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PALEOGEOGRAPHY

DIGITALIZATION OF ISOLATED BASINS PALEOGEOGRAPHIC RECONSTRUCTIONS: A CASE STUDY OF THE EARLY OLIGOCENE SOLENOVIAN CRISIS IN THE EASTERN PARATHETIS

© 2025 I. S. Patina*, V. V. Fomina**, A. A. Tkacheva***, and Corresponding Member of RAS N. B. Kuznetsov****

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Abstract. A new methodology for paleogeographic reconstructions of regressive stages of sedimentary basins, which experienced isolation from the World Ocean, has been tested using the example of the Eastern Paratethys. The application of this methodology makes it possible to fill the gaps in understanding the development history of the Paratethys and other similar sedimentary basins (such as Pricaspian and South Atlantic), which experienced isolation at various stages of their existence. Digital modeling of the results and consequences of the Early Oligocene Solenovian regression manifested in the Eastern Paratethys has been carried out. Based on the synthesis of paleogeographic reconstructions and data on changes in the geodynamic setting of the Black Sea-Caspian region, a digital model has been created depicting the depth changes of the Paratethys during its initial (transgressive), transitional, and final (regressive) stages in the Solenovian time of the Early Oligocene. This model takes into account relative sea level fluctuations, as well as the influence of later tectonic deformations superimposed on the structure of the Oligocene infill of the Eastern Paratethys sedimentary basin.

Keywords: *Paratethys, Maykopian series, seismic stratigraphy, regression, paleogeography*

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INTRODUCTION

The basis of paleogeographic reconstructions is the study of the distribution of sediments of ancient basins. In most cases, data on sedimentation conditions are obtained by analyzing geological and paleontological data. These approaches work well for open-type marine basins, where the water level is determined by the level of the World Ocean. However, when studying closed "Mediterranean" basins, standard methods of paleontological and lithological analysis are uninformative and do not provide complete data on their depth, erosion basis, and development mode.

Such basins periodically became isolated not only from the World Ocean but also lost connection with neighboring basins. The history of water level variations in such closed basins is difficult to directly correlate not only with the global eustatic curve of the World Ocean level fluctuations but also with data from other intracontinental basins with which connections were interrupted. During isolation periods, each basin with its watershed area transformed into a separate tectono-sedimentary system with a unique development history and its own erosion base determined by the water level within it. Examples include the Atlantic and Arctic basins in the early stages of their formation, Neoproterozoic aulacogens of the East European Platform, Paleozoic basins of the Caspian region, the Mediterranean Sea, as well as the Paratethys sea system located along the southern margin of Western Eurasia during the second half of the Cenozoic.

One of the most significant, but still poorly studied isolation episodes is the Solenovian event at the end of the Rupelian age of the Early Oligocene. According to geological data, clear signs of regression have been identified in the Solenovian layers [5, 13, 14, 16]. However, the scale of this event and the expression of its consequences in the closed parts of the basin have practically not been discussed earlier.

Geological Institute, Russian Academy of Sciences, Moscow, Russian Federation
**e-mail: irina.patina@gmail.com*
***e-mail: valery.fomina17@gmail.com*
****e-mail: a.a.tkacheva1@yandex.ru*
*****e-mail: kouznikbor@mail.ru*

The task of tracing and evaluating events similar to the Solenovian event can be solved using seismostratigraphic interpretation methods of CDPM seismic data. Seismostratigraphic analysis allows tracking over considerable distances both lateral variations in the structural plan of geological bodies and the profile of erosional-sedimentary equilibrium, as well as seismofacial parameters of elements in the sedimentary section.

In this work, based on the results of seismostratigraphic analysis, an attempt has been made to reconstruct the events of the Solenovian crisis in the Eastern Paratethys.

SOLENOVIAN CRISIS

The deposits of the Solenovian horizon are represented by clays with interlayers of sands and

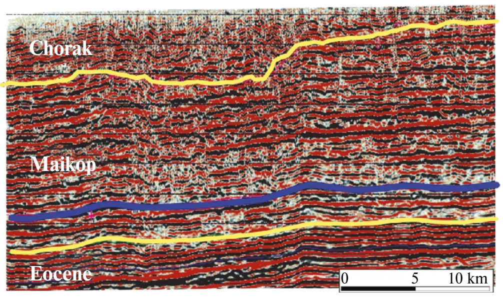
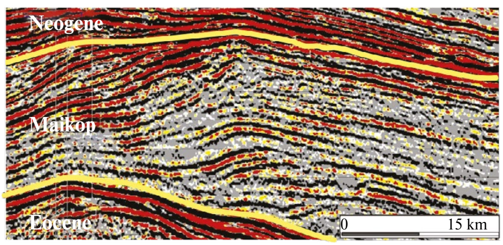
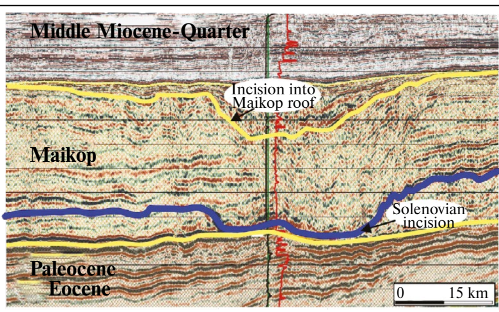
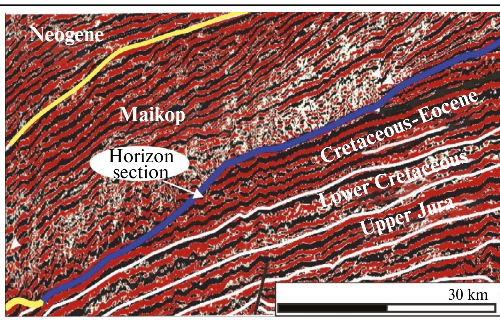
	Seismic facies (vertical section)	The nature of the wave field	Estimated composition and conditions of sedimentation	Distribution areas
a)		Alternation of bright, extended, and intermittent reflections, as well as consonantal and erosive boundaries	Facies of shallow Shelf sedimentation conditions. The alternation of transgressino-regressive phases is expressed in a change in the nature of seismic activity.	Western Pre-Caucasus, North East and Central Pre-Caucasus, Northern Caspian, periphery Mangyshlak depression
b)		Wedge-shaped oblique reflections detected within the Maikop seismic complex areas of transition from the shallow shelf to the deeper parts of the basin	Areas of transition from the shallow shelf to the deeper parts of the basin	West Kuban Trough, East Pre-Caucasus, Middle Caspian, Mangyshlak, Ustyurt
c)		The erosive surface is a milling cutter with a deep cut into the underlying strata and chaotic filling	Buried river cutters in the offshore part of the Maikop seismic complex. The first incision was formed during the Solenovian regression and has an inherited character: subsequent regressions formed milling cutters in the same place.	Kanevskoy-Berezansky val, South of Timashevskaya step, Kumo-Manych trough, Prikum lifting system, Nogai step
d)		Abrupt interruption of horizons as a result of erosion	The erosion board. The depth of the erosion corresponds to the amplitude of the sea level drop	The Azov, West Kuban and Tersko-Caspian troughs

Fig. 1. Characteristic seismofacies of the Maykop seismic complex. a – parallel seismofacies of the shallow shelf (fragment of regional profile No. 10 in the Eastern Ciscaucasia, b – clinoform seismofacies of the shelf (fragment of regional profile FR050916 in the Western Ciscaucasia), c – erosional incisions of river systems (fragment of regional profile FR060722a in the Western Ciscaucasia), d – abrasion scarp (fragment of regional profile No. V in the Eastern Ciscaucasia). 1 – boundaries of the Maykop seismic complex; 2 – surface of Solenovian age; 3 – other seismostratigraphic boundaries.

sandstones, as well as a characteristic layer of light marl at the base (named the "ostracod layer"). The horizon is distinguished in the lower (Khadum) part of the Maikop series and is of Early Oligocene age.

The Maikop seismic complex is distributed over almost the entire territory of the Black Sea-Caspian region (except for areas of its post-sedimentation erosion). It is characterized by variability in thickness (from tens to 2500 m) and internal structure with an almost monotonous lithological composition (dark clayey rocks with sandy interlayers). The structure of the seismic complex is examined in detail in our previous publications [11, 21] and in the works of predecessors [6, 7, 8]. The main results of the conducted research can be summarized as follows. In the shallowest shelf areas, parallel reflecting horizons of varying degrees of expression were formed (Fig. 1a). The deeper part of the Maikop seismic complex consists of large clinoform sedimentary bodies (Fig. 1b), which sequentially filled the basin from the platform towards the open sea.

Inside the shelf part of the Maikop seismic complex, we traced an erosional surface corresponding to the regression of the Late Solenovian time (Fig. 2). It is characterized by regional distribution and is expressed throughout almost the entire territory of Ciscaucasia and the Middle Caspian. The surface is complicated by a system of incised valleys, which were inheritedly formed by river channels during the Oligocene-Miocene regressions, starting from the Solenovian time (Fig. 1c). The degree of erosion expression and erosion of complexes underlying the identified surface increases from north to south towards the northern flanks of the Ciscaucasian and Caspian troughs. Along them, a steep abrasion escarpment about 500 m high is distinguished (Fig. 1d). Here, the underlying complexes are eroded down to the Cretaceous. Further in the direction of the open basin, the reflecting horizons lie conformably, and the erosional surface is absent [21].

Geological data on the Solenovian crisis (incisions, rewashing, areas of zero sedimentation and traces of planar erosion, wavy surface, bioturbation of sediments, coal accumulation, coarse terrigenous facies, sedimentary brecciation, olistostromes, etc.) have been established practically throughout the northern shelf of the Eastern Paratethys – in the territory of Ciscaucasia, Northern Yergeni, Northern Caspian and Kazakhstan 2, 5, 15, 16]. Its traces are also present on the Black Sea coast. For example, in the Karburun outcrop (Istanbul, Turkey), an eroded Eocene

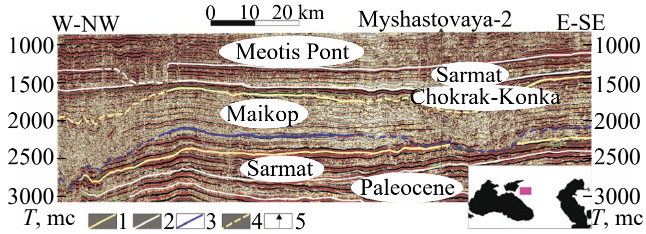


Fig. 2. Seismostratigraphic profile 040823ab [4], showing the erosional surface of Solenovian age within the Maykop seismic complex and the inherited system of river incisions. 1 – boundaries of the Maykop seismic complex; 2 – boundaries of other seismic complexes; 3 – surface of Solenovian age, 4 – boundaries of incisions, color corresponds to the legend; 6 – wells. The inset shows the position of the profile.

surface filled with coarse terrigenous facies and debris flow deposits was mapped. Paleontological studies confirm the Solenovian age of the deposits [23]. Similar incisions are described in the Getian depression (Romania) [22] and mapped on the Odessa and Romanian shelf of the Black Sea [18], where Early Oligocene and even Eocene strata were eroded, however, data on the age of the incisions themselves are absent here.

METHODOLOGY FOR RECONSTRUCTING PALEOBATHYMETRY

During paleogeographic reconstructions of basins similar to the Eastern Paratethys, a regional seismostratigraphic analysis of their closed parts (not currently exposed on the surface) is first conducted with the identification and mapping of shallow and deep-water areas of the shelf, slopes, and deep-water depressions. Based on this zoning, indicators of water level fluctuations in the basin characteristic of its various areas are identified.

For the Eastern Paratethys, the most effective approach for determining paleobathymetry and the amplitude of relative sea level fluctuations has been measuring the heights of clinoform complex edges (defining the depth difference between shallow and deep shelf), as well as the heights of abrasion escarpments and incisions (defining the amplitude of relative sea level fall during regression). It is the sum of such markers and the characteristics of their distribution, supported by geological data, that can be interpreted as the result of water level drops and changes in erosion base level, whereas singular observations of one of the features described above do not always mark transgressive-regressive events specifically.

Based on the synthesis of paleogeographic data on the transgressive stages of the Oligocene in the Eastern Paratethys, we have developed a structural-palinspastic scheme (model) of the seafloor relief of the Solenovian basin (Fig. 3). The depths of the paleosurface were determined based on the results of our own research [21] and previous reconstructions [13]. The base map for creating the relief was the map of the Eastern Paratethys during the Pshekhian time [14] and palinpastic data for the Early Oligocene [1]. The base maps were updated with refined depth values obtained from seismostratigraphic analysis. The relative sea level marks at the transgression maximum at the beginning of the Solenovian time were accepted as the zero surface. Then, by interpolating the data array, depth values were extended to areas where paleosurface depth data were absent. This process involved controlling and correcting the interpolated values according to the tectonic position and known facies environments.

The model takes into account changes in the geodynamic structure of the region. To accomplish this, the consequences of shear along the Crimean-Kopetdag zone of concentrated deformations of pre-Pliocene age were removed. Detailed description and palinspastic reconstruction of movements along this zone were presented earlier [9, 12]. The zone represents a transregional post-collisional right-lateral strike-slip fault that extends from southeast to northwest from the Kopetdag through the Apsheron Sill and the Greater Caucasus to the Crimean Mountains. The active phase of the strike-slip zone formation coincides with the end of the Alpine stage and the collision stages of the Eurasian and Arabian plates. The main movements along the strike-slip zone occurred in the Late Miocene or even in the Pliocene-Quaternary time. During this same period, the Caucasian source of clastic material first actively manifested itself [19]. The amplitude of the strike-slip during this period was about 150-200 km, which was determined based on geological and seismostratigraphic data on the distance between marker paleogeographic elements located on different sides of the strike-slip zone [9, 11]. Currently, movements in the northeastern direction continue, as recorded by

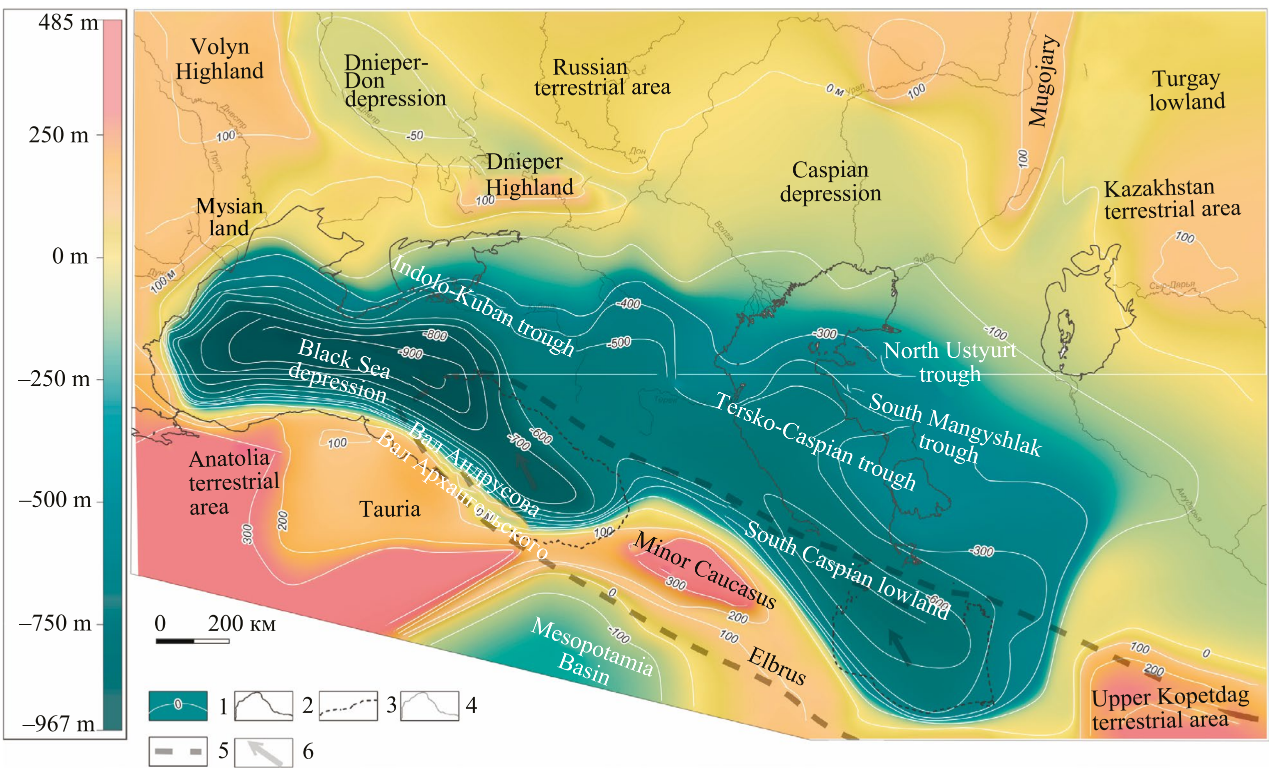


Fig. 3. Structural-palinspastic scheme of the Eastern Paratethys relief during the Solenovian time of the Early Oligocene based on digital modeling results. 1 – isolines of the Solenovian paleosurface, calculated from the relative sea level mark at the beginning of the Solenovian time, taken as zero; 2 – modern coastlines of seas; 3 – coastlines of seas, relocated taking into account movements along the Crimean-Kopetdag deformation zone; 4 – rivers; 5 – boundaries of the Crimean-Kopetdag strike-slip deformation zone; 6 – direction of movement of the hanging wall of the strike-slip fault (during Pliocene-Quaternary time).

GPS observations. Modern velocities are 26–28 mm per year [10]. At similar rates of movement, since the end of the Pliocene, the Eastern Black Sea block would have covered a distance of about 140 km, which practically corresponds to the amplitude of the strike-slip. The total amplitude of the strike-slip was determined using paleogeographic analysis. The reconstruction made it possible to restore the original contours of sedimentary basins that were disrupted and separated by the strike-slip zone. Thus, the Andrusov and Arkhangelsky ridges in the Black Sea, when reconstructing the strike-slip movement, connect into a single structure representing an elevated part of a relatively deep-water shelf; a single deep-water basin was located in the western and eastern parts of the Black Sea.

It is also important to note that detailed study of the material composition of the Solenovian horizon did not reveal any influence from the Caucasian source area [15, 16]. The results of our seismostratigraphic analysis indicate that sediment transport from the Caucasus during the Oligocene time is also not evident. Recent studies on the distribution pattern of detrital zircon grain ages extracted from Cenozoic strata in the Caucasus region [19] have shown that the Greater Caucasus mountain range did not exist as a major source of clastic material until the end of the Miocene. Sedimentary flows into the Western Kuban Trough from the Greater Caucasus are not recorded earlier than the Pliocene-Quaternary boundary. Thus, based on seismostratigraphic data, tectonic and lithological analysis, we assume the existence of open basin conditions in the area of the modern Greater Caucasus mountain range during the Solenovian time. During major regressions, this area became significantly shallower, which may explain the presence of shallow-water and deltaic sand facies, as well as remnants of terrestrial vegetation [17] that grew on the dried shelf surface and was brought in by rivers flowing into the basin.

Thus, the obtained relief model combines the structural-paleogeographic scheme of the Early Oligocene Eastern Paratethys with palinspastic reconstructions. This reconstruction allows for the most adequate assessment of changes in the area and relationship between sedimentation and erosion zones during water level fluctuations in the basin.

RECONSTRUCTION OF THE SOLENOVIAN TRANSGRESSION AND REGRESSION

For the compiled terrain model, changes in the coastline and contours of the sedimentary basin were reconstructed with changes in water level during the Solenovian Age of the second half of the Early Oligocene (Fig. 4).

During the transgressive stage (beginning of the Solenovian time), the main part of the shelf (North Ciscaucasia, Yergeni, Northern Caspian, and Kazakhstan) represented areas of shallow-marine sedimentation (Fig. 4a). In deeper shelf areas (southern and central regions of Ciscaucasia, Middle Caspian, Kara-Bogaz-Gol, Mangyshlak depression), clinoform bodies were formed. Based on the heights of the clinoform complex edges, it was determined that the depths of the northern shelf of the Eastern Paratethys were about 150–300 m, increasing in the southern direction. Here, the relatively shallow shelf transitioned into a system of depressions (Indolo-Kuban, East Kuban, Terek-Mangyshlak, and North Ustyurt troughs and the Kura depression), where depths reached 500 meters or more. Towards the basin, these troughs opened into the deep-water basins of the Black Sea and Southern Caspian.

When the water level fell with the amplitude of 100–150 m, the basin boundaries changed insignificantly in spatial terms, without forming any marker elements that clearly define their contours (Fig. 4b). The coastline of southern outskirts adjacent to orogenic areas retreated by a few kilometers. On the northern platform shelves, the changes were more extensive, but nevertheless, the main part of the shelf remained covered with water. The water retreated gradually here, forming shallow bays. Deposits characterizing such facies environments occurred in the northern parts of Ciscaucasia, Yergeni, on the flank parts of the South Mangyshlak depression and southern regions of the Transcaspian mainly during the Early Solenov time. In deeper areas, conditions of uncompensated sedimentation persisted.

With further fall of the relative sea level at the end of the Solenovian age, the basin underwent more large-scale changes (Fig. 4c). Almost the entire territory of the northern shelves dried up, and the coastline boundary shifted southward by 100 kilometers or more. Water remained only in the most deeply submerged areas: the Kuban and Terek-Mangyshlak depressions, the Black Sea and Caspian basins. The amplitude of sea level fall during the regression in the Late Solenovian time was estimated based on measurements of the abrasion scarp height and incision depth. It was about 450–500 m [21].

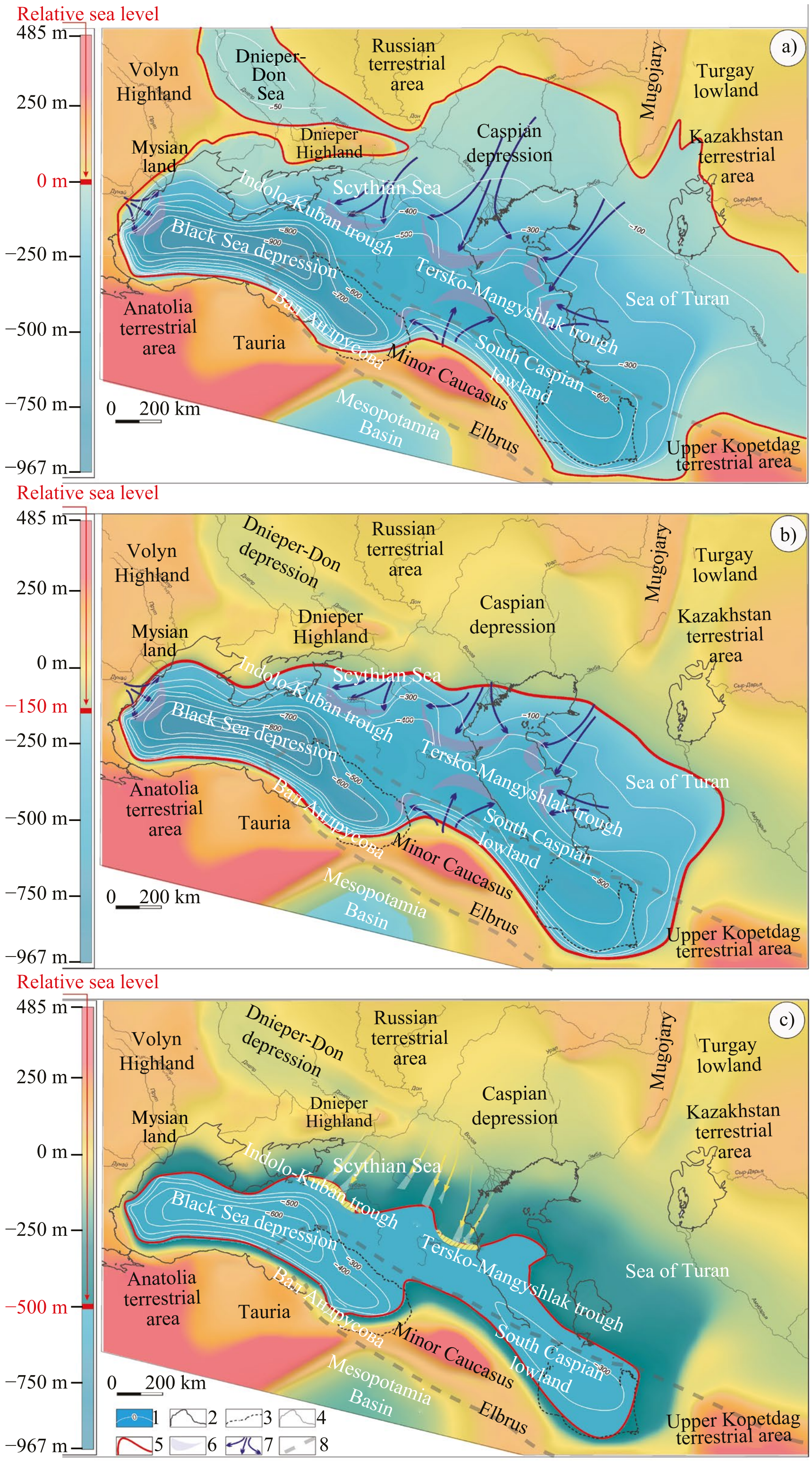


Fig. 4. Migration of the Eastern Paratethys coastline during relative sea level fluctuations: a – maximum of the transgressive stage at the beginning of the Solenovian Age. Relative sea level taken as 0 m; b – beginning of regression in the second half of the Early Solenovian time. Relative sea level – 150 m; c – maximum regression. Late Solenovian time. Relative sea level – 500 m. 1 – presumed paleodepth contours; 2 – modern sea coastlines; 3 – sea coastlines displaced considering movements along the Crimean-Kopetdag deformation zone; 4 – rivers; 5 – Eastern Paratethys coastline; 6 – areas of clinoform formation; 7 – direction of terrigenous material transport; 8 – abrasion scarps; 9 – incised paleoriversvalleys and direction of terrigenous material transport within them; 10 – boundaries of the Crimean-Kopetdag shear deformation zone.

CONCLUSION

The conducted research allowed testing a number of methodological approaches to seismostratigraphic analysis applicable for reconstructing the paleogeography of regressive episodes in closed-type basins using the Eastern Paratethys as an example.

Analysis of the distribution of seismic facies (parallel seismic facies of shallow shelf, clinoform seismic facies of slopes, depression deposits in basins, etc.) made it possible to identify various facies zones and trace paleotopography elements across the area (erosional surfaces, incisions and abrasion scarps) and amplitudes of water level fluctuations characteristic for different stages of basin development. Accounting for geodynamic changes allowed for an adequate assessment of changes in the area and the relationship between sedimentation and erosion zones during transgressive and regressive regimes.

This seismostratigraphic analysis helps solve the problem of identifying developmental patterns of isolated sedimentary basins with unique evolutionary histories. The applications of this approach are quite broad and diverse. Identification and mapping of the described structural features and erosion-sedimentation regimes of closed basins, as well as considering the depths of paleobasins, can be used in modeling sedimentary basins and hydrocarbon systems, when instead of an eustatic curve, it is necessary to set specific values for water level fluctuations. Also, determining the relationship between areas and types of sedimentation with areas of erosional processes is important when compiling local and regional stratigraphic schemes and assessing potential mineral resources.

CONFLICT OF INTEREST

The authors of this paper declare that they have no conflict of interest.

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