van Baak et al., 2015; Sant et al., 2017; Palcu et al., 2019a; Pilipenko et al., 2019; van der Boon et al., 2019; Mandic et al., 2019; Lazarev et al., 2020). Critically, the use of this method has solved the challenges presented by diachronous events in the fragmented basins of the Paratethys during times of disconnection from the ocean (e.g., Palcu et al., 2021). In recent decades, efforts to date the Paratethys regional stages using paleomagnetism have proven very successful (Fig. 2), opening the way for more detailed local cyclostratigraphic studies (Rybkina & Rostovtseva, 2014; Rybkina et al., 2015; Rostovtseva & Rybkina, 2017; Popov et al., 2022) and reshaping the interpretations of the paleogeographic evolution of Paratethys (Steininger & Rögl, 1984; Rögl, 1998; Magyar et al., 1999; Popov et al., 2004, 2019; Kováč et al., 2007).

Main stages in the Paratethys history

Paleogene basins (60–34 million years ago). During the first half of the Paleogene period, a wide and deep marine basin known as the Tethys Ocean existed between Africa and Eurasia. Throughout this period, the seas of Eurasia maintained stable connections with the Tethys through straits located in relief depressions between the folded zones (Palcu & Krijgsman, 2021). Communication with the North Atlantic occurred via the Pre-Alpine and Pre-Carpathian troughs, as well as depressions in the territory of modern northern Poland and the Dnieper–Donetsk depression (Palcu & Krijgsman, 2021).

Around 40 million years ago, during the middle Eocene epoch, the uplift of the Alpine Mountain ranges and the volcanic belt that accompanied it intensified (Fig. 1, for more detail see Popov et al., 2004, map 1). By the end of the Eocene, further convergence of the African–Arabian plate with Eurasia, along with eustatic sea-level changes, resulted in a reduction of open marine basins space (Schmid et al., 2020). The activation of tectonic processes led to the emergence of new folded areas along the collision boundary of the plates. These newly formed uplifts hindered the free communication of water masses in the basins and set the stage for the future isolation of Paratethys (van der Boon et al., 2019; Cramwinckel et al., 2023).

Oligocene–Early Miocene (Maikopian) Basin (34–15 million years ago). Approximately 34 million years ago, at the onset of the Oligocene epoch of the Paleogene period, the growth of the Alpine Mountains (Schmid et al., 2020) and a drop in eustatic sea levels (Westerhold et al., 2020; Hutchinson et al., 2021) significantly reduced the connection between the Paratethys area and open seas (Baldi et al., 1984; Rögl, 1996; Popov et al., 2002, 2004). Consequently, a unique hydrological regime developed in it, leading to the formation of endemic species and genera (Melinte, 2005). This marked the beginning of the Paratethys as an intracontinental sea with unstable characteristics, including salinity, pH, and oxygen regimes (Baldi et al., 1984; Popov et al., 2002; Schulz et al., 2005; Sachsenhofer et al, 2017). Connections with the North Atlantic (Fig. 3), occurred during first part and end of the Early Oligocene, facilitating the influx of marine fauna and phytoplankton. The biogeographical connection with the Central Iranian and Mesopotamian basins, which open into the Indian Ocean, was more limited, hindered by both terrestrial and climatic barriers that impeded faunal migrations (Fig. 3). During the peak of the Early Oligocene transgression, the flooding of the Paratethys basin into the southwest part of the West Siberian Lowland acted as an obstacle to the spread of terrestrial mammals (Popov et al., 2002).

Similar to the modern Black Sea, the Oligocene–Early Miocene Paratethys had a stagnant (estuarine) water circulation system. Saltwater from the open sea entered the basin through straits, sinking to the bottom, while freshwater from river runoff washed over the upper layers. Due to the lack of vertical mixing, the lower layers of water (deeper than 200m in the Black Sea) contained very little oxygen, making life on the sea floor impossible for all taxa except extremophiles. Dead organisms and animal remains from the oxygenated upper layer fell and settled on the bottom of the sea, creating an oxygen-deprived zone. These sediments became enriched in organic matter, triggering the formation of hydrogen sulphide. It is estimated that in the Maikopian basin, the entire deep-water zone was devoid of life and contaminated with hydrogen sulphide (Sachsenhofer et al, 2017).

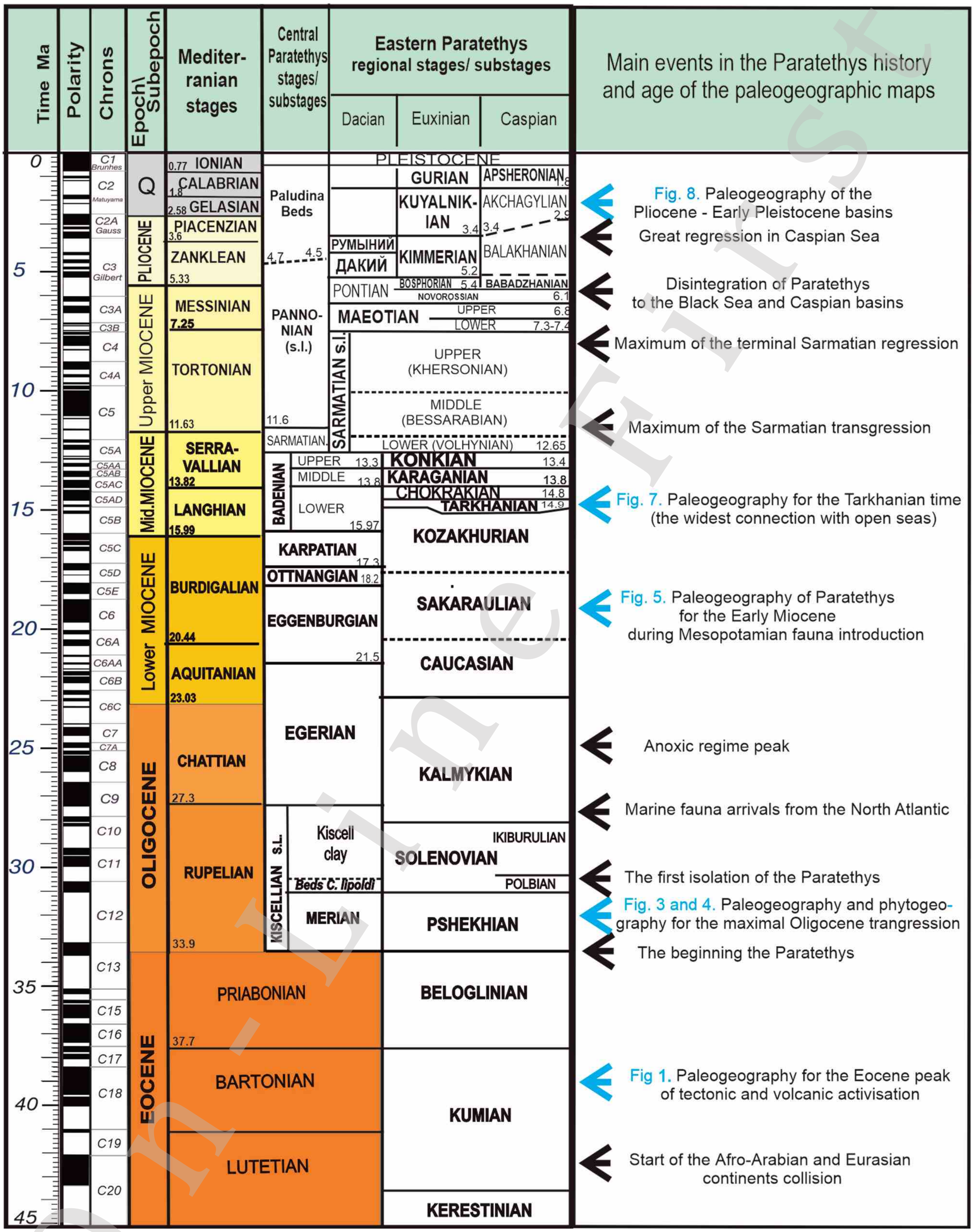

Fig. 2. *Stratigraphic scales of the Mediterranean, Central and Eastern Paratethys (according to* Palcu *et al., 2017, 2019;* Gradstein*, 2020;* Popov *et al., 2022) and the main events of the Paratethys evolution. The blue arrows show the stratigraphic levels for which the paleogeographic maps are given.*

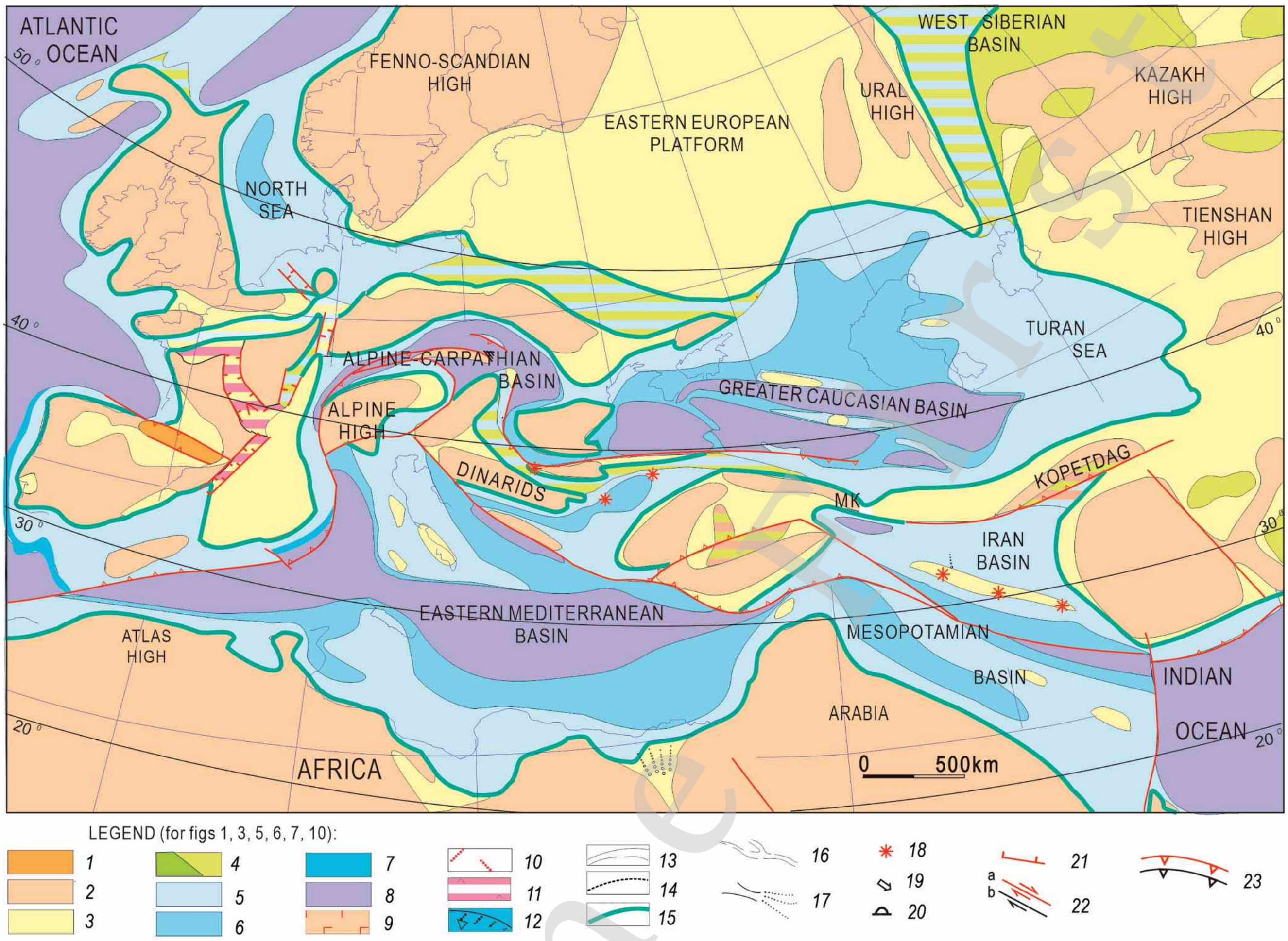

Fig. 3. Paleogeographic map of the Western Eurasia in the first half of the Early Oligocene (32–34 Ma) (after Popov *et al., 2004, modified). Legend (for all paleogeographic maps):* ***1.*** *mountains;* ***2.*** *high lands;* ***3.*** *low lands;* ***4.*** *lagoons and lakes;* ***5.*** *shallow shelf;* ***6.*** *deep shelf;* ***7.*** *depressions; 8. bathyal;* ***9.*** *intrusive massifs;* ***10.*** *acidic extrusives;* ***11.*** *salt marches and lagoons;* ***12.*** *slopes of depressions;* ***13.*** *paleogeographic boundaries;* ***14.*** *facial boundaries;* ***15.*** *sea\continental boundary;* ***16.*** *river valleys;* ***17.*** *river deltas, fans;* ***18.*** *volcanoes;* ***19.*** *sediment source;* ***20.*** *bioherms;* ***21.*** *faults;* ***22.*** *thrusts (active - red, subsequent – black);* ***23.*** *shifts active and subsequent.*

The Eastern Paratethys fauna composition was influenced by limited water exchange with warm southern seas and inflow of relatively cold waters from the North Atlantic, placing it in the North European biogeographic region (Popov et al., 2002). Adjacent basins hosted tropical-subtropical faunas, including various reef-forming corals and nummulites (*N. intermedius, N. vascus*, and *N. fichteli* in the Carpathian part of the basin).

The vegetation along the shores of the Paratethys exhibited a wide range of compositions and requirements for climatic conditions and humidity levels. Stretching across the entire northern coast were forests characterized by deciduous, moderately moisture-loving coniferous-broadleaf species including laurels, castanopses, and the other primitive Fagaceae (in the Pasekovo association: Akhmetiev data in Popov et al., 2002). On the Kazakh Upland and the low northern slopes of the Tian Shan Mountain range, drought-resistant oak-laurel forests and hard-leaved shrubs formed by legumes and ericaceans thrived. In the southern territories, an arid Central Asian province emerged, dominated by shrubby-herbaceous formations containing salt-tolerant plants like *Ephedra* and *Artemisia*. Meanwhile, islands and the southern coast of Paratethys were enveloped by moist subtropical forests characteristic of the Tethyan region (Fig. 4).

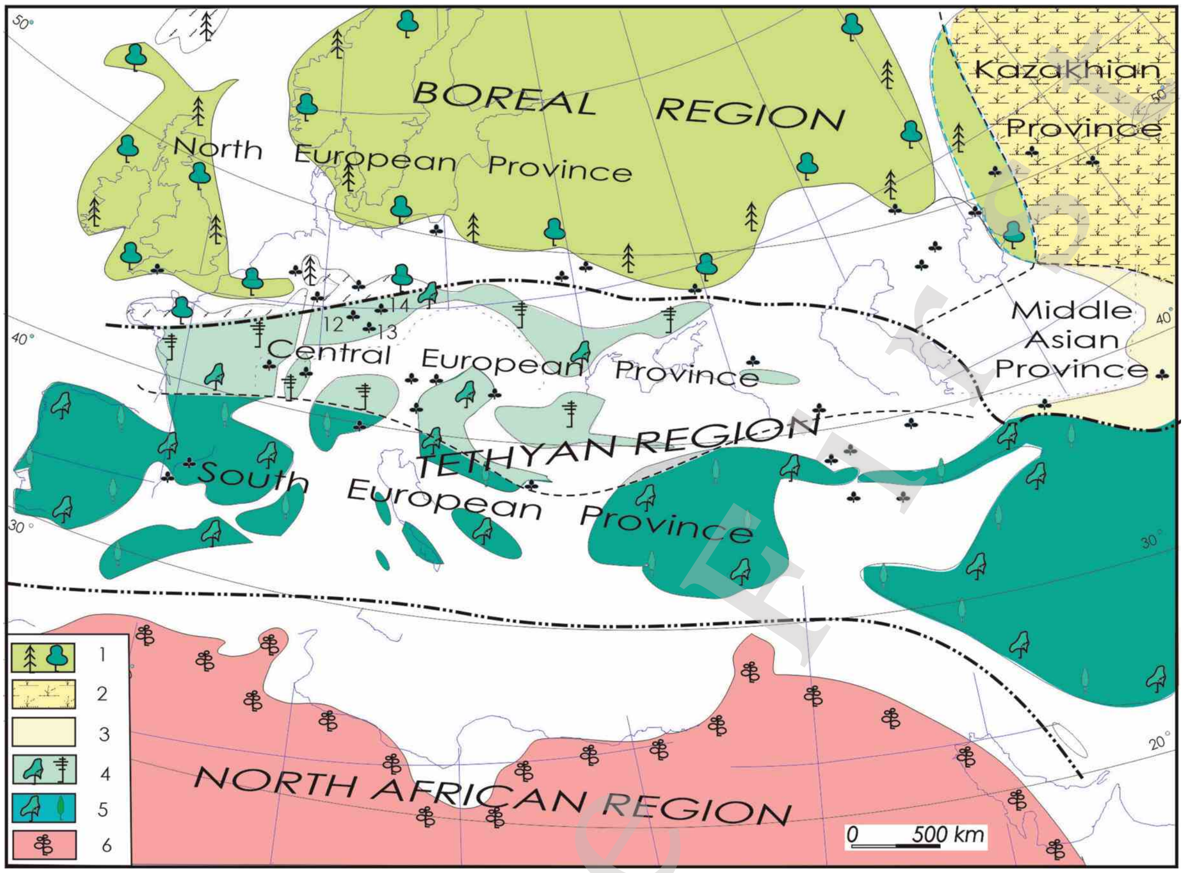

Fig. 4. Phytogeographic zonation of the Western Eurasia continental frame for the first half of the Early Oligocene (after Popov *et al., 2001, modified). Phytoprovinces are marked with numbers:* ***1.*** *Northern European;* ***2.*** *Kazakhian;* ***3.*** *Central Asian;* ***4.*** *Central European;* ***5.*** *South European;* ***6.*** *North African.*

Around 27 million years ago, the Maikopian Basin lost its initial direct connection with the open seas. Consequently, the marine biota within the basin faced extinction, paving the way for the colonization of its waters by a depauperate, highly endemic fauna of lagoon origin. Among these forms, there were *Ergenica, Urbnisia, Janschinella, Corbula (Lenticorbula)*, and some species of *Cerastoderma* among Bivalvia. At the same time, gastropods of this basin were mainly the lagoonal forms that had wide geographic and stratigraphic ranges.

By the onset of the Late Oligocene, approximately 25 million years ago, the basin witnessed the return of marine organisms from the North Atlantic. The most typical among these is *Chlamys bifida,* the zonal bivalve species of the Chattian A. This species was an abundant, widely distributed form that reached as far as the Kyzylkum and Kopetdagh.This event marked the final direct connection between the Paratethys Sea and the Atlantic Ocean via the North Sea and Dnieper-Donets depressions.

Since the onset of the Miocene, approximately 22 million years ago, warm-water species and genera of southern origini.e., *Arca, Barbatia (Obliquarca), Isognomon, Ctena, Arcopagia, Cardita calyculata, Cerithium,* and *Olivia flammulata* among mollusks have started to emerge as part of the Paratethyan fauna, indicating the establishment of a migration route from the Eastern Mediterranean and/or the Mesopotamian basins. Despite the relatively low diversity of fauna (number of genera and species) in the Maikopian Basin, the biomass of the organisms inhabited it was substantial. This was facilitated by the abundance of biogens, primarily nitrogen and phosphorus, supplied by the river discharge. Large quantities of dead organic matter were carried into the deeper parts of the basin, where they settled as sediment due to stagnant, anoxic conditions that

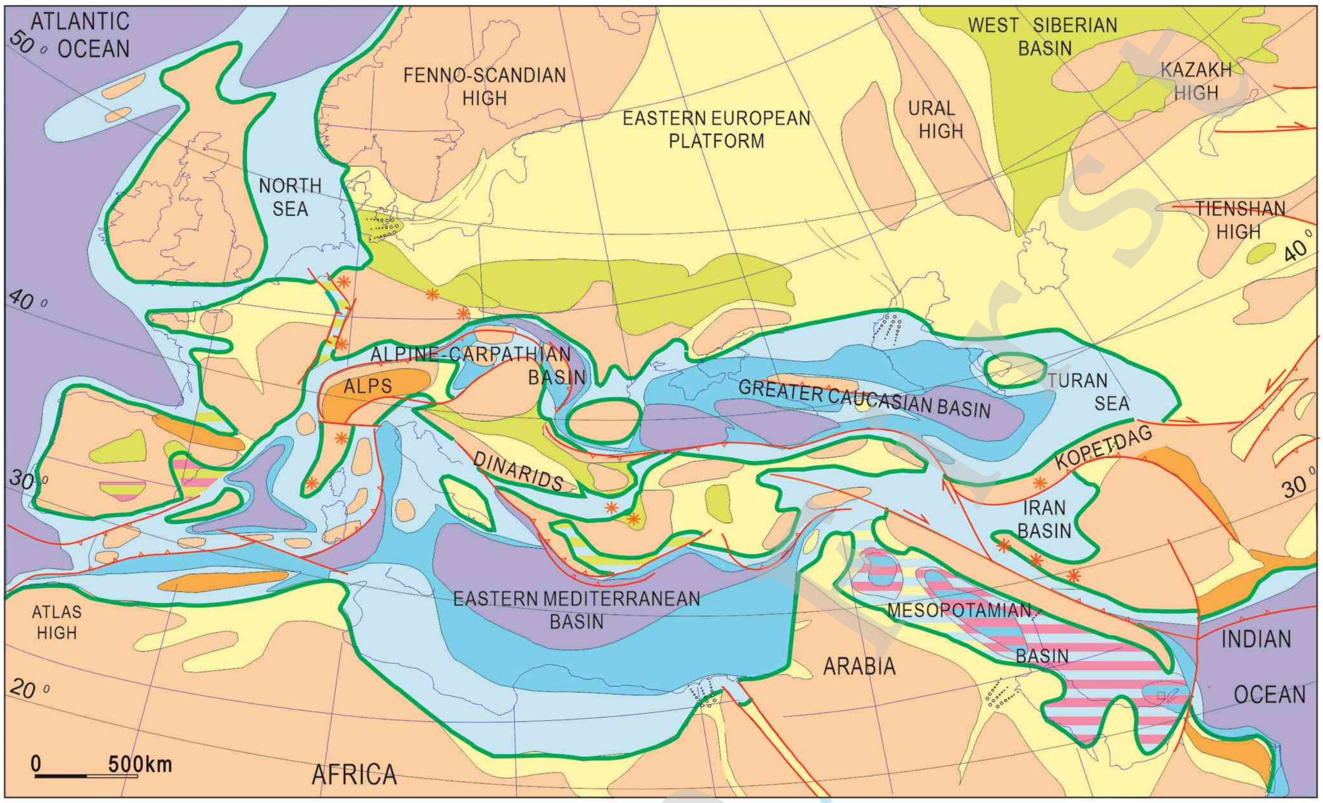

Fig. 5. *Paleogeographic map of the Western Eurasia in the first half of the Early Miocene (18–20.5 Ma) (after* Popov *et al., 2004).*

inhibited decomposition. The organic remains of plant and animal origin buried in these deposits made them prone to oil formation (Sachsenhofer et al., 2017), serving as a source material for hydrocarbon generation. This mechanism is common in water bodies of inland basins like the Paratethys, where a combination of nutrient-rich environments and anoxic deep-water conditions contribute to the high enrichment of oil and gas.

Around 20 million years ago, during the Sakaraulian regional stage (Fig. 2), the basin contracted compared to the Oligocene (Fig. 5), and the southern coast of the Paratethys was colonized by a diverse thermophilic genera and species *(Atrina, Isognomon, Megaxinus, Divalinga, Venus* cf. *multilamella, Callista lilacinoides, Glycymeris pilosa deshayesi,* and *Glossus maior*). This migration wave involved fauna migrating from the Anatolian-Iranian basin (*Fragum, Europicardium*) and spreading north-westward to the Alpine-Carpathian part of the Paratethys during the Eggenburgian.

Beginning approximately 17.5 million years ago, at the end of the Early Miocene and during the regional Kozakhurian stage and Late Ottnangian substage (Fig. 2), as well as throughout the earliest part of the Middle Miocene (in the Eastern Paratethys), the basin faced another period of challenges in connecting with open seas, resulting in the emergence of communities with endemic benthic fauna (*Rzehakia dubiosa, Eoprosodacna, Corbula (Lenticorbula), Melanopsis*). It is noteworthy that the basin supported the coexistence of both marine and brackish-water species. The presence of endemic brackish mollusks and oceanic phytoplankton suggests the existence of two distinct water masses in the basin: a lower marine water mass and an upper brackish water mass, reminiscent of the modern-day Sea of Marmara (Popovet al.,2022).

Middle Miocene to Pliocene (15–2.7 Ma) basins. Towards the end of the early Miocene, the Paratethys Sea underwent a division, giving rise to two distinct basins: the Central Paratethys and the Eastern Paratethys, each following its own unique evolutionary path. By the conclusion of the early Miocene, the pre-Alpine region, known as the Western Paratethys, had already transformed into a landmass. During the Middle Miocene period (15–12 Ma), the Pannonian-Carpathian region, representing the Central Paratethys, maintained broader connections with the Mediterranean through the Slovenian Corridor compared to the primary (Eastern) part of the Paratethys. In contrast, the Black Sea–Caspian basin, part of the Eastern Paratethys, primarily experienced a semi-marine regime characterized by limited seawater inflow and occasional discharge of brackish water. Periodically, it transitioned into an enclosed brackish lake environment.

A correlation scale for the Neogene deposits of the primary eastern part of the Paratethys was developed in the late 19th to early 20th century based on the sequence of marine and various non-fully marine biological assemblages and the reconstruction of evolutionary faunal processes (Andrusov, 1961, 1963). However, with advancements in stratigraphy through the study of fossil plankton remains, paleomagnetic analysis, and absolute dating methods, these subdivisions have been more accurately correlated with Global and Mediterranean stratigraphic scales, leading to refined age estimations (see Fig. 2).

In the Middle Miocene (approximately 14.9 million years ago) during the Tarkhanian regional stage (Fig. 2), the Eastern Paratethys boasted the widest connection with the World Ocean in the Neogene period. It was populated by marine biota and probably connected to the global ocean through two straits: the Badenian Sea of the Central Paratethys opened to the west, while connections with the Turkish-Iranian basins to the south are hypothesized to have provided access to the Eastern Mediterranean Sea (Fig. 6).

Despite these extensive connections, sea regression persisted, continued, reflecting the eustatic drop of the World Ocean. This regression reached its peak in the Late Tarkhanian–Early Chokrakian time (around 14.8 million years ago, according Palcu et al., 2019a). During this regressive interval, the newly exposed territories of the northern and southern shelves merged with the island structure of the Greater Caucasus. For the first time, the landmass, including the Dzirula Massif in Georgia, the Caucasus Island, and the Stavropol Upland, temporarily separated the Black Sea and Caspian basins. This land bridge facilitated the migration of terrestrial vertebrates, leading to the expansion of African vertebrates into Eurasia and the widening of the Eurasian species habitat. This is evidenced by the composition of the famous Belomechetka vertebrate fauna found in the Central Pre-Caucasus on the right bank of the Kuban River, which includes African

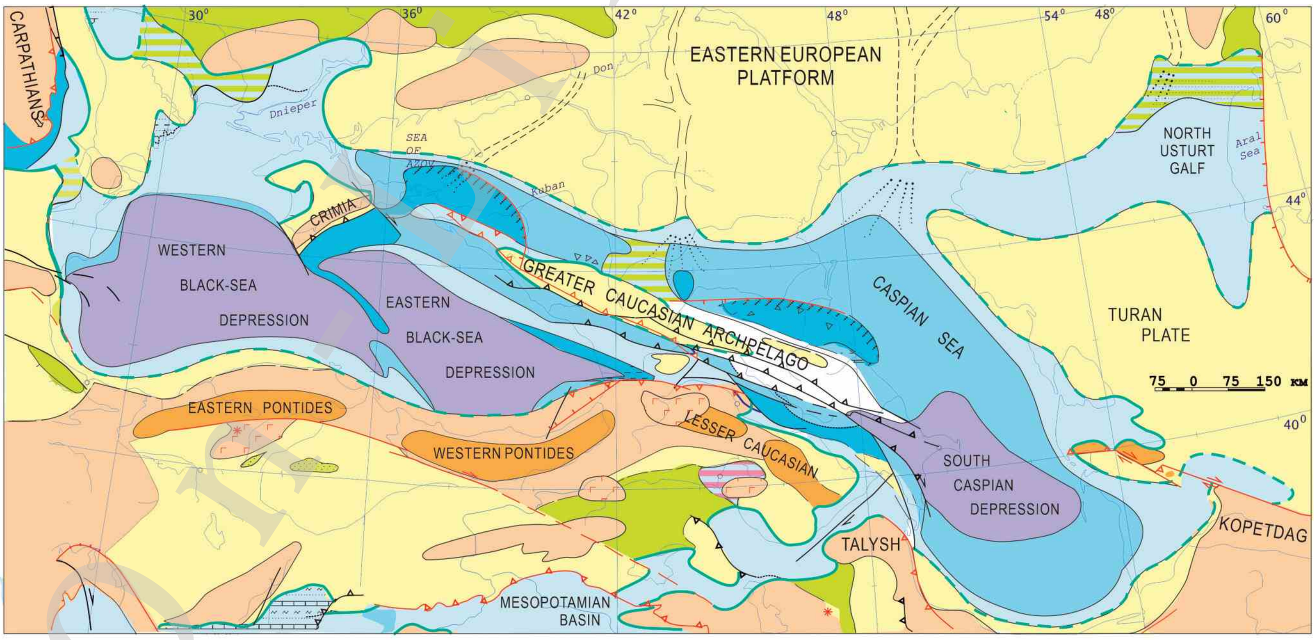

Fig. 6. Paleogeographic map of the Eastern Paratethys in the Middle Miocene (Tarkhanian) (14.8–14.9 Ma) (modified after Popov & Patina, 2023).

aardvarks (genus *Orycteropus*) and swine (genus *Kubanochoerus*), as well as Eurasian bears and deer. It was also during this period that the endemic Caucasian genus of equids, *Paranchiteria*, was able to migrate to the Balkans (Gabunia, 1973).

The most significant events in the subsequent history of the Miocene Eastern Paratethys were the maximum transgressions during the Middle Chokrakian (approximately 14.5–13.8 million years ago, according Palcu et al., 2019a, Palcu data in Popov et al., 2022), Karaganian (13.8–13.4 million years ago), and Early–Middle Sarmatian s.l. (12.6–9.76 million years ago) stages. During these intervals, the Caucasus once again became an island for an extended period. During the Sarmatian transgression, the basins of the Central and Eastern Paratethys merged again (12.6–11.6 Ma) and were characterized by a common endemic fauna. Later 11.6 million years ago Central and Eastern parts of the Paratethys developed their own history.

The last major transgression of the Eastern Paratethys occurred during the Early Pontian regional stage (6.1–5.6 Ma). During this period, the sea level rose approximately 70 meters, the connection with the World Ocean was only partial and brief. This was followed by a deep intra-Pontian regression (~5.6 million years ago) when the Eastern Paratethys sea level dropped by 200–250 meters.

The lowest sea level occurred during the Messinian salinity crisis in the Mediterranean Sea. As result of this drop, the Black Sea basin lost its connection to the Caspian basin and remained separate. Later on, the Caspian Lake only periodically overflowed into the Black Sea when it became overfilled.

In the first half of the Pliocene (approximately 5.2–3.4 million years ago), the Caspian Lake basin experienced its deepest regression. The water level in it dropped by 800–1000 meters, and water remained only in the South Caspian depression. During this time, sediment from the paleo-Volga river delta accumulated near the Apsheron Peninsula (Baturin, 1937).

During this period the Balakhan Grouproughly terrigenous sediments were formed, as a result of erosion caused by the uplift of the Caucasus and Kopetdag. These sediments now are the main oil and gas reservoirs in Azerbaijan, southern Dagestan, and Turkmenistan. After this regression, the Caspian basin was refilled with marine waters featuring a limited fauna (Fig. 7). The origin and pathways of these waters remain a subject of debate.

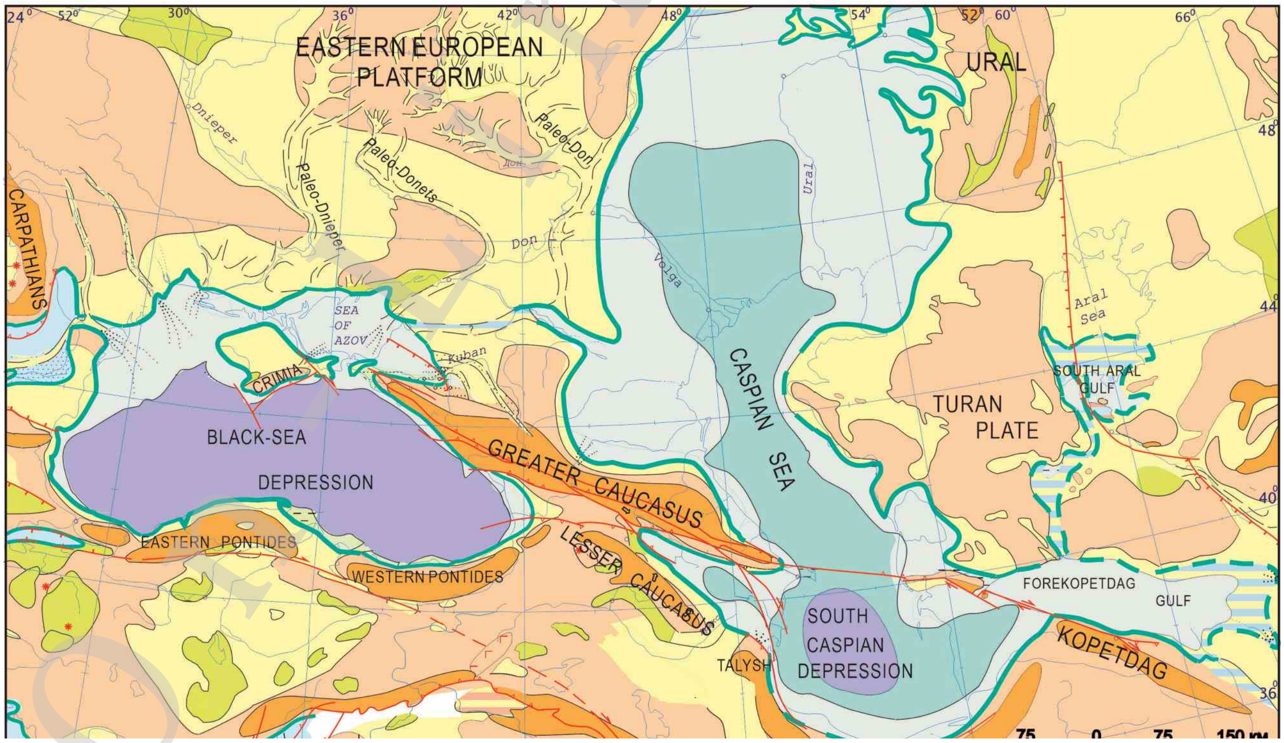

Fig. 7. Paleogeographic map of the Eastern Paratethys in the Pliocene-Early Pleistocene (2.2–2.6 Ma) (modified after Popov et al., 2004).

Advancements in Paleogeographic Research: Investigating Regressive Stages

The concise history of the Paratethys in the Paleogene and Neogene periods was depicted in the "Atlas of Lithologic-Paleogeographic Maps of the USSR" (1967). Compiled over six decades ago by a distinguished group of geologists, this atlas remains relevant and accurately portrays the distribution of-basins during transgressive phases. However, akin to all subsequent paleogeographic maps (Popovet al., 2004), it relies on facies analysis and sediment accumulation over extensive mapped intervals. Consequently, most existing paleo-basin reconstructions solely depict the maximal (transgressive) evolutionary stages when the sea level reached its peak. The distribution of transgressive sedimentary sequences naturally furnishes the most comprehensive factual basis for research, as these deposits typically showcase complete facies sets (including coastal ones) and are often exposed in natural outcrops, in addition to being penetrated by a significant number of boreholes.

The distribution pattern of deposits formed during significant water level decreases differs fundamentally. Sedimentary rocks from such periods usually endure only in deep basins and seldom emerge to the surface. Moreover, drilling data are scarce due to the considerable depth of these facies locations and the limited number of wells available for studying these deposits. Furthermore, subsequent marine transgressions frequently obliterated shelfal and coastal deposits from these intervals. Another intricate aspect is that water level decreases are typically associated with the boundary intervals between geological epochs, permitting dating solely in the most thoroughly studied areas.

Until recent times, methods for reconstructing paleogeographic conditions during hydrological crises were practically non-existent. Only in the last few decades, with the advancement of geophysical research methods, have series of intersecting seismic profiles with sufficiently high resolution become accessible. These data were acquired during regional and large-scale geophysical studies using the seismic reflection method.

The information obtained through seismic stratigraphy interpretation of the acquired data enables the spatial mapping of the structural features of intracontinental sedimentary basins, including the sequences accumulated during the baselevel fall. Significant regressions eroded portions of sedimentary layers and created unconformity surfaces between geological bodies formed before and after the sea level fall (Fig. 8).

Rivers and ephemeral streams flowing into the basin formed extensive and deep incisions, subsequently filled with sediments. It was during the most significant baselevel falls that the deepest incisions were carved, and the formation of a new river network occurred. Such structures and surfaces are exposed in boreholes and are clearly evident in seismic profiles as uneven erosional boundaries of several orders. Deciphering these surfaces and determining the depth of the river incisions enabled the reconstruction of resulting topography from these erosions and quantification of basin base-level fall amplitudes during the major regressions (Popov et al., 2010).

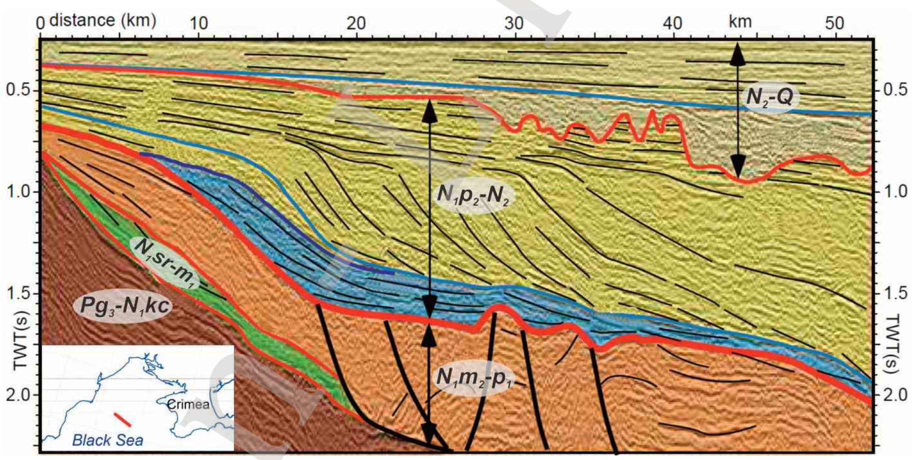

Fig. 8. *Seismic section of the western (Romanian) shelf of the Black Sea (Munteanu et al., 2012). The boundaries of the unconformities which reflect erosion of the underlying rocks are marked by red lines. Indices show the rock age:* ***Pg_3-N_1kc*** *–Oligocene–Miocene;* ***N_1sr-m_1*** *– Sarmatian–Lower Maeotian;* ***N_1m_2-p_1*** *– Upper Maeotian–Lower Pontian;* ***N_1p_2-N_2*** *– Upper Pontian–Pliocene;* ***N_2-Q*** *– Pliocene–Quaternary. The inset on the lower left shows its location.*

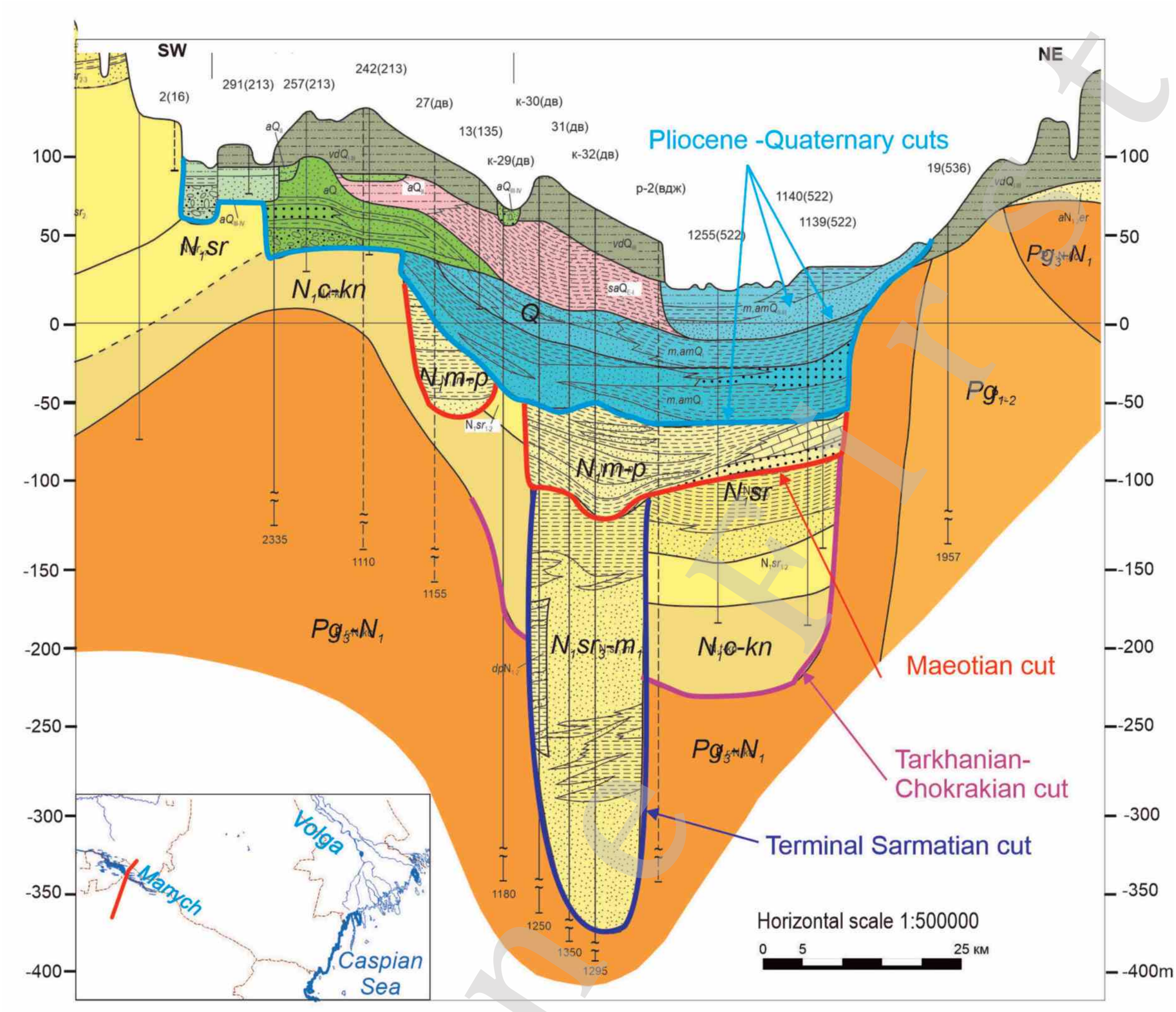

*Fig. 9. Two generations of the paleo-Don River Neogene incisions in the Manych area as a result of falls of the erosion basis at the end of Sarmatian and at the end of Maeotian–Pontian, filled with marine sediments of subsequent transgressions (*TIMOKHIN *et al., 2009).*

Subsequently, the rivers mainly inherited previously established channel patterns. This situation is very indicative for the paleo-Don River Neogene incisions (Fig. 9) (TIMOKHIN et al., 2009). While sea level drops, the paleo-Don River embedded in the underlying sediments, forming its valleys. The most ancient was the valley at the end of the Tarkhanian (14.8 Ma). Then, it was filled with marine sediments of the Neogene: Chokrakian–Konkian (N_1c-kn) and Sarmatian (N_1sr). The next and the deepest incision occurred at the end of the Sarmatian (about 8 Ma) when the canyon cut through the same Oligocene-Miocene sediments to a depth of –380 m, and was filled with marine Upper Sarmatian–Maeotian sediments (N_1sr_3-m_1). The last Miocene cut occurred at the end of the Maeotian-Pontian ($N_{1\text{-}2}$m-p), about 6 million years ago. The youngest incision was formed at the beginning of the Pliocene (about 5 Ma) and cut out the underlying sediments to the level of –60 m.

We posit that the maximal drop in sea level occurred during the Neogene period, specifically at the end of the Sarmatian stage (8.0–7.6 Ma). Erosive features of this age were extensively developed and traced in various regions: on the open shelf of the Black Sea (TUGOLESOV et al., 1985), the shallow north-western shelf of the Black Sea; in the Dacian basin (MUNTEANU et al., 2012), on the north step of the West Kuban trough, in the Terek and Kura depressions. The existence of an entire network of channels and a deltaic complex was determined in the north part of West Kuban (Postnikova et al., 2024) and southwest part of the Tuapse troughs (Afanasenkov et al., 2005; Baskakova, 2022). The width of the canyons is 10-12 km, the depth is 450–500 m, and the total length is up to 250–300 km. Studying these incisions and their filling points to their fluvial and deltaic origin as a result of the 500 m fall in water level. Based on the results of these seismic profile interpretations, it is possible to reconstruct the paleogeographic picture for the maximum regression (Fig. 10).

The exposed areas have acted as vital land bridges facilitating the movement of terrestrial vertebrates between the African, Asian, and European continents. The basin's isolation has fostered conditions conducive to the rapid evolution of unique endemic organisms, communities, and life forms, distinctly different from marine counterparts.

The abundant water influx from river runoff, enriched with biogenic compounds–particularly nitrogen and phosphorus–has fuelled colossal biomass

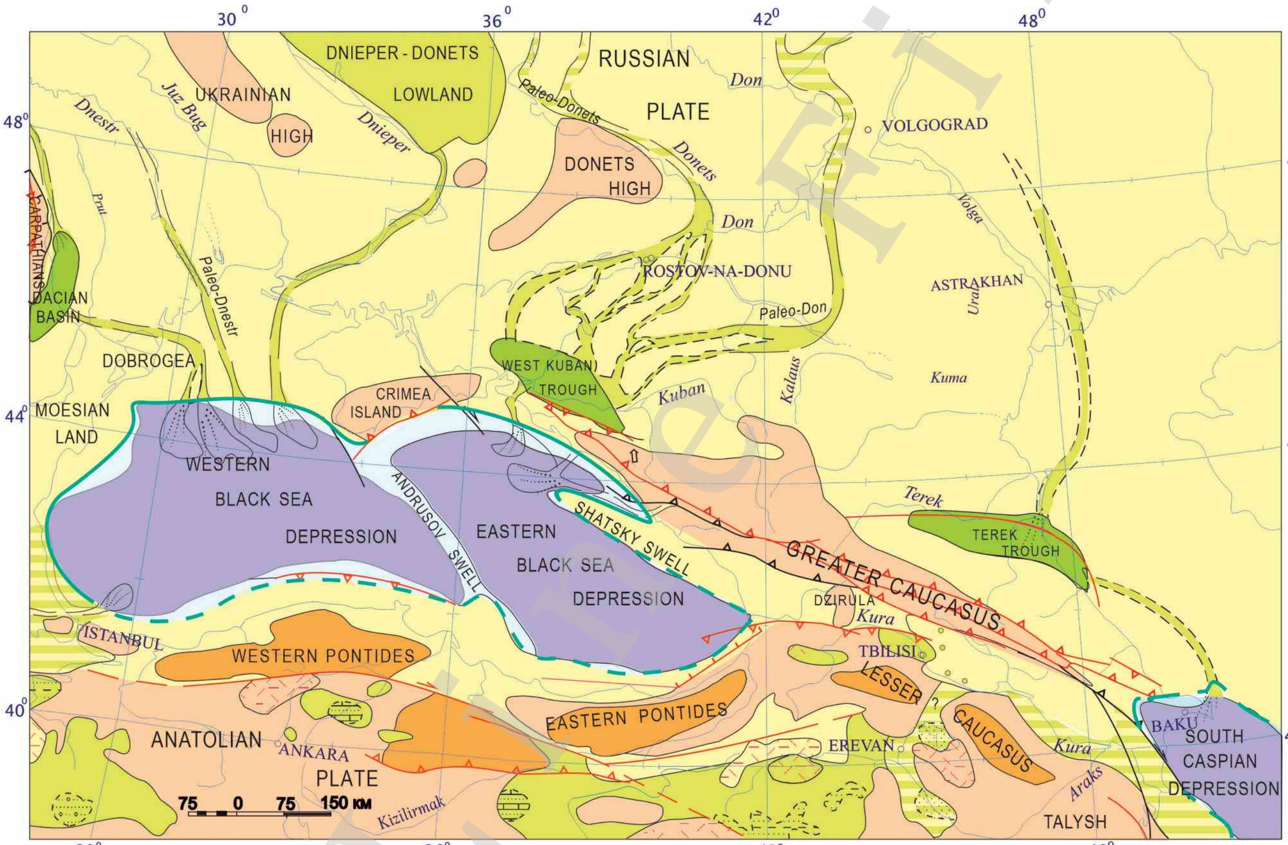

Fig. 10. Paleogeographic map of the Eastern Paratethys during the terminal Sarmatian regression, 7.6 Ma.

Conclusions

The Paratethys, an expansive sea basin with a rich and distinctive history, has often diverged from global events in the World Ocean. Characterized by alternating open, hemi-closed, and closed hydrological regimes, its repeated shifts between regressive and transgressive episodes have profoundly influenced both aquatic and terrestrial ecosystems, shaping migration patterns and opportunities. within these intracontinental basins. Concurrently, the anoxic conditions prevailing at the basin floor have facilitated the burial of organic material, contributing to the formation of hydrocarbons.

Understanding the palaeogeographical conditions during maximum regressions holds significance not only for historical-geological insights and evaluating migration dynamics for terrestrial and marine fauna amidst landscape and trophic network changes but also for practical applications.

Such knowledge aids in the exploration of hydrocarbon deposits and artesian groundwater. During regressions, the formation of powerful alluvial cones, horizons, and lenses of coarse-clastic material provided excellent reservoirs for oil and gas accumulation, also acting as filters for drinking and industrial water.

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Резиме

Усклађивање интерпретације Паратетиса коришћењем палеогеографских реконструкција и геохронолошких изучавања

Паратетис представља велики марински басен са јединственим геолошким развојем, формиран на северном ободу Тетиса и одвојен од њега алпским орогеним појасом. У раду је разматрана историја стварања басена, његова еволуција и нестанак огромног интерконтиненталног мора - Паратетиса, од његовог настанка у олигоцену (34 Ma) до коначне поделе на Црно море и Каспијско језеро на крају миоцена (5,6 Ma). Посебна карактеристика Паратетиса представља смењивање отвореног, полузатвореног и затвореног хидролошког режима. Смене регресивних и трансгресивних секвенци имале су значајан утицај на водене и копнене екосистеме, одређујући и могућности миграције организама. Откривена подручја су служила као копнени мостови за миграцију копнених кичмењака између афричког, азијског и европског континента. Изолација басена створила је услове за брзу еволуцију јединствених ендемичних организама, заједница и животних облика, који се значајно разликују од маринских форми.

Обиље азотних и фосфорних једињења из речног прилива утицало је на импозантан развој живог света у овим интраконтиненталним басенима, док су аноксични услови на дну басена довели до стварања угљоводоника таложењем органске материје.

Када су се мореузи затворили, Паратетис се претворио у огромно језеро, у коме су ниво воде и салинитет зависили од равнотеже између речног прилива и испаравања: са позитивним билансом воде, басен је почео да се шири и постаје бочатни, а са негативним билансом, смањивао се, формирајући слане заливе и лагуне. Са таквим променама, марински организми су нестали, а само неколико организама способних да издрже драстичне промене у салинитету, саставу јона и режиму кисеоника је еволуирало и формирало јединствене ендемске групе фауне прилагођене бракичној средини.

У палеогеографији Паратетиса добро су изучени периоди високог нивоа воденог стуба у басену, али не и интервали значајног опадања нивоа мора током периода изолација. До недавно није било метода за палеогеографске реконструкције таквих циклуса. Данас, са развојем методе сеизмичке стратиграфије, појављује се прилика за проучавање обима и просторне дистрибуције палеогеографских промена које су пређене значајним смањењем басена током регресивних периода.

Реконструкција палеогеографских услова током периода максималних регресија је важна не само за историјско-геолошка изучавања и правилну процену могућности миграције копнене и маринске фауне, већ и за примењена геолошка истраживања као што су истраживање лежишта угљоводоника и артеских издани. Дебеле наслаге алувијалног наноса, хоризонти и сочива од грубокластичног материјала који настају током регресије представљају одличне колекторе нафте и гаса, а такође акумулирају и филтрирају воду за пиће и индустрију.

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