Late Miocene megalake regressions in Eurasia

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The largest megalake in the geological record formed in Eurasia during the late Miocene, when the epicontinental Paratethys Sea became tectonically-trapped and disconnected from the global ocean. The megalake was characterized by several episodes of hydrological instability and partial desiccation, but the chronology, magnitude and impacts of these paleoenvironmental crises are poorly known. Our integrated stratigraphic study shows that the main desiccation episodes occurred between 9.75 and 7.65 million years ago. We identify four major regressions that correlate with aridification events, vegetation changes and faunal turnovers in large parts of Europe. Our paleogeographic reconstructions reveal that the Paratethys was profoundly transformed during regression episodes, losing ~1/3 of the water volume and ~70% of its surface during the most extreme events. The remaining water was stored in a central salt-lake and peripheral desalinated basins while vast regions (up to 1.75 million km²) became emergent land, suitable for development of forest-steppe landscapes. The partial megalake desiccations match with climate, food-web and landscape changes throughout Eurasia, although the exact triggers and mechanisms remain to be resolved.

A tectonically trapped sea turns into a megalake. At the beginning of the late Miocene (11.6 Ma) the European continent was very different from today (Fig. 1). In the west it was separated from Africa by an archipelago1-2. To the south the Anatolian—Balkan landmass was splitting apart, giving way to lakes that would become the modern Aegean Sea3-4, while the landmasses of modern Italy were scattered in a cluster of islands in the central Mediterranean Sea5-6. However, the most striking feature was the Paratethys—a water body the size of the Mediterranean that stretched between the Eastern Alps and modern Kazakhstan6,7.

The Paratethys was initially an epicontinental sea that formed at the beginning of the Oligocene (~ 34 Ma) from the remnants of the northern Tethys Ocean7. The sea was characterized by progressive fragmentation, gateway restrictions and sediment filling, mostly due to tectonics8. Progressive uplift of the central European mountain ranges gradually isolated the Paratethys from the global ocean. At the onset of the late Miocene, the ancient sea transformed into a megalake characterized by anomalohaline salinities (generally ranging between 12–14‰)9,10 and developed a unique endemic fauna (e.g., mollusks and ostracods). The landlocked Paratethys underwent extreme hydrological crises and partial desiccation episodes9. This had devastating effects on the aquatic fauna as the diversity of the endemic ecosystem was greatly reduced and multiple groups, such as foraminifera and nannoplankton, disappeared almost entirely11,12. The wider impacts and implications of these hydrological crises, in particular beyond the Paratethys area, are still poorly understood.

Chronology of late Miocene megalake regressions in Eurasia. Upper Miocene Paratethys sedimentary successions are exposed extensively in Eurasia but are often incomplete or interrupted by continental deposits (Fig. S1). In the western Black Sea region, carbonate platform deposits crop out and are truncated by repeated erosion and karstification episodes13, while in the northwestern region riverine-lacustrine successions of an extensive deltaic system developed14. Well-preserved aquatic records have been reported in peripheral basins of the southwest Caspian7 and south Carpathians15, but limited biostratigraphic information prevents development of integrated stratigraphies in these regions. More suitable fossiliferous sections are available on the eastern Crimean and western Taman peninsulas16. The classical Neogene sections of Taman were first described at the

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end of the nineteenth century and beginning of the twentieth century and have been used as reference sections for development of the Eastern Paratethys regional stratigraphic chart. Attempts to retrieve cores of the late Miocene record from the deeper central Black Sea basin during Deep-Sea Drilling Project (DSDP) Leg 42b had limited success, leaving the Neogene sections on the Black Sea coast of Taman (Fig. 1) as the only viable option for developing a chronology of late Miocene megalake fluctuations.

Taman Peninsula, Russia (Figs. 1, S2), contains several key stratigraphic sections including Cape Panagia (45°15′57.81″N/26°25′31.91″E), the only place known to host a continuous sedimentary record of the late Miocene Paratethys hydrological crises. The sedimentary succession of Cape Panagia (Fig. S3) belongs to the Kuban basin, adjacent to the Black Sea basin, the central and deepest part of the Paratethys. The section has been subject to extensive lithological and paleontological investigations, synthesized in a recent monograph that we use as a litho-biostratigraphic reference. Our sedimentologic analyses (see “Methods” and Fig. S4), correlated with biostratigraphic data, indicate that the Panagia section is characterized by deep-water sediments, interrupted by four major water-level regressions identified throughout the Paratethys.

The first regression interval is ~50 m thick and contains organogenic carbonate buildups (bryozoan-algal and microbial-algal mats), interbedded with finely laminated dolomitized limestones and clays (Figs. S2–S5, Table S1). Biostratigraphic correlations indicate that this interval corresponds to a significant base-level fall, freshening and shrinking of the basin. According to estimations of Paratethys water level fluctuations and shore migrations, this regression involved a ~230 m drop (from +80 to −150 m). It corresponds to the collapse of saltwater Paratethys fauna at the regional Bessarabian-Khersonian substage boundary. Multiple faunal groups disappeared, and the endemic fauna was greatly reduced, indicating a significant biological crisis for aquatic life. The second regression phase contains organogenic carbonate buildups (bryozoan-algal mats), interbedded with finely laminated limestones and clays, indicating paleobathymetric reductions alternating with incomplete recovery phases. This regression is not clearly described in the literature, likely because it occurred shortly after the previous episode. Based on its lithological expression we tentatively estimate a lowstand similar to the first event. Carbonate levels, similar to the previous levels but less developed are correlated to a third regression documented in Paratethys, when water levels dropped by ~100 m (from +50 to −50 m). The fourth and final regression is the most severe and is known as the Great Khersonian Drying (event kd, in Fig. 3). It corresponds to a water level drop of more than 250 m (from +50 to > −200 m) at the end of the Khersonian regional stage, when Panagia environments became terrestrial for a brief time. The Maeotian transgression (event mt, in Fig. 3, Fig. S4), widely documented throughout Eurasia, marks the end of this dry period and progressively refilled the basin.

Paleomagnetic measurements allow development of a polarity pattern that can be used to date the partial Paratethys desiccations. The Panagia polarity pattern (Fig. 2, Fig. S6) consists of 17 polarity intervals, 9 of normal polarity and 8 of reversed polarity, plus two additional short polarity fluctuations, that can be correlated with...
Figure 2. Paleomagnetic results from Cape Panagia. (a) Examples of demagnetization plots with normal and reversed polarities (AF alternating field, Th thermal demagnetization) with intervals used for interpretation highlighted in red; (b) Thermal behaviour of samples from Cape Panagia, obtained from Curie balance experiments with multiple cooling and heating steps; (c) Magnetic directions plotted in stratigraphic order and local magnetic polarity pattern. Log and lithological unit numbers are edited, from Popov et al.\textsuperscript{16}; the coloured bar indicates Paratethys high-stands (light blue) and low-stands (red).
the geomagnetic polarity time scale (GPTS) \(^{24}\) and are inferred to correspond to the 11–7.5 Ma interval (Fig. 3, Fig. S6 for a detailed correlation). This correlation provides the first direct age constraints for regression episodes in the Paratethys realm and permits chronological adjustment of the late Miocene Paratethys water level curve of Popov et al. \(^{7}\) (Fig. 3).

The first regression episode occurred between 9.75 and 9.6 Ma with a climax at 9.66 Ma (event 1, in Fig. 3, Fig. S6). The next partial desiccation episodes (events 2 and 3, in Fig. 3, Fig. S6) date between 9.5 and 9.3 Ma and between ~ 9.0 and ~ 8.7 Ma. The fourth regression episode began at ~ 8.3 Ma but became more severe between ~ 7.9 and 7.65 Ma. This partial desiccation episode was terminated by the Maeotian transgression (mt) at 7.65 Ma \(^{15,26}\), and was linked to a late Miocene global cooling episode \(^{27}\).

**Paleogeographic simulations of lake regressions.** The late Miocene paleogeographic configuration of the Paratethys realm is poorly known for the 11–7.5 Ma interval. We combine existing paleogeographic reconstructions, lithofacies maps and shoreline data to develop a digital elevation model and simulate water level fluctuations, revealing configurations during the most extreme lake regressions. According to these quantitative paleogeographic reconstructions, we show that the Paratethys had a surface area of more than 2.8 million km\(^2\) (slightly larger than the present-day Mediterranean Sea) and contained a water volume of more than 1.77 million km\(^3\) (representing more than 1/3 the volume of the modern Mediterranean), which is larger than any other megalake in the geological record \(^{28}\).

Next, we use our 3D paleogeographic model to simulate the maximum regression (~ 280 m water level drop)\(^{7}\), and resulting paleogeography of the partially desiccated megalake (Fig. 1). In this scenario, the shore significantly retreats on the relatively flat eastern (400–600 km) and northern (100–350 km) margins, while coastlines moderately shift in the western margin (~ 100 km) and the limited steep southern margin (Fig. 1). In addition, regressions fragment the Paratethys into a system of subbasins separated by land bridges. The final paleogeographic configuration implies salt re-distribution in various subbasins, similar to the situation documented during desiccation of Lake Aral \(^{29}\). Peripheral basins receive most of the freshwater from precipitation, and outflow from these basins transfers salt to the central basin, a natural process of desalination (Fig. 1). In the heart of the system, deprived of direct discharge from major rivers and fed by salty outflow rivers from peripheral basins, the Black Sea Basin becomes a salt lake, concentrating most of the Paratethys salts\(^{30}\). During arid episodes, this central basin will be the most affected, shrinking further as diminished outflow from surrounding peripheral lakes will not compensate for evaporation.

Simulation of the maximum water level drop (to ~ 200 m) indicates that the remaining lakes would be reduced to 31% of the initial surface and would retain 66% of their initial water volume (Table S2). Simulation of complete desalination of peripheral basins indicates that the Black Sea basin salinity would increase from 12–14‰ in the Paratethys high-stand \(^{16}\) to 28.2–32.8‰, which is insufficient to precipitate halite.
Landscape and environmental changes in inner Eurasia. The Paratethys consisted of a chain of deep sub-basins, connected by shallow zones, distributed roughly along the same latitude (Fig. 1). Due to its isolation from the ocean, the megalake expanded or contracted, determined by the balance between precipitation, river run-off and evaporation. The landlocked paleogeographic configuration made the lake levels prone to water-level instability episodes that occurred when dry or rain belts moved over this latitudinal zone. Initially, water-levels were relatively stable due to the humid regions lying closer to the Atlantic in the west, with positive water budgets that compensated the drier basins of the Eurasian interior (Fig. 4). Disconnection of Lake Pannon in the western periphery led to increased sensitivity to droughts for the remaining Paratethys.

During regression, much of the Paratethys megalake desiccated while remaining sub-basins became independent freshwater, brackish or saline lakes. In a paradoxical twist, regression allowed formation of large desalinated lakes in the Paratethys periphery. A significant area of the Paratethys periphery, particularly the gentle landscape of the northern shelf zone (> 1.75 million km²), emerged during regressions and was flooded during transgressions. This ongoing instability hampered permanent development of woodlands, favouring the more flexible grassland-shrub vegetation and giving rise to a late Miocene forest-steppe belt that stretched over 3000 km along the 45° latitude between Central Europe and Central Asia. Pollen records from Panagia indicate that these late Miocene lake regressions corresponded to the expansion of more open landscapes and increased charcoal in sediments hints at the augmentation of natural fires. Similar late Miocene vegetation changes toward more open landscapes are documented throughout inner Eurasia in Kazakhstan, Ukraine, Moldova and Bulgaria. Opening of the forest-steppe belt and formation of land bridges during lake regressions (Fig. 5) probably provided an ideal moment of dispersal for mammal populations, living in open Central Asian landscapes through these new passageways to Europe, which in turn would have impacted the food-webs of western Eurasia. Estimations of such dispersals remain poorly constrained because our new age model prompts chronological revision for mammal sites around the Paratethys.

Lake regressions correlate with environmental changes in Europe and Central Asia. The Paratethys water crises correlate with climate and landscape changes on the continent. At the beginning of the late

Figure 4. Climate and connectivity impacts on the Paratethys water-basins, a theoretical model illustrating the humid and dry climate impacts on an endorheic Paratethys system. (a) Stable system; (b) System during partial desiccation episodes.
Miocene, most of inner Eurasia was covered by forests, gradually fading from tropical mixed forests in the south-west to cold conifer forests in the mountains and the far north\textsuperscript{35}, except for the East Mediterranean region where drier climates favoured diverse and more open landscapes\textsuperscript{36}. Steepwise climatic changes throughout the late Miocene led to increased aridification and seasonality, accompanied by expanding open landscapes (Fig. 3).

The first change occurred at ~9.7 Ma, contemporaneous with the onset of Paratethys instability (events 1 and 2 in Fig. 3). An episode of diminished water cycling is observed in Europe in the 9.7–9.5 Ma time interval\textsuperscript{37}. In the northern Black Sea region, relatively closed forest environments were replaced by more open environments\textsuperscript{38} and in Panagia, the first evidence of xeric vegetation is documented\textsuperscript{39,40}. In western Europe marked decrease of the fruit-rich evergreen (subtropical) forests and their replacement by deciduous forests and open landscapes.

Figure 5. Schematic paleogeographic maps of lake regressions and landscapes of inner Eurasia. Dark green shading represents closed (forest) landscapes, light green shading shows former lake regions transformed to semi-open landscapes and brown shading indicate mountainous regions. Red dotted line indicates potential mammal dispersal routes across dry land and landbridges during lake-level regressions. (a) Paratethys megalake during high-stand configuration, (b) water distribution during the maximum lake regression. Note that a significant stretch of semi-open landscapes formed in the northern peripheral regions of the former megalake, providing potential passageways for mammal dispersals. (c) Paratethys during the partial water level recovery episodes, pushing back open landscapes.
began at 9.7 Ma\textsuperscript{41–43}, as a consequence of increased seasonality\textsuperscript{44}. Fauna changed too: most humidity-adapted and forest-dwelling faunal groups disappeared and immigrants from the peri-Mediterranean and Asia (e.g., murids) arrived in Europe\textsuperscript{45}. The next important climate and paleoenvironmental change occurred at ~ 8.7 Ma, contemporaneous with Paratethys instability (event 3 in Fig. 3). European humid forest landscapes were lost\textsuperscript{46} and replaced by dry, open woodland and grasslands\textsuperscript{46,47}, followed by diminished water cycling\textsuperscript{44,47} and increased aridity\textsuperscript{47,48}.

Peak aridity in Europe is documented between 8 and 7.5 Ma\textsuperscript{37,47}, while central-eastern Asia experienced increased aridity at ~ 8 Ma\textsuperscript{49}, corresponding to the largest lake regression documented in Paratethys (event kd in Fig. 3). Our results fill a blank spot in the chronology of inner Eurasia and Eurasian climate and landscape dynamics. Drought episodes in Europe and Asia correlate with water availability crises in the Paratethys megalake. Paleogeographic simulations provide a basis for future studies that are required to understand the triggers and dynamics of the late Miocene drying of Europe and the role that the inner Eurasian megalake Paratethys played in these events.

Conclusions

We constrain the age of the late Miocene hydrological crises in the Eurasian megalake Paratethys by integrating sedimentological analyses and magnetostratigraphic dating and resolve four main hydrological crises during the period from 11 to 7.5 million years ago. Using a 3D paleogeographic model, we calculate that the megalake lost ~ 70% of its surface and 1/3 of its volume during regressions, which impacted the climate, hydrology and vegetation of surrounding regions. The model predicts that the remaining water would be split between a central salt lake and peripheral low-salinity or freshwater lakes. Emergent land was preconditioned to become forest-steppe belts that better connected Central Asia with Europe and allowed terrestrial faunal exchanges between east and west. In an endorheic state, the Eurasian Paratethys megalake became unstable and experienced partial desiccation episodes. These events correlate stepwise drying and landscape opening in Europe with dry climate episodes in central Asia, which raises questions about whether the Paratethys crises were trigger, contributor or mere expressions of dry climatic episodes in Europe and central Asia.

Materials and methods

Sedimentology. We focus here on a ~ 500 m thick stratigraphic interval containing the Khersonian regional sub-stage\textsuperscript{19} that was logged, sampled and mapped in high-resolution. Detailed sedimentological studies focused on the uppermost Bessarabian–Khersonian–Maeotian interval of Panagia (Fig. S4) and are based on field observations focused on lithofacies descriptions (lithology, grain-size, colour, sedimentary structures) and associated trace fossils. The descriptive terminology follows the field guide of Tucker\textsuperscript{60}, while the general facies concept is based on Miall\textsuperscript{51,52}. Later, commonly occurring lithofacies were combined into eight distinct facies associations following the concept of Collinson\textsuperscript{53,54}. Facies associations were correlated to specific depositional environments based on sedimentological reasoning and comparison with literature examples (Table S1).

Paleomagnetism. Magnetostratigraphy can provide age dating for rock successions if the established polarity pattern of studied sections can be correlated to the reversal pattern of the Geomagnetic Polarity Time Scale\textsuperscript{24} (GPTS). This approach has proven successful with Paratethys sediments, when adequate demagnetization techniques are applied to deal with the generally high concentration of iron sulphides in anoxic sediments, and particularly with the magnetic mineral greigite\textsuperscript{55,56}.

The Panagia section is a cliff affected by active coastal erosion and erosion-induced instability. We drilled and oriented in situ 694 paleomagnetic samples, corresponding to 347 discrete stratigraphic levels (Fig. 2), and measured bedding planes for each sample level. Samples corresponding to distinct lithological units have been subjected to thermomagnetic measurements to determine the chemical nature of the magnetic carrier and to identify the most suitable heating profile for thermal demagnetization.

Rock magnetism. Thermomagnetic measurements of the induced magnetization (J-T curves) in air at high temperatures were conducted with a modified horizontal translation-type Curie balance with a sensitivity of ~ 5 × 10\textsuperscript{−9} Am\textsuperscript{2}. A field, cycled between 100 and 300 mT, was applied to powdered sediment samples (~ 70 mg). Multiple heating (6°/min) and cooling runs (10°/min) were performed between room temperature and steps of 150 °C, 250 °C, 350 °C, 450 °C, 525 °C and 700 °C. In terms of rock-magnetic properties (Fig. 2b), we divided the samples into three types: type 1 is characterized by the presence of greigite, indicated by the typical irreversible magnetization decrease after heating to ~ 320 °C and pyrite as indicated by a magnetization increase after heating to 380–420 °C (due to its oxidation)\textsuperscript{68}. Type one samples are rare (less than 5%). Type 2 samples are characterized by weak iron oxides. The presence of pyrite indicates that reductive dissolution of iron oxides has occurred, which causes lower magnetisations of sediments\textsuperscript{59}. These samples are abundant and are mainly found in the Bessarabian and lower Khersonian, suggesting a stratified environment and frequent bottom water anoxia. Finally, type 3 samples are characterized by iron oxide magnetic carriers. Sulfides such as pyrite and greigite are lacking in these samples found in carbonatic beds and the upper Khersonian continental levels.

Magnetostratigraphy. We use progressive thermal demagnetization and/or progressive alternating field demagnetization to isolate the characteristic remanent magnetization (ChRM). The natural remanent magnetization (NRM) was thermally demagnetized and measured using a 2G Enterprises DC Superconducting QUantum Interference Device (SQUID) cryogenic magnetometer (noise level of 3 × 10\textsuperscript{−12} Am\textsuperscript{2}). Heating was performed in a laboratory-built, magnetically shielded furnace, with a residual field less than 10 nT. The presence of pyrite,
indicated by J-T runs, informed the thermal demagnetization runs strategy, which were limited to a maximum temperature level of 380 °C. Due to pyrite oxidation at 420 °C, we restricted heating to well below this point (380 °C) to avoid pyrite oxidation artefacts from contaminating our results. Also, alternating field demagnetization was performed, with small field increments, up to a maximum of 100 mT with an in-house robotized sample handler, attached to a horizontal 2G Enterprises DC SQUID cryogenic magnetometer.

Thermal and alternating field demagnetization of Cape Panagia samples reveal a weak, low-temperature (LT), viscous overprint that is generally removed at 150 °C and 15 mT (Fig. 2a). A second higher temperature (HT) component that we consider to correspond to the ChRM is demagnetized at temperatures between 120 and 380 °C or fields between 15–45 mT. This component is averaged from four or more consecutive temperature/field steps and calculated using principal component analysis. We obtained ChRM directions for 614 samples of both reversed and normal polarities.

We used only one sample per level for plots and statistics, discarding duplicates with lower mean angular deviation (MAD). The 456 samples that resulted after the selection are assigned to four qualitative groups. The highest quality directions represent samples with MAD values (unanchored) below 6° and are attributed to and 12°. The third group Q3 represents poor quality directions with MAD > 12° (Fig. 2, labelled with lilac diamonds—167 specimens) and comprise samples with abnormal orientations and MAD values between 6° with patterns documented at other sites throughout Paratethys for the end Khersonian-Maeotian interval15,26,66,68.

For the Panagia section, the reversal and Watson tests give negative results, due to high ChRM directions scatter which makes the angle γ between mean normal and reversed polarities larger than the critical angle γc. Paleomagnetic directions (inclinations) for the normal polarity samples from Group Q1 have an average inclination of ~ 346°, suggesting a counter-clockwise rotation of 14°, which is significantly different from the 14° clockwise rotation revealed by the average declination of reverse polarity samples (~ 194°). The one explanation for this result is the incomplete removal of a secondary NRM component as observed by other authors on similar sections where multiple magnetic carriers are present. Overlapping unblocking spectra may also lead to overestimation of inclinations for normal polarity directions and, hence, to a negative reversal test. However, this does not disqualify the magnetostratigraphic results. The polarity results from Panagia are robust with clustered ChRM directions that define a complex pattern that can be correlated with the GPTS and that is in agreement with patterns documented at other sites throughout Paratethys for the end Khersonian-Maeotian interval15,26,66,68.

Paleogeographic reconstructions. Paratethys paleogeography has been the subject of intense research in recent decades resulting in local paleogeographic maps, tectonic reconstructions and regional paleogeographic maps. Popov et al. compiled and refined local maps in a series of paleogeographic and paleo-facies maps for the Paratethys region, supplemented by shoreline reconstructions for platform regions of
southern Russia and Ukraine\cite{10}. However, these reconstructions generally avoid the time interval between 11.6 and 7.2 Ma.

To reconstruct the paleogeography in this interval, we present two digital elevation models (DEM), based on the late Serravallian (\(>11.6\) Ma—Map 6) and late Tortonian–early Messinian (\(~7.2\) Ma Map 7) reconstructions of Popov. The first DEM is used to estimate the maximum megalake expansion (Fig. 5a). The second DEM (Fig. 5c), closer to the largest partial megalake desiccation episodes (\(~8–7.65\) Ma), is used to simulate the water-level drop and obtain the partially desiccated megalake paleogeography (Fig. 5b).

These Paratethys paleogeographic reconstructions are complemented by paleogeographic data from a range of regional studies of northern Europe\cite{17}, western Europe\cite{18}, Alps and Central Europe\cite{19}, Panonian basin\cite{20}, Gibraltar region\cite{51,52}, Aegean Sea\cite{53}, Marmara Sea paleobathymetry\cite{50,51}, Mediterranean paleobathymetry and paleotopography\cite{57,66} and a Middle East tectonic map\cite{67}.

Reconstructing the paleogeography of the Paratethys realm required conversion from facies on existing paleogeographic maps to bathymetry, based on digitizing facies zones and converting them to depths using facies-depth estimations and references from the modern analog Black Sea, Azov Sea, and Caspian Lake. For the Black Sea and Caspian Lake basins, maximal depth zones are based on analogies with present-day bathymetry of the above-mentioned basins.

To generate a Paratethys DEM, we used the ANUDEM method applied in ESRI ArcGIS Pro, version 2.1\cite{68}, which calculates topographical surfaces sensitive to shape and drainage structure resulting in hydrologically correct models. The model was then used to calculate the total water volume. Subsequently, DEMs for various base-level drops were obtained by applying simple map algebra additions and subtractions to the Paratethys DEM. For each newly created DEM, the volume, 2D area and 3D area were estimated below specific thresholds. This was accomplished using the Surface Volume tool from ArcGIS Pro, version 2.1\cite{69}.

Data availability
All data are available in the main text or supplementary materials.

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References
1. Flecker, R. et al. Evolution of the Late Miocene Mediterranean-Atlantic gateways and their impact on regional and global environmental change. Earth Sci. Rev. 150, 365–392 (2015).
2. Booth-Rea, G., Ranero, C. & Grevemeyer, I. The Alboran volcanic-arc modulated the Messinian faunal exchange and salinity crisis. Sci. Rep. 8, 1–14 (2018).
3. Göürün, N. et al. Neogene Paratethyan succession in Turkey and its implications for the palaeogeography of the eastern Paratethys. Geol. Soc. Spec. Publ. 173, 251–269 (2000).
4. Krijgsman, W., Palcu, D. V., Andreetto, F., Stoica, M. & Mandic, O. Changing seas in the late Miocene Northern Aegean: A Paratethyan approach to Mediterranean basin evolution. Earth Sci. Rev. 210, 103386 (2020).
5. Govers, R., Meijer, P. & Krijgsman, W. Regional isostatic response to Messinian Salinity Crisis events. Tectonophysics 463, 109–129 (2009).
6. Popov, S. V. et al. Late Miocene to Pliocene palaeogeography of the Paratethys and its relation to the Mediterranean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 238, 91–106 (2006).
7. Popov, S. V., Antipov, M. P., Zastrozhnov, A. S., Kurina, E. E. & Pinchuk, T. N. Sea-level fluctuations on the northern shelf of the Black Sea and Caspian Lake basins, maximal depth zones are based on analogies with present-day bathymetry, based on digitizing facies zones and converting them to depths using facies-depth estimations and references from the modern analog Black Sea, Azov Sea, and Caspian Lake. For the Black Sea and Caspian Lake basins, maximal depth zones are based on analogies with present-day bathymetry of the above-mentioned basins.
8. Popov, S. V. Late Miocene to Pliocene palaeogeography of the Paratethys and its relation to the Mediterranean. Palaeogeogr. Palaeoclimatol. Palaeoecol. 238, 91–106 (2006).
9. Popov, S. V. et al. Lithological-paleogeographic maps of paratethys. CFS Courier Forschungsinstitut Senckenberg 1–46 (2004).
10. Steinerger, E. F. & Rögl, F. Paleogeography and palinspastic reconstruction of the Neogene of the Mediterranean and Paratethys. Geol. Soc. Spec. Publ. 17, 659–668 (1984).
11. Suess, E. Untersuchungen über den Charakter der osterr. tertiärablagerungen II. Uber die Bedeutung der sogennanten, brackischen Stufeöder, Cerithischiichten, Sitzungsb. Österr. Akad. Wiss. Math. Naturwiss 54 (1866).
12. Maissuradze, L. & Koiava, K. Biodiversity of Sarmatian foraminifera of the Eastern Paratethys. Comptes Rendu l’ Academie Bulg. des Sci. 188–204 (2000).
13. Radionova, E. P. Sarmatian (Bessarabian) carbonate tempestites from Cape Kaliakra, North-Eastern Bulgaria. Bull. Georg. Natl. Acad. Sci. 55, 251–269 (2000).
14. Koleva-Rekalova, E. Sarmatian (Bessarabian) carbonate tempestites from Cape Kaliakra, North-Eastern Bulgaria. Cent. Eur. J. Geosci. 5, 188–204 (2012).
15. Koleva-Rekalova, E. Sarmatian (Bessarabian) carbonate tempestites from Cape Kaliakra, North-Eastern Bulgaria. Comptes Rendu l’ Academie Bulg. des Sci. 53, 71–74 (2000).
16. de Leuw, A. et al. Late Miocene sediment delivery from the axial drainage system of the East Carpathian foreland basin to the Black Sea. Geology 48, 761–765 (2020).
17. Palcu, D. V. D. V., Vasiliiev, I., Stoica, M. & Krijgsman, W. The end of the Great Khersonian Drying of Eurasia: Magnetostatigraphic dating of the Mesoic transgression in the Eastern Paratethys. Basin Res. 31, 33–58 (2019).
18. Popov, S. V. et al. Paleontological and stratigraphy of the Middle–Upper Miocene of the Taman Peninsula: Part 1. Description of key sections and benthic fossil groups. Palaeontol. J. 50, 1039–1206 (2016).
19. Neveskaja, L. A., Goncharova, I. A., Iljina, L. B., Paramonova, N. P. & Khondkarian, S. O. A. The Neogene stratigraphic scale of the Eastern Paratethys. Stratigr. Geol. Korrelyatsiya 51(2), 3026 (2003) (see 105–127).
20. Vasiliiev, I., Reichart, G. J., Krijgsman, W. & Mulch, A. Black Sea rivers capture significant change in catchment-wide mean annual temperature and soil pH during the Mioceene–Pliocene transition. Glob. Planet. Change 147, 428–439 (2019).
21. Golovina, L. A., Radionova, E. P., van Baak, C. G. C. C., Krijgsman, W. & Palcu, D. V. A Late Maotian age (6.7–6.3 Ma) for the enigmatic “Pebbly Breccia” unit in DSDP Hole 380A of the Black Sea. Palaeogeogr. Palaeoclimatol. Palaeoecol. 533, 109269 (2019).
22. Popov, S. V., Rostovtseva, Y. V., Pinchuk, T. N., Patina, I. S. & Goncharova, I. A. Oligocene to Neogene paleogeography and depositional environments of the Euxinian part of Paratethys in Crimean–Caucasian junction. Mar. Pet. Geol. 103, 163–175 (2019).
23. Goncharova, I. A. & Rostovtseva, Y. V. Evolution of organogenic carbonate buildups in the Middle through Late Miocene of the Euxine-Caspian Basin (Eastern Paratethys). Palaeontol. J. 43, 866–876 (2009).
24. Rostovtseva, Y. V. & Kuleshov, V. N. Carbon and oxygen stable isotopes in the middle-upper miocene and lower plicocene carbonates of the Eastern Paratethys (Kerch–Taman Region): Palaeoenvironments and post-sedimentation changes. Lithol. Miner. Resour. 51, 333–346 (2016).
23. Krigsman, W. & Kent, D. V. Non-uniform occurrence of short-term polarity fluctuations in the geomagnetic field? New results from middle to late miocene sediments of the North Atlantic (DSDP site 608). Geophys. Monogr. Sci. 145, 161–174 (2004).

24. Hilgen, F. J. et al. The Neogene Period. In *The Geologic Time Scale 2012* vols 1–2 (eds Gradstein, F. M. et al.) 923–978 (Oxford University, 2012).

25. Gradstein, F. M. & Ogg, J. G. The chronostratigraphic scale. In *Geologic Time Scale 2020* 21–32 (Elsevier, 2020).

26. Filipenkov, O. V., Trubikhin, V. M., Rostovtseva, T. V., Rybkina, A. I. & Filina, E. V. Magnitostratigraphic studies of the upper Sarmatian-lower Maeotian deposits in the Panagia Cape section (the Taman Peninsula). Bull. Kamchatka Reg. Assoc. "Educational-Scientific Center" Earth Sci. 42, 67–76 (1999).

27. Herbert, T. D. et al. Late Miocene global cooling and the rise of modern ecosystems. Nat. Geosci. 9, 843–847 (2016).

28. Gornitz, V. *Encyclopedia of Paleoclimatology and ancient environments* (2007).

29. Plotnikov, I. S. & Aladin, N. V. An overview of hybrid marine and lacustrine seas and saline lakes of the world. *Lake Res. Manag.* 16, 97–108 (2011).

30. Kojumgsieva, E. Palaeogeographic environment during the desiccation of the Black Sea. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 43, 195–204 (1983).

31. Razumkova, E. S. Palynological characterization of the Sarmatian deposits of the Eastern Paratethys (Section Zelenskii Mountain–Cape Panagiya, Taman Peninsula). Stratigr. Geol. Correl. 20, 97–108 (2012).

32. Feurdean, A. & Vasiliev, I. The contribution of fire to the late Miocene spread of grasslands in eastern Eurasia (Black Sea region). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 178, 19–37 (2002).

33. Panova, L. A. & Gromova, N. S. Palynostratigraphy of Neogene Deposits. In *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology* (Springer, 2013).

34. Ivanov, D., Ashraf, A. R., Mosbrugger, V. & Palamarev, E. Palynological evidence for Miocene climate change in the Forecarpathian Basin (Central Paratethys, NW Bulgaria). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 290, 29–45 (2011).

35. Strömbäck, C. A. E., Werdelin, L., Friis, E. M. & Sarac, G. The spread of grass-dominated habitats in Turkey and surrounding areas during the Cenozoic: Phytolith evidence. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 250, 18–49 (2007).

36. Böhme, M., IgL, A. & Winklhofer, M. Late Miocene ‘washhouse’ climate in Europe. *Earth Planet. Sci. Lett.* 275, 393–401 (2008).

37. Syhryti, S., Utescher, T., Mochanoff, S. & Bruch, A. A. Vegetation and palaeoclimate in the Miocene of Ukraine. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 253, 153–168 (2007).

38. Kovar-Eder, J., Jechorek, H., Kvaček, Z. & Parashiv, V. The integrated plant record: An essential tool for reconstructing neogene zonal vegetation in Europe. *Palaeo* 23, 97–111 (2008).

39. Bruch, A. A., Utescher, T. & Mosbrugger, V. Precipitation patterns in the Miocene of Central Europe and the development of continentality. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 304, 202–211 (2011).

40. Casanovas-Vilar, I. et al. Updated chronology for the Miocene hominoid radiation in Western Eurasia. *Proc. Natl. Acad. Sci. U.S.A.* 108, 5554–5559 (2011).

41. Fortelius, M. et al. Late Miocene and Pliocene large land mammals and climatic changes in Eurasia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 238, 219–227 (2006).

42. Böhme, M., Van Baak, C. G. C., Prieto, J., Winklhofer, M. & Spassov, N. Late Miocene stratigraphy, palaeoclimate and evolution of the Sandanski Basin (Bulgaria) and the chronology of the Pekermian faunal changes. *Glob. Planet. Change* 170, 1–19 (2018).

43. Roy, M. H. & Ding, Z. L. A palynological insight into the Miocene aridification in the Eurasian interior. *Palaeoworld* 22, 75–85 (2013).

44. Miall, A. & Postma, G. The geology of fluvial deposits, sedimentary facies, basin analysis and petroleum geology. *Sediment. Geol.* 110, 149 (1997).

45. Miall, A. D. *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology* (Springer, 2013).

46. Collins, J. D. The sedimentology of the Grindslow shales and the Kinderscout grit; a deltaic complex in the Namurian of northern England. *J. Sediment. Res.* 39, 194–221 (1969).

47. Posumurzher, H. W. & Walker, R. G. Facies models revisited (2006).

48. Miller-Collins, S. E. & Maxwell, P. A. Greigite-based magnetostatigraphic time frame for the late Miocene to recent DSDP Leg 42B cores from the Black Sea. *Front. Earth Sci.* 4, 1–18 (2016).

49. Liu, S., Krigsman, W., Dekkers, M. J. & Palcu, D. V. Early diagenetic greigite as an indicator of paleosalinity changes in the middle Miocene Paratethys Sea of central Europe. *Geochim. Geophys. Geosyst.* 18, 2634–2645 (2017).

50. Mullender, T. A. T. T., van Wijlen, A. J. & Dekkers, M. J. Continuous drift of marine magnetic and paramagnetic contributions in thermorigemic runs. *Geophys. J. Int.* 114, 663–672 (1993).

51. Wang, L., Pan, Y. X., Li, J. H. & Qin, H. F. Magnetic properties related to thermal treatment of pyrite. *Sci. China Ser. D Earth Sci.* 51, 1144–1153 (2008).

52. Roberts, A. P. *Magnetic mineral diagenesis. Earth Sci. Rev.* 151, 1–47 (2015).

53. Mullender, T. A. T. et al. Automated palaeomagnetic and rock magnetic data acquisition with an in-line horizontal “2G” system. *Geochim. Geophys. Geosyst.* 17, 3546–3559 (2016).

54. Kirschvink, J. L. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophys. J. R. Astron. Soc.* 62, 699–718 (1980).

55. Roberts, A. P. & Lewin-Harris, J. C. Marine magnetic anomalies: Evidence that ‘tiny wigglies’ represent short period geomagnetic polarity intervals. *Earth Planet. Sci. Lett.* 183, 375–388 (2000).

56. McFadden, P. L. & McElhinny, M. W. Classification of the reversal test in palaeomagnetism. *Geophys. J. Int.* 103, 725–729 (1990).

57. Watson, G. S. Analysis of dispersion on a sphere. *Geophys. Suppl. Mon. Not. R. Astron. Soc.* 7, 153–159 (1956).

58. Dallanave, E. et al. Eocene (46–44 Ma) Onset of Australia–Pacific plate motion in the Southwest pacific inferred from stratigraphy in New Caledonia and New Zealand. *Geochim. Geophys. Geosyst.* 21(7), e2019GC008699. https://doi.org/10.1029/2019GC008699 (2020).

59. Vasiliev, I. et al. Magnetostatigraphy and radio-isotope dating of upper Miocene-lower Pliocene sedimentary successions of the Black Sea Basin (Taman Peninsula, Russia). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 310, 163–175 (2011).
67. Hüsing, S. K., Hügen, F. J., Abdul Aziz, H. & Krijgsman, W. Completing the Neogene geological time scale between 8.5 and 12.5 Ma. Earth Planet. Sci. Lett. 253, 340–350 (2007).
68. Trubshkin, V. M. & Pilipenko, O. V. Rock magnetism and paleomagnetism of Meso-Tertiary deposits of the Popov Kamen reference section (Taman Peninsula). Izv. Phys. Solid Earth 47, 233–245 (2011).
69. Torsvik, T. H. et al. Phanerozoic polar wander, palaeogeography and dynamics. Earth Sci. Rev. 114, 325–368 (2012).
70. Tauze, L., Kodama, K. P. & Kent, D. V. Detection corrections for paleomagnetic inclination error in sedimentary rocks: A comparative approach. Phys. Earth Planet. Inter. 169, 152–165 (2008).
71. Koymans, M. R., Langeretis, C. G., Pastor-Galán, D. & van Hinsbergen, D. J. J. Paleomagnetism.org: An online multi-platform open source environment for paleomagnetic data analysis. Comput. Geosci. 93, 127–137 (2016).
72. Kovač, M. et al. Paleogeography of the Central Paratethys during the Karpatian and Badenian. Sc. Fac. Sci. Nat. Univ. Masaryk. Brno. Geol. 31, 7–17 (2004).
73. Rögl, F. Paleogeographic considerations for Mediterranean and Paratethys seaways. Ann. Naturhist. Mus. Wien 99A, 279–310 (1999).
74. Magyar, I., Geary, D. H. & Müller, P. Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. Palaeogeogr. Palaeoclimatol. Palaeoecol. 147, 151–167 (1999).
75. Barrier, E., Vrîlesync, B., Brouillet, J.-F. & Brunet, M. F. Darius Paleotectonic Reconstruction of the Central Tethyan Realm (2018).
76. Meulenkamp, J. E. & Sissingh, W. Tertiary palaeogeography and tectonostratigraphic evolution of the Northern and Southern Peri-Tethys platforms and the intermediate domains of the African–Eurasian convergent plate boundary zone. Palaeogeogr. Palaeoclimatol. Palaeoecol. 196, 209–228 (2003).
77. Gibbard, P. L. & Lewin, J. André Dumont medalist lecture 2014: Filling the North Sea Basin: Cenozoic sediment sources and river styles. Geol. Belgica 19, 201–217 (2016).
78. Alvinerie, J. et al. Synthetic data on the paleogeographic history of Northeastern Atlantic and Betic-Rifian basin, during the Neogene (from Brittany, France, to Morocco). Palaeogeogr. Palaeoclimatol. Palaeoecol. 95, 263–286 (1992).
79. Kuhlemann, J. Palaeogeographic and paleotopographic evolution of the Swiss and Eastern Alps since the Oligocene. Glob. Planet. Change 58, 224–236 (2007).
80. Magyar, I. et al. Progradation of the paleo-Danube shelf margin across the Pannonian Basin during the Late Miocene and Early Pliocene. Glob. Planet. Change 103, 168–173 (2013).
81. Suc, J. P. et al. The region of the Strandja Sill (North Turkey) and the Messinian events. Mar. Pet. Geol. 66, 149–164 (2015).
82. Sakinç, M. & Yaltıtrak, C. Messinian crisis: What happened around the northeastern Aegean? Mar. Geol. 221, 423–436 (2005).
83. Barrier, E. & Vrîlesync, B. Paleotectonic maps of the Middle East. MEBE Programme. Atlas of 14 maps. CCGM I, 1–14 (2008).
84. ArcGIS Pro | ArcGIS Desktop https://pro.arcgis.com/en/pro-app/latest/get-started/view-help-for-arcgis-pro.htm.
85. Surface Volume—Help | ArcGIS Desktop https://desktop.arcgis.com/en/arcmap/10.3/tools/3d-analyst-toolbox/surface-volume.htm.

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Author contributions
D.P. and W.K. designed the study; D.P., I.V. M.S., and S.L. participated in field observations; M.S. logged the section and coordinated the sampling, D.P., I.V., and W.K. developed the age model; I.P. and D.P. developed the paleogeographic review; S.L. conducted sedimentological observations on site and developed the sedimentological interpretation; I.S. and D.P. developed the digital elevation model; D.P., W.K. and I.P. discussed the results and developed the concepts; all mentioned authors participated in manuscript writing and refinement.

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