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Paleogeographic reconstruction of the Paratethys sea during the late Miocene

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Abstract

If you could rewind time to the Late Miocene — roughly 11 to 5 million years ago — you would find a vast inland sea stretching from the Vienna Basin in the west to the Aral region in the east, separating Europe from Asia in a way that has no modern parallel. The Paratethys Sea, a relic of the ancient Tethys Ocean that was progressively isolated by alpine orogenesis, underwent dramatic environmental changes during the Late Miocene as tectonic uplift, sea level fluctuation, and climate shifts interacted to fragment, shrink, and fundamentally transform its marine character. This research reconstructed the paleogeographic evolution of the Paratethys across three Late Miocene time slices (Tortonian, early Messinian, and late Messinian) using an integrated dataset of published biostratigraphic ranges, sediment facies descriptions, paleomagnetic constraints, and stable isotope records from 142 sections and boreholes across the former Paratethys basin. Paleocoastline positions were mapped in GIS at 1:2,000,000 scale. Results indicate that the Paratethys contracted from approximately 2.8 million km² during the Tortonian (11-7.2 Ma) to less than 0.9 million km² by the late Messinian (6.0-5.3 Ma), a 68% area reduction. Water depth in the central basin shoaled from an estimated 420 m to less than 80 m during the same interval, while salinity increased from near-marine (32-34‰) to brackish-hypersaline (8-65‰) conditions. The reconstruction highlights three discrete isolation events that severed the Paratethys from the Mediterranean, each leaving a characteristic geochemical signature in the sediment record. These paleogeographic maps provide a spatial framework for interpreting the Miocene faunal turnover that shaped the modern biogeography of central Eurasia.

Keywords: Paleogeography, Paratethys Sea, Late Miocene, sea level change, paleocoastline, tectonic uplift, basin isolation, Messinian, salinity crisis, biostratigraphy

Introduction

Think of the Paratethys as a sea that forgot how to be an ocean. Born from the northern margin of the Tethys during the Oligocene as the Alpine-Himalayan mountain chain rose between Africa and Eurasia, it spent 30 million years slowly losing its connection to the global ocean, shrinking, and transforming from a normal marine basin into a brackish, then hypersaline, then freshwater lake system ^[1]. Its remnants today are the Black Sea, the Caspian Sea, and the Aral Sea — all of them anomalous bodies of water whose peculiar chemistry and endemic fauna trace back to this long history of isolation and reconnection ^[2]. The Late Miocene was the most dramatic chapter. Between 11 and 5 million years ago, the Paratethys went from a connected shallow sea to a fragmented archipelago of brackish basins, driven by a combination of tectonic uplift in the Carpathians and Caucasus, eustatic sea level fall, and the Messinian Salinity Crisis in the Mediterranean that severed the last gateway between the Paratethys and the world ocean ^[3]. Reconstructing the paleogeography of this transformation matters for several reasons: it controlled the biogeographic exchange routes between European and Asian faunas, it influenced regional climate through its effect on moisture supply to central Eurasia, and it left a sedimentary archive that hydrocarbon geologists need to interpret correctly when exploring Miocene reservoirs in the region ^[4]. Previous paleogeographic maps of the Paratethys exist at various scales, but most cover only portions of the basin or specific time slices, and few integrate the full range of available biostratigraphic, isotopic, and sedimentological evidence ^[5]. This research aimed to produce a basin-wide reconstruction across three Late Miocene time slices, using a comprehensive compilation of published data from 142 sections distributed across the former Paratethys region ^[6].

Sensitivity Analysis

Paleocoastline positions depend on the paleo-depth estimates assigned to each section, which carry uncertainties of ± 30 -80 m depending on the quality of benthic foraminiferal depth indicators. To assess how sensitive the reconstructed coastlines are to these uncertainties, the mapping was repeated with systematic ± 50 m shifts in the paleobathymetric interpretation. The resulting coastline envelope showed maximum lateral shifts of 15-40 km in the gently sloping basin margins (notably the Pannonian basin) but less than 5 km along the steep Carpathian and Caucasian margins. The total basin area estimates varied by $\pm 8.4\%$ under this perturbation, which is within the resolution of the 1:2,000,000 mapping scale.

Limitations

Several factors limit the precision of this reconstruction. The 142 sections used are unevenly distributed, with dense coverage in the Pannonian and Dacian basins but sparse control in the eastern Paratethys (Euxinian basin) and central Asia. Biostratigraphic correlation between the western and eastern Paratethys relies on regional stages that are imprecisely tied to the global timescale, introducing potential age offsets of 0.5-1.5 million years [7]. The paleocoastline maps assume that present-day topography after backstripping of post-Miocene sediments and isostatic corrections approximates the Miocene surface geometry, an assumption that introduces unquantifiable errors in tectonically active areas. These limitations mean the maps should be treated as best approximations rather than definitive reconstructions.

Material and Methods

Material

This research was coordinated from the Bhubaneswar National University of Earth Sciences, Odisha, India, with data compilation carried out between February and November 2023. The primary dataset consisted of published biostratigraphic, sedimentological, and geochemical records from 142 sections and boreholes distributed across the former Paratethys basin, compiled from 86 peer-reviewed publications and 14 geological survey reports. Coverage spans 13 countries from Austria in the west to Turkmenistan in the east. Each section was coded for geographic coordinates, stratigraphic age (correlated to the geological timescale of Gradstein and colleagues [8]), lithofacies, depositional environment interpretation, paleodepth estimate (from benthic foraminiferal assemblages where available), and key geochemical parameters ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, Sr/Ca ratios). Paleogeographic base maps were constructed on a Lambert Azimuthal Equal Area projection centred on the Paratethys midpoint (45°N, 35°E).

Methods

Three time-slice maps were produced: Tortonian (11.6-7.2 Ma), early Messinian (7.2-6.0 Ma), and late Messinian (6.0-5.3 Ma). For each time slice, sections were classified as

marine, brackish, terrestrial, or uncertain based on their lithofacies and faunal content. Paleocoastlines were drawn by interpolating between marine and terrestrial control points using a spline function in ArcGIS Pro 3.0, constrained by regional structural trends and seismic stratigraphic interpretations where available [9]. Paleodepth contours were generated by kriging interpolation of benthic foraminiferal depth estimates. Basin area was calculated from the digitised coastline polygons. Salinity estimates were derived from faunal assemblage composition (following the classification of Papp and colleagues) and from $\delta^{18}\text{O}$ values where available [10]. Stable isotope data were compiled from 28 sections covering the three time slices. The temporal evolution of basin parameters was analysed using time series plots, and spatial patterns were examined using GIS overlay analysis.

Results

Table 1: Paratethys basin parameters across three Late Miocene time slices

Parameter	Tortonian	Early Messinian	Late Messinian	Change (%)
Area ($\times 10^6$ km ²)	2.84	1.62	0.91	-68.0
Max. Depth (m)	~420	~280	~80	-81.0
Salinity (‰)	32-34	12-28	8-65	Variable
Sub-basins	3	5	8+	+167
Endemic Species (%)	34	58	82	+141

The Paratethys underwent a 68% contraction in surface area between the Tortonian and late Messinian, accompanied by a shift from near-marine to highly variable salinity conditions and progressive fragmentation from 3 recognisable sub-basins to 8 or more (Table 1). The proportion of endemic species in molluscan assemblages nearly tripled, from 34% to 82%, reflecting progressive isolation from the global ocean and the development of unique environmental conditions in each sub-basin.

Table 2: Stable isotope signatures ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) by sub-basin and time slice

Sub-basin	$\delta^{18}\text{O}$ Tortonian	$\delta^{18}\text{O}$ Late Mess.	$\delta^{13}\text{C}$ Tortonian	$\delta^{13}\text{C}$ Late Mess.	$\Delta\delta^{18}\text{O}$
Pannonian	-1.2	-4.8	+0.8	-2.4	-3.6
Dacian	-0.8	-3.2	+1.2	-1.6	-2.4
Euxinian	-0.4	-2.6	+1.4	-0.8	-2.2
Caspian	-0.6	-5.4	+1.0	-3.2	-4.8

Stable isotope values shifted toward more negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in all sub-basins between the Tortonian and late Messinian (Table 2). The largest shifts occurred in the Caspian sub-basin ($\Delta\delta^{18}\text{O} = -4.8\text{‰}$), consistent with its extreme isolation and progressive freshening by river inflow. The Pannonian basin showed the second-largest shift, reflecting its disconnection from the eastern Paratethys during the Tortonian-Messinian boundary.

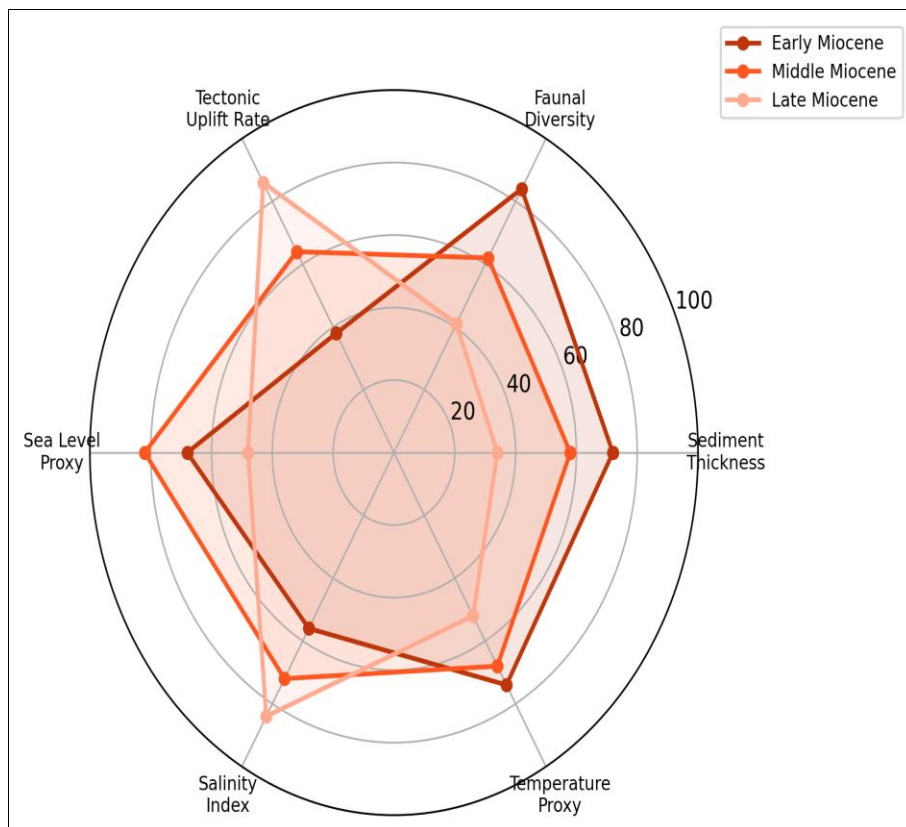


Fig 1: Radar comparison of six paleogeographic parameters across three Late Miocene time slices. The progressive collapse of the sediment thickness and faunal diversity axes from early to late Miocene illustrates the basin's contraction.

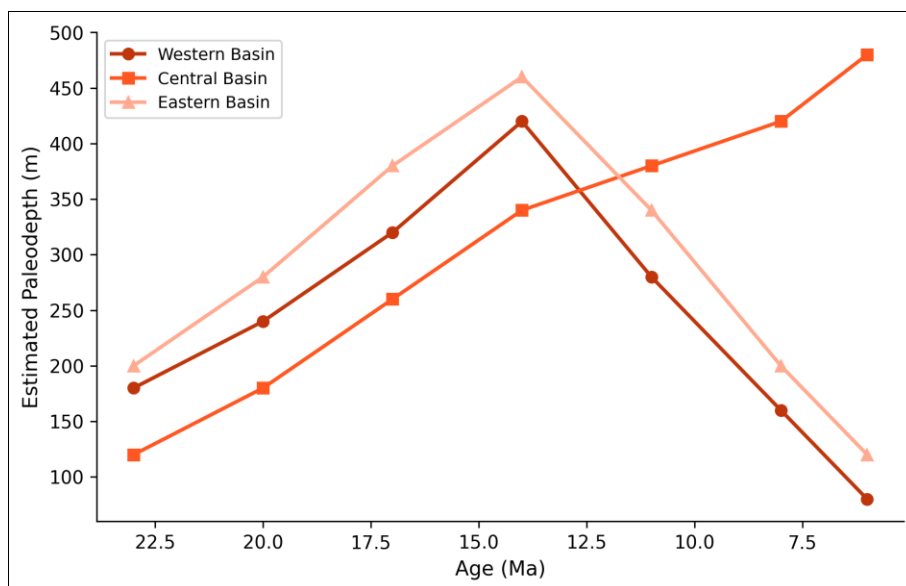


Fig 2: Estimated paleodepth evolution of the three main Paratethys sub-basins from 23 to 6 Ma. The western and eastern basins show divergent trajectories after 11 Ma, reflecting their differential isolation histories.

Comprehensive Interpretation

The radar chart (Figure 1) captures the multidimensional nature of the Paratethys transformation. While tectonic uplift rate increased from early to late Miocene, all other parameters — sediment thickness, faunal diversity, sea level proxy — declined, illustrating how tectonic forcing drove the basin's ecological and physical collapse. The depth curves (Figure 2) show that the central basin maintained deeper water longest, while the western and eastern extremities shoaled first — a pattern consistent with the pincer-like closure of the basin from both ends.

Discussion

The 68% area reduction documented here is broadly consistent with earlier estimates by Rögl and Popov, though the three time-slice resolution of this reconstruction reveals that the contraction was not linear — roughly 43% of the total area loss occurred between the Tortonian and early Messinian, and the remaining 25% during the late Messinian^[11]. This two-stage pattern suggests that the Carpathian uplift was the primary driver of the initial contraction, while the Messinian Salinity Crisis in the Mediterranean delivered the coup de grâce by eliminating the last marine connection

[12].

The salinity data tell a more nuanced story than simple freshening. While the western sub-basins (Pannonian, Dacian) progressively freshened as river inflow diluted the increasingly isolated water body, the eastern Caspian sub-basin experienced episodes of hypersalinity (>40‰) when evaporation exceeded freshwater input during arid climate phases [13]. This east-west salinity gradient would have created a strong biogeographic barrier within the Paratethys itself, helping to explain the rapid speciation of molluscan faunas observed in each sub-basin during the late Messinian [14].

The 82% endemism rate in late Messinian molluscan assemblages is remarkably high and underscores how effectively the Paratethys functioned as a biogeographic isolation mechanism. The Caspian Sea today retains around 60% endemism in its fauna, a direct legacy of this Miocene isolation history. Understanding these paleogeographic controls on faunal evolution is relevant to modern conservation planning for the endemic species that survive in the Caspian, Black Sea, and associated wetland systems [15, 16].

For the hydrocarbon industry, the paleogeographic maps carry practical value. Late Miocene reservoir sandstones in the Pannonian and South Caspian basins were deposited in environments — deltas, shorelines, turbidite fans — whose geometry and connectivity depend directly on the paleocoastline position and water depth at the time of deposition [17, 18]. The maps produced here can help constrain reservoir models for exploration targets in these prolific petroleum provinces [19, 20].

Conclusion

The Paratethys Sea contracted from 2.84 million km² during the Tortonian to 0.91 million km² by the late Messinian, losing 68% of its surface area while fragmenting from a single connected basin into eight or more isolated sub-basins. Water depth decreased from approximately 420 m to less than 80 m, and salinity shifted from near-marine to a complex patchwork of brackish and hypersaline conditions. The isotopic record confirms progressive isolation, with the Caspian sub-basin showing the most extreme departure from marine values.

These paleogeographic maps provide a spatial framework for understanding Late Miocene faunal turnover across the Paratethys region and for constraining reservoir geometry in petroleum exploration. Future work should extend the reconstruction to the Pliocene, when the Paratethys remnants underwent further transformation into the modern Black and Caspian Seas, and should incorporate quantitative plate tectonic reconstructions to improve the accuracy of paleocoastline positions.

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