

# *Middle to upper Eocene dysoxic-anoxic Kuma Formation (northeast Peri-Tethys): Biostratigraphy and paleoenvironments*

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## ABSTRACT

In the late middle to earliest late Eocene, a vast dysoxic to anoxic basin extended from the Crimea in the West through the northern Caucasus to the Aral Sea in the East, and a huge amount of organic carbon was deposited in the organic-rich sediments of the Kuma Formation. We document the paleo-environmental conditions in the basin using benthic foraminiferal and organic carbon data. Oxygen levels were lowest during the deposition of the middle part of the Kuma Formation, a time of relatively cool climate. We estimate the time of deposition and its duration as ranging from planktonic foraminiferal zones upper P11 through P14, and calcareous nannofossil zones CP13c to lowermost CP15 (~44–36.5 Ma). We argue that this large-scale storage of organic carbon over ~7 m.y. resulted from a complex interaction of tectonic and climatic factors, and that it may have influenced the global carbon budget in the ocean-atmosphere system. It probably was at least a contributing factor to the global cooling in the middle Eocene that led to the establishment of ice sheets on the Antarctic continent by the end of the Eocene.

## INTRODUCTION

By the late middle Eocene, a large epicontinental dysoxic basin, which at times became anoxic, was established on the southern margin of the Russian Platform and the Scythian Platform (Fig. 1). The sediments deposited in this basin form the sapropelitic, widespread Kuma Formation, described in the early twentieth century as “coffee-brown marls with *Lyrolepis caucasica* (fish scales)” and also referred to as the “fish formation” (Vassoevich, 1934). The Kuma Formation can be traced over 2000 km, from the northwest coast of the Black Sea in the

west to the Aral Sea in the east; its surface area is ~500,000 km<sup>2</sup>, its thickness varies between 20 and 50 m.

Nannofossil studies in the Northern Caucasus (Kheu Section; Muzylov, 1980; Bugrova et al., 1988) suggested that the Kuma Formation is time equivalent to the upper part of the *Discoaster bifax* Subzone [CP14a or NP16; Okada and Bukry (1980) and Martini (1971) respectively], the *D. saipanensis* Subzone (CP14b or NP17), and the lowermost part of the *Chiasmolithus oamaruensis* Subzone (lowermost CP15 or NP18). Sedimentation in this dysoxic-anoxic basin thus mainly occurred during the Bartonian.

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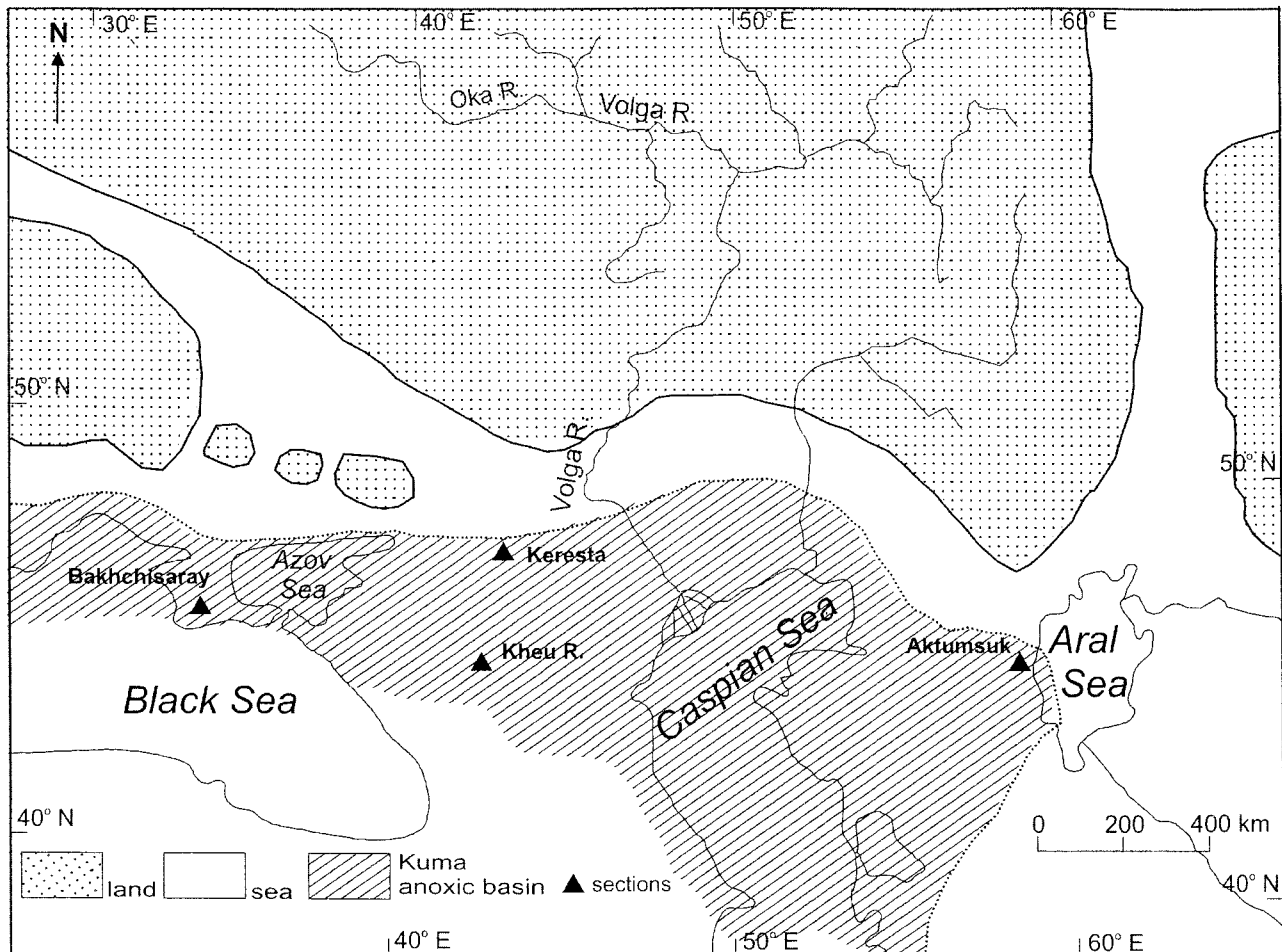


Figure 1. Outline of the late middle Eocene Kuma anoxic basin in the northeastern Peri-Tethys and locations of the four studied sections in the modern geographic setting.

The most prominent feature of the Kuma Formation is its high organic carbon content, with total organic carbon content (TOC) between 2 and 15 wt% (Zhabrev et al., 1966; Eisenstadt et al., 1967; Gavrilov, 2000). We suggest that burial of such a large mass of organic carbon must have affected the dynamics of the global carbon cycle. In this paper we discuss (i) the age of the onset of the dysoxia-anoxia (ii) the depositional environments in the Kuma Basin, and (iii) the duration of the period of deposition of the organic-rich facies.

## LITHOSTRATIGRAPHY

We present information on the planktonic foraminiferal and calcareous nannofossil zonation in four sections: (i) the Bakhchisaray Section, north of Bakhchisaray in the Crimea (44°47' N, 33°53' E) (ii) the Kheu Section, southeast of Nalchik, near Gerpegesh Village (43°24' N, 43°38' E) (iii) the Keresta Section in the Rostov Region, near Pervomayskoe Village (46°20' N, 43°42' E), and (iv) the Aktumsuk Section, on the southwest coast of the Aral Sea (44°37' N, 58°20' E) (Fig. 1).

The composite Bakhchisaray Section (Fig. 2), the most complete section of the Kuma Formation sapropelites in the Crimea, was first described by Dubois de Montpéroux (1837) and later by Menner (1971). The formation was sampled in 1998 in the quarry of a concrete factory (samples 1–46) and in a ravine cutting the southwest slopes of the Kazantash Mountain (samples 47–111). This composite section contains the Keresta Formation in its lower part (quarry outcrop), overlain by the Kuma Formation (quarry and ravine outcrops) and the Belaya Glina Formation (outcrop at the steep hill face). The lower part of the Keresta Formation (32 m exposed) consists of marls, its upper part of alternating marls and limestone. The Kuma Formation conformably overlays the Keresta Formation. Between the quarry and the ravine sections a few meters of the lowermost Kuma Formation are not exposed because of the dense vegetation (Fig. 2).

The Kuma Formation (57 m thick) mainly consists of grey and black marls (light coffee-colored when weathered) with grey-green intercalations in its uppermost part (Fig. 2). Fine (mm-scale) lamination and rhythmical alternation (~0.5 m) be-

## Bakhchisaray section

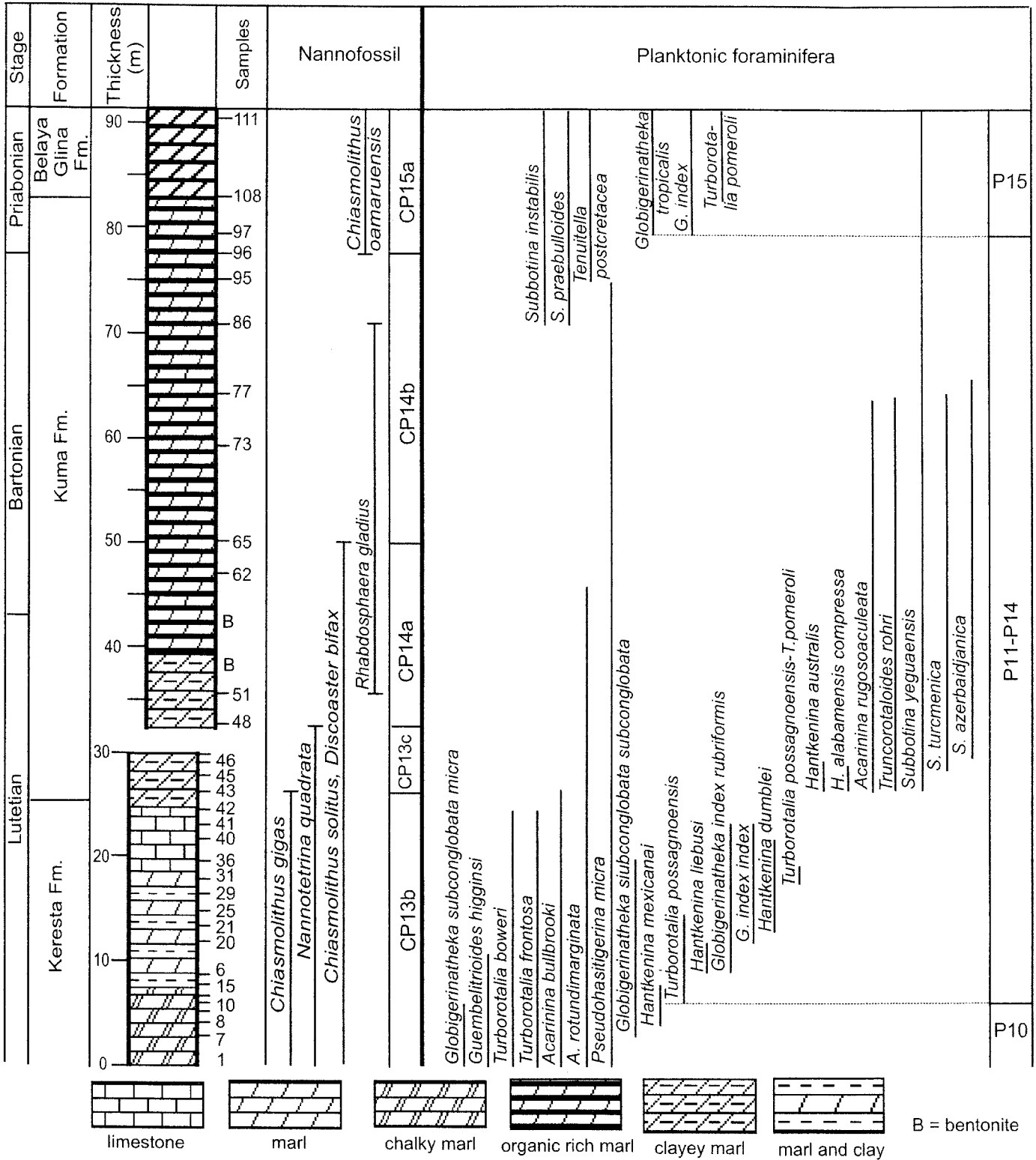


Figure 2. Distribution of planktonic foraminifera and most important datum levels of calcareous nannofossils in the upper middle through lower upper Eocene in the Bakhchisaray Section (Crimea).

tween relatively light marls and 3–5 cm thick beds of darker marls are typical for the middle part of the Kuma Formation, as is the occurrence of abundant fish remains (scales and fragmented bones). Several bentonite layers occur in the lower part of the Kuma Formation. In the upper part of the Kuma Formation plant debris becomes abundant. Only a few bivalves (*Lucina* sp.) were found. The overlying Belaya Glina Formation is up to 150 m thick and consists of green-grey marls, which are white when dry, and intensively bioturbated.

The most complete Northern Caucasus section of the Kuma Formation, the Kheu Section, is continuously exposed on the banks of the Kheu River (Gavrilov et al., 2000). We discuss the Keresta Formation, consisting of ~15 m of white limestones and marls, and the Kuma Formation, which consists of 55 m of coffee- to dark-brown marls (Fig. 3). The lithology is very similar to that in the Crimea. Twenty bentonite interlayers (several mm to 10 cm thick) occur in the lowermost part (CP14a).

The Keresta Section, the stratotype of the Keresta Formation, represents the northernmost Kuma facies (Figs. 1, 4). The sediments were recovered in a drill-hole on the bank of the Keresta Ravine in 1995; recovery was 100%. The core was described and sampled by Muzylov et al. (1999). The Keresta Formation is 10 m thick and consists of white clayey marls and calcareous marls in the lower part, and thin limestone beds (1 m thick) at the top. The Solonka Formation is the time equivalent of the Kuma Formation. It consists of 6 m of brown-grey calcareous clays in its lower part, with green-grey clays in the top-most 5 m, and it unconformably overlies the Keresta Formation. There are no bentonites in this section.

We use the lithostratigraphic nomenclature of northern Turkmenistan (Saperson and Zheleznyov, 1962; Muzylov et al., 1990; Khodzakhmedov, 2001) for the description of the Aktumsuk Section, the easternmost studied outcrop. The Ilyaly Formation (20 m thick; equivalent to the Keresta Formation) consists mainly of white marls and soft limestones, and contains several bentonite beds (Fig. 5). The Kurtysh Formation is 15 m thick and time equivalent to the organic-rich Kuma Formation. It consists of light-grey and brownish marls with numerous bentonites and is unconformably overlain by the white marls of the Akhchakaya Formation (>7 m thick; equivalent to the Belaya Glina Formation).

## BIOSTRATIGRAPHY

In order to develop a more detailed time frame for the onset and duration of dysoxic-anoxic deposition, we studied planktonic foraminiferal and calcareous nannofossil assemblages. Some biostratigraphic markers of both groups present problems in correlation to global zonation schemes. These problems may be caused by the relatively high paleolatitude (41° to 44°N) of the sections (Fig. 6), or, more likely, by the existence of relatively shallow gateways to the open oceanic basins located to the south and west. The planktonic foraminiferal assemblages include few marker species and not

all calcareous nannofossil markers have the stratigraphic ranges found in the pelagic Tethyan and subtropical open oceanic sites. Therefore independent regional zonations have been proposed by several authors (Subbotina, 1953; Shutskaya, 1970; Krashennikov and Muzylov, 1975).

Foraminiferal samples were washed by standard methods, over a screen with a mesh width of 50 µm. The species identification was made in the size fraction of >150 µm. Calcareous nannofossils were studied using a standard method of decantation; smear slides were examined under a light microscope (Zeiss Axiolab, × 1500). Two hundred nannofossil specimens were counted per sample.

## Calcareous nannofossils

The middle Eocene presents one of the most intricate problems of Paleogene nannofossil zonation and biostratigraphic correlation in the northeastern Peri-Tethys. The zonal concepts of Okada and Bukry (1980) are most suitable for this basin. We could recognize most of their subzones and correlate them to Martini's (1971) zonation. There is a problem, however, with the determination of the boundary between Zones NP15/NP16 or CP13/CP14 (Shcherbinina, 2000). The Last Occurrence (LO) of *Nannotetrina* is at the boundary between the Keresta and the Kuma Formations in most of the studied sections, in agreement with Perch-Nielsen (1985), who pointed out that the LO of *Nannotetrina* occurred close to the LO of *Rhabdosphaera gladius*, the marker of the top of Zone NP15. In many sections in the northeastern Peri-Tethys, however, the latter species ranges as high as Zone CP14 (NP16).

In the northeastern Peri-Tethys, the First Occurrence (FO) of large *Reticulofenestra umbilicus* (~14–16 µm) cannot be used as a marker for this boundary because it usually first occurs much earlier, in Subzone NP13b. In addition, all taxa in the nannofossil assemblage from the Aktumsuk Section are very small, and *R. umbilicus* never exceeds 10–12 µm. We conclude that coccolith size appears to be ecologically controlled and thus should not be used as a stratigraphical marker. The reticulofenestrid bloom, at the time when large specimens of *Reticulofenestra* become common worldwide (Shcherbinina, 2001), occurs close to the LO of *Nannotetrina*. The LO of the genus *Nannotetrina* thus can be used to define the NP15/NP16 zonal boundary as well as the CP13/CP14 zonal boundary in the northeastern Peri-Tethys, and provides the possibility to correlate both zonal schemes.

The base of the Keresta Formation corresponds to the bottom of Zone NP15. At this level, *Nannotetrina quadrata* occurs while the zonal markers of NP14 (*Discoaster sublodoensis* and *Rhabdosphaera inflata*) disappear near it in all sections. Subzone CP13b is clearly defined by the range of *Chiasmolithus gigas*. This species, however, is absent at the northern periphery of the basin, so that Subzone CP13b could not be identified in the bore hole at Keresta. Its range also seems reduced in the Aktumsuk Section, possibly because of its low abundance.

## Kheu River section

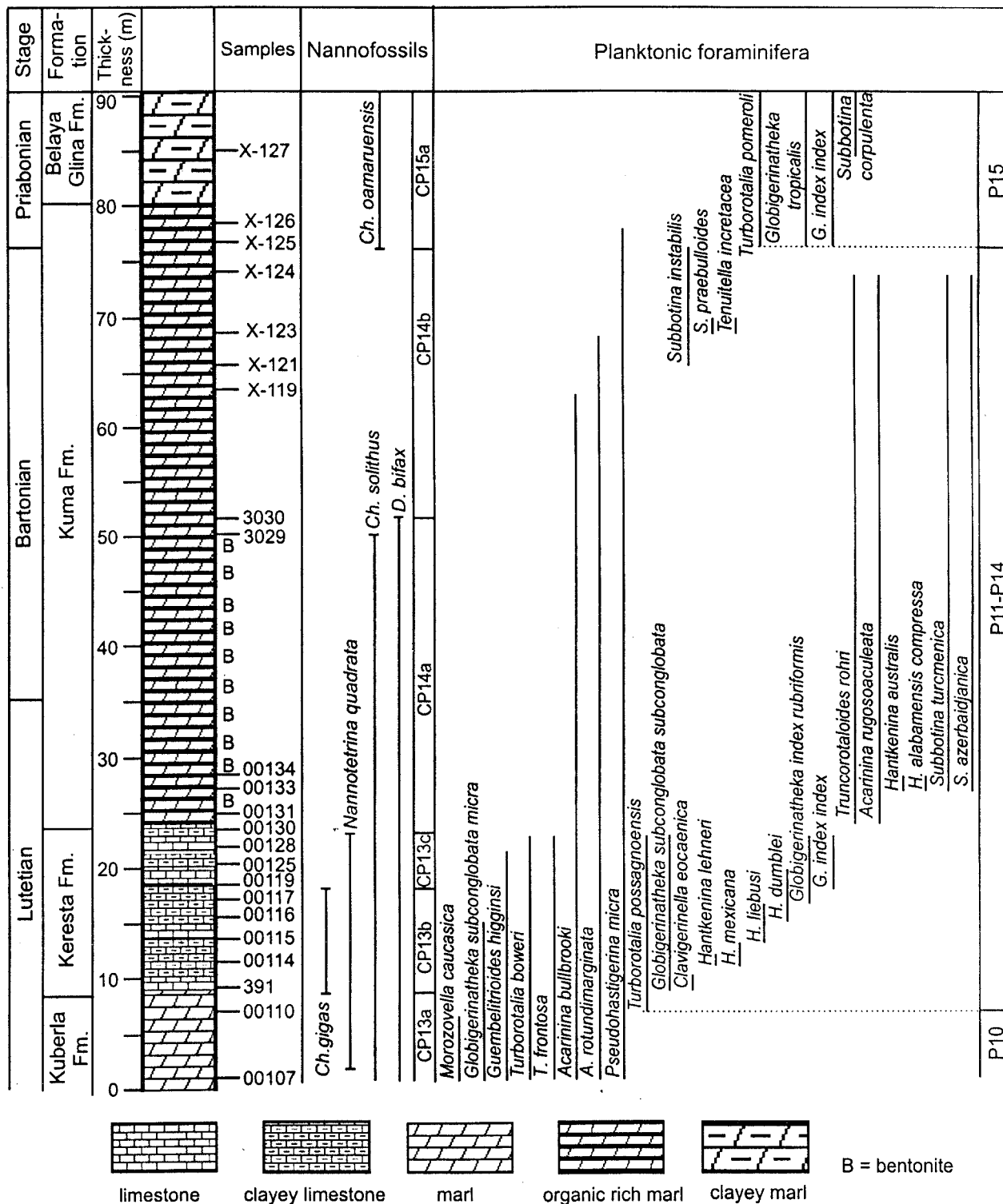


Figure 3. Distribution of planktonic foraminifera and most important datum levels of calcareous nannofossils in the upper middle through lower upper Eocene of the Kheu Section (Northern Caucasus).

## Keresta section

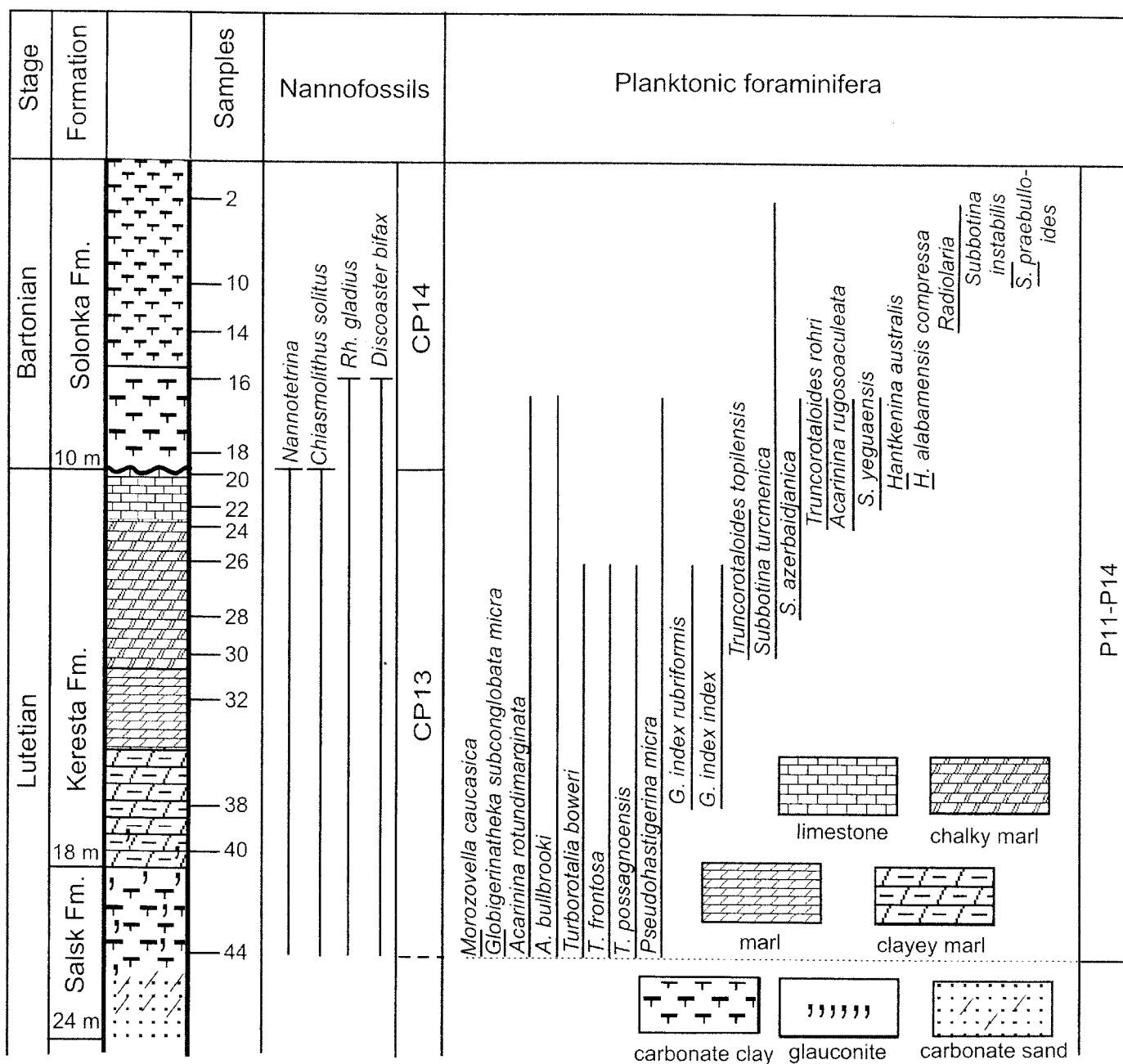


Figure 4. Distribution of planktonic foraminifera and most important datum levels of calcareous nannofossils in the upper middle Eocene of the Keresta Section (Pre-Caucasus).

# Aktumsuk section

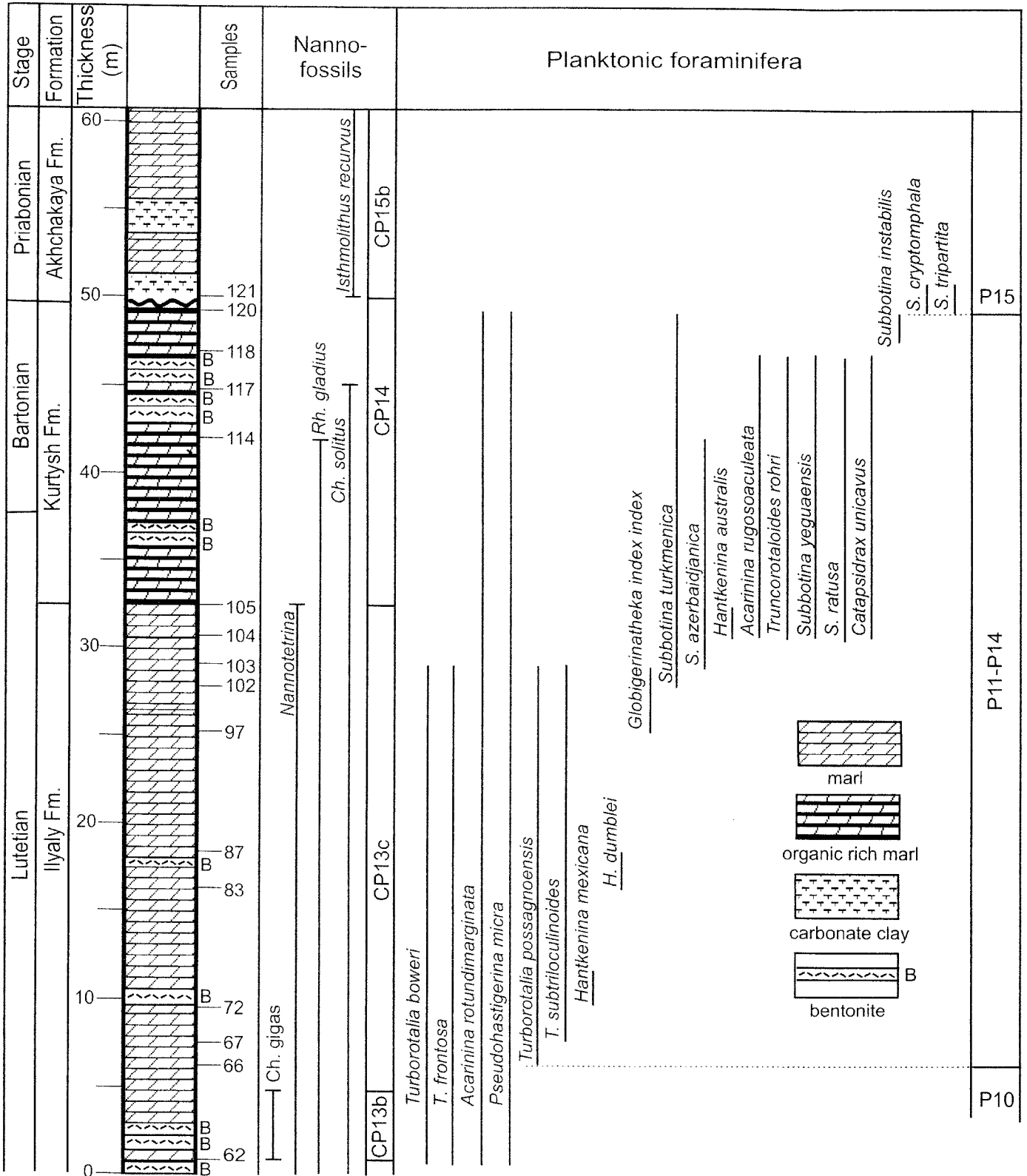


Figure 5. Distribution of planktonic foraminifera and most important datum levels of calcareous nannofossils in the upper middle and lower upper Eocene of the Aktumsuk Section (western shore of the Aral Sea).

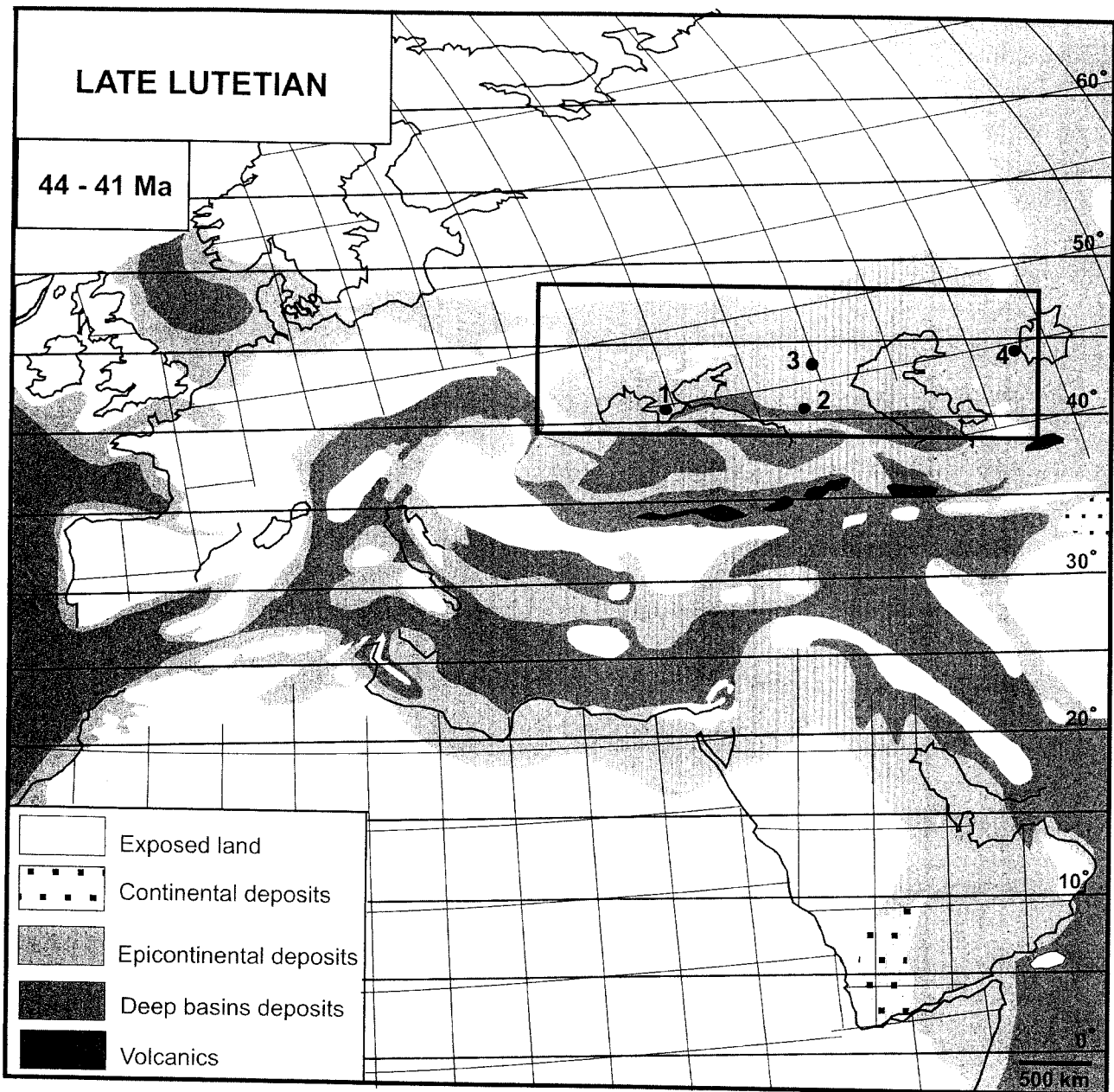


Figure 6. The paleo-position of the studied sections shown in a simplified paleogeographic map of the Peri-Tethyan area, based on the map for the late Lutetian in the Peri-Tethys Atlas (Meulenkamp et al., 2000).

### *Planktonic foraminifera*

An independent planktonic foraminiferal zonation for the southern part of the former USSR (Crimea-Caucasus Province) was proposed by Subbotina (1953) and Shutskaia (1970), and later modified and correlated to the nannoplankton zonation by Krasheninnikov and Muzylov (1975). Only a few biostratigraphic events can be used to correlate the planktonic foraminiferal zonation for the Crimea-Caucasus Province with standard oceanic zones. The zonal scheme (including subzones)

was recently modified by Beniamovski (2001) and Beniamovski et al. (2001), based on a detailed study of planktonic foraminifera in the Bakhchisaray and Kheu River sections and other sections in the northeastern Peri-Tethys. These authors documented the succession of such taxa as *Turborotalia*, *Subbotina*, *Hantkenina*, and *Globigerinatheka* in the middle Eocene (Figs. 7 and 8).

In this paper we do not use this recently proposed zonation because it has only regional importance with few possibilities for global correlation. We use several faunal events in the plank-



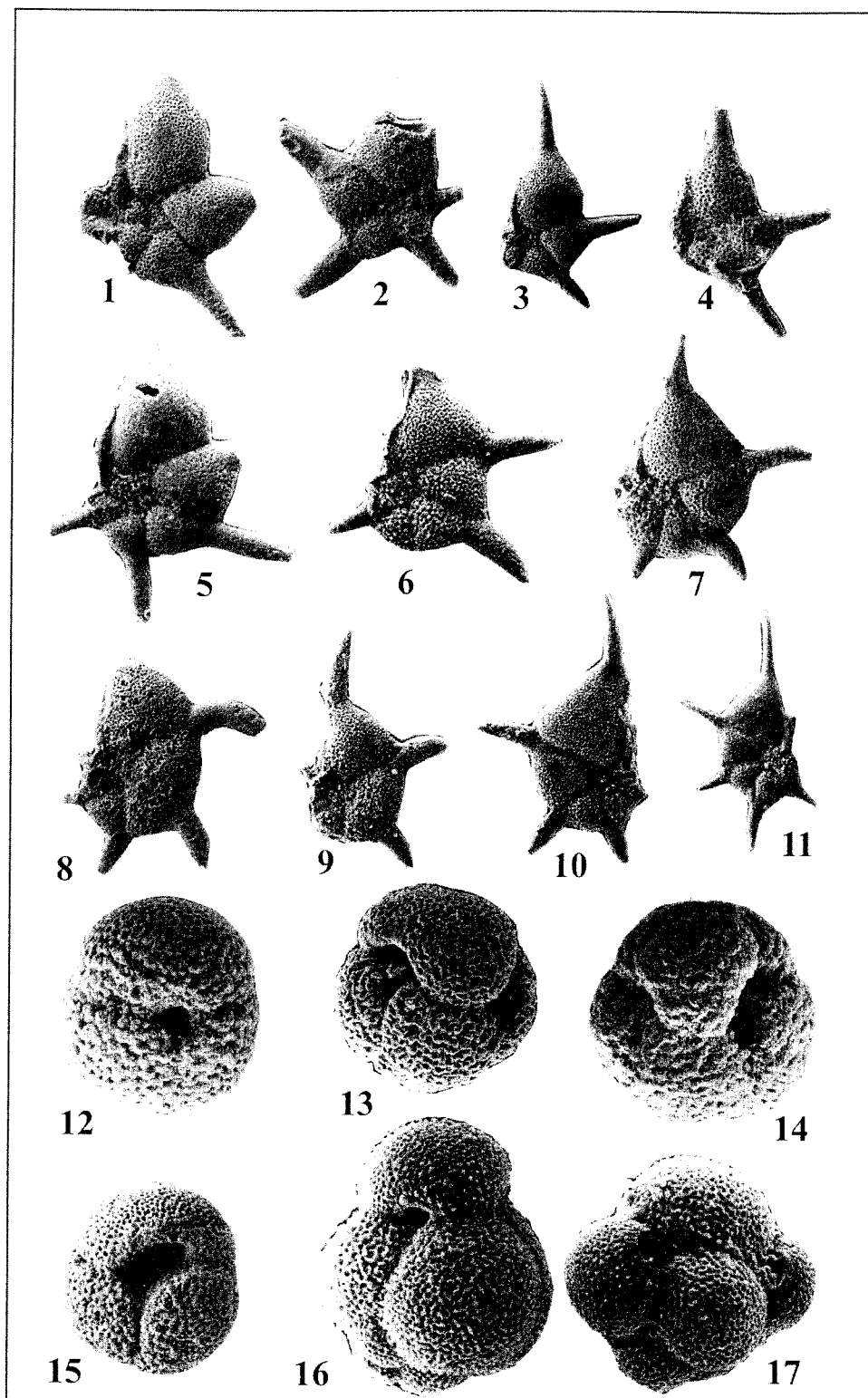


Figure 7. Planktonic foraminifera from the middle Eocene of the Crimea (Bakhchisaray Section), Pre-Caucasus (Keresta Section) and western coast of the Aral sea (Aktumsuk Section). 1-4—*Hantkenina mexicana* Cushman: Bakhchisaray: 1—sample 9 ( $\times 70$ ), 2—sample 34 ( $\times 70$ ), 3—sample 19 ( $\times 70$ ), 4—9 ( $\times 70$ ); 5—*Hantkenina liebusi* Shokhina, sample 19 ( $\times 100$ ); 6—*Hantkenina alabamensis compressa* Parr, sample 43 ( $\times 70$ ); 7-10 *Hantkenina australis* Finlay: 7—Bakhchisaray, sample 43 ( $\times 70$ ), 8—Bakhchisaray, sample 43 ( $\times 70$ ), 9—Bakhchisaray, sample 43 ( $\times 70$ ), 10—Aktumsuk, sample 104 ( $\times 70$ ); 11—*Hantkenina dumblei* Weinzierl and Applin, Bakhchisaray, sample 43 ( $\times 80$ ); 12—*Globigerinatheka micra* (Shutskaya), sample 1 ( $\times 120$ ); 13-14 *Globigerinatheka subconglobata* (Shutskaya) transition to *Globigerinatheka index* (Finlay), 13—Keresta, sample 38 ( $\times 80$ ), 14—Bakhchisaray, sample 19 ( $\times 100$ ), 15—*Globigerinatheka index* (Finlay), Bakhchisaray, sample 38 ( $\times 100$ ), 16—*Catapsydrax unicavus* Bolli, Loeblich and Tappan, Aktumsuk, sample 104 ( $\times 130$ ), 17—*Catapsydrax dissimilis* (Cushman and Bermudes), sample 104 ( $\times 100$ ).

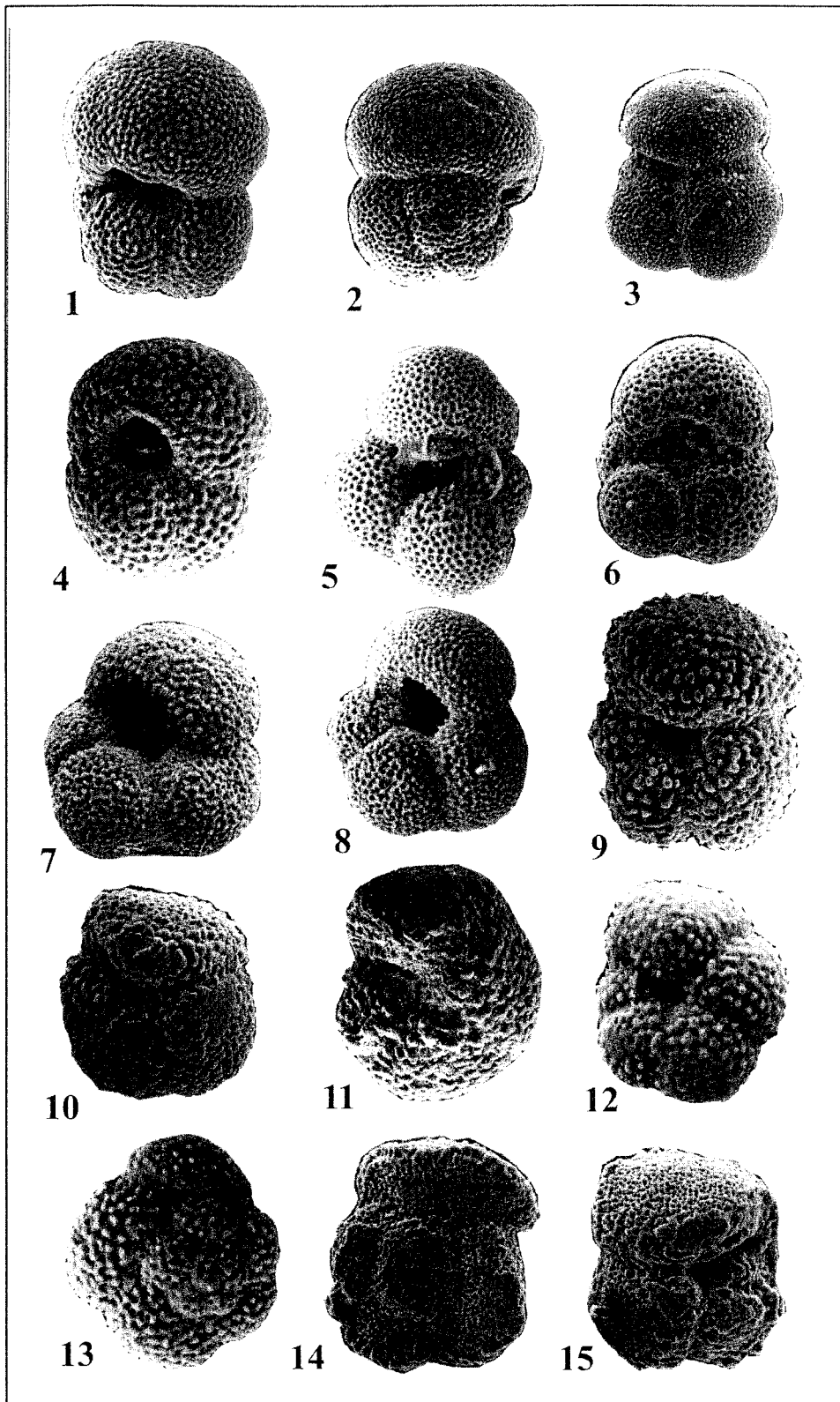


Figure 8. Planktonic foraminifera from the middle Eocene of the Crimea (Bakhchisaray Section) and Pre-Caucasus (Keresta Section). 1, 2—*Turborotalia boweri* (Bolli), Keresta, sample 36 ( $\times 100$ ); 3—*Turborotalia possagnoensis* (Toumarkine and Bolli), Keresta, sample 36 ( $\times 80$ ); 4—*Turborotalia frontosa* (Subbotina), Bakhchisaray, sample 1 ( $\times 150$ ); 5—*Subbotina turcmunica* (Khalilov), Bakhchisaray, sample 48 ( $\times 130$ ); 6—*Subbotina azerbaijanica* (Khalilov), Keresta, sample 20 ( $\times 120$ ); 7—*Subbotina yeguaensis* (Weinzierl and Applin), Bakhchisaray, sample 48 ( $\times 130$ ); 8—*Subbotina turcmunica* (Khalilov), Keresta, sample 20 ( $\times 120$ ); 9—*Acarinina triplex* Subbotina, Keresta, sample 44 ( $\times 130$ ); 10—*Acarinina bullbrooki* Bolli, Keresta, sample 40 ( $\times 130$ ); 11—*Acarinina rotundimarginata* Subbotina, Bakhchisaray, sample 98/1 ( $\times 130$ ); 12, 13—*Acarinina rugosoaculeata* Subbotina, Bakhchisaray, sample 48 ( $\times 180$ ); 14, 15—*Truncorotaloides topilensis* (Cushman), Keresta, sample 30 ( $\times 100$ ).

tonic foraminiferal succession in order to correlate the formations in the northeastern Peri-Tethys to the zonation of Berggren et al. (1995) (Fig. 9).

In the Bakhchisaray section (Fig. 2), the P10/P11 boundary could be drawn at about the level of sample 10 in the Keresta Formation, at the first occurrence of *Turborotalia possagnoensis*. According to Berggren et al. (1995), this species has its earliest appearance just below Zone P11. *Globigerinatheka micra* has its last appearance in the earliest part of Zone P11 (Bolli, 1972). This species has its highest occurrence in sample 11 in the Bakhchisaray section.

There is a sharp faunal break at the top of the Keresta Formation: all species of *Globigerinatheka* disappear in samples 40 and 41. *Turborotalia frontosa* and *T. boweri* have their highest appearance in sample 42, and *Acarinina bullbrooki* in sample 43. Five species (*Hantkenina alabamensis compressa*, *H. australis*, *Truncorotaloides rohri*, *Acarinina rugosoaculeata* and *Subbotina yeguaensis*) have their lowest appearance in sample 43.

This sharp break may have been caused by change from one to another part of the composite section between samples 42 and 43. The two parts of the section are ~600 m apart, and the area between the sections is not exposed, so that we might have missed several meters of section because of uncertainty in the correlation. This hypothesis, however, is contradicted by data in an unpublished manuscript by Grossheim (1974), describing the planktonic foraminiferal succession in two Bakhchisaray reference boreholes. One of these was drilled in a field close to the quarry and the second ~15 km to the northeast, close to Kochergino Village. In both cores, the highest occurrence of *Globigerinatheka micra* is 20–21 m below the base of the Kuma Formation, which is very similar to its location in the Bakhchisaray composite section. We thus conclude that the sharp faunal break is probably not caused by the break in the section between samples 42 and 43.

The break could also be caused by the presence of an unconformity between the Keresta and Kuma formations. The contact between the light-colored Keresta marls and the brown or coffee-colored marls of the Kuma Formation is abrupt, but there are no signs of an unconformity. In addition, all the studied sections show the same rapid faunal change. We thus consider it most probable that the rapid faunal event was caused by a rapid environmental shift, i.e., a change from a subtropical Keresta basin to a relatively cold, anoxic Kuma basin (see below).

The LOs of *Turborotalia frontosa* and *T. boweri* coincide with the top of Zone P12 (e.g., Toumarkine and Luterbacher, 1985; Premoli Silva and Boersma, 1988). In Italy (Umbria), the species have a coeval LO with *Morozovella aragonensis* at the top of Zone P11 (Nocchi et al., 1988). In the Bakhchisaray section, however, the use of this criterion for the top of Zone P11 would place the base of nannofossil Subzone CP13c in the upper part of zone P11 (sample 43), in disagreement with Berggren et al. (1995). We think that this discrepancy could be caused by an unusually late LO of *Chiasmolithus gigas* in the Peri-Tethys. This species is a cold-water taxon, and thus might have an ex-

tended range in boreal regions. We cannot, however, exclude reworking as cause for the extension of nannofossil ranges, because redeposited Cretaceous taxa (*Micula decussata* and *Eiffelolithus turiseiffelii*) occur in the lowermost (sample 55a) and upper (sample 95) parts of the Kuma Formation (Ovechkina, 1999).

The Bakhchisaray section shows the typical succession of *Hantkenina* species, from the more "primitive" *H. mexicana*, *H. liebuseri* and *H. dumblei* to the more "progressive" *H. alabamensis compressa* and *H. australis*. Their ranges, however, are very short relative to their ranges in oceanic regions (e.g., Coxall et al., 2000). We thus cannot use their FOs and LOs for correlation, and we cannot place the P11/P12 Zonal boundary in this section. The Belaya Glina Formation is placed in Zone P15, suggesting that in the Bakhchisaray section the whole Kuma Formation could possibly be correlated to the uppermost (?) part of oceanic standard Zone P11, Zones P12–14, and lowermost P15.

In the Kheu River section (Fig. 3), we recognized the same sequence of foraminiferal events as in the Crimea. The FO of *Turborotalia possagnoensis* was used as marker of the P10/P11 zonal boundary. All *Turborotalia* species had their LO at the same level as that of *Globigerinatheka subconglobata* and *G. index*, at the top of the Keresta Formation. The planktonic fauna characterized by *Truncorotaloides rohri*, *Acarinina rugosoaculeata*, *Subbotina turcmunica*, and associated forms occur first in the lowermost Kuma Formation.

The Keresta section (Fig. 4) is more condensed than the two sections described above. Sediments from the Keresta Formation, with an erosional lower boundary, are placed in Zone P11: *Turborotalia possagnoensis* occurs from the bottom of the formation. The sharp faunal change, however, at the LO of all *Turborotalia* species, occurs within the uppermost Keresta Formation, ~1.5 m below its upper boundary. *Truncorotaloides rohri* and *Acarinina rugosoaculeata* also have their LO in this interval. The Solonka Formation, which is time equivalent to most of the Kuma Formation, contains only few planktonic foraminifera, and has a relatively rich assemblage (*Subbotina turcmunica*, *S. yeguaensis*, *Acarinina bullbrooki* and others) only in its lowermost part. Higher in the section radiolarians are the predominant component of the microfauna, because of the shallow setting and the low temperatures.

The Aktumsuk Section (Fig. 5), situated far to the northeast, is very similar to the Keresta Section. Most of the Ilyaly Formation (from sample 66 upward) is placed in Zone P11, and the most important faunal break is in the uppermost part of this formation (sample 103). The Kurtysh Formation, representing sedimentation in anoxic environments in the Aral Sea region, accumulated in Zones P12–P14.

## PALEOENVIRONMENTS

We used quantitative analysis of calcareous nannoplankton (this paper; Shcherbinina, 2000) and planktonic and benthic foraminifera in the Bakhchisaray and Kheu sections to identify paleoenvironmental changes in the Kuma Basin.

Subbotina, 1953		Shuiskaya, 1970		Krashennikov and Muzylov, 1975		Beniamovski, 2001		This paper			
North Caucasus	Crimea	North Caucasus and western part of Middle Asia		North Caucasus		NE Peri-Thetys		Bakhchisaray section			
		Planktonic foraminifera		Nannofossil		Planktonic foraminifera		Nanno-fossil	Biostratigraphic events	Planktonic foraminifera	Standard Zones
Globigerinoides conglobatus and large globigerinas Zone		Globigerinoides conglobatus and large globigerinas Zone		Discoster Zone		Globigerinatheka tropicalis Zone					
Thin walled pelagic foraminifera Zone		Thin walled pelagic foraminifera Zone		Discoster Subzone		Subbotina turmenica Zone		NP17	CP14b	G-lka tropicalis	Kuma
Thin walled pelagic foraminifera Zone		Bolivina asiatica Subzone		Discoster Subzone		Subbotina azerbaijanica Subzone		NP16	CP14a	S. instabilis	
		Globigerina turmenica Subzone		Reticulofenestra umbilica (s.s.) Subzone		Hantkenina alabamensis Zone		NP15c	CP13c	Hantkenina australis H. alabamensis compressa	
Hantkenina alabamensis Zone		Hantkenina alabamensis/ Globigerinoides subconglobatus Zone		Reticulofenestra umbilica Zone		Hantkenina alabamensis Zone		NP15b	CP13b	G-lka subcon-globata G-lka index G-lka micra	P11-P14
Acarinina rotundimarginata Zone		Acarinina rotundimarginata Zone		Nannotetrina fulgens Zone		Acarinina rotundimarginata Zone		NP15a	CP13a	H. dumblei H. liebusi H. mexicana	
Acarinina rotundimarginata Zone		Acarinina rotundimarginata Zone		Nannotetrina fulgens Zone		Acarinina rotundimarginata Zone		NP15b	CP13b	G-lka micra	P10
Acarinina rotundimarginata Zone		Acarinina rotundimarginata Zone		Nannotetrina fulgens Zone		Acarinina rotundimarginata Zone		NP15c	CP13c	A. rotundimarginata	

Figure 9. Correlation of planktonic foraminiferal and calcareous nannofossil zonations in the middle and upper Eocene of the northeastern Peri-Thetys.

**Planktonic foraminifera**

In the Kuma Formation, planktonic foraminifers are abundant but have a low species diversity. The few species mainly belong to the genus *Subbotina*, although *Pseudohastigerina* commonly form >30% of the assemblage, and biserial and triserial taxa are common at a few levels. *Hantkenina australis* and *H. alabamensis compressa* are abundant at the base of the Kuma Formation. Both taxa are cold-water surface dwellers, and characteristic for areas with high productivity and possibly relatively low salinity. Biserial taxa prefer a poorly oxygenated environment (Boersma et al., 1987; Premoli Silva and Boersma, 1988), and the hantkeninids inhabited intermediate water-depths within the oxygen minimum level (Boersma et al., 1987). In most samples the planktonic/benthic ratio is >90%, but this decreases drastically when the organic carbon content increases up to 8%.

**Benthic foraminifera**

The species richness of benthic foraminifera in 75 samples from the Kuma Formation in the Bakhchisaray section varies between 13 and 20 species (Fig. 10), while the mean "coefficient of specialization" (defined as the relative abundance of the three most abundant species) is high, with values >80% in many samples (Nezlina, 1996). The most important taxa are bolivinids, which constitute >80% of the total fauna in most samples, except for the lowest and the uppermost part of the section. Common species are *Brizalina karakemeric*, *Br. jacksonensis*, *Br. budugensis*, *Br. tuberna* and *Bolivina crenulata*.

The low diversity, high dominance, and abundance of bolivinid species all indicate deposition in dysoxic conditions (e.g., Kaiho, 1994). Benthic foraminiferal species indicative of dysoxic conditions are abundant throughout the section, while

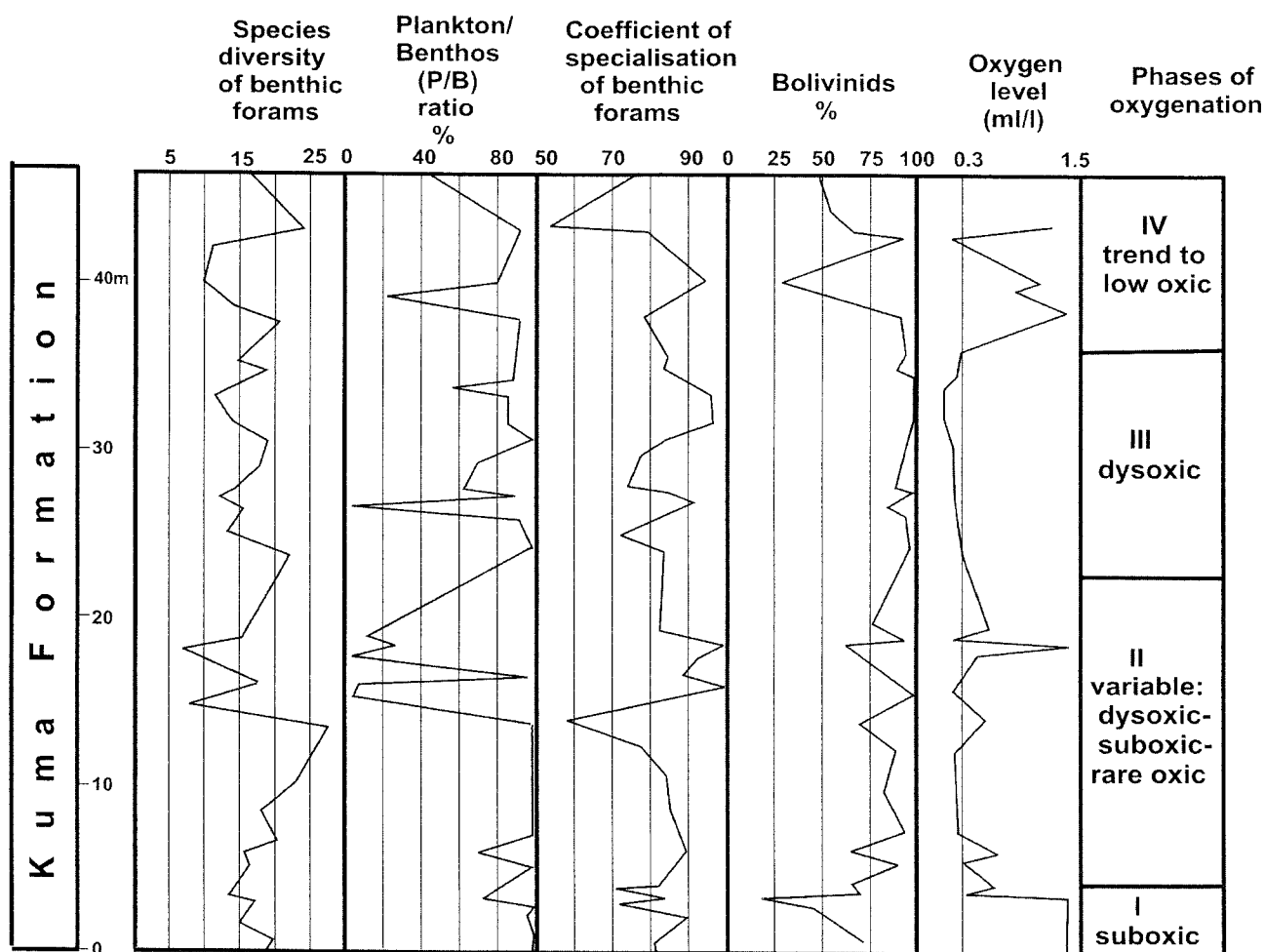


Figure 10. Main indices of benthic foraminiferal assemblages and phases of bottom water oxygenation in the Kuma Basin (Bakhchisaray Section).

suboxic species (Kaiho, 1994) are restricted to the lowest and uppermost samples. The oxygen index (OI, calculated from the benthic species assemblage according to Kaiho, 1994) varies from 0 to +2 in the lower part of the Kuma Formation, decreases sharply to -40 to -50 in the middle part, and increases again in the uppermost samples, where *Baggina iphigenia* is an important component. We can distinguish 4 phases in the deposition of the Kuma Formation (Fig. 10), using the oxygen index to estimate the oxygen content in bottom waters (Kaiho, 1994).

During deposition of the lowermost part of the Kuma Formation (Phase I, Figure 10) the bottom waters in the basin were suboxic to moderately oxygenated (1.5 mL/L). The oxygen content decreased to <0.5 mL/L (severely dysoxic) during the deposition of most of the Kuma Formation (Phases II and III, Figure 10). When the oxygen levels started to decline (Phase I/Phase II boundary), the foraminiferal number increased to a maximum, suggesting that productivity was very high. During Phase II, oxygenation fluctuated from suboxic to dysoxic or possibly even anoxic (-0.3–1.5 mL/L), as indicated by the occurrence of abundant *Brizalina* species with different morphology, and the absence of benthic foraminifera in a few samples. During Phase III conditions were more uniformly dysoxic and the occurrence of *Cibicidoides* aff. *perlucidus* indicates a slight warming of bottom waters. During the last several hundred thousand years of Kuma Basin history (Phase IV, Figure 10), the oxygen content increased to suboxic levels (~1.5 mL/L), *Br. jacksonensis* disappeared and was replaced by the sculptured *Br. costifera* and *Br. antegressa*, both indicators of more oxygenated conditions.

In the Kheu section the species richness of benthic foraminifera is between 24 and 26 (coefficient of specialization 25%–50%) in the upper part of the Keresta Formation, where benthic assemblages are dominated by indicators of oxic conditions such as *Heterolepa eoacena* and *Broezenella granosa*, so that the samples are characterized by a high oxygen index (66–97). In the Kuma Formation, the species diversity of benthic foraminifera drastically decreases to 13 and then down to 0, and the coefficient of specialization increases to 56%–100%. Only a few taxa, mainly nodosariids and bolivinids (*Nodosaria* ex gr. *elegans*, *N. ewaldi*, *Brizalina karakemeric*, *B. jacksonensis*), are abundant. These taxa are classified as suboxic and dysoxic indicators by Kaiho (1994). In the lowest part of the Kuma Formation the suboxic nodosariids dominated (66%–77%), and the oxygen index decreased first to about -4, then to -15. Above the lower part of the Kuma Formation the environment of deposition was very variable: In some samples suboxic nodosariids are dominant, in others dysoxic bolivinids (up to 100%), with fluctuations in the oxygen index from -36 to -44. In the middle and upper parts of the Kuma Formation benthic foraminifera are absent, suggesting anoxic conditions. In the overlying Belaya Glina Formation, consisting of light gray marls, benthic assemblages are rich, with a species richness of ~41 (coefficient of specialization 27%). In these samples benthic foraminiferal assemblages consist of a mixture of oxic, suboxic and dysoxic species, including *Baggina iphigenia*, *Melonis* cf. *affinis*, *Robulus diaphanus*, and

*Latibolivina reticulosa*, so that the oxygen index is between 22 and 66. During deposition of the lower part of the Kuma Formation in the Kheu Section the bottom waters were suboxic (~1 mL/L of dissolved oxygen), but they later became dysoxic to anoxic (<0.5 mL/L). In the Belaya Glina Basin the bottom waters were well oxygenated (2.5 mL/L).

#### Calcareous nannofossils

Changes in the relative abundances of warm water taxa such as *Discoaster* and *Sphenolithus* on the one hand, and cool water taxa such as *Chiasmolithus* species and *Reticulofenestra* on the other hand, indicate changes in sea surface temperature (e.g., Muzylov, 1980; Pospichal and Wise, 1990; Wei and Wise, 1990; Madile and Monechi, 1991). The environmental preferences of many taxa were discussed in detail by Dmitrenko (1993), using a biogeographic map of the distribution of the most important Eocene nannofossil species. According to this author, all species of discoaster and most species of *Sphenolithus* and *Heli-cosphaera* are warm-water taxa, whereas different species of *Chiasmolithus* differ in their environmental preferences, with *Ch. grandis* a tropical species, *Ch. bidens* subtropical, *Ch. altus* and *Ch. oamaruensis* temperate. *Reticulofenestra* is mainly subtropical to temperate.

In all sections there is a series of changes in the nannofossil assemblages in the lowermost Kuma Formation (Shcherbinina, 2000). This change occurs not exactly at the base of the Kuma Formation in the Bakhchisaray section (Fig. 11), but close to the CP13c/CP14 Zonal boundary. At this level, *Discoaster* species sharply decrease in relative abundance to a few percent, and *Reticulofenestra* species increase in abundance to a maximum of 60%–70%. Species of *Chiasmolithus* become more abundant than those of *Discoaster*. These assemblages dominated by cool-water species are typical for most of the Kuma Formation. The transition from the Kuma into the overlying Belaya Glina formation coincides with slight warming in the Bakhchisaray Section.

#### Organic carbon accumulation

High organic carbon contents are typical for the Kuma Formation in all sections (Zhabrev et al., 1966; Eisenstadt et al., 1967; Gavrilo, 2000). In the Bakhchisaray section, the basal part of the Kuma Formation (coffee marls) has a low  $C_{org}$  content (~0.2%), but the organic carbon content sharply increases up to a maximum of 8% in the cyclic lower interval (Fig. 12). In the upper part of the Kuma Formation  $C_{org}$  values are somewhat lower again (2%–4%). The distribution of  $C_{org}$  is similar in the Kheu section (Gavrilo et al., 2000). The mean  $C_{org}$  content of the complete Kuma Formation is ~3%.

A rough estimate, using this value and the average extent (500,000 km<sup>2</sup>) and a low estimate of average thickness (20 m) of the Kuma Formation, indicates that a huge amount of carbon (~6 × 10<sup>16</sup> g of  $C_{org}$ ) is stored in this formation. The average  $C_{org}$

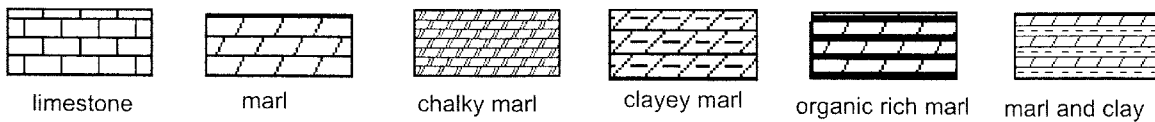
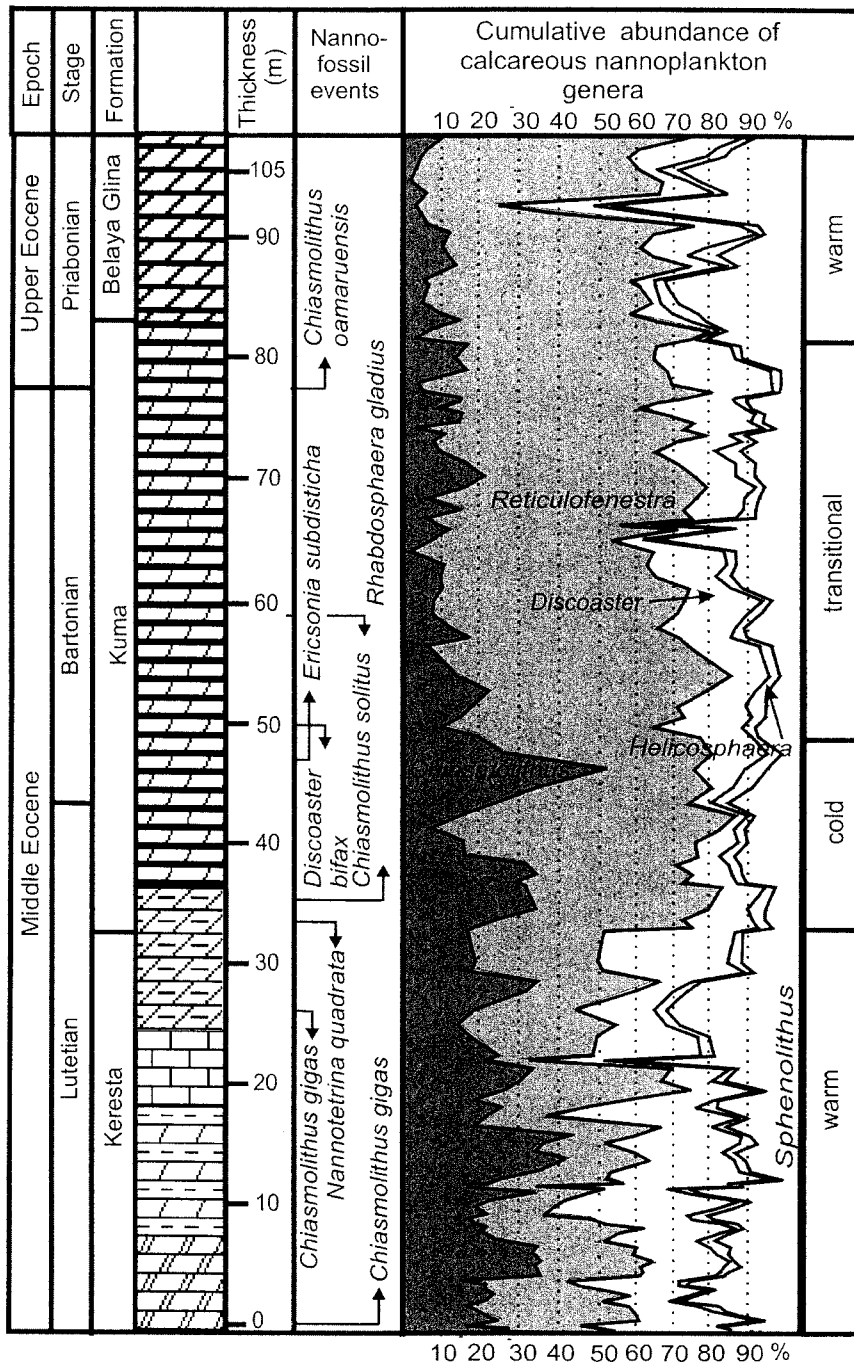


Figure 11. Quantitative analysis of calcareous nannofossils in the upper middle through lower upper Eocene of the Bakhchisaray Section.

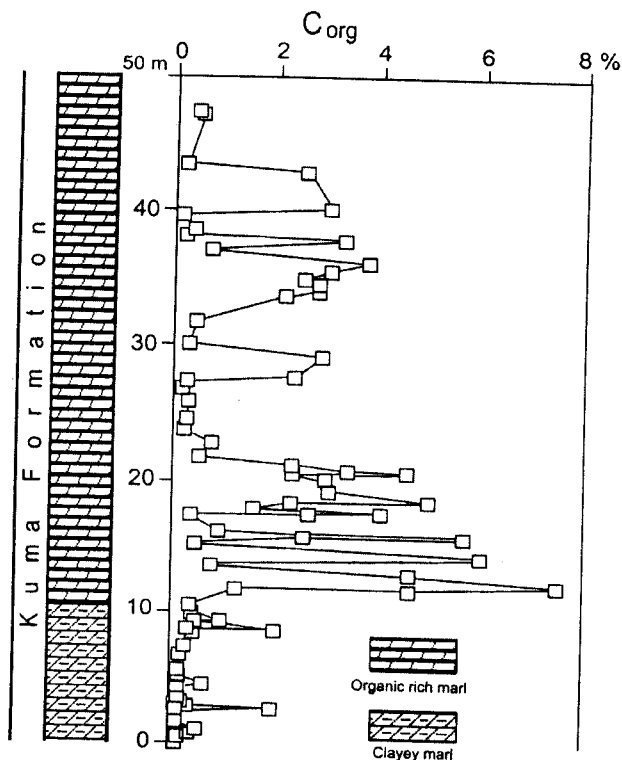


Figure 12. Stratigraphic distribution of organic carbon in the Kuma Formation of the Bakhchisaray section.

accumulation rate of during the 7 m.y. of persistent dysoxic-anoxic conditions was  $\sim 1 \times 10^{15}$  g per 100 k.y., but in the early Bartonian (CP14a) it was 2–3 times as high.

#### Volcanism

Numerous bentonite beds occur in all studied Kuma sections except the Keresta section. In the northeastern part of the Kuma Basin (Mangyshlak) there are also thin, crystal-bearing volcanic ash layers (A. Alekseev, 2002, personal commun.). This volcanic material was probably derived from the subduction- and rift-related Eocene volcanic belt, which stretched from the eastern Pontides in Turkey to eastern Iran (Kazmin et al., 1986; Koronovsky et al., 1997; Okay and Mahintürk, 1997; Nikishin et al., 2001). This volcanic activity reached its maximum intensity during the middle Eocene (Bartonian), and ash was transported to the north by monsoonal winds. The input of volcanic material could have contributed to the high productivity in the Kuma Basin (Muzylov, 1996).

#### DISCUSSION

A vast dysoxic to anoxic basin (the Kuma Basin) became established in northeastern Peri-Tethys during the latest Lutetian

and persisted through the Bartonian and into the earliest Priabonian. In the easternmost and northernmost parts of the basin highly dysoxic to anoxic conditions were limited to the early Bartonian. The anoxia in this basin probably had a complex origin. Tectonic events in the Caucasus fold belts narrowed the straits connecting the basin to western Siberian and northern European basins, thus making water circulation less vigorous, so that stratification could occur. The fast-growing middle Eocene volcanic belt (Nikishin et al., 2001) added volcanic material that may have contributed to increased surface productivity. In addition, the onset of dysoxic and anoxic conditions coincided with cooling (persisting into the Priabonian), as seen from the changes in planktonic foraminiferal and calcareous nannofossil assemblages. In the Crimea, cool and humid climates during the deposition of the Kuma Formation are also documented in palynological data (Panova, 1978).

In open ocean environments in the Southern Hemisphere (Kerguelen Plateau) the oldest ice-rafted material was reported from the middle Eocene, topmost CP13 and CP14a (Barron et al., 1991a, 1991b), and more intensive glaciation occurred from the end of the latest middle Eocene into the beginning of the late Eocene. The Kuma anoxic basin in the Crimea became established during latest nannofossil Zone CP13, approximately at the onset of glaciation in the Antarctica. At this same time, planktonic foraminiferal assemblage and isotope data indicate an increasing input of run off in the Kuma Basin (Beniamovski et al., 2001) with the continental run off probably enriched in nutrients. This interpretation is in agreement with the occurrence of low-diversity dinocyst assemblages dominated by the genera *Horologinella* and *Paucilobomorpha* (Zaporozhets, 2001), as also described from the Asse Clays in South Holland (de Coninck, 1986). The larger volume of runoff might have enhanced stratification of the water column as well as high productivity, which both would have contributed to the establishment of highly dysoxic to anoxic conditions.

#### CONCLUSIONS

Our observations document that the onset of dysoxic and anoxic conditions as indicated by the sedimentological and micropaleontological features of the Kuma Formation (and its lateral facies equivalents) are close to synchronous throughout the Kuma Basin. In the Crimea (Bakhchisaray Section), the oldest organic-rich deposits are uppermost Lutetian (ca. 44 Ma, Berggren et al., 1995). Persistently oxic conditions were reestablished in the early Priabonian ( $\sim 36.5$  Ma, Berggren et al., 1995). In the northern Caucasus, these events occurred at the same time as in the Crimea. In the Aktumsuk Section (close to the Aral Sea), dysoxia started at the same time as in the Crimea and the Caucasus, but the timing of the reestablishment of oxic conditions is not known because the top of the Kurtysch Formation (Kuma facies equivalent) is truncated. In the northern part of the Kuma Basin (Keresta Section), dysoxic-anoxic conditions were present only during the early Bartonian ( $\sim 41.3$ – $37.0$  Ma, Berggren et al., 1995).



Eocene calcareous nannoplankton assemblages in the northeastern Peri-Tethys are characteristic for midlatitudes, and the relative abundance of warm water *Discoaster* species decreased rapidly during the transition of the Keresta into the Kuma Formation, at the same place in the section where the planktonic foraminiferal faunas also indicate a rapid cooling. Most of the Kuma Formation accumulated during a relatively cool period. Regional cooling in the Peri-Tethys region thus started rapidly in the later part of Zone P11, at the CP13c/CP14 zonal boundary (ca. 44 Ma, Berggren et al., 1995), synchronous with the global cooling trend (e.g., Zachos et al., 2001). During the deposition of the Kuma Formation (~44–36.5 Ma) an estimated  $6 \times 10^{16}$  g C<sub>org</sub> was stored in the dysoxic-anoxic sediments. The carbon isotope curve in Zachos et al. (2001) shows an excursion of ~0.5‰ to heavier values at ca. 40 Ma, about the midpoint of the deposition of the Kuma Formation. We speculate that the carbon storage during the latest Lutetian through Bartonian may have been at least one of the causes of lowered atmospheric levels of CO<sub>2</sub> and global cooling that led to the establishment of the East Antarctic ice sheet in the earliest Oligocene.

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