Paleocene-Eocene boundary events in the northeastern Peri-Tethys

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ABSTRACT

In the northeastern Peri-Tethys epicontinental basin stretching from the Black Sea to Tadzhikistan, a sapropelitic bed with total organic carbon (TOC) contents up to 20% and enriched in redox-sensitive elements was deposited during the Initial Eocene Thermal Maximum (IETM), recognized by the occurrence of a negative carbon isotope excursion in organic carbon and carbonate. In the sapropelic bed, calcareous plankton decreased in abundance, a benthic foraminiferal extinction occurred, dinocysts were abundant, and there were abnormally thick-walled dinocysts and asymmetric calcareous nanoplankton species. We argue that the sapropelic bed accumulated as a result of high productivity, triggered by an influx of nutrients that reached the basin when organic- and P-rich sediments in low-lying coastal areas were flooded during a rapid transgression. High productivity led to oxygen depletion, decimating benthic foraminiferal assemblages. Organic biomarkers suggest that at least in some places even waters in the photic zone became anoxic. The dinoflagellate rich muds have been hitherto described as of stratification, resulting from high run-off in the humid western region, high evaporation in the arid eastern area. Anoxic deposits ended gradually. We suggest that deposition of large amounts of organic matter in the northeastern Peri-Tethys may have been a factor in terminating the IETM.

INTRODUCTION

During the last decade many scientists have investigated events that occurred during the latest Paleocene and earliest Eocene (e.g., Kennett and Scott, 1991; Zachos et al., 1993; Dickens et al., 1995; Thomas and Shackleton, 1996; Schneider et al., 1998; Aubry et al., 1998; Koch et al., 1992; Wing et al., 1995; Katz et al., 1999). The most prominent event during this period was the Initial Eocene Thermal Maximum (IETM), which has been documented in sections deposited in such different environments as the open ocean, marginal basins, and on the continents. During this extreme warm period marine and continental biota show rapid change, coeval with distinct negative excursions in oxygen and carbon isotope values in carbonate and organic matter. In some areas, sediments deposited during the IETM are enriched in organic matter (e.g., Gavrilov et al., 1997; Speijer et al., 1997). One of these areas is the northeastern Peri-Tethys, where organic-rich sediments can be traced over >2500 km, from the Caspian to Central Asia (Mazzylov et al., 1999; Mazzylov and Shcherbinina, 1995). The properties of the organic-rich sediments, called the sapropelic bed, are relatively constant over this large area, although they accumulated in different environments in different parts of the region.

The origin of the sapropelic bed has been discussed extensively, after Mazzylov et al. (1989) first documented that its
deposition was synchronous over a large area (e.g., Gavrilov and Muzyllov, 1991; Muzyllov, 1994; Muzyllov et al., 1996; Gavrilov et al., 1997; Skopin and Muzyllov, 2001), but no comprehensive discussion of its deposition has been presented. We describe the sedimentological, geochemical, and paleoecological changes during the IETM in the northeastern Peri-Tethys, and propose a scenario for the accumulation of the sapropelitic bed.

**METHODS**

The mineralogy and geochemistry of the sapropelitic bed and its surrounding sediments were studied in many sections (Fig. 1), six of which are described in this paper, while two more are mentioned. Clay minerals were analyzed using X-ray diffraction. A range of elements and compounds were analyzed in the Laboratory of Analytical Chemistry at the Geological Institute of the Academy of Sciences of the USSR. The samples were analyzed by instrumental neutron activation analysis (INAA), and by X-ray fluorescence analysis. In two sections (Kheu in the northern Caucasus and Kurpai in Tajikistan), the organic matter was examined by pyrolysis analysis using Rock-Eval II, chromatography, molecular mass-spectrometry, and IR-spectrometry.

Nannofossils were studied in the bulk sediment using light microscopy. We counted the relative abundance of major nannofossil taxa. In most samples, 300 specimens were counted, but in a few samples with a low abundance of nannofossils 100 specimens only could be counted. In some intervals, there were so few specimens of nannofossils (<100 specimens per sample) that no statistically significant counts could be made.

**RESULTS**

We present results from six most important sections in the northeastern Peri-Tethys, covering a large area in the central and eastern Caucasus, the western shores of the Aral Sea, the western parts of the Kopeisk Range, and the Tadjik depression (Fig. 1). Generally, the sapropelitic bed is dark in color and fissile on weathering (Figs. 2, 3). The lower boundary is always sharp, and in some sections erosional, whereas the upper boundary is more gradual. In most sections the sapropelitic bed can be subdivided into three units, with a more calcareous middle unit that is less rich in TOC between lower and upper units with high TOC. Toward the northern margin of the basin, TOC content decreases significantly in the sapropelitic bed. Locally, sediments coeval to the bed contain abundant fish detritus, and in some localities in Central Asia (e.g., the Kyzyl Kum Desert, Tadjik depression) the bed is either associated with or replaced by ophiolite-bearing deposits.

**Lithology and paleontology**

In the Kheu River section (Central Caucasus) the sapropelitic bed is ~0.5 m thick, and exposed along the riverbank near the village of Gerpegeit (20 km southeast of the city of Nalchik).
within bluish-gray calcareous clays. The bed is dark brown (Plate 1, Figures 1–6) and contains abundant fish remains, ostracods, sulfide nodules, and rare pyritized wood fragments. It is underlain by a nanocalcareous light brown clay (0.1 m) with scarce nanofossils and no foraminifera (Gasikolov et al., 2000). Within this layer are the first occurrences (FOs) of the calcareous nanofossils Transversigopontis pulcher and Clophalosphera oedela (Fig. 4A, Appendix A). The FO of the latter species marks the bottom of Subzone CP9b in pelagic sections (Okada and Bukry, 1980).

Within the sapropelitic bed there is a poorly preserved and low-diversity nanoflora, dominated by various species of Toweiria. Compared to the underlying clays, the planktic/benthic foraminiferal ratio in the bed is high (Stokjin and Muzyllov, 2001). Nanofossils are rare and foraminifera are absent in the lowermost 5 cm of the sapropelitic bed where the TOC is highest. Slightly higher in the bed, Protophalosphera and the calcareous dinocyst Thoracosphaera become significant components of the assemblage. In the more calcareous middle part of the bed, the nanofossil content and diversity increase, and the first, rare thromboasters (R. branfetteri s.l.), occur. In the upper, TOC-rich part of the bed, thromboasters and discostaasters are abundant (including the FO of Discostaaster araneus). The abundance of benthic foraminifera, mainly calcareous species, is low (Stokjin and Murzilov, 2001).

In the Sulik River section (Dagestan, eastern Caucasus, near the Chirikty Hydroelectric Power Station), the sapropelitic bed is charcoal-black and occurs intercalated in a series of alternating dark red and green marls (Fig. 3). It is 0.3 m thick, with the lowermost 0.1 m slightly disturbed, possibly as the result of minor slumping. The nanofossil assemblage has a high relative abundance of Fasculithuris and Discostaaster species (Fig. 5A, Appendix B). In some intervals, we observed abundant calcareous diatoms and reworked Cretaceous nanofossils.

The underlying homogeneous green sediments are calcareous in their lowermost part, with abundant nanofossils. Toward the top of these sediments the carbonate content decreases and nanofossils disappear. In the lowermost part of the sapropelitic bed (0.20 m), there are almost no nanofossils. In the uppermost part, various species of Toweiria dominate, and thromboasters, Protophalosphera, Discostaaster araneus and asymmetric D. araneus first appear. The total number of Thoracosphaera specimens...
Figure 3. Sапропеличный слой в палеоцен-эоценовых границных отложениях Дагестана (восточное Кавказское, Сулак Река).
increases up-section within the sapropelic bed, and \textit{Camptolepis etodae} Eest occurs above the bed. A sharp increase in the abundance of calcareous detritus at the base of the overlying sediments, the reduced thickness of the bed, and the lack of a threefold division suggest that erosion removed the uppermost part of the bed.

In the Akhmatus Cape section (western Azal Sea, Uzbekistan, at the base of the cliff of the Usutut Plateau), the sapropelic bed is 1 m thick, dark gray, and intercalated in white limestone (Fig. 2). It is finely laminated and shows significant fluctuations in TOC. Sharp negative excursions in both $^{87}$Sr and $^{87}Sr$ are marked in the bed (Boelle et al., 2000). The underlying thin limestone bed, which has been assigned to calcareous nannofossil zone NPP (Martin, 1971), overlies upper Cambrian sediments with a sharp erosional contact (Fig. 5B, Appendix C). The high carbonate concentration is the result of a high content of calcareous detritus (Plate 1, Figures 7, 8), and nannofossils are less common than in the sapropelic bed. Various protosiphonids and the first species of rhizosphaerids (\textit{Rhzosphaera} cf. solis) occur. As in most other sections, TOC is most enriched in the lowermost part (0.43 m) of the sapropelic bed where the beginning of carbon isotope excursion and FO of \textit{R. brumleitii} were established. Unique for the studied region, species of \textit{Coelosialus} become more abundant in this section, while species of \textit{Toxemia} are rare, as was observed in other regions near the Palaeocene-Eocene transition (Fantawy et al., 2000, Morechi et al., 2000).

TOC is lower and the nannofossil abundance increases in the calcareous middle part of the sapropelic bed, but the nannofossil assemblage does not change significantly. Nannofossils and planktonic foraminifera become more abundant in the organic-rich uppermost part of the sapropelic bed. The abundance of \textit{Thalassiosira} and calcareous debris increases sharply in the overlying sediments. The sapropelic bed has common benthic foraminifera, equally divided between agglutinated and calcareous taxa (Stupin and Murylo, 2001), although the later are more common in its middle part.

In the Torony section (western Kopejask Mountains, Turkmenistan, exposed in the northern slope of the Kurendag anticline), the SB is 1.2 m thick and consists of brown clays, rich in fish scales, intercalated in gray, slightly calcareous clays (Fig. 5B, Appendix D). TOC is relatively low, possibly because the sampled sediment was rather weathered. In this section, the first chonobasters occur in sediments just below the sapropelic bed, which are not enriched in TOC but have increased concentrations of some elements (e.g., Mo, Zn) characteristic of the sapropelic bed in other sections (Fig. 7). We suggest that there was an erosional event at the time of deposition of the lowermost part of the sapropelic bed, so that only the middle and upper parts of the bed are present, as is also the case in the Baksan River section (Murzylov et al., 1996). The abundance of \textit{Fasciculithus}, which is believed to be an ellipsopteris taxon, sharply increases in the sapropelic bed, while planktonic foraminifera are absent. C. etodae first occurs in the overlying sediments. In the upper part of the bed, nannofossils are very rare, and calcareous species dominate the benthic foraminiferal assemblage (Stupin and Murzylov, 2001).

In the Kurpai section (Tadjik depression, Tadjikistan; Figure 6A), the sapropelic bed is 1.3 m thick and consists of black mud, with rare poorly preserved and low-diversity nannofossil assemblages dominated by \textit{Fasciculithus} and \textit{Discoaster} species. It is intercalated in slightly calcareous sediments with a significant fraction of terrigenuous silty material. In the underlying foraminifers layers nannofossils are absent and tiny calcareous benthic foraminifera are present. In the lowermost part of the sapropelic bed, the CaCO$_3$ content increases, mainly due to the presence of calcareous detritus and, to a minor extent, calcareous benthic foraminifera, but nannofossils are absent. Within the light-colored intercalation nannofossils are present, and \textit{Fasciculithus} is abundant ($>$50%) together with \textit{Coccolithus}. The uppermost part of the sapropelic bed is an oil shale with very high TOC, and nannoplankton and foraminifera are absent. In the sediments overlying the bed, nannofossils including protosiphonids are rare and calcareous detritus is common.

In the Guma-Etarma section (Tadjik depression) the sapropelic bed is 1.3 m thick, black oil shale with TOC $>$15%, intercalated in low-carbonate gray clays (Fig. 6B). There is a prominent erosional surface at the NPP/NP boundary below the bed. In the lowermost part of the bed, where TOC is highest, nannofossils are rare and their diversity is low. \textit{Braurhodo- sphera bigelovii} (57%), a long-ranging nannoplankton species (\textit{Lower Cretaceous}-\textit{Quaternary}) which is abundant in sporadic blooms, is dominant. Calcereous detritus is abundant. Nannoplankton are not common but diverse (though species of \textit{Toxemia} dominate the assemblage) higher in the sapropelic bed, despite the low CaCO$_3$ content, and rare benthic foraminifera are common (Stupin and Murzylo, 2001). Up-section, TOC decreases gradually, and calcareous nannofossils become rare or are absent. In the uppermost part of the bed, rare nannofossils occur, and the abundance of \textit{Toxemia} sharply decreases while various \textit{Fasciculithus} and \textit{Discoaster} species become more abundant. The overlying sediments contain rare various nannofossils and planktonic foraminifera only.

In the Kheu river (N. Zaporozhets, 2002, personal communication), Medani (Transcaucasus, Georgia) and Torony (\textit{Abhnozov} and Zaporozhets, 1996) sections, organic-walled dinoflagellates show good preservation without reworking within the sapropelic bed and surrounding sediments. \textit{Sarcocystis} spp. are found in the sediments surrounding the bed. Within the bed, however, \textit{Apectodinium homomorphic}, \textit{A. augustum}, \textit{A. parvus}, \textit{A. quinqualepatus}, \textit{A. hyperacanthum}, \textit{A. paniculatum}, and \textit{A. timuromu}, are abundant, and co-occur with \textit{Keilinlla}, \textit{Rhombodinium}, \textit{Hystrixkotschyanum}, and \textit{Filro- cytis}. This assemblage was assigned to the dinoflagelates \textit{Apecto- dinium hyperacanthum} zone (Poll, 1992). The sapropelic bed thus corresponds to the \textit{Apectodinium} zone observed in
many parts of the world during the IETM (e.g., Biju and Bhandarkar, 1998; Crouch et al., 2000; Steurbaut et al., 2000; Crouch et al., 2001).

The sapropelic bed contains unusual forms of the genus *Aptediscus* with extremely thick-walled paracysts, which constitute up to 60% of the diatom assemblage. These forms are endemic to the northeastern part of the Tethys and indicate eutrophic conditions (Altkaves and Zuparozsics, 1996). Organic-walled planktonic remains are abundant in the bed, but their total amount is only a part (15% in Khe river section; 65% in Medani section) of the amorphous matrix, which consists of solid organic matter and other algal remains.

Mineralogical and geochemical characteristics of the sapropelic bed

We analyzed the clay fraction in samples from all sections. Clay mineral assemblages consist of varying proportions of smectite, illite, mixed-layer illite-smectite, chlorite, and rarely kaolinite. In most cases there is no significant difference between the clay mineral assemblages in the sapropelic bed and those in the surrounding sediments. Kaolinite is absent in most sections, and found only in the Akumusk section (northwestern Uzbekistan) and, to a lesser extent, in the Medani section (western Georgia). In these sections, the sapropelic bed contains kaolinite, but it is slightly more abundant in the bed.

The oil shale collected near the Amu-Darya River (Fig. 1) contains an admixture of pyrolyserite, which is a common mineral in the Palaeocene-Lower Eocene sediments along the eastern margin of the basin (Fergana embayment, eastern Uzbekistan). indicating that the climate was arid in these areas. In the Torqan (Turkmenistan) and Sarak River (Dagestan) sections, Palaeocene-Eocene sediments contain illite with a low percentage of expanding interlayer clays (5-10%) and chlorite, as a result of deep burial.

The TOC in the sapropelic bed is highly variable (Fig. 7). In the Amu Darya region (Suzak oil shale sample; Figure 1), the TOC content is higher than 10%, but in the Lower Volga region it does not exceed 1%. In the areas of predominantly carbonate sedimentation (Caucasus and Aral Sea region), where the sapropelic bed is organic-rich, the TOC is usually negatively correlated with the CaCO3 content, but this correlation does not hold in the regions of essentially terrigenous sedimentation (Central Asia).

The P:S are enriched in the sapropelic bed whereas Mn is slightly depleted. The mineral elements can be divided into two groups. V, Cu, Mo, Ni, Ag, Au, Se, Co, Zn, Cr, Sn, Ge, Br, Te, Ti, Bi, Sh, Cd are generally enriched to a variable extent in the bed. Some elements show enrichment throughout the area, others in some sections only. Ti, Zr, Nb, Re, Sr, Sc, Cs, Hf, and the REE have a very low concentration in the sapropelic bed (Gurvich et al., 1970). The pattern of elemental enrichment in the bed is similar to that in the Quaternary sapropels of the Black Sea and Mediterranean (e.g., Fomin and Volkov, 1970; Volkov, 1973; Calvert, 1990; Pruessers et al., 1991; Sutherland et al., 1984).

In the Kheea section, the organic matter in the sapropelic bed is enriched in 14C (B~30.5% to ~30.8%) relative to the organic matter in the surrounding sediment (~27% to ~28%), Figure 8). The carbonate show the same isotopic excursion (Kodina et al., 1995; Gurvich et al., 1997), as also reported for the Akumusk section (Bolte et al., 2000).

Geochemical analyses show a strong increase in the abundance of marine, planktonic organic matter in the sapropelic bed relative to the surrounding sediments, but the sources of the organic matter vary by location (Gurvich et al., 1997). In the Kheea River section, organic matter is mainly derived from marine plankton, but there is a minor amount of terrestrial organic material. Terrestrial organic matter is absent in the Kurpaq section. This variability in the composition of organic matter may reflect the regional variability in setting, rain off, and climate. Climate was more humid in the western region, and a terrestrial organic matter was derived from the vegetated coastal areas, whereas the eastern regions were much more arid, and there was minimal input from vegetation.

Biomarkers derived from the antherid photosynthetic green sulphur bacteria *Chlorobium* (Sromovics and Powell,
Recent studies (Muzylów, 1994; Muzylów et al., 1989; Muzylów and Steinbergmann, 1995) documented that the sapropelitic bed corresponds in age to the boundary between late Paleocene Subzones CPhu/CPhb of Okada and Bikry (1980), based on the PD of Rhamnoberaster cupris within the sapropelitic bed. According to Martini (1971), the PD of R. branitleri (base of Zone NP10) marks the Paleocene-Eocene boundary. Recently, however, the taxonomy of rhomboaster has been revised, with the proposition to establish two sub-species of Rhamnoberaster branitleri, R. branitleri branitleri and R. branitleri cupris (Hybrell and Self-Trull, 1994, 1997; von Sald et al., 2000). In this revision, the base of Zone NP10 is close to that boundary between Subzones CPha/CPhb. In addition, the paleo of the global Carbon Isotope Excursion has now been proposed as the Paleocene-Eocene (P-E) boundary by the International Subcommission on Paleocene Stratigraphy (Luterbacher et al., 2000). If we follow this revision, the P-E boundary falls at the base of the sapropelitic bed. We do not have isotopic data in all studied sections, and in the figures for this paper have still placed the P-E boundary at the NP10/NI10 zonal boundary.

Consistent biotic changes in our sections include a major change from mainly calcareous-walled phytoplankton in sediments below the sapropelic bed to mainly organic-walled plankton remains within the bed, separated in some sections (Kheie, Sulak, Akhunsk, and Kurgan) by a thin layer of sediment just below the bed which lacks both planktic and benthic calcareous microfossils. Some nanofossil taxa (ponospherids and rhaphidophorids), which are common in epicontinental sediments in subsequent epochs, evolved at this time as seen in some sections (Figs. 4, 5, and Muzylów, 1994).

The sapropelic bed itself contains both nanofossils and planktic foraminifers, but the nanofossil assemblages within the bed differ from those in the surrounding sediments. Generally, within the sapropelitic bed the nanofossil diversity is low, and one or two taxon dominate. Sections with carbonate sediments (Kheie, Akhunsk) show a strong dominance of I. crassus, and those with mostly terrigenous sediments (Torugary, Kurgan, and Guru-Fatima sections) contain assemblages dominated by Fusuliniforis, probably reflecting shallow water depth and oligotrophic environments. The nanofossil changes in the northeastern Peri-Tethys sections thus differ from those in sections in Spain (Trabakua Pass section), where the I. crassus occurs in a diatomaceous horizon (Ore-Exechebarria et al., 1996), and is marked by a low abundance of the cool water species of the genera Chiasmolithus and Primeus and a high abundance of Fusuliniforis. An abrupt decline in abundance of Fusuliniforis and the appearance of abundant Zygiaphylloides above the base of the I. crassus have been observed in epicontinental and oceanic sections (Audry et al., 1996; Ore-Excebarria et al., 1996; Monechi et al., 2000; Braslaw and Prentice-Silva, 2002). In our sections, Zygiaphylloides is generally absent and Fusuliniforis are common, showing increased abundance above the sapropelitic bed in the Gura-Fatima section only.

In most sections, the lowest part of the sapropelitic bed which contains the highest TOC content is characterized by a poor nanofossil, and an increased abundance of Thalassios- sphaera. A bloom of Brunsadiophora is found only in the Gura-Fatima section, situated in the arid eastern part of the basin. These two taxa are abundant after the Cretaceous-Paleogene boundary, when other nanofossil taxa were rare. Occasional Brunsadiophora blooms have been recognized in mid- Oligocene sediments from the South Atlantic, possibly due to voluminous freshwater influx resulting from the melting of Antarctic ice. In Miocene and Pliocene sediments in the Mediterranean and Black Sea, Brunsadiophora-rich sediments are associated with sapropellic layers (L.A. Golovina, 2001, personal communication). Bikry (1974) concluded that B. ingens may thrive at relatively low salinities, but Pech-Nielsen (1977) speculated that the taxon is euryhaline, and thus more common where salinity fluctuations limit the occurrence of other species. Experimental data on modern Thalassiossphaera brevis in culture show a minimum growth rate and productivity at 27 °C in a nutrient-rich medium (Kawashita et al., 2000), suggesting that the sapropelitic bed accumulated at relatively high temperatures, in agreement with the occurrence of abundant warm-water dis- coasters within the bed. Besides, this species has its maximal productivity during periods of stratification of the upper water column and a well-developed thermocline (Viko et al., 2002).

The microfossil assemblages thus indicate that conditions were warm during the deposition of the sapropelitic bed, and locally salinity variations occurred. In addition, the occurrence of some nanofossil forms such as chonborasters, asymmetric di- coasters, morphotypes of Fusuliniforis with a very high curved cone, and extremely thick-walled Vechnithinctyocysta sp. testify to the occurrence of unusual environmental circumstances.
Figure 6. Lithological and microfossil changes around the Paleocene-Eocene boundary in the Central Asia (Tadjik depression): A) Kurbat section. B) Gur-Fariba section. Arrows indicate levels of enrichment in calcitic detritus. Data on foraminifera after Shapin and Murylova, 2001. Note that the Paleocene-Eocene boundary was drawn at the N2/N110 zonal boundary. For legend see Figure 4.

Figure 5. Lithological and microfossil changes around the Paleocene-Eocene boundary: A) Sulak River section (Eastern Caucasus). B) Torunyky section (Turkmensistan). Arrows indicate levels of enrichment in calcitic detritus. Data on foraminifera after Shapin and Murylova, 2001. Note that the Paleocene-Eocene boundary was drawn at the N10/N110 zonal boundary. For legend see Figure 4.
Figure 7. Concentrations of various compounds and elements in the sapropelic bed in selected sections. The concentrations of C<sub>org</sub>, CaCO<sub>3</sub>, P, Ti, Fe, Mn, are given in percent, those of the other elements in ppm.
The planktic/benthic foraminiferal ratio increased sharply in the sapropelic bed, with benthic foraminifera represented mostly by dymosic species of benthic foraminifera, indicating varying degrees of dysoxia/anoxia within the basin (Stupin and Mryasov, 2001). The benthic foraminifera recovered partially in the middle part of the sapropelic bed, concurrent with the recovery of calcareous plankton and a decrease in TOC, suggesting that dysoxia/anoxia weakened temporarily. The changes in benthic foraminiferal assemblages in the sapropelic bed of the northeastern Peri-Tethys thus resemble those documented in coeval sediments in Egypt (Spieijer et al., 1997; Speijer, 2003). In the Taranjelq section, benthic foraminifera, generally thought to indicate a high food supply, were abundant (Spieijer et al., 1997).

The calcareous microplankton apparently recovered during the deposition of the sapropelic bed, after the "presapropelic" crisis (thin interval without microplankton). We do not consider that carbonate dissolution caused the absence of calcareous plankton in this layer; in fact, dissolution appears to have been somewhat more important in the sapropelic bed. Remains of organic-walled plankton dominated during the accumulation of the bed. The acme in dinoflagellate Apectodinum exists in sediments deposited during the IETM has usually been explained as the result of high temperatures as well as high nutrient levels (e.g., Crough et al., 2001). Dinoflagellates form a major part of primary planktonic production in oceans, and their blooms usually occur in warm, eutrophic waters. Dinoflagellates are also known for producing toxins in the so-called "red tide" blooms, causing fish and plankton kills (e.g., Taylor and Seliger, 1979; Steidinger and Baden, 1984). When the sapropelic bed accumulation gradually came to an end, the nanofossils recovered slowly in abundance and diversity. In the Taranjelq section, the benthic foraminifera also showed a gradual recovery (Speijer et al., 1997), as they did at ODP Site 1051 (Katz et al., 1999) and at several other sites globally (Thomas, 1998). Low-diversity nanofossils persisted for a long time after the accumulation of the sapropelic bed, although the relative abundances of the most important taxa recovered in pre-sapropelic bed levels. Dinocyst morphotypes appeared just after the deposition of the sapropelic bed, with a FO apparently synchronous over the Tethys, as well as in a number of sections in Spain and Egypt (Moro et al., 2000).
climate obtained by assuming that the illumination of the sapro-
pelic bed represents annual laminae (Plate 1, Figure 3) indi-
cates that the whole of the bed accumulated in 10–12 k.y. How-
ever, correlation of the carbon isotope record of the sapropelic bed (Fig. 8) with records in oceanic sections suggests that the main part of the bed formed during the peak of the CIE, which lasted 60 k.y. (3 procurement cycles; Rohrl et al., 2000). We can presently not explain this disagreement.

The formation of organic-rich sediments is usually thought to result from increased biological productivity (e.g., Pedersen and Calvert, 1991). We agree with these authors that high pro-
ductivity was the most important factor in the accumulation of the sapropelic bed, while stratification of the water column may have played a role, but was not the main cause of low-
oxide conditions. Models proposed for the genesis of the Piocence-Pliocene eastern Mediterranean sapropels (e.g., Kidd et al., 1978; Calvert, 1983; Sutherland et al., 1984) and the Black Sea (Srivastav, 1971) are probably not relevant to the dep-
sition of the sapropelic bed, because the northeastern Peri-
Tethys was a very large, epicontinental, relative shallow-water basin, separated from the open ocean by a system of archipelagoes, and thus had an oceanographic setting very different from that of the eastern Mediterranean and the Black Sea.

The sapropelic bed accumulated during a rapid transgres-
sion, as documented by its sharp, sometimes erosional lower boundary. This transgression was preceded by a short regression (Muyzilov et al., 1996; Gavrilov et al., 1997), very similar to in-
terpretations of the setting of coeval TOC-rich sediments at the southern Peri-Tethyan margin (Speijer, 2003; Speijer and Morsi, 2001). These authors argue that both increased productivity and increased preservation of organic matter were important factors in the deposition of the organic-rich sediments, and that the high productivity was driven by increased upwelling of nutrient-rich waters through offshore Ekman transport.

In contrast to these authors, we think that upwelling cannot have been efficient throughout the large, shallow epicontinental basin of the northern Peri-Tethys, and argue that high produc-
tivity throughout this vast region was mainly caused by an in-
creased supply of nutrients into the basin from coastal regions during a rapid transgression (Fig. 9) (Gavrilov, 1994; Gavrilov and Kopaevich, 1996; Gavrilov et al., 1997).

This increased nutrient flux resulted from a rather complex series of events. During the rapid regression just before the IETM, large lowland areas with little relief formed along the peri-
phery of the basin and around archipelagoes in a relatively shal-
low epicontinental sea. Non- or weakly lithified sediments in the newly exposed, widespread coastal plains underwent soil for-
mation, and the soils became enriched in nutrients. In hilly areas, such as the Caucasus and adjacent areas, lakes and water-
logged bogs developed rapidly in the extensive coastal plains. In present-day peat bogs, P is very soluble and becomes enriched in surface waters (Kovaliev, 1985). Water-logged basins contain abundant dissolved and particulate organic matter from the de-
composition of vegetation.

We argue that a rapid transgression flooded the coastal plains at the beginning of the formation of the sapropelic bed (Fig. 9). Because most of the northeastern Peri-Tethys was a peatland before the Late Cretaceous and earliest Paleogene, even minor sea-level fluctuations resulted in a major change in basin outline. The sea-level rise was at least several tens of me-
 ters (Haq et al., 1987; Gavrilov et al., 1997) in agreement with uncerainty (Speijer et al., 2003) and Speijer (2003) for the southern margin of Peri-Tethys. During the sea-level rise, par-
ticulate and dissolved organic matter was transported into the sea from the drowned peat bogs and soils. The particulate or-
ganic matter was partially redeposited, enhancing enrichment of En-
TOC in some regions (e.g., the Suez river section). The dis-
olved organic matter and nutrients (including P which is en-
riched in most sapropelic bed sections) were transported into the basin, triggering a strong increase in productivity of organic-
wallied and possibly prokaryote phytoplankton. The blooms of organic-walled phytoplankton may have adversely affected other plankton groups and fish, as observed in present-day "red tides" in coastal upwelling regions.

The hypothesis that the transgression played a major role in triggering increased productivity was also invoked to explain the origin of Pennsylvania black shales (Wepener and Bakker, 1986). In addition, data on events during the filling of reservoirs behind dams, which simulates a transgression, supports this hypothesis: During the initial filling of reservoirs, phytoplankton productivity is extremely high because large amounts of nutrients are washed from the flooded soils into the basin (Petrou, 1990).

In some sections in the eastern and part of the basin (e.g., the Kourai section) only a negligible amount of terrestrial organic matter accumulated in the sapropelic bed, but the bed is closely associated with phosphate-bearing rocks and phosphorites. The lowermost part of the Suez Formation (underlying the oil shale unit) contains abundant phosphate concretions. We argue that a significant amount of P, concentrated in soils and produced by weathering in pre-sapropelic bed time, was supplied to the basin during the transgression, triggering phytoplankton blooms and causing high organic matter concentrations.

The high productivity of organic-walled plankton supplied most of the organic material present as TOC in the sapropelic bed, while productivity of calcareous plankton was low; al-
though we may underestimate calcareous plankton productivity as a result of slight dissolution. This high productivity was the major cause of the anoxia/dysaeria in the water column, as indic-
ed by the impoverished benthic foraminiferal faunas, sedi-
ment accumulation, and organic biochemical tracers. In addition, it has been argued that open-ocean waters were overall low in oxygen during the IETM (e.g., Thomas, 1998), and these global low oxygen levels could have influenced oxygen levels in mar-
ginal basins (e.g., Speijer, 2003).

We cannot, however, completely exclude the possibility that the anoxia/dysaeria was exacerbated by stratification and re-
sulting stagnation. Increased runoff of fresh water could have caused stratification in western parts of the basin. The only ev-
idence for such an increase in runoff can be seen in the low values of oxygen isotopes in bulk carbonates in the sapropelitic bed in the Aktsinsk section (Fig. 8). But the thick-walled dinocyst abundance, the blooms of the calcareous dinocyst Thaumatinospira, and diverse nanofossil assemblages indicate eutrophic environments and normal salinity, and the biota thus do not indicate lowered salinity. At other times, the biota very clearly documented increased runoff. For instance, well-documented episodes of high freshwater influx in the northeastern Peri-Tethys (e.g., in the middle Oligocene part of the Maykop Formation) are characterized by the occurrence of abundant monospecific nanofossil assemblages associated with small thin-walled dinocyst remains (M. A. Shvarts, 2002, personal communication). We thus have no solid evidence for increased runoff resulting in lowered salinity, and conclude that deposition of the sapropelitic bed was probably not caused by stagnation resulting from stable stratification as a result of increased runoff, even in the more humid western parts of the basin.

In the eastern part of the area conditions were arid, as documented by the higher palynoflora content in sediments in the Ferghana embayment and the Aral-Dar’iA region, Uzbekistan. Over the whole basin, and not just in the western regions where climatic was humid, the transgression was followed by the deposition of TOC-rich sediments, with maximal TOC concentrations in arid areas (e.g., in the Nurata and Guru-Fatami sections). In these areas and easternmost part of the basin, increased stratification might have resulted from higher evaporation rates during the warm IETM, similar to the correlative episode of extensive evaporation documented in Spanish sections (Schmitz and Pujalte, 2001). Hypersaline lagoons and lakes may have formed during pre-sapropelic bed regression, and supplied saline water to the marine basin during the following transgression, possibly increasing local salinity and causing density stratification. Stable density stratification thus may have been a contributing factor to the high concentrations of organic matter in sediments (e.g., TOC >20% in the Sturak oil shales).

The accumulation of organic matter in the sediments caused sulfate-reduction and the generation of H2S that diffused into the water, accumulated close to the bottom, and locally reached the phytic zone, as shown by the biomarkers. The development of anoxic and dysoxic conditions caused extinction of benthic fauna, the appearance of anomalous planktonic taxa and possibly impoverished planktonic assemblages where these conditions reached the phytic zone. The intensity of dysoxic/anoxic varied in different parts of the basin, as indicated by differences in benthic foraminiferal assemblages (Stupin and Musylov, 2001).

The presence of H2S affected the geochemical signature of the sediments, too. In all sections, the sapropelitic bed is strongly enriched in Mo with respect to the surrounding sediments (Fig. 7), and enrichment patterns are similar for Se and
Re (Gavrilo et al., 1997). These elements (Mo, Se, Re) are redox-sensitive and form insoluble sulfides in the presence of H_2S in the water column. This process caused the observed enrichment in the sapropellitic bed, in combination with other mechanisms for the concentration of minor elements, such as sorption by clay particles and organic matter, and possibly diagenetic enrichment.

In some sections, we observed that biotic changes started below the base of the sapropellitic bed, whereas the thin layer of sediment contains neither plankton nor benthos. We have no biochemical or geochemical evidence of major taphonomic changes during diagenesis in this layer (e.g., calcite redistribution). We suggest that a dramatic decrease in productivity may have occurred during the regression, which occurred before the rapid transgression that led to deposition of the sapropellitic bed. During this regression, the waters had a high turbidity in some parts of the basin, as a result of erosion of weakly lithified sediments, as documented by the occurrence of detrital carbonate and reworked Cretaceous mammal fossils in some sections. The increased turbidity would have decreased light penetration in the water column, thus reducing primary productivity, and influencing floral and faunal composition.

After the peak of the transgression, the rich supply of nutrients gradually decreased with the deposition of the organic matter in the sapropellitic bed, and the intense blooms of various forms of plankton ended, ending the dysoxic to anoxic conditions (e.g., Thomas, 1998), which may have assisted in helping to alleviate the environmental conditions in the marginal basins (e.g., Speijer, 2003). In addition, the world cooled gradually (e.g., Zachos et al., 2001), which made it possible to dissolve more oxygen in the waters.

There has been much speculation regarding the cause of the end of the IETM, and the prevention of a runaway greenhouse effect. It has been argued that increased productivity on land (Beerling, 2008) or in open ocean (Bains et al., 2000) was responsible for the removal of carbon dioxide from the atmosphere, thus ending the IETM. We suggest that the deposition of huge amounts of organic material in the sapropellitic bed in the vast, northeastern Peri-Tethys may very well have contributed to the end of the IETM and restoration of more normal environmental conditions.

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- *Chiasmolithus consutor*  
- *Coccolithus pelagicus*  
- *C. subperforatus*  
- *Elcosaster baculus*  
- *D. leucoceras*  
- *D. multiradiatus*  
- *D. mobili*  
- *Ellipsoplagium distichus*  
- *Eocycluslithus Wilaniae*  
- *F. supertus*  
- *F. sympyanformis*  
- *Jarcuslithus inversus*  
- *Neochiasmatozys concinnus*  
- *N. distans*  
- *Pantosphaera ducavius*  
- *P. plana*  
- *Phacozoysus sigmoids*  
- *Spherolitohus primus*  
- *Thoreacysphaera operculata*  
- *Toneus callosus*  
- *T. occultatus*  
- *Transversopalis pulcher*  
- *Campylophaera eodens*  
- *Fassocrithus subterae*  
- *Rhombobaster bramletti*  
- *Discocoaster anartos*  
- *Neochiasmatozys sp*  
- *Zygotisicus herlym*  
- *Fassocrithus involitus*  
- *Discocoaster annies*  
- *Fassocrithus sp.*
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