

The Aktulagay section, west Kazakhstan: a key site for northern mid-latitude Early Eocene stratigraphy

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ABSTRACT: A section at Aktulagay (west Kazakhstan), in the Peri-Tethys realm, exposes mid-neritic to upper bathyal Ypresian marls, clays and silts. These range from Zone NP10 to lower Zone NP14, with abundant and diverse microfossil assemblages. Multidisciplinary analysis has identified dinoflagellate cyst, nannofossil, planktonic and benthic foraminiferid and pteropod zones and events. Calibration of a key interval in the evolution of the shark *Otodus* has been possible for the first time.

Episodic low-oxygen facies, including sapropelic clays widely distributed in Peri-Tethys, are represented here and can be placed within a detailed biostratigraphic framework.

The current lithostratigraphic terminology is modified, with the introduction of the Aktulagay Formation. Paleoenvironmental aspects are discussed; five depositional sequences are tentatively identified.

This section can be correlated in detail with the succession in the North Sea Basin, with implications for paleogeographic reconstructions. High-resolution biostratigraphic calibration between disparate fossil groups makes this a key reference section for northern mid-latitude Ypresian biostratigraphy.

INTRODUCTION

The Aktulagay section (text-fig. 1) is within the Peri-Tethys realm, a wide area to the south of the East European Platform (text-figs 2, 3), extending over parts of southern Russia, Kazakhstan, Uzbekistan, Turkmenistan and Tadzhikistan. The East European Platform is interpreted as mainly a land area during the Eocene, fringed to the south by inner neritic clastic sediments. The Peri-Tethys is characterised by dominantly neritic marine clastic and carbonate shelf sediments, grading southwards into the deeper-water Neotethys. It is connected to the West Siberian Basin by the Turgay Strait. Most paleogeographic reconstructions (e.g. Akhmetiev and Benyamovsky 2006) show no (or very limited) westward marine connections to the North Sea Basin, but evidence from Aktulagay has recently been used to revise this interpretation (Knox et al. 2010). The Neotethys was subsequently largely deformed and uplifted to form the Alpine-Himalayan foldbelt, but in the Peri-Tethys Paleogene sediments are largely undeformed and often relatively flat-lying.

Paleogene sediments of the Peri-Tethys are mainly < 1000 m in thickness, except for those in differentially subsiding areas, including the Pre-Caspian Depression and the Dnieper-Donetz Basin. According to Thomas et al. (1999) Eocene sediments in the SE Peri-Tethys (Turan Platform and adjacent areas) are characterised by steady regional subsidence in shelf environments with limited differential tectonics, until the shift to a re-

gional compressional regime 5 in the Early Oligocene following the onset of India-Asia collision (Aitchison, Ali and Davis 2007). There is however a widespread mid-Eocene hiatus, also identified in the Turgay Strait and the West Siberian Basin (Radionova et al. 2003).

The Aktulagay hills in western Kazakhstan provide a well-exposed section through the Peri-Tethys Early Eocene, in mainly mid to outer neritic marine environments, with abundant and diverse dinoflagellate cyst, nannofossil and foraminiferid assemblages. The stratigraphy of this section has been analysed in detail to provide a reference section for the area, and for comparison with the North Sea Basin.

The present account includes a relatively detailed description of the site and its lithostratigraphy, partly in order to facilitate calibration with any future investigations in this rather remote area. It is part of an ongoing project on Early Eocene marine shelf successions in differing paleogeographic contexts, in order to evaluate the relative role of tectonic and eustatic controls in depositional sequence stratigraphy.

THE AKTULAGAY SITE AND ITS REGIONAL CONTEXT

Regional context

In the Pre-Caspian area, clastic Eocene marginal-marine and inner neritic sediments in proximal areas adjacent to the East European Platform (e.g. Vasilieva and Musatov 2010) grade

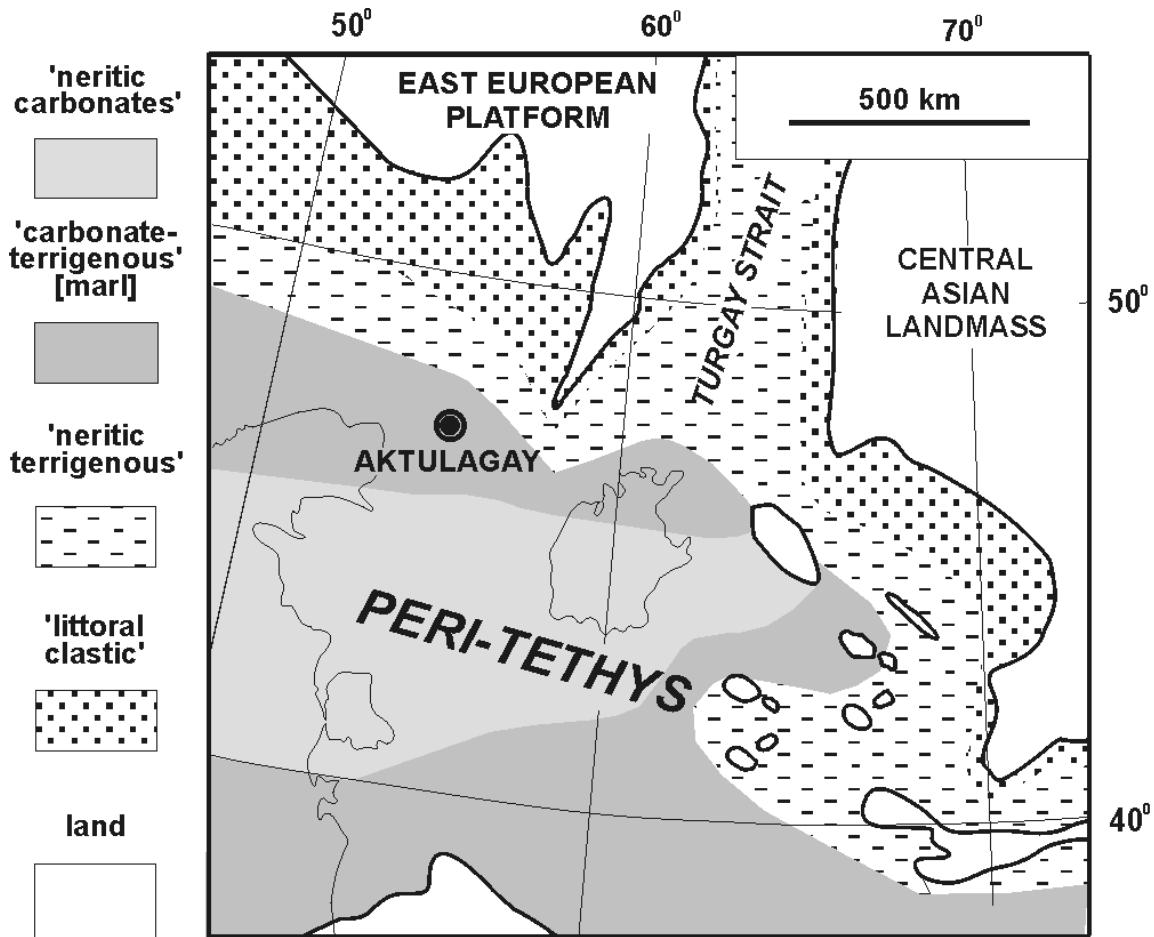


TEXT-FIGURE 1
Location of the Aktulagay section in western Kazakhstan. The Ustyurt Plateau is stippled. River names are in italics.

distally southwards into marls and chalks deposited in outer neritic environments (text-fig. 2). In NW Kazakhstan the Eocene outcrops are located on the SE margin of the Cis-Caspian (Pre-Caspian) depression. This relatively low-lying area, mainly semi-arid steppe, traversed by the Embi (Emba) River, extends from north of the Caspian Sea eastwards to the southern tip of the Ural Mountains. Its southern margin is the high escarpment fringing the Ustyurt Plateau, on which slightly warped and eroded Paleogene sediments are capped unconformably by flat-lying Neogene limestones of the Paratethys (text-fig. 3). In the Pre-Caspian depression Lower Eocene (Ypresian) sediments are intermittently and often poorly exposed, mainly in escarpments on the margins of river valleys and salt lakes. They are mostly relatively flat-lying, and disconformably overlie thin Upper Paleocene (Thanetian) (sediments, overstepping in some areas onto Upper Cretaceous (Maastrichtian) chalks.

The Aktulagay hills

The Aktulagay hills (Gora Aktulagay) are situated 150km NE of the town of Kulsary and 35km north of the Embi [Emba] River. Maastrichtian chalks crop out on and around the lower slopes of the hills, and are extensively exposed on their western margin, adjacent to the Tolagaysor Lake (*sor* = salt lake) (Naidin and Beniamovski 2006). The overlying Paleogene sediments comprise a localised very thin Thanetian limestone, underlying ~ 70m of lower and middle Eocene marls, clays and silts. These are exposed in the high escarpment forming the western boundary of the hills, dipping gently northwards. The Aktulagay hills are capped by a thin sheet of flat-lying 'Sarmatian' (Serravallian) limestones, forming a summit plateau. These are an isolated outlier of the Miocene limestones of the Paratethys which form the surface of the Ustyurt Plateau, 200km to the south (text-fig. 1).



TEXT-FIGURE 2

Generalised Ypresian lithofacies and paleogeography of western Kazakhstan and adjacent areas. Modified from Zhelezko and Kozlov (1999, fig. 6). Fa-
cies descriptions are from Zhelezko and Kozlov (1999).

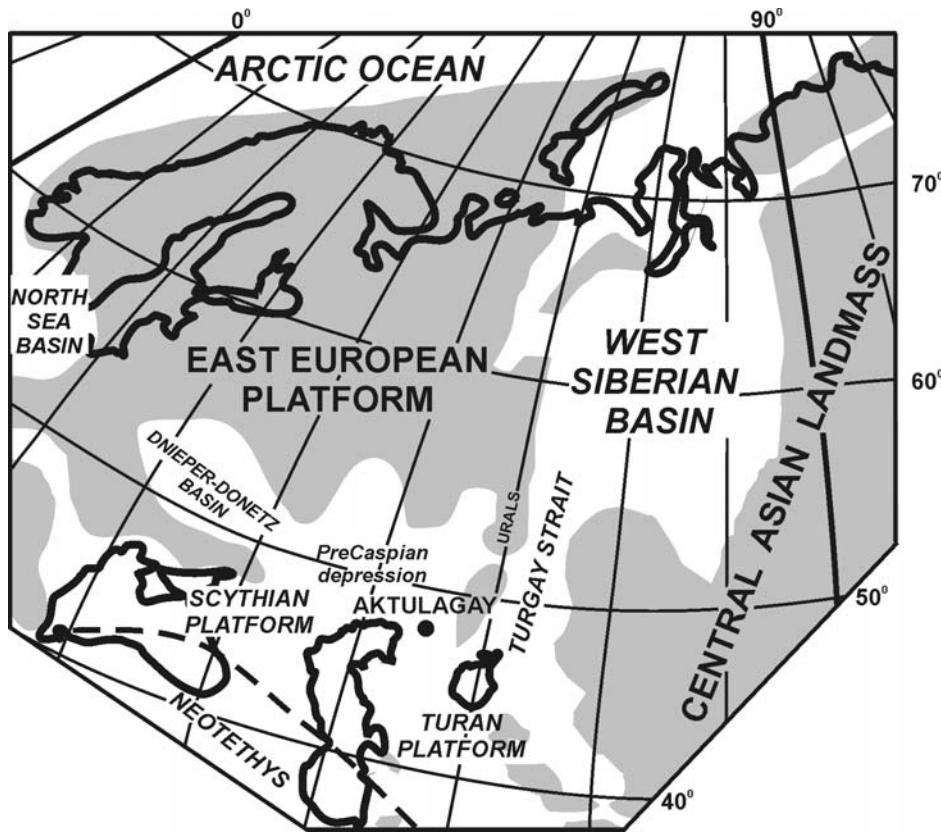
The limestones forming the Aktulagay summit plateau, relatively resistant to erosion, are responsible for the steep-sided slopes formed by the underlying softer Eocene sediments, and have largely protected them from superficial weathering and decalcification. The main section described here is a steep slope in a small valley on the western flank of the Aktulagay hills ($47^{\circ} 32' 31.47''$ N, $55^{\circ} 09' 13.75''$ E) (text-fig. 4). This section (cited here as 'Aktulagay section') is mostly well exposed, with well-preserved calcareous and organic-walled microfossils almost throughout. It provides a key section for analysing the Ypresian stratigraphy of the middle Embi region (text-fig. 5).

The Aktulagay section is (as of 2005) ~30km from the nearest hard-surfaced road. Access is by infrequently used and often deeply rutted tracks. A four-wheel drive vehicle is required; in winter and spring, access may be difficult or impossible, due to mud and snow-covered or waterlogged terrain.

Previous research and the present study

The Aktulagay section was not cited or described in earlier literature on this area (e.g. Yanshin et al. 1970), although smaller outcrops of the same age on the Embi River had been known for many years and foraminiferids had been described from them (e.g. Morozova 1939). It was discovered by V. I. Zhelezko in

1967 and was sampled in 1968 by Glikman, Zhelezko and Lebedeva. A description was first published by Benyamovsky et al. (1990). They divided the lower Eocene sediments in this section into two new units, the Alashen and Tolagaysor Sviti [Formations], with their stratotypes at Aktulagay (text-figs. 5, 7). They gave brief lithological details and generalised data on foraminiferid and calcareous nannoplankton assemblages. Nannofossil Zones NP11, NP12, NP13 and (tentatively) NP14 were identified, and the presence of sapropelic clays at several levels was noted. Naidin, Beniamovskii and Kopaevich (1994) briefly summarised the regional Eocene paleogeography, biostratigraphy, lithostratigraphy and depositional environments of the Pre-Caspian region (text-fig. 6), placing Aktulagay in a regional context. Zhelezko and Kozlov (1999, pp. 184–186, fig. 32) gave a more detailed description of the Aktulagay section, in some respects differing from the description of Benyamovsky et al. (1990), and divided it into numbered lithostratigraphic units (text-fig. 7). They cited the previous biostratigraphic data, calibrating them more precisely to lithostratigraphic units, and ascribed shark teeth recovered from several levels to newly defined shark zones. They identified a phosphatised pebble bed overlying the Tolagaysor Formation, followed by a thin clay unit. The clay was dated as Lutetian, apparently on the basis of a record of *Morozovella* [*Globorotalia*]



TEXT-FIGURE 3

Mid-late Ypresian paleogeography of northern and eastern Europe and western Asia, with location of Aktulagay. After Akhmetiev and Benyamovsky (2006, fig. 11). The Peri-Tethys realm lies between the East European Platform and Neotethys. Land areas are shaded. N.B. The present study suggests direct connection between the Pre-Caspian area and the North Sea Basin: see the text.

caucasica. This record (taken from Benyamovsky et al. 1990) was however from the highest part of the Tolagayor Formation. Benyamovsky et al. (1990) apparently included this clay unit in the ‘Sarmatian’ (Miocene) (text-fig. 7).

The present study is based on initial logging and sampling by CK and DJW in 2000, supplemented by more detailed study of parts of the section in 2001 and 2003. The upper part of the section is well exposed, but the lower part is somewhat degraded and was excavated in order to expose unweathered sediments. Samples were collected at close intervals (mostly = 1m) for paleontological analysis, and surface collecting was carried out for macrofauna.. Dinoflagellate cysts, calcareous nannofossils, foraminiferids, pteropods, ostracods and shark teeth have been analysed. Samples were collected from the lower part of the section for magnetostratigraphic analysis, but there is evidence of a post-depositional overprint (J. Ali, personal communication) and so the results are not presented here.

LITHOSTRATIGRAPHY

In earlier publications (e.g. Yanshin et al. 1970) the Eocene of this area was not assigned to formal lithostratigraphic units. Formal semi-lithostratigraphic units (*sviti*) were introduced mainly by Benyamovsky et al. (1990). A *svita* (suite) is comparable to a formation, but combines lithostratigraphic and biostratigraphic criteria (see discussion in Tverdokhlebov et al.

2005); the boundaries of a *svita* are generally considered isochronous. Due to lateral facies changes in this area, several stratigraphic units are differentiated in the lower, middle and upper Embi regions (text-fig. 5) (Naidin, Beniamovskii and Kopaevich 1994; Zhelezko and Kozlov 1999). The Ypresian–lower Lutetian succession in the middle Embi region (including Aktulagay) was divided by Benyamovsky et al. (1990) from base to top into the Alashen Svita (mainly marls), and the Tolagayor Svita (mainly clays). The stratotype of both of these units was designated at Aktulagay. The application of this terminology is discussed below.

Upper Paleocene

A thin (~ 0.3m) and apparently localised unit of chalky limestone intervenes between the Eocene sediments and Maastrichtian chalk in exposures several hundred meters east of the Aktulagay section. It is poorly exposed, but contains phosphatic pebbles at and near the base, and a macrofauna including echinoids and sponges. Planktonic foraminiferids are common, but have not been studied in detail. A poorly preserved nannofossil association, heavily overgrown, including *Heliolithus aktasii*, *H. riedelii*, *Hornbrookina arca* and *Discoaster mohleri*, indicates upper Zone NP8 (mid-Thanetian). The unconformable contact with the overlying Eocene section is not exposed. This unit does not appear to have been recognised previously at Aktulagay; it is presumably referable to the carbon-

ate-dominated Shputuz Svita (text-fig. 5; see Zhelezko and Kozlov 1999).

Eocene

The current study differentiates four major lithostratigraphic units with sharply defined boundaries, here labelled Units A to D (text-fig. 9; detailed logs of Units A and B are given in text-figs 10 and 12). All beds are thoroughly bioturbated, unless stated otherwise. All measurements cited in the text and figures (e.g. 12.7m) are from a zero datum at the base of Unit A. In the Aktulagay section, Unit A (lowest Ypresian; text-figs 14, 16) overlies Maastrichtian chalk. The highest part of the chalk is somewhat indurated and impregnated by iron oxide, probably representing a hardground. Its top surface is apparently approximately planar; the contact is exposed only over a small area, and any interburrowing has not been identifiable.

Unit A

Relatively homogenous, light gray to gray-green marl and calcareous clay (text-fig. 10). Three subdivisions have been differentiated:

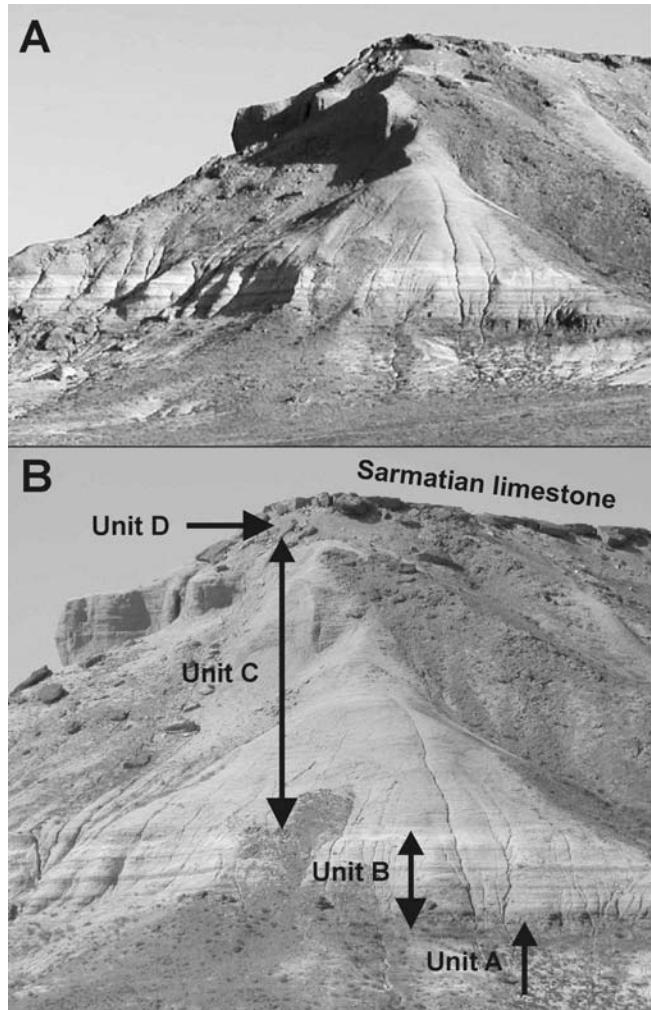
Unit A1 (0–0.20m). Gray-green clay, less calcareous than the overlying unit (A2). The basal contact is sharp. This very thin but lithologically distinct unit is covered everywhere by talus, and was exposed only by excavation.

Unit A2 (0.20m–10.80m). The base of Unit A2 is marked by an abrupt change to calcareous, foraminiferid-rich clay with small dispersed phosphatic granules at the base. This contact is probably an interburrowed omission surface, but is mainly concealed beneath talus, and only a very small area could be examined. Unit A2 comprises mainly calcareous clay and marly clay, grading to marl. The interval from 5.65m–6.80m is darker and less calcareous. Detailed logging has identified 13 omission surfaces, intensely interburrowed, mainly by *Chondrites* but also including thalassinoid burrows and (at 5.65m and 6.80m) *Zoophycos* (text-fig. 10). It is possible that additional less obvious surfaces may be present. Most of the omission surfaces form the base of minor depositional sequences (parasequences), each characterised by an upward decrease in carbonate content, typically from marl to calcareous clay. Foraminiferids are concentrated into the basal part of each parasequence (text-fig. 11). Fish scales are frequent; rare mollusc moulds and small thin-shelled smooth pectinid bivalves occur.

Unit A3 (10.80m–13.45m). This comprises mainly marl. The lower part is marly chalk, with the highest carbonate content in the Eocene section. The basal contact is an omission surface, and there is a further omission surface within Unit A3. Small bivalves are common between 12.80m and 13.45m, including smooth pectinids and poorly preserved nuculids and nuculanids.

Unit B

Unit B is lithologically heterogeneous, comprising four interbedded lithologies: light gray marly clay/marl, blocky light gray-brown clay, brown ‘shaly’ (fissile) non-calcareous clay and black sapropelic clay (text-fig. 12). The latter two facies are discussed in detail below. The base is defined at the contact of a 0.05m black sapropelic clay on the underlying light gray marl of Unit A3. The contact is sharp and planar, without interburrowing.



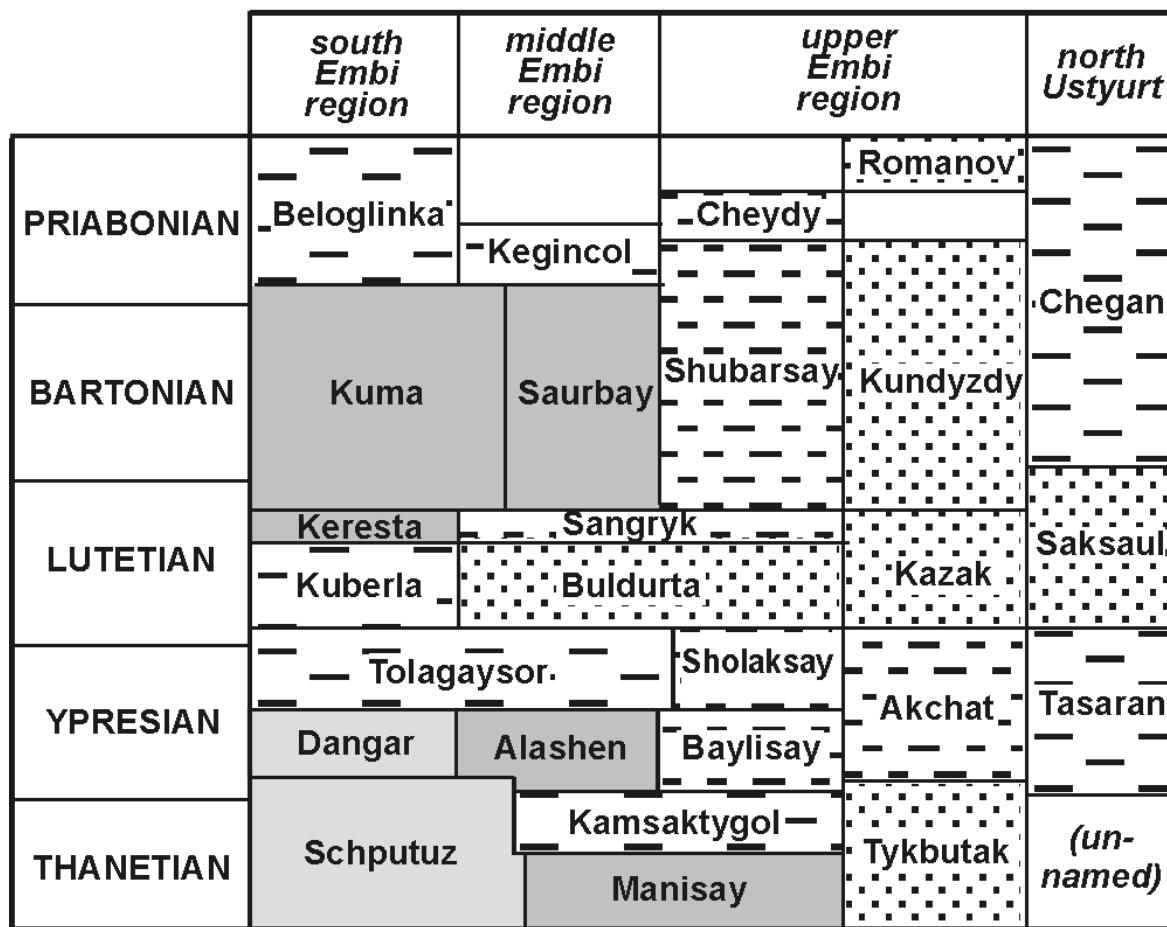
TEXT-FIGURE 4

A. The Aktulagay section, viewed from the SW. The boundary between the Ypresian and the underlying Maastrichtian chalcs is poorly exposed here, close to the base of the escarpment. The escarpment comprises mainly Ypresian sediments, capped by Miocene ('Sarmatian') limestones. Height of the escarpment is c. 75m.
B. Detail of the Aktulagay section. The upper part of the pale marls of Unit A (mostly covered by downwash), the 'banded' lithology of Unit B, dominated by light gray marly clays, and the thick silts of Unit C, can be differentiated. Unit D is largely covered by talus.

Two subdivisions are differentiated within Unit B:

Unit B1 (13.45m–16.22m). Dominantly light gray-brown, slightly calcareous to non-calcareous, ‘waxy’ clay, with four black sapropelic clay beds, rich in amorphous organic matter (AOM), and a single light brown ‘shaly’ (fissile) clay bed. The gray-brown clays have apparently been partially secondarily decalcified. The sapropelic beds are mostly very thin, but the second from the base is 0.20m thick. The contacts between the sapropelic beds and the gray-brown clays are mostly sharp, but the top of the third sapropelic clay is an interburrowed omission surface.

Unit B2 (16.22m–23.57m). The base of Unit B2 is a prominent omission surface, densely and deeply interburrowed by *Chondrites*. Phosphatised coprolites and fish debris are concen-



TEXT-FIGURE 5

Late Paleocene and Eocene lithostratigraphic units (svita) of Aktulagay and adjacent areas (see text-fig. 6). Based on Naidin, Beniamovskii and Kopaevich (1994, fig. 27), Zhelezko and Kozlov (1999, table 2) and Radionova et al. (2003). Legend mostly as for text-fig. 2; closely-spaced dashed lines indicate non-calcareous clays. Chronostratigraphic calibration is approximate, and lithology and relationships of units are highly generalised; hiatuses are omitted. Only limited documentation of these aspects is available.

trated at the base, together with dispersed limonitic concretions, apparently originally pyritic. Unit B2 comprises mainly interbedded light gray marly clay, with thin non-calcareous ‘shaly’ gray clay interbeds. Small poorly preserved aragonitic molluscs, crushed, partly decalcified and ‘chalky’, are common in the marly clays. The non-calcareous ‘shaly’ clay beds are fissile, due to the presence of abundant very fine plant debris and fish scales. There is no evidence of formerly calcareous fossils. They are more resistant to weathering than the intervening marly clays, and stand out as ‘ribs’ on the outcrop (text-figs 12, 16). The base of the non-calcareous clay beds is generally sharp; their upper boundary is generally an omission surface interburrowed by *Chondrites*. Foraminiferids and molluscs tend to be concentrated at the base of the marly clay beds. At least four black sapropelic clays have been identified, within the marly clay units. They have mostly been highly disrupted by bioturbation, and the lower three are represented only by diffuse black streaks.

Unit C

Mid-gray silty clay and silt (text-fig. 9). This is the only unit in the section (apart from D1), in which sediment coarser than

clay-grade is present in significant proportions. The basal contact is sharp, but apparently not interburrowed, and is marked by an abrupt increase in grain-size and a decrease in carbonate content. No well-defined lithological boundaries are recognisable within Unit C, but it can be subdivided into two units with an apparently transitional boundary.

Unit C1 (23.57m–~27.25m). Sandy clayey silt; many thin diffuse lensoid layers and laminae of very fine silty sand, often laminated, mostly variably disrupted by bioturbation.

Unit C2 (~27.25m–56.20m). The base of this interval is defined at an apparently transitional upward decrease in grain-size. It is suspected that it may be an omission surface which has been largely obliterated by interburrowing. The basal part of Unit C2 is a silty clay/clayey silt with very common foraminiferids and common poorly preserved small molluscs. This grades up rapidly to sandy clayey silt and clayey silt, with numerous very thin and very diffuse partings of very fine sand, partly disrupted by bioturbation. These give a thinly banded appearance to the outcrop. Several very diffuse layers of widely spaced calcareous siltstone concretions are present between 41.5m and 44.5m. Very fine-grained glauconite is present in some samples from

the upper part. Small, poorly preserved bivalves occur sparsely at some levels.

Unit D

The base of this unit is sharply defined. Biostratigraphic data indicate that it marks a disconformity.

Unit D1 (56.2m–56.45m). Sandy clayey silt with abundant phosphate and phosphatised sandstone pebbles. Abraded shark teeth occur fairly commonly.

Unit D2 (56.45m–~78.0m). Homogenous mid to dark gray, silty, non-calcareous clay.

Only the lowest 3m of this unit is represented in the Aktulagay section, beneath the overlying unconformable Miocene limestones. At the north end of the main Aktulagay plateau, 1km northwards, a much thicker section is exposed. The middle of Unit D2 is very poorly exposed, but there is apparently no significant lithological change through this interval.

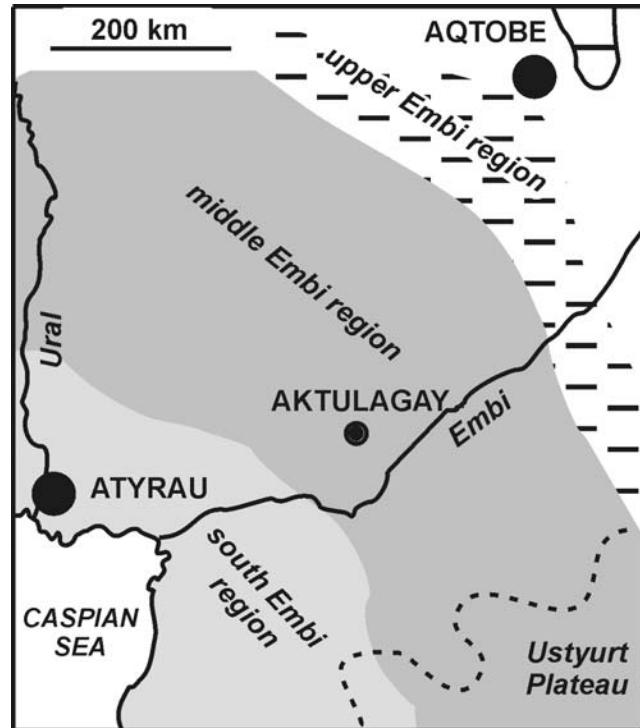
Lithostratigraphic terminology

The previous division of the Eocene section into the Alashen Svita and Tolagaysor Svita needs some discussion. The Alashen Svita was divided by Benyamovsky et al. (1990) (text-fig. 7) into units 1 and 2. Unit 1 corresponds to our Unit A, unit 2 to the lowest 2m of Unit B. The overlying Tolagaysor Svita corresponds to the majority of Unit B together with Unit C. It thus includes two quite distinct lithological entities. Benyamovsky et al. (1990) divided it into four lithological units (1 to 4), but it is difficult to relate these to our measured section. Their highest unit (4) was described as green calcareous clay with benthic and planktonic foraminiferids, and is thus probably part of Unit C. They did not appear to recognise our Unit D, apparently regarding it as part of the overlying Sarmatian, which they described as ‘clay and limestone’ (our translation). The description of Zhelezko and Kozlov (1999) is more detailed (text-fig. 7). They recognised a 7m clay unit (‘layer 8’) above the Tolagaysor Svita, with a layer of phosphatised pebbles at the base. This corresponds to our Unit D. The thickness of individual units given in both these publications differs somewhat from our figures (which were rechecked to ensure accuracy). All have presumably been measured in the same section as ours (the only well-exposed section in the area), although their precise location was not specified.

Here we propose to modify the original definition of the Alashen Svita slightly, following Zhelezko and Kozlov (1999), to correspond to our Unit A. It is thus a relatively homogenous unit of gray calcareous clay and marl, and can be designated the *Alashen Formation*. The Tolagaysor Svita includes two distinct lithological units: here we propose to define a new *Aktulagay Formation* for Unit B, and to redefine the Tolagaysor Svita (as *Tolagaysor Formation*) for Unit C (text-fig. 7). We have observed these units in other outcrops in the Pre-Caspian area, but currently have insufficient data for a full regional picture. The lowest part of Unit D contains late Middle Eocene (Bartonian) dinoflagellate cysts (see below), and Unit D can probably be assigned to the Sangryk Svita (Formation) (text-fig. 5) (Zhelezko and Kozlov 1999).

DINOFLAGELLATE CYSTS

39 samples were analysed after standard palynological processing. The processing involved successive treatments with HCl,



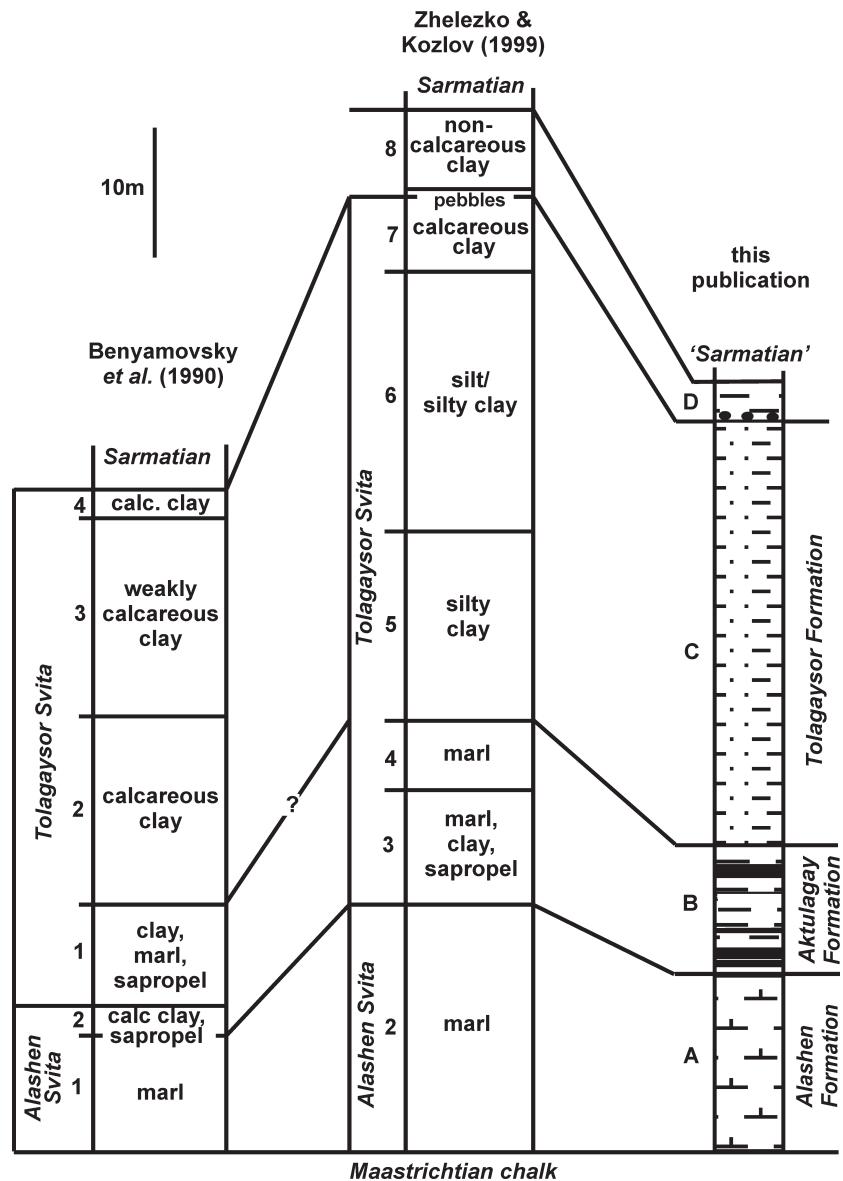
TEXT-FIGURE 6

Generalised Ypresian lithofacies and paleogeography of the eastern Pre-Caspian area. Modified from Naidin, Beniamovskii and Kopaeivich (1994, fig. 30). Legend as for text-fig. 2. ‘South Embi region’ etc. after Zhelezko and Kozlov (1999), see text-fig. 5.

HF and HCl. After neutralization with H₂O the residues were sieved on 20µm nylon filters (two samples with small residues were sieved on 10µm filters). The sieved residues were mounted in gelatine-glycerine on slides for light microscopy. No heavy-liquid separation was used, and only one sample (AK85 from a sapropelic layer at c. +14.70m) was oxidized, using HNO₃. The palynological preparations are stored at the Department of Geoscience, Aarhus University.

Proportions of taxa based on counts of 200 specimens were carried out on 24 samples; 15 additional samples were studied qualitatively (i.e. recording presence/absence of taxa). Palynomorph assemblages are dominated by dinoflagellate cysts. They also include rare acritarchs, prasinophytes and only few bisaccate pollen grains. Almost all samples are rich in well preserved dinoflagellate cysts (dinocysts) and assemblages are of high diversity. Approximately 194 taxa of dinocysts and other organic-walled algae have been recognised. The relative abundance of dinocyst eco-groups is shown on text-fig. 13. The main biostratigraphic events (e.g. first and last occurrences) are shown on text-fig. 14. Further details of the dinocyst assemblages, including taxonomic comments, will be provided in a future publication by A. Iakovleva and C. Heilmann-Clausen.

Dinocyst taxa recorded from Aktulagay are largely cosmopolitan, except for a single species, *Wetzelia coronata*, recognised previously only in the West Siberian Basin and the eastern Peri-Tethys (e.g. Iakovleva and Heilmann-Clausen 2010). *Hesleria* sp. aff. *H. hesleritonensis* (in Heilmann-Clausen and Costa 1989) is previously recognized only from the North Sea



TEXT-FIGURE 7

The Aktulagay section as interpreted by Benyamovsky et al. (1990), Zhelezko and Kozlov (1999) and the present study. The localised Thanetian unit is omitted. Lithological symbols are shown on text-fig. 8.

Basin. Several species previously recorded only from the North Sea Basin, Norwegian Sea and West Siberian Basin are also represented (*Cleistosphaeridium polypetellum*, *Hystrichostrogon holohymenium*, *Hystrichosphaeropsis costae* and *Wetzelia articulata* subsp. *brevicornuta*). Most samples (except in Unit C) are characterised by high numbers of *Spiniferites* spp.; in a few samples the *Arealigera/Glyphyrocysta*-group, *Cribroperidinium* spp., *Deflandrea*-group, *Thalassiphora pelagica*, wetzeliooids and *Cleistosphaeridium diversispinosum* are common. Unit C has an extreme dominance of *Eatonicysta ursulae* (text-fig. 13). Typical “oceanic” taxa (*Impagidinium* spp.) are very rare, except in Unit B2, where a peak of 25% (represented by a single species) is recorded in one sample. N.B. Here and in the following sections, LO indicates the lowest (earliest) occurrence and HO the highest (latest) occurrence of taxa.

Dinoflagellate cyst zonation

Since the 1970s a number of zonal schemes have been proposed for the Ypresian in NW Europe (Costa and Manum 1988; Heilmann-Clausen 1988; Köthe 1990; De Coninck 1991; Powell 1992; Bujak and Mudge 1994; Mudge and Bujak 1996; Luterbacher et al. 2004), the south of the former Soviet Union (Andreeva-Grigorovich 1991), the South Urals (Vasilieva 1990) and more recently for southern Russia and northern Kazakhstan (Akhmetiev and Zaporozhets 1992; Vasilieva, Zhelezko and Lubchenko 1994) and the West Siberian Basin (Kulkova and Shatsky 1990; Iakovleva and Kulkova 2003; Iakovleva and Heilmann-Clausen 2010). Recently new Paleogene dinocyst data has been recorded from a borehole drilled in the northern Pre-Caspian area (Vasilieva and Musatov 2010). The succession of many events is now relatively well documented and apparently consistent through these areas.

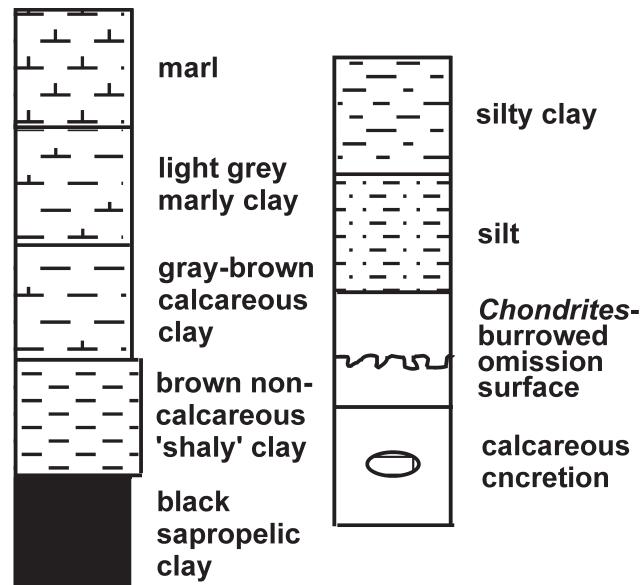
N.B. We distinguish between biostratigraphic and biochronologic nomenclature in differentiating between spatially Lowest Occurrence (LO) and Highest Occurrence (HO) of fossil taxa versus evolutionary first/earliest temporal occurrence (FAD) and last/latest temporal occurrence (LAD) of a taxon when calibrated to a radioisotopically, paleomagnetically or astronomically-based chronology. The former are referred to as biostratigraphic zones; the latter as biochronozones or biochrons (see Aubry, 1995: 215-217; figs 2, 3; Berggren and Pearson, 2005: 282).

The zonation used here is mainly that of Heilmann-Clausen (1988). The zonation of the interval between the *W. mecklenfeldensis* Zone and *D. varielongitudum* Zone is modified as follows (text-fig. 15): *Dracodinium solidum* and *Eatonicysta furensis* are not used in the present zonation. Instead the revised *Dracodinium simile* Interval Zone is defined as the interval from the lowest occurrence (LO) of *D. simile* to the LO of *Eatonicysta ursulae*. The revised *Eatonicysta ursulae* Interval Zone is defined as the interval from the LO of *E. ursulae* to the LO of *D. varielongitudum*. These modifications allow a better application of the zonation for long distance correlations, as discussed below. The LO of *D. simile* was used as a zonal marker in pioneer NW European zonations by Costa and Downie (1976) and Chateauneuf and Gruas-Cavagnetto (1978) and the LO of *E. ursulae* was first used in the zonation of Bujak et al. (1980). The *E. ursulae* Zone of Heilmann-Clausen (1988) should be renamed *Eatonicysta furensis* Zone; the base of the zone is not based on *E. ursulae*, but on the LO of atypical, early specimens then considered to fall within the morphological range of *E. ursulae* (Heilmann-Clausen 1982, 1993). These early forms are now the type material of *E. furensis* (Heilmann-Clausen and Costa) Stover and Williams 1995.

General comments on basal Ypresian dinocyst assemblages

The earliest Eocene dinoflagellate succession in the North Sea Basin, and other regions from which detailed data are available, is characterized by two successive events:

1. The globally widespread influx (usually > 50% of the assemblage) of *Apectodinium* spp., comprising a number of intergrading morphotypes. This *Apectodinium* acme generally corresponds to the earliest Eocene carbon isotope excursion (CIE), reflecting the Paleocene-Eocene Thermal Maximum (PETM) (Crouch et al. 2001; Bybell et al. 2001; Steurbaut et al. 2003; Sluijs et al. 2006), although locally in the Southern Ocean a ‘precursor acme’ has been recorded (Sluijs et al. 2011). In widely separated regions of the Northern Hemisphere the *Apectodinium* acme includes the extreme morphotype *A. augustum* and, additionally, the species *Wilsonidium pechoricum* (Iakovleva and Heilmann-Clausen 2007). *Apectodinium augustum* has been recorded in parts of the North Sea Basin (e.g. Heilmann-Clausen 1985; Steurbaut et al. 2003), northern Tethys (Austria) (Egger et al. 2003), Norwegian-Greenland Sea (Boulter and Manum 1989), Svalbard (Harding et al. 2011), parts of the USA Atlantic Coastal Plain (e.g. Edwards 1996; Sluijs and Brinkhuis 2009), eastern Peri-Tethys (Akhmetiev and Zaporozhets 1996; Aleksandrova and Radionova 2006; Vasilieva and Musatov 2010), Turgay Strait (Iakovleva et al. 2001), West Siberian Basin (Iakovleva and Kulkova 2003), Pechora Depression (Iakovleva et al. 2000) and the Polar Basin (Sluijs et al. 2006). In these regions *A. augustum* tends to occur in the more offshore settings.



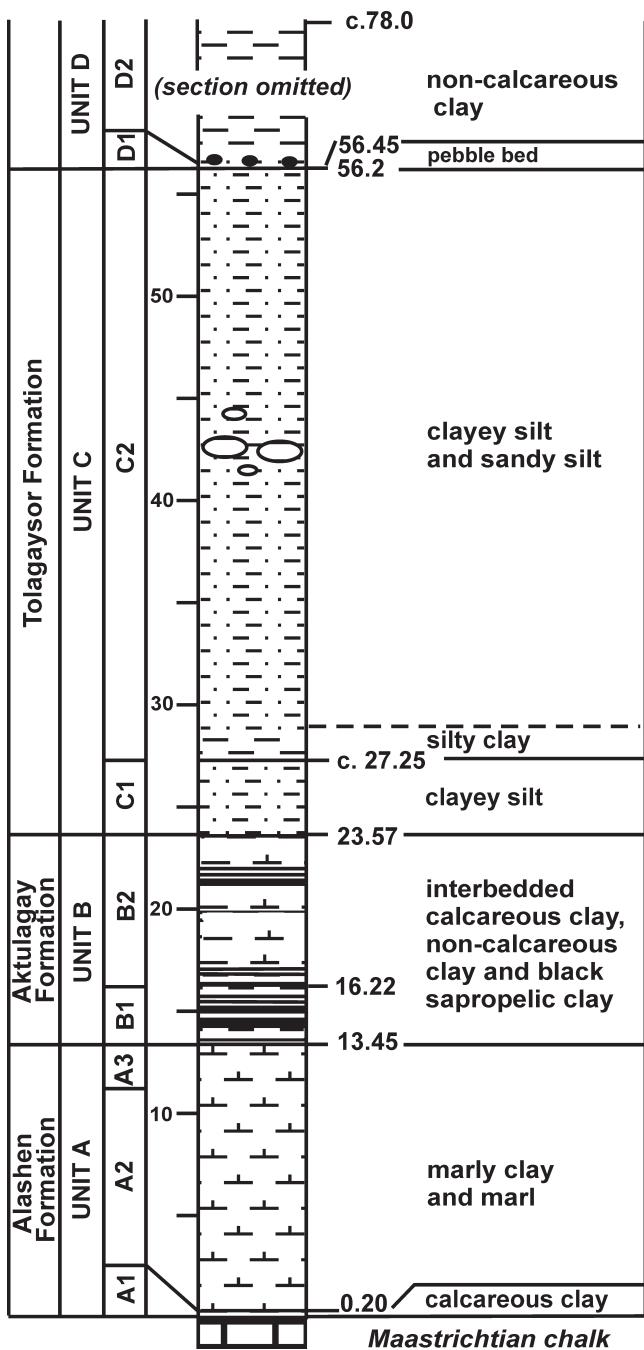
TEXT-FIGURE 8
Lithological symbols used in following figures.

2. The first occurrences of other wetzelelloids, including *Wetzelella* spp., *Wilsonidium tabulatum*, *Charlesdownia crassiramosa* and (at a slightly later date) *Dracodinium* spp. and *Rhombodinium* spp. These events have been documented in NW Europe, Switzerland, Austria, the USA Atlantic Coastal Plain, the south of the former USSR and Western Siberia. As pointed out by Edwards (1996, p. 991) the presence and succession of the species differ in detail when comparing these regions. However, the lowest/earliest occurrences are closely spaced, and apparently they are the result of a strong evolutionary radiation which took place within Zones NP10 and earliest NP11.

In the central North Sea, and some onshore areas of the North Sea Basin (particularly in Denmark), the interval between the *Apectodinium* acme and the LO of *Wetzelella* spp. is usually characterised by assemblages with common *Deflandrea oebisfeldensis*, *Glaphyrocysta ordinata* and *Hystrichosphaeridium tubiferum* (which all range below and above the interval), and with *Apectodinium* rare or absent. This assemblage was originally recognized from various localities and named the *Deflandrea oebisfeldensis* acme by Knox and Harland (1979). It was later recorded in Denmark as Zone 7 (Heilmann-Clausen 1985). The Gor Zone of Powell (1992) corresponds to this interval, and also (approximately) to Zone E1 of Bujak and Mudge (1994). Due to the lack of taxa with restricted ranges, this interval may be difficult to recognize in short sections. In the southern marginal parts of the North Sea Basin (e.g. Köthe 1990) and in northern Tethys (Jan Du Chêne et al. 1975; Egger et al. 2003) *Apectodinium* may continue to be common in this interval, although it is not as abundant as in the CIE-interval. In these areas other species, such as *Homotryblium tenuispinosum* and *Polysphaeridium zoharyi*, may also be common, as discussed in Egger et al. (2003).

Unit A1

Diversity is relatively high in the single sample from this unit. The assemblage is dominated by *Spiniferites* spp. (~ 40-50%).



TEXT-FIGURE 9

Summarised lithology and lithostratigraphy of the Aktulagay section. Units A and B are shown in detail in text-figs 10 and 12. Measurements (here and in following figures) are in meters above the base of Unit A. The Thanetian unit is omitted.

Relatively long-ranging species including *Oligosphaeridium* complex, *Thalassiphora delicata* and *Lanternosphaeridium lanosum* are common, *Deflandrea oebisfeldensis* is moderately common and *Hystrichosphaeridium tubiferum* and *Glaphyrocysta ordinata* are rare. *Apectodinium* spp. and other wetzelilloids are absent.

The assemblage resembles that in the *D. oebisfeldensis* acme interval of the North Sea Basin. *D. oebisfeldensis* is present in relatively low but significant numbers (18 specimens out of > 100 dinoflagellates). The similarity is enhanced by the moderate diversity of the assemblage, which comprises only long-ranging taxa, and the absence of *Apectodinium* spp. Diagnostic taxa of overlying intervals in the North Sea Basin, including *Wetzelella* spp., *Dracodinium simile*, *Hystrichokolpoma cinctum* and *Deflandrea phosphoritica*, are absent, but are recorded at the base of Unit A2. It is therefore concluded that Unit A1 is probably synchronous with the North Sea Basin *D. oebisfeldensis* acme.

Units A2 and A3

Assemblages are generally characterised by high taxonomic diversity. Samples at 0.65m and 1.0m are dominated by the *Areoligera*-group (34–46%) and *Cribroperidinium giuseppei* (20% at 0.65m). Through the overlying interval, the *Spiniherites*-group becomes dominant (42–79%). This upward replacement of an *Areoligera*-dominated assemblage by a *Spiniherites*-dominated assemblage suggests a change to a more offshore water mass.

Many stratigraphically significant taxa have their LO in Unit A2. In the basal meter appear *Dracodinium simile*, *Achilleodinium biformoides*, *Biconidinium longissimum*, *Hystrichokolpoma bulbosum*, *Wetzelella meckelfeldensis*, *W. lunaris* and *W. samlandica*. At higher levels appear *Deflandrea phosphoritica*, *Eatonicysta ursulae*, aff. *Heslertonia heslertonensis* in Heilmann-Clausen and Costa (1989), *Cleistosphaeridium polypetillum*, *Cannospaeropsis utinensis*, *Diphyes ficusoides*, *Dracodinium varielongitudum*, *Glaphyrocysta? vicina*, *Pentadinium laticinctum*, *Wetzelella articulata* subsp. *articulata*, *Cerebrocysta bartonensis*, and *Rhombodinium glabrum*. The HO of *Alisocysta* sp. 2 of Heilmann-Clausen (1985) is in the lower part of Unit A2. The LO of *Areoligera undulata*, *Charlesdowniea coleothrypta*, *Corrudinium incompositum* and *Dracodinium condyllos* is in the topmost sample in Unit A3 (13.25m).

The assemblage in the sample at the base of A2 (0.2–0.5m) is similar to that in A1, with the addition of very rare *Apectodinium quinquelatum* and *A. cf. parvum* (one specimen of each). However this assemblage may be largely reworked, as for the nannofossils (see below). The LO of *Dracodinium simile* and *Wetzelella meckelfeldensis* is in the lower part of Unit A2 (~0.65m and ~1.0m respectively). *W. meckelfeldensis* first occurs closely above the base of the London Clay Formation in southern England (Costa and Downie 1976), in the basal Ieper Group of the Kallo borehole in Belgium (De Coninck 1991) and at a correlative level in the Wursterheide borehole in NW Germany (Heilmann-Clausen and Costa 1989) (all early Ypresian). Its LO defines the base of the *W. meckelfeldensis* Zone. In Denmark *W. meckelfeldensis* first occurs close to the base of the Knudshoved Member in NW Jutland. In other parts of Denmark, including Albækhoued, this interval is characterised by strong condensation or non-deposition (Heilmann-Clausen 1982).

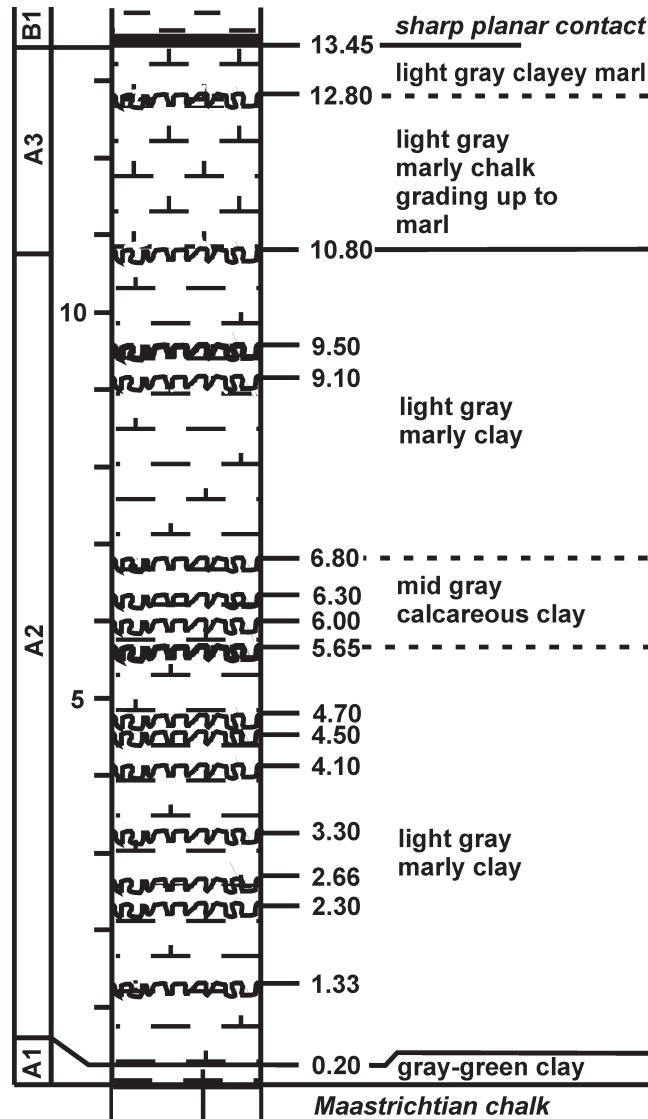
The LO of *Dracodinium simile*, first used in the biozonation of Costa and Downie (1976), is stratigraphically higher than the LO of *W. meckelfeldensis* in the North Sea Basin, but still within the lower Ypresian (below the LO of *Eatonicysta ursulae*), both in the Kallo and Wursterheide boreholes (De Coninck 1991; Heilmann-Clausen and Costa 1989). The LO of *D. simile* has

been used to define the base of a *D. simile* Zone (Costa and Downie 1976; Chateauneuf and Gruas-Cavagnetto 1978; De Coninck 1991), and as a key event within the LC-1 Zone in the London Clay of southern England (Bujak et al. 1980). In the Aktulagay section the LO of *D. simile* is below the LO of the nannofossil *Chiphragmalithus calathus* (middle NP11). The LO of *D. simile* is however slightly below the LO of *W. meckelfeldensis* at Aktulagay, suggesting a hiatus at the base of Unit A2, with the intervening *W. astra* Zone and *W. meckelfeldensis* Zone unrepresented.

The LO of *Eatonicysta ursulae* at ~4.6m marks the base of the *E. ursulae* Zone, as here redefined. *E. ursulae* first occurs at the base of the LC2 Zone of Bujak et al. (1980), within Zone NP11 in the London Clay Formation of southern England. In NW Jutland the first typical *E. ursulae* occur in a similar stratigraphical position closely above the top of the Knudshoved Member, while intermediate forms between *E. ursulae* and its probable ancestor *Eatonicysta furensis* are present in the underlying transition to the Knudshoved Member (Heilmann-Clausen 1993). In Belgium, De Coninck (1999a) observed the first/lowest typical *E. ursulae* at the transition between the Orchies and Roubaix Members in the Kallo borehole (at 330.5m), shortly above similar intermediary forms. The first/lowest occurrence of *Eatonicysta ursulae* is probably synchronous also in the Wursterheide borehole in NW Germany. Throughout the North Sea Basin, where data are adequate its LO is always bracketed between the HO of *Discoaster multiradiatus* and the LO of *C. calathus* (important lower Ypresian nannofossil events, see below), illustrating the correlation potential for this distinctive species. However at Aktulagay its LO is just above the LO of *C. calathus* (mid-Zone NP11). This may reflect sample collecting bias.

The LO of *Dracodinium varielongitudum* at 6.89m defines the base of the *D. varielongitudum* Zone. Generally, in northern mid- and high latitudes, the LO of *D. varielongitudum* has been recognized in the same position relative to other bioevents. The *D. varielongitudum* Zone is presumably equivalent to the upper part of the LC-2 Zone of Bujak et al. (1980). At Aktulagay, and probably also in the Albækholv key-section in Denmark (unpublished data), the LO of *D. varielongitudum* coincides closely with the base of NP12. This is in agreement with early observations from the NE Atlantic (Rockall Plateau) (Costa and Müller 1978).

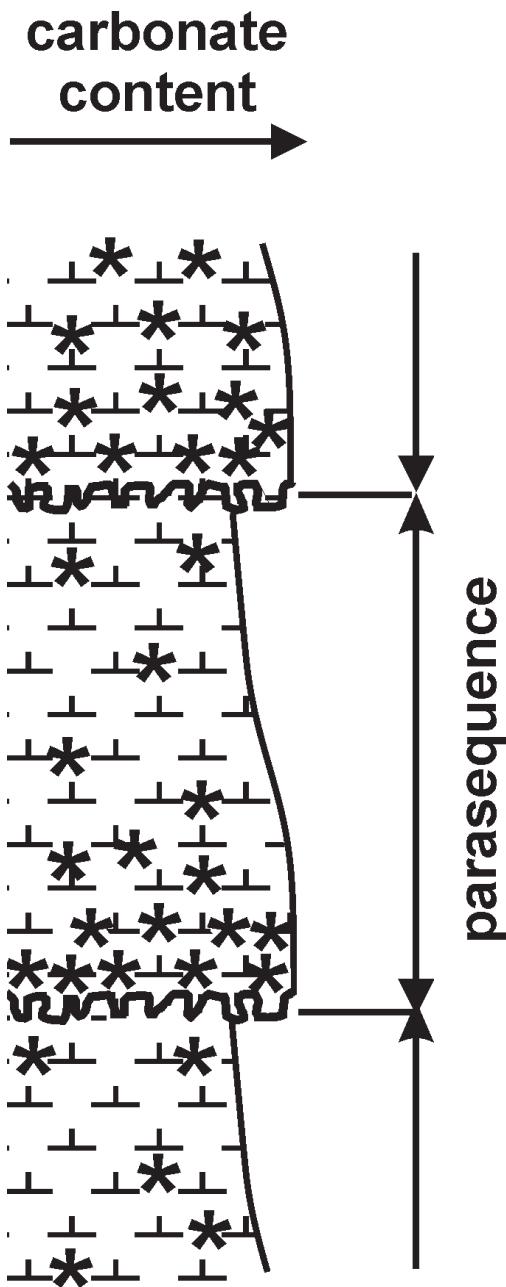
The LO of *Charlesdownia coleothrypta* 0.15m below the base of Unit B1 defines the base of the *C. coleothrypta* Zone. *Charlesdownia coleothrypta* and *C. clathrata* are here interpreted as probably synonymous or at least closely related taxa, following De Coninck (1976, pp. 61–62; 1981, p. 313). Generally, the LO of *C. coleothrypta* indicates a mid Ypresian age (within Zone NP12). In Belgium (e.g. Marke section, as *C. clathrata*: unpublished data, C. Heilmann-Clausen), as in NW Germany (Heilmann-Clausen and Costa 1989; Köthe 1990), Denmark (Heilmann-Clausen 1988), the London Basin (unpublished data) and the West Siberian Basin (Iakovleva and Heilmann-Clausen 2010), its LO is stratigraphically higher than the LO of *D. varielongitudum*, although in the Kallo borehole (Belgium) (De Coninck, 1991) both lowest occurrences seem to coincide, but this may reflect insufficient sampling. In the Aktulagay section the LO of *C. coleothrypta* is in the middle of Zone NP12, just below the HO of *P. exilis*.



TEXT-FIGURE 10
Lithostratigraphy of the Aktulagay section (Unit A). Positions of omission surfaces are indicated.

Unit B

Dinocyst diversity is high in unit B1. The LOs of *Dracodinium politum* (at 14.70m), *Diphyes brevispinum* and *Heteraulacocysta everruculata* are recorded in this interval. In the lower part, the assemblage is dominated by the open-marine *Spiniferites*-group (60%). At 15.5m there is a substantial influx of wetzeliooids, especially *Dracodinium* spp. (24%), together with the *Arealigera/Glyphyrocysta*-group (20%), and the *Homotryblium*-group (17%). In the middle of B2 there is a major influx (24%) of *Impagidinium* sp. A (in Iakovleva and Heilmann-Clausen 2010) at 18.95m, and the *Spiniferites*-group becomes common (32%). At higher levels, assemblages include common *Thalassiphora pelagica* (22% at 21.5m), *Spiniferites* spp. (28–41%) and *Cordosphaeridium* spp. At 23.5m is an influx of *Eatonicysta ursulae*, associated with its close relative *Membranilarnacia glabra*.



TEXT-FIGURE 11

Schematic illustration of parasequences in Unit A, showing sharp interburrowed base, foraminiferid concentration in lowest part, and upward decrease in carbonate content. Asterisks indicate relative foraminiferid abundance. Average thickness of parasequences is = 1m.

Ochetodinium romanum is rare at Aktulagay, with its LO at the base of Unit B2. In Belgium the LO of this distinctive form is shortly above the LO of *C. coleothrypta*, as is its only record at Aktulagay, and its short range defines an *Ochetodinium romanum* Zone (De Coninck 1991). In the West Siberian Basin *O. romanum* has a short range above the successive LOs of *C. coleothrypta* and *Dracodinium politum* (Iakovleva and Heilmann-Clausen 2010). The same order of these events is seen at Aktulagay. At Albækhouved, Denmark (C. Heilmann-Clausen, unpublished data), *O. romanum* also occurs above the

LO of *C. coleothrypta* and *D. politum*. These observations testify to the high value of *O. romanum* for long distance correlation. The LO of *Samlandia chlamydophora* is in the middle Ypresian in northern mid- and high latitudes (Bujak et al. 1980; De Coninck 1991). Both in the Albækhouved section (unpublished data) and at Aktulagay this event is in the upper part of Zone NP12. In the West Siberian Basin (Iakovleva and Heilmann-Clausen 2010) and at Albækhouved (unpublished data) the LO of *Samlandia chlamydophora* is above the LO of *O. romanum*. At Aktulagay the lowest occurrences of the two species coincide at the base of Unit B2. This may support the presence of a hiatus here, as indicated also on basis of calcareous nannofossils (see below), or may reflect the rarity of *O. romanum* here.

The LO of *Areosphaeridium diktyopllokum*, at 17.95m, defines the base of the *A. diktyopllokum* Zone of Heilmann-Clausen (1988) and of the similarly named zone in Belgium (De Coninck 1991). *A. diktyopllokum* appears within the B-2 Zone in southern England (Bujak et al. 1980). In the North Sea Basin the range of *A. diktyopllokum* begins from the E2c Subzone of Mudge and Bujak (1996), which was indirectly calibrated with the NP12/NP13 boundary interval. At Albækhouved the LO of *A. diktyopllokum* is directly calibrated with the topmost part of Zone NP12, very close to the NP12/NP13 boundary (Steurbaut 1998). Precisely the same relationship is seen at Aktulagay, reinforcing the importance of this event.

Further stratigraphically important species with their LOs in Unit B2 include the *Charlesdownia columnata*-group (17.0m), *Areosphaeridium michoudii* (19.25m), and near the top (at 23.5m) *Hystrichosphaeropsis cf. costae* and *Wetzelia coronata*. The HO of *Dracodinium politum* is in unit B2.

Unit C

Dinoflagellate cysts are very abundant throughout Unit C. Assemblages in C1 and the lowest part of C2 (to 28.5m) are characterised by an extreme dominance of *Eatonicysta ursulae*, forming an almost monotypic assemblage at some levels (up to 96% of the assemblage). The LOs of *Deflandrea truncata* and *Wetzelia articulata* subsp. *brevicornuta* are at the top of C1. At higher levels in C2 *E. ursulae* remains dominant (40–50%) with an important influx of *Cleistosphaeridium diversispinosum* at 41.5m (22–31%). (*C. diversispinosum* is often in the literature erroneously identified as *Systematophora placacanthum*, as pointed out by Eaton et al. (2001) and Heilmann-Clausen and Van Simaeys (2005)). In higher samples, at 48.0m and 55.5m respectively, there is an influx of *Spiniferites* spp. (24–41%) and *Deflandrea* spp. (30% at 55.5m).

In the highest part of Unit B2 and through Unit C a succession of lowest occurrences are recorded. These include the LO of *Hystrichosphaeropsis cf. costae* (Unit B2), *Wetzelia articulata* subsp. *brevicornuta* (Unit C1), *Duospaeridium nudum*, *Hystrichosphaeropsis costae* and *Wetzelia eocaenica* (jr. syn. *Dracodinium pachydermum*) (Unit C2). At Albækhouved these events are almost coincident, within a very thin interval (< 1m) in the middle of Bed L2 of the Lillebælt Clay Formation (unpublished data), but at Aktulagay they are spread over a vertical interval of 22m. This indicates a high degree of condensation at this level in Denmark. The LO of *Wetzelia eocaenica*, in the highest sample analysed in Unit C (55.5m), defines the base of the *W. eocaenica* (*D. pachydermum*) Zone. Several of these events are almost coincident

within the Upper Lulinvor Formation in the 011-BP borehole in W. Siberia, testifying to the widespread nature of this dinocyst turnover, as discussed by Iakovleva and Heilmann-Clausen (2010). The LO of the stratigraphically important species *Areoligera tauloma* is within the upper part of Unit C2.

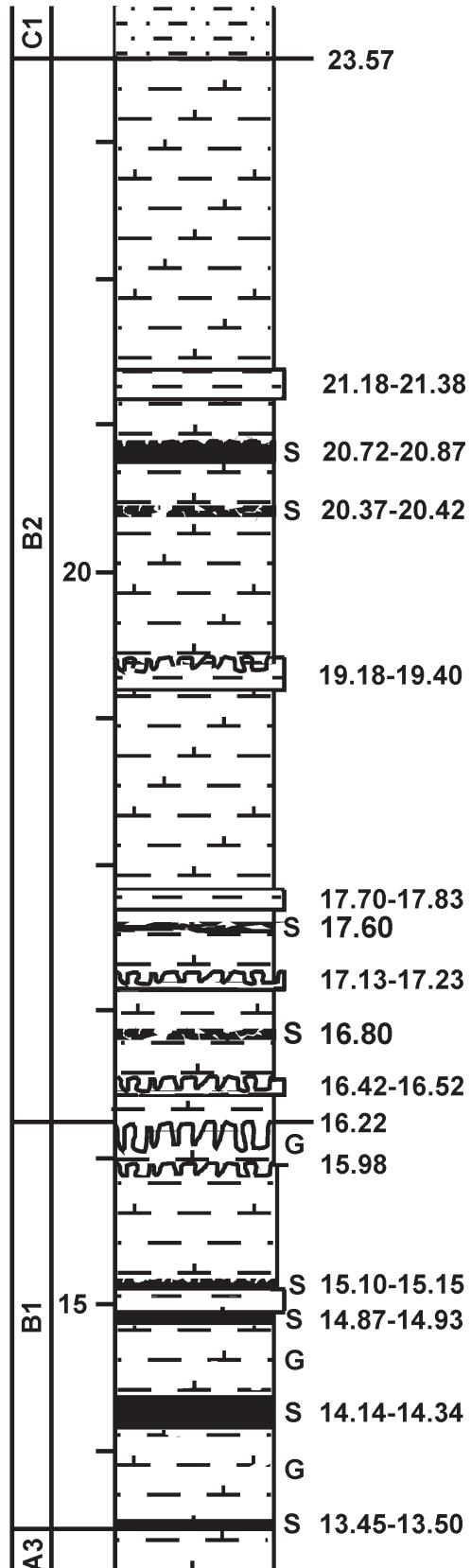
The extreme dominance of *Eatonicysta ursulae* in Units C1 and lower C2 at Aktulagay represents a very widespread phenomenon. Nielsen and Heilmann-Clausen (1986) recorded a prominent acme (> 45%) of *E. ursulae* in the highest Røsnæs Clay Formation to lower Lillebaelt Clay Formation (Beds R6-L3) in Denmark. Also Heilmann-Clausen and Costa (1989) recognized common *E. ursulae* within Zone D9 in NW Germany, identified as an interval between the LO of *A. diktyoplakum* and the extinction of *E. ursulae*. Later Bujak and Mudge (1994) established the *E. ursulae* acme Subzone (E3c) in the North Sea and indirectly calibrated it to upper Zone NP13-NP14. According to the present data from Aktulagay, the *E. ursulae* acme interval corresponds to middle and upper Zone NP13.

According to De Coninck (1977, 1981, 1990), the LO of *W. eocaenica* [*D. pachydermum*] characterizes the Ypresian-Lutetian transition. In the North Sea Bujak and Mudge (1994) established the *D. pachydermum* Subzone (E4a), with its top defined by the HO of *D. pachydermum*, indirectly calibrated to mid-late NP14 (Lutetian). In Belgium *W. eocaenica* has been recorded in a short interval in two boreholes. According to Schnetler and Heilmann-Clausen (2011), *W. eocaenica* probably spans the Ypresian/Lutetian boundary in Denmark. Data from the Aktulagay section have confirmed the LO of *W. eocaenica* to be in lowermost NP14 (uppermost Ypresian as now defined).

Unit D

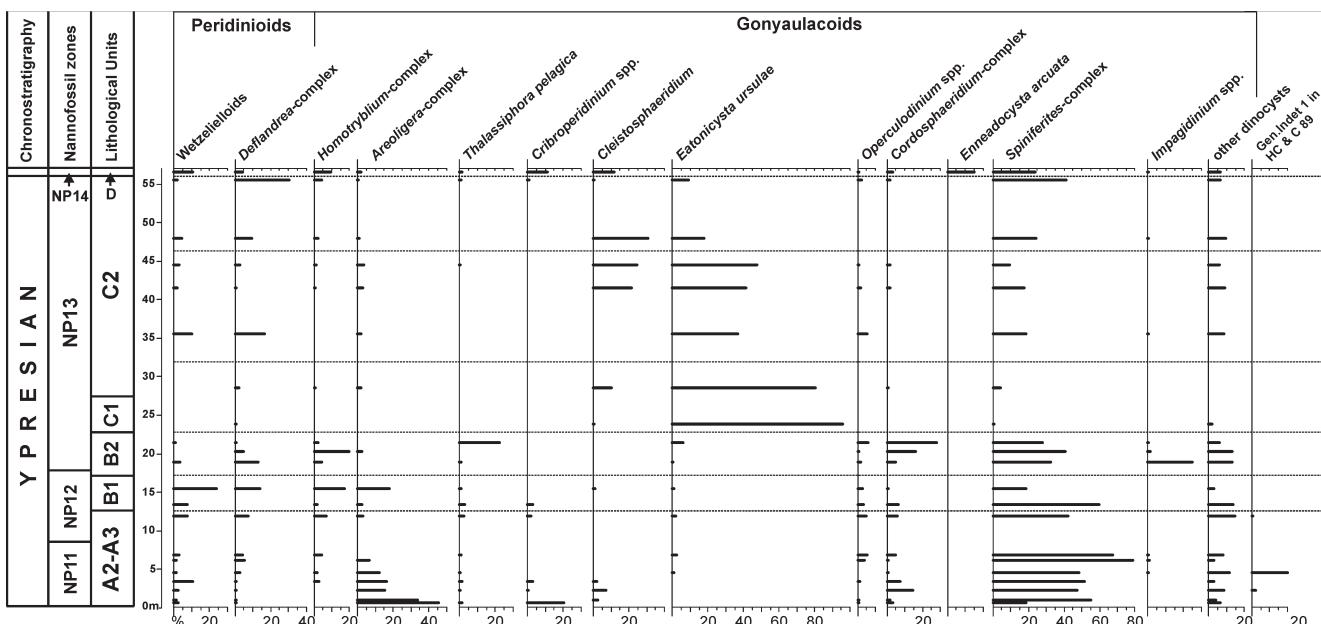
A sample near the base of Unit D, at 56.5m, contains a rich assemblage characterised by abundant *Spiniferites* spp. (24%), *Enneadocysta arcuata* (15%) and *Cribroperidinium giuseppei* (11%), with the stratigraphically important species *Enneadocysta arcuata*, *Rhombodinium draco*, *Wetzelia ovalis* and *Wilsonidinium echinosuturatum*. The dinoflagellates indicate a probable late Lutetian-Bartonian age. A similar abundance of *Enneadocysta arcuata* is recorded in the North Sea Basin in the late Lutetian and Bartonian (see overview in Heilmann-Clausen and Van Simaeys 2005). The greatest similarity is with the Bartonian (upper NP16-NP17), based on the combined presence of *Rhombodinium draco*, *Wetzelia ovalis* and *Wilsonidinium echinosuturatum*. A few specimens of *Eatonicysta ursulae* are also represented, but these are considered reworked from Unit C, in which it is very abundant. A sample at ~77.2m, near the top of the section, was palynologically barren, probably due to recent weathering.

Rhombodinium draco is included in several overviews of stratigraphically important species, e.g. Luterbacher et al. (2004), who, apparently in error, calibrated its lowest/initial occurrence to lower Zone NP17. In southern England its lowest/initial occurrence is in Zone BAR-1 (Bujak et al. 1980), in strata referred to Zone NP16 by Aubry (1983). In Ukraine *R. draco* first occurs in Zone NP16 (Andreeva-Grigorovich and Iakovleva, personal communications). In northern Germany *R. draco* first occurs in an interval without calcareous nannofossils, above strata with Zone NP16 nannofossils (Köthe 1986, 1990). In Denmark *R. draco* has been recorded from near



TEXT-FIGURE 12

Lithostratigraphy of the Aktulagay section (Unit B). S: sapropelic clays. G: light grey-brown, mainly calcareous clay. Brown 'shaly' clay beds stand out to right of column.



TEXT-FIGURE 13
Relative abundance of major dinoflagellate cyst groups and taxa in selected samples.

the base of biozone NP17 (Heilmann-Clausen and Van Simaeys 2005), but its LO may be delayed due to its rarity.

CALCAREOUS NANNOFOSSILS

The calcareous nannofossil investigation is based on 50 samples, evenly distributed through Units A to C. Smear-slides, processed according to standard procedures, have been examined with a light microscope at 1000 \times or 1250 \times magnification and are stored in the collections of the Royal Belgian Institute of Natural Sciences (Brussels, Belgium). The taxonomy is essentially from Perch-Nielsen (1985), taking into account subsequent modifications by Aubry (1995). Calcareous nannofossils are common to abundant and fairly well preserved through most of this interval. The uppermost part of the section (Unit D), together with a substantial interval within the upper part of Unit B1, and some thin intervals within Unit B2, are decalcified and, consequently, devoid of nannofossils. The numerically richest assemblages (> 50 specimens/field of view at $\times 1000$, with a maximum of 71) occur within Unit A2, at the base and in the upper part. The highest diversity (35–44 taxa) is within Unit A1, at the base of A2, in the lower and middle part of B2, at the top of C1 and at the base of Unit C2. New taxa of nannofossils from this section are described by Steurbaut (2011).

Nannofossil zonation

Most of the nannofossil units first identified in the North Sea Basin (essentially in Belgium and Denmark) (Steurbaut and Nolf 1989; Steurbaut 1990, 1991, 1998; Schmitz et al. 1996; latest update in Steurbaut 2006) can be recognised in the Aktulagay section (text-fig. 16). These subzones are subdivisions of Martini's (1971) standard NP-nannofossil zones. The NP10/NP11 boundary is at the base of Unit A2. Zone NP11 is subdivided into 6 subzones in the North Sea Basin (Ia, Ib, I, II, IIIa1 and IIIa2). Subzones Ic and II, whose boundary is defined at the LO of *Blackites solus*, cannot be differentiated at Aktulagay, because this nannofossil event seems to occur much

lower/ earlier in lower latitudes (within Subzone NP9b at Dababiya, Egypt, GSSP for the P/E boundary: Steurbaut, personal observations), and in Austria (Egger et al. 2000) and Peri-Tethys (Zone NP10 at Aktulagay). The lower boundary of NP12, defined by the LO of *Discoaster lodoensis*, is recorded at 9.0m, within the upper part of Unit A2. In the North Sea Basin it can be subdivided into Subzones IIIa3, IIIa4, IIIb1, IIIb2, IIIb3, IV, V, VI, VII, VIIIa and VIIIb. The lower boundaries of NP13 (defined by the HO of *T. orthostylus*) and NP14 (LO of *D. sublodoensis*) are recorded at ~18.50m (middle of Unit B2) and ~50m (upper part of Unit C2) respectively. The succession of nannofossil events identified within NP13 and NP14 at Aktulagay has not been recorded as such in the North Sea Basin, because of decalcification (essentially in Denmark), non-deposition (essentially in the Paris Basin), or marginal-marine episodes (essentially in Belgium and the Hampshire Basin), or by a combination of these. The associations of the Aalter Sand Formation in Belgium (Steurbaut and Nolf 1989) and the Earnley Formation in southern England (Steurbaut in King 1996), which are correlative, at least in part, are strongly taphonomically biased. They show a certain degree of selective dissolution and are partly too proximal to record the complete sequence of events as identified at Aktulagay, creating the false image of diachronous appearances between the North Sea Basin and Kazakhstan.

Unit A1

The lowermost sample in Unit A1 has a fairly abundant (16 specimens/field of view at $\times 1000$), moderately preserved, high diversity assemblage (36 taxa), in which small *Toweius* spp. (48%) and *Coccolithus pelagicus* (28%) dominate. It reflects a fully marine environment, with normal salinity, although with coastal influence, as shown by the significant proportions of *Micrantholithus* spp. (6%). The nannoflora is almost completely renewed compared to that of the locally underlying Thanetian limestone. More than 80% of the taxa represent new

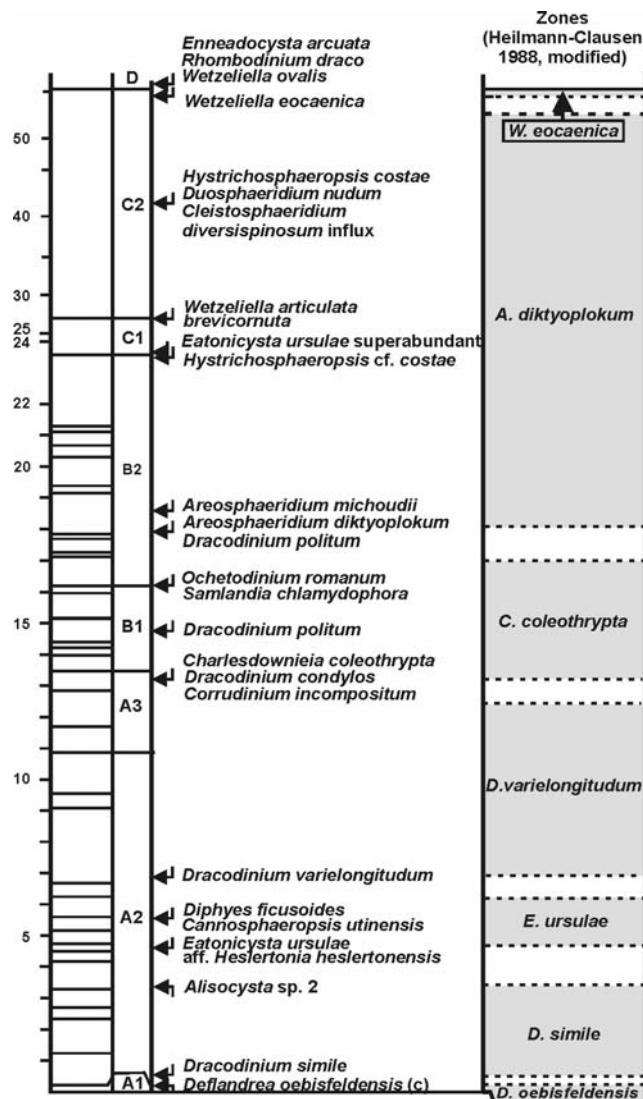
entries, of which the following are considered to be biostratigraphically significant: *Rhomboaster cuspis*, *R. bitrifida*, *Discoaster multiradiatus*, *D. mahmoudii*, *D. binodosus*, *Tribrachiatus digitalis*, *Blackites solus*, *Campylosphaera eodela*, *Lophodolithus nascens*, *Neococcolithes dubius* and *N. protenus*. Similar rich associations, including *D. multiradiatus*, *D. salisburyensis*, *B. solus*, *T. digitalis* and *C. eodela*, have been identified elsewhere in low and mid latitudes, indicating the middle of Zone NP10 (Subzone NP10b of Aubry, 1996). The presences of *D. mahmoudii*, *R. cuspis* and *R. bitrifida* at Aktulagay may be due to reworking, as the ranges of these taxa seem to predate the LO of *T. digitalis* at low latitudes (Monechi, Angori and Von Salis 2000; Dupuis et al. 2003).

Units A2 and A3

The assemblages are well-diversified and substantially richer in specimens (generally two to three times) than those from Unit A1. Small *Toweius* spp. and *Coccolithus pelagicus* remain the dominant taxa throughout, although with slightly varying frequencies: the former between 55% and 83%, with a mean of 69%, the latter between 4% and 16%, with a mean of 9%.

There are substantial shifts in the quantitative distribution of the taxa throughout this interval. These are essentially due to paleoenvironmental changes. The lowermost samples (0.20m to 2.25m) are marked by relatively high frequencies of *Micrantholithus* spp. (5–10% of the association), suggesting deposition within proximity of the coastline. The high numbers of reworked forms in the lowermost meter corroborate this observation. These are reworked from the underlying Thanetian limestone unit (*Heliolithus knoxii*, *H. riedelii*), from former earliest Ypresian sediments, now eroded (the PETM/Paleocene-Eocene Thermal Maximum-taxon *D. araneus*) and from Unit A1 (*R. cuspis* and *T. digitalis*). The association in the lowermost sample in unit A2 (0.20m–0.25m) is quite similar to that of Unit A1 in diversity (~35 taxa) and in composition (presence of *R. cuspis*, *R. bitrifida*, *T. digitalis* and *D. mahmoudii*), although much richer in specimens (2 to 3 times). At first sight it also appears attributable to Subzone NP10b. However, this is due to intensive reworking. *Tribrachiatus orthostylus* has been found *in situ*, although very rarely (a few specimens only, after careful screening of several slides). Its presence, in association with the absence of *T. contortus*, indicates Zone NP11. Associations from samples between ~0.5m and ~1.0m are (in terms of diversity and dominant taxa) very similar to the lowermost A2 sample, but are definitely richer in *Tribrachiatus orthostylus* and include a series of lowest/first occurrences (*Pontosphaera fimbriata* and *Chiasmolithus eograndis* at ~0.5m; *Imperiaster obscurus* at 1.0m). The sample at ~1.9m differs through a decrease in *D. multiradiatus* (from ~5% to very rare). Nannofossils in the sample at 2.35m are considerably dissolved and marked by a major increase in *Discoaster diastypus* and by the absence of *D. multiradiatus*.

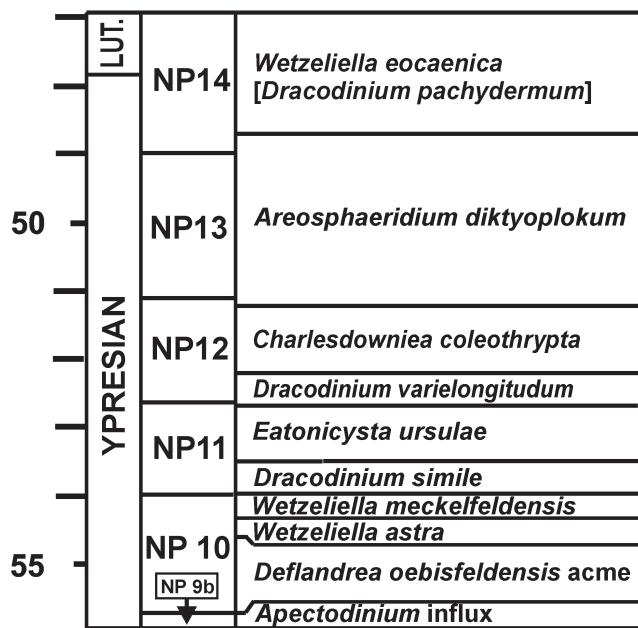
Assemblages from the middle and upper part of Unit A2 (~3.7m upwards) and Unit A3 have several features in common, which allow them to be differentiated from the underlying samples. Among the most striking changes are: the increase in small *Toweius* spp. (mean of 71% versus 61% below), the major decrease in *Micrantholithus* spp. (from a mean of 7% to 2.5%), and (last but not least) the conspicuous increase in *Pontosphaera* spp. (from 2% to a mean of 8%). No substantial quantitative differences are noted within the interval itself, except for a series of short species blooms, including the sharp rise in



TEXT-FIGURE 14

Dinoflagellate cyst events and Zones. Unshaded intervals between zone boundaries represent unsampled sections. Horizontal lines in lithostratigraphy column, here and in later figures, are bed boundaries (see text-figs 9, 10, 12). *D. oebisfeldensis* (c) = common. N.B. Here and in later figures, the vertical scale changes at 24m to accommodate the increase in sedimentation rates in Unit C.

Blackites solus from 4.15 to 5.05m (from 2% to > 10%), in *Imperiaster obscurus* at ~6.8m (~4%) and in *Blackites truncatus* (6%) at 12.75m. Although the general composition of the associations remains fairly uniform, there is substantial evidence of permanent evolutionary changes within the associations. Many lowest and highest occurrences have been recorded throughout upper A2 and A3. The LO of *Chiphragmalithus calathus* and *Discoaster pacificus* is at ~3.7m, the LO of *B. dupuisii* and *B. truncatus* at 5.05m. The HO of *Zygrhablithus bijugatus nolfii* is at 5.68m, the HO of *Ellipsolithus macellus* at ~8.8m. The LO of (very rare) *Discoaster lodoensis* is at 9.0m, the LO of *Neochiastozygus rosenkrantzi* at 9.55m, the first/lowest consistent occurrence (LCO) of *D. lodoensis* (2.5%) and the LO of *Aubrysphaera deconinckii* and *Blackites thiedei* at 10.75m. The LO of *Micrantholithus mirabilis* is at 12.75m.



TEXT-FIGURE 15
North Sea Basin Ypresian dinoflagellate cyst zones: from Heilmann-Clausen (1988), modified as in text.

and the LO of *Chiphragmalithus barbatus* at 12.8m. The HO of (*in situ*) *Pontosphaera exilis* is at 13.25m.

From 0.5m upwards the assemblage is marked by the consistent presence of *T. orthostylus* and *D. multiradiatus* and the high frequency of *Micrantholithus* spp., indicating lowermost Zone NP11. This interval can be subdivided into Subzones Ia and Ib, with tops defined respectively by the LO of *Imperiaster obscurus* (at 1.0m) and the HO of *D. multiradiatus* (at 2.0m). The base of Subzone Ib corresponds to the base of the Roubaix Clay Member in Belgium (Sturbaut 1998) and the base of Division B in the Dieppe-Hampshire Basin (Sturbaut, personal observations), both coinciding with the base of Chron C24BN (Ali, King and Hailwood 1993) (now C24n.3n; e.g. Berggren and Pearson 2005). The top of Subzone Ib corresponds to a major planktonic foraminiferid influx (event I1 of King 1991a) and the lowest occurrence (LO) of the dinocyst *Eatonicysta ursulae* (Sturbaut 1998; De Coninck 1999a, b).

The LO of *Chiphragmalithus calathus*, defining the base of Subzone IIIa1, is recorded at 3.7m. The underlying interval (2.25m–3.4m) is attributable to the combined Subzones Ic-II (undifferentiated, because *B. solus* is occurring much earlier in the Aktulagay area, see above). The LO of *C. calathus* is recognised throughout the North Sea Basin (Belgium: Sturbaut 1998; Denmark: Sturbaut in Schmitz et al. 1996; borehole 81/46, southern North Sea: E. Sturbaut, personal observations), falling within the top of C24AR (currently termed C24n.2r: Berggren and Pearson 2005). In Belgium it coincides with event I4 of King (1991) in the middle of the Roubaix Clay Member and the Mons-en-Pévèle Sand Formation (Sturbaut and King 1994). The base of Subzone IIIa2, defined by the LO of *Blackites dupuisii*, is at c. 8.80m. Coincident events at the base of IIIa2 are the LO of *Zyghralithus bijugatus nolfii*, the

top of the peak abundance of *B. solus* (decreases shortly afterwards from 3–7% to <1%), and event I5 of King (1991).

The LO of *D. lodoensis*, delineating the base of Zone NP12, is difficult to pinpoint in the North Sea Basin, as it is scarce at its initial appearance. Consequently, Steurbaut (1998) used its slightly higher/later lowest consistent occurrence (LCO) to define the base of Subzone IIIb1. At Aktulagay the LO of *D. lodoensis* (at 9.0m) immediately postdates the HO of *Ellipsolithus macellus* (at 8.8m), used to define the base of Subzone IIIa3 in the North Sea Basin. At Aktulagay the latter is very close to the HO of *B. dupuisii*, pointing to a very thin Subzone IIIa2. The HO of *Neochiastozygus rosenkrantzi*, defining the base of Subzone IIIa4, is at 9.55m.

Unit A3

The base of Unit A3 coincides with the base of Subzone IIIb1, defined by the lowest consistent occurrence (LCO) of *D. lodoensis* (increasing from a few specimens to 2%), the LO of *Aubryphaera deconinkii* and the LO of *Blackites thiedei*. In the southern North Sea Basin it seems to equate to the base of Chron C23R (Ali, King and Hailwood 1993) (now C23r; e.g. Berggren and Pearson 2005). The LO of *Micrantholithus mirabilis* and the LO of *Chiphragmalithus barbatus*, within the upper part of Unit A3, defining the base of Subzones IIIb2 and IIIb3, respectively, are only separated by 0.05m. In Belgium these events are separated by 7m. This may reflect much higher sedimentation rates in Belgium, and/or a hiatus at this level at Aktulagay (text-fig. 10).

Unit B1

The associations in Unit B1 have much lower diversity (20 versus 30 taxa) and abundance (generally <10 specimens/field of view versus over 30) than in Unit A3 or Unit B2. Small *Toweius* spp. still dominate (30–5%), although less than in the adjacent units. The base of Unit B1 is marked by influxes of *Micrantholithus mirabilis* (to 18%) and *Imperiaster obscurus* (from <1% to 15%), indicating somewhat shallower water, reflecting major changes in the sea surface waters in the Aktulagay area. Several first occurrences, represented by single or very few specimens, include the LO of *Lophodolithus reniformis* (13.46m), *Lophodolithus mytiliformis* (13.46m) and *Helicosphaera seminulum* (14.45m). The middle part is decalcified and devoid of nannofossils. The upper part of Unit B1 is marked by a strong decrease in *M. mirabilis* (to <1%), a substantial decrease in *I. obscurus* and a slight increase in discoasters.

The start of the blooms of *Micrantholithus mirabilis* and *Imperiaster obscurus*, which have also been identified in Belgium, Denmark and the southern North Sea (borehole 81/46), is coeval with the LO of *Lophodolithus reniformis* and the absence of *Pontosphaera exilis*, defining the base of Subzone V. The HO of *Toweius pertusus*, defining the base of Subzone VI, is recorded in the middle of B1 (14.5m) and coincides with the end of the acme of *M. mirabilis* and *I. obscurus*. These events are identified above the top of the Roubaix Clay Member and the Mons-en-Pévèle Formation in Belgium. The HO of *Chiphragmalithus armatus* and *Blackites creber*, although in very low numbers, in association with the LCO of *Helicosphaera seminulum*, occurs at ~0.25m below the top of Unit B1 (15.95m). The HO of *M. mirabilis* is at the top of Unit B1 (16.07m).

Unit B2

The associations in Unit B2 are diversified and rich in specimens, especially in the lower half (16.27m–20.0m). Small Prinsiaceae (*Toweius* spp. and *Reticulofenestra* sp.) dominate (up to 40% of the assemblage). Additional characteristics are the high proportions of the nearshore taxon *Pontosphaera* spp. (essentially *P. pulchra*) (12–20%), *Coccolithus pelagicus* (10–20%) and discoasters (6–10%), and an increase in *Blackites creber* (from < 0.5% to 3–6%).

The most conspicuous nannofossil turnover in the Ypresian section is at the base of Unit B2 (sample at 16.27m), including nine first/lowest occurrences (*Blackites herculeus*, *Chiasmolithus grandis*, *Discoaster cruciformis*, *Ectalithus crassus*, *Girgisia gammation*, *Pentaster lisbonensis*, *Reticulofenestra* sp., *Scyphosphaera biarritzensis* and *S. columella*), and several last/highest occurrences. The consistent (and common) occurrence of *Blackites creber* and the LO of *Discoaster cruciformis*, which in the North Sea Basin define the base of Subzones VII and VIIIa respectively, coincide at Aktulagay, indicating a substantial hiatus at the base of Unit B2. This hiatus encompasses Subzone VII, of which the duration is estimated at ~55 kyr (age estimates compiled from Steurbaut, 1998). The base of Unit B2 is therefore close to the top of Chron C23N (C23N.2r in Steurbaut 1998 (corresponding to C23n.1r in Berggren and Pearson 2005). The next wave of first/lowest occurrences, at 18.05m, includes *Nannoturba robusta*, marking the base of Subzone VIIIb, and *Scyphosphaera tubicena*.

The NP12/NP13 zonal boundary, defined by the HO of *T. orthostylus*, is within the lower part of Unit B2 (18.05m) (placed midway between this depth and the next sample at 18.95m on text-fig. 16). The first/lowest specimens of *Discoaster praebifax* have been recorded in the next sample, at 18.95m. At higher levels, correlation with the southern North Sea Basin is difficult, as noted above. The upper part of Unit B2 is characterised by the LO of *Blackites perlongus* (22.35m) and *Helicosphaera lophota* (23.5m). Both events occur much later in Belgium, probably due to taphonomic bias.

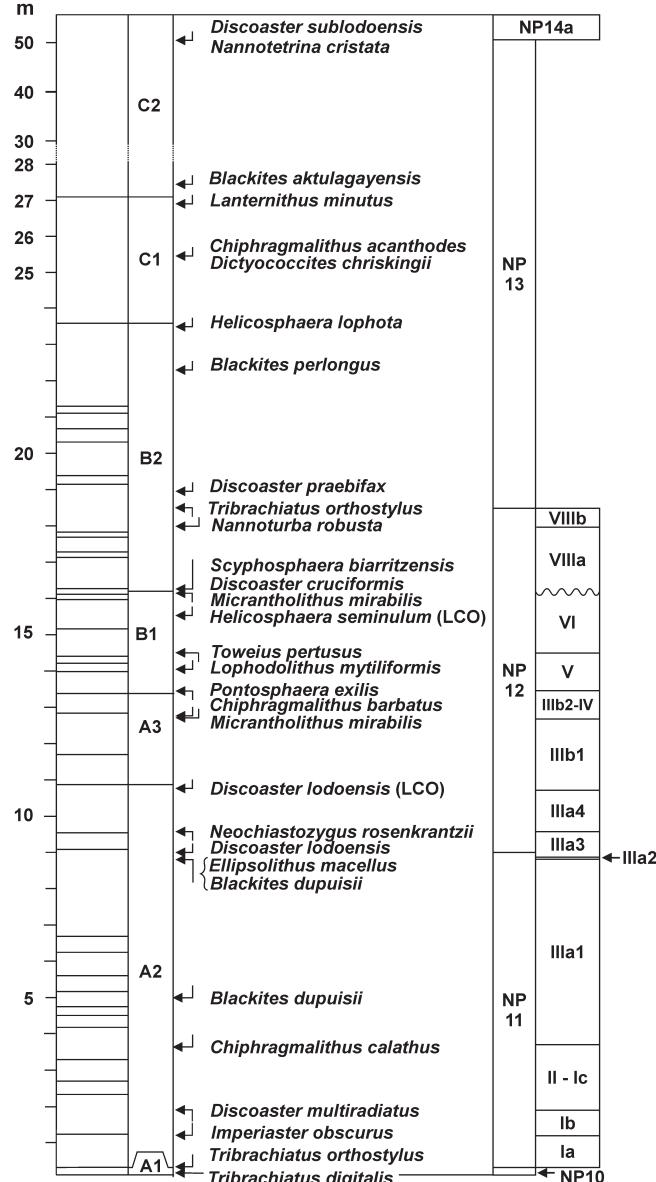
Unit C

The lowest 1.3m of Unit C is partially decalcified and marked by poorly preserved, very impoverished associations (~1 specimen/field of view). The overlying associations are substantially richer in specimens, although poorer than those from Unit B2 (< 10 versus > 25 specimens/field of view). Small to moderately-sized Prinsiaceae (*Toweius* spp. and *Reticulofenestra* sp.) dominate (35–55%). The associations are also characterised by the high proportions of *Pontosphaera* spp. (essentially *P. pulchra*) (15–25%) and the generally relatively low proportions of discoasters (mostly <2%). Associations from the upper 2/3 of Unit C2 (from 33.5m) essentially differ from those of C1 and the lower part of Unit C2 by the higher proportions of *Chiasmolithus* (from <1% to >5%), a cool-water taxon according to Wei and Wise (1990). The relatively high proportion of discoasters (14%, essentially *D. kuepperi*) in a single level at the base of Unit C2 (27.5m), is also noteworthy, as well as those of *Braarudosphaera bigelowii* (6%), *Zygrhablithus bijugatus* (6%) and *Lanternithus minutus* (6%) at 33.5m, indicating substantial paleoenvironmental changes within this unit.

Unit C1

The lowest carbonate-rich sample of Unit C1 (25.5m) is marked by the LO of *Chiphragmalithus acanthodes*, *Dictyococcites*

Fig A13



TEXT-FIGURE 16

Nannofossil events, Zones and Subzones. LCO: lowest consistent occurrence. LCO: lowest consistent occurrence. N.B.: Zonal boundaries are placed midway between sample positions.

chriskingii, *D. strictus*, *Nannoturba spinosa* and *Pemma* spp. (although the last are extremely rare). *C. acanthodes* has not yet been recognised in the North Sea Basin. In California its LO is coeval with or slightly earlier than that of *D. sublodoensis* (Bramlette and Sullivan 1961). The LO of *Blackites rugosus*, *Lanternithus minutus*, *Pontosphaera* sp. A and *Reticulofenestra* aff. *umbilica* is at the top of Unit C1 (26.9m). *L. minutus* appears much later in Belgium, within the middle of Zone NP14.

Unit C2

The LOs of *Blackites aktulagayensis*, *B. aff. gladius*, *Chiphragmalithus vandenberghaei*, *Discoaster barbadiensis* and *Pontosphaera megapachydisca* are at the base of Unit C2

(27.5m). There is also a major decrease (disappearance?) of *N. spinosa* at this level. The HO of *N. spinosa* occurs within the lower part of the Aalter Sand Formation in Belgium (upper NP13). The LO of *Toweius brusselensis* and *Discoaster boulangeri* is at 46.25m. A substantial diversity increase occurs at 50.8m, including the LO of *Discoaster sublodoensis* (a few specimens only), *Nannotetrina cristata* and *Cyclococcolithus* sp. 2, marking the base of Zone NP14. These events co-occur within the middle part of the Aalter Sand Formation at its type-locality in Belgium and in the Earmley Formation in the Hampshire Basin, where they also mark the base of NP14. The latter taxa are not recorded at higher levels in Unit C2; a similar temporary disappearance has also been identified in Belgium. *Chiphragmalithus acanthodes*, *Discoaster lodoensis*, *Ectalithus crassus* and *Dictyococcites chriskingii* seem to persist up to the top of Unit C2 (55.5m). *Toweius occultatus* probably also ranges up to the top, but is notably very rare in the uppermost 3m. The top of Unit C2 seems to be still within the lower part of Zone NP14, based on the persistence of *T. occultatus*, *D. lodoensis* and *D. cruciformis* (the latter may be reworked, inasmuch as its HO/LAD is normally in lower Zone NP13). The LO of *Blackites inflatus*, corresponding to the base of the Lutetian (Molina et al. 2011), has not been identified, and is presumably younger than the top of Unit C.

FORAMINIFERIDS

Samples of c. 50–200 grams for microfaunal analysis were dried at c. 80° C, disaggregated with hydrogen peroxide and washed on a 60 µm sieve. Approximately 60 samples were analysed. Calcitic microfossils (foraminiferids and ostracods) are common to abundant almost throughout the section, and generally very well-preserved, except for several thin non-calcareous intervals (< 1m) in Units B2 and C. Some of these non-calcareous intervals contain limonitic casts of foraminiferids, and are evidently secondarily decalcified. Foraminiferid abundance is high at most levels in Units A2, A3 and B2, with 10^3 – 10^4 specimens per 100 grams of sediment, but is significantly lower in Unit C.

Planktonic foraminiferids

Planktonics dominate the foraminiferid assemblages at almost all levels. P (percentage of planktonic foraminiferids in the 120–250 µm fraction; King 1989) is generally > 50%, rising to > 90% at some levels (text-fig. 17). Diversity is low; *Acarinina* is the dominant genus at most levels, comprising almost entirely long-ranging ‘globular-chambered’ taxa (see Berggren et al. 2006). Significant proportions of *Subbotina* and *Pseudohastigerina* are present at some levels. *Planorotalites* and *Globanomalina* occur in low proportions in most samples. *Morozovella* is very rare; only 10 specimens have been recorded in > 10^5 planktonics examined. A single specimen of *Igorina* has been recorded. Full taxonomic analysis has not been carried out at this stage, but some key species are cited here.

Planktonic foraminiferid zonation

The standard Soviet Union Paleogene planktonic foraminiferid zones were based on the lower-latitude and predominantly deep-water successions of the Caucasus and Crimea (see Berggren and Norris 1997 and references cited there). These zones have however very limited applicability in the higher-latitude and predominantly neritic Peri-Tethys, in which many of the zonal indicators are rare or absent. In the past these zones have however been applied in the Peri-Tethys, but mainly

through second-order (often inaccurate and misleading) calibration via benthic foraminiferid assemblages. A modified version for the eastern Pre-Caspian area was introduced by Naidin, Beniamovskii and Kopaevich (1994) (text-fig. 18), but this is difficult to apply at Aktulagay for similar reasons. Similarly, none of the events defining the standard low-latitude Eocene zones (Berggren and Pearson 2005) can be identified at Aktulagay, but some approximate calibration is possible by reference to other taxa. However, the ranges of individual taxa are likely to be constrained by environmental factors, and hence zonal boundaries are indefinite. Ranges cited here are taken from Pearson et al. (2006).

Unit A

Very low proportions of planktonics are represented in Unit A1 ($P < 10\%$). There is an abrupt increase in abundance (to $P > 70\%$) at the base of Unit A2. Very rare *Morozovella* gr. *aqua/subbotinae* are recorded between 1.9m–13.3m. These indicate Zone E5 or older (Pearson et al. 2006). There is an abrupt influx of *Subbotina* between 7.6m–9.9m. In this interval *Subbotina* comprises > 95% of the planktonic foraminiferid assemblage, compared with < 40% immediately below and above. The LO of *Pseudohastigerina wilcoxensis* is at 9.0m; it occurs consistently through the overlying Ypresian section. The FAD of *Pseudohastigerina wilcoxensis* in low latitudes is at the base of Zone E2 (Pearson et al. 2006) (corresponding to lower NP10). Its delayed LO in mid- and high latitudes was noted by Berggren et al. (1995, p. 152). In the North Sea Basin its LO is recorded much later, within Zone NP12, but interpreted as a synchronous datum within this area by King (1989) and Schmitz et al. (1996). Renewed study of the Albækholved section (Denmark) has, however, shown that here it appears earlier/lower in Zone NP12, although in very low numbers (C. King, personal observations). At Aktulagay its LO is close to the base of Zone NP12.

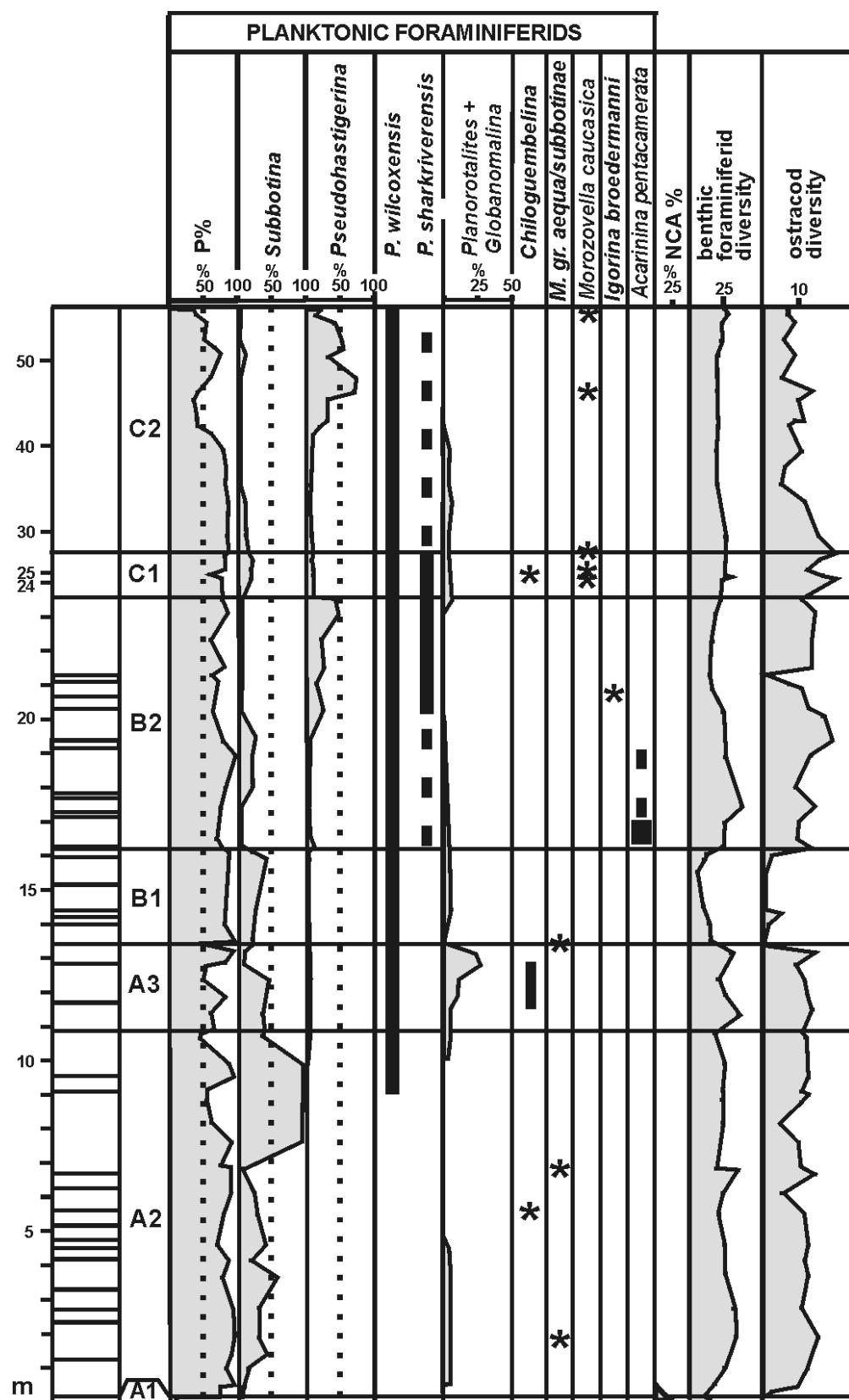
There is an influx of *Chiloguembelina* (in the <125 µm fraction) between 11.45m–12.8m, and a minor influx of *Planorotalites* (up to 20% of the assemblage) between 11.9m–13.25m.

Unit B

The LO of (rare) *Pseudohastigerina sharkriverensis* is at ~ 16.1m. It is common between ~ 20–26m. The LO of *P. sharkriverensis* in low latitudes is within Zone E7 (Pearson et al. 2006), corresponding to Zone NP13 or Subzone NP14a. In the North Sea Basin its LO is within Zone NP13 (C. King, personal observations). At Aktulagay specimens transitional between *wilcoxensis* and *sharkriverensis* appear at the base of Unit B2 (within Zone NP12), and fully developed *sharkriverensis* in the upper part of B2 (within Zone NP13). The LO of *Acarinina pentamerata* is at 16.55m. This indicates Zone E5 or younger/stratigraphically higher (Pearson et al., 2006). *Acarinina pentamerata* is common between 16.55m–17.0m, and occurs rarely at higher levels. There is a progressive increase in the relative abundance of *Pseudohastigerina* from ~ 20m to 23.5m (to a maximum of > 40% of the planktonic assemblage).

Unit C

A lone specimen of *Igorina broedermannii* is recorded at 25.1m. The LO of *Morozovella caucasica* is at 25.0m. Single specimens were recorded at higher levels, the highest at 55.5m. *Morozovella caucasica* ranges through Zones E6 and E7 and into Zone E8 (Pearson et al. 2006). There is an influx of



TEXT-FIGURE 1

Distribution and relative proportions of planktonic foraminiferids (plotted as percentage of planktonic population) and diversity of benthic microfauna (number of taxa/sample). Isolated records are shown by asterisks. The remaining (unplotted) planktonic foraminiferids are mostly *Acarinina* spp. *M.*: *Morozovella*. *P*: *Pseudohastigerina*.

Pseudohastigerina (to > 70% from baseline levels of <10%) between ~ 42m and the top of Unit C.

Non-calcareous agglutinating foraminiferids

In Unit A1 and the base of Unit A2, the proportion of non-calcareous agglutinants (NCAs; King 1989) is relatively high (15–25%). *Ammodiscus cretaceus*, *Glomospira charoides*, *Haplophragmoides walteri* and *Rhabdammina* spp. are dominant. Rare specimens of *Spirolectammina spectabilis* are recorded in Unit A1. At higher levels NCAs are very rare or absent (< 0.1% of the benthic assemblage), but two or three species are present in most samples from Unit A2, mainly *A. cretaceus* and *Rhabdammina* sp. (text-fig. 17).

Benthic foraminiferids (excluding NCAs)

Moderately diverse assemblages occur at most levels, typically comprising 20–30 taxa (text-fig. 17). Diversity is lowest in Units A1 and B1 (< 15 taxa). A total of ~ 120 taxa have been differentiated. A number of Eocene taxa described in Russian-language literature (often difficult to access) have their types from the Peri-Tethys. These publications date largely from the Soviet era, when direct comparison with Eocene taxa from western Europe was difficult, and it is clear that there is likely to be significant synonymy. Comparison is hindered by the lack of adequate photographic imagery for almost all these taxa. A systematic review and comparison of the faunas is necessary, but has not been possible for the present study; full taxonomic analysis is projected for the future. Here ‘western’ names have been used where identity seems probable, but this does not necessarily imply that these have priority. Taxa which occur commonly through most of the section include *Anomalinooides* spp., *Bulimina aksuatica*, *Euvigerina batjesi*, *Loxostomoides applinae*, *Oridorsalis* gr. *umbonatus*, *Sigmoilina* sp. and *Turritilina brevispira*. *Turritilina brevispira* occurs commonly and consistently through much of the section, but is entirely absent in the intervening intervals. This pattern of abrupt disappearance and reappearance, presumably related to environmental factors, has also been identified in the correlative interval in the North Sea Basin (C. King, unpublished data). *Cancris plana* occurs commonly and consistently through the interval 5.5m–31.5m. *Pulsiphonina prima* occurs consistently through Unit A. In Unit B1 and the lower part of Unit B2 in a proportion of the population the aperture develops a short neck with a phialine lip, the diagnostic character of *Siphonina* (Loeblich and Tappan 1988, p. 571). Other aspects of the morphology remain unchanged. From the upper part of Unit B2 and in Unit C, the *Siphonina* morphology occurs consistently. This appears to mark the evolution of *Siphonina* from *Pulsiphonina*; according to Loeblich and Tappan (1988, p. 571) *Pulsiphonina* ranges from Maastrichtian to Early Eocene, and *Siphonina* from Eocene to Recent. A similar and synchronous morphological change has been documented in the North Sea Basin (C. King, unpublished data). Key taxa are shown in text-fig. 19.

Benthic foraminiferid zonation

A benthic foraminiferid zonation for the Paleogene of the eastern Pre-Caspian area was introduced by Naidin, Beniamovskii and Kopaevich (1994) (text-fig. 18). These are essentially assemblage-zones, and their limits are probably not sharply defined (there is apparently no published record of the ranges of individual taxa in specific sections). The *Bifarina millepunctata* Zone can be identified by the occurrence of *Loxostomoides applinae* [= *B. millepunctata*] below the LO of *Bulimina*

mitgarziana. The *P. pseudonavarroana*-*B. mitgarziana* Zone can be identified by the range of *B. mitgarziana*. The *Hopkinsina bykovae* Zone is represented by the occurrence of *H. bykovae* (text-figs. 19, 23).

Unit A

A number of taxa are restricted to Unit A, including *Anomalinooides* gr. *grosserugosus*, *Gaudryina hiltermanni*, *Nuttallides truempyi* and *Osangularia expansa*.

Unit B

Many taxa disappear at the base of Unit B1, returning/reappearing at the base of Unit B2. *Bulimina mitgarziana* has a well-defined range from ~ 16.0m–29.5m. It is common to abundant in this interval. There is an influx of miliolids, including *Spiroloculina* and *Triloculina*, in the lower part of Unit B2 (16.2m–18.1m). Miliolids (apart from *Sigmoilina*) are almost absent at other levels. *Chilostomella* ranges consistently through a short interval in Unit B2 (17.4m–20.9m).

Unit C

Several taxa, including *Alabaminoides* sp., *Fursenkoina* sp., *Globobulimina* sp. and *Hopkinsina bykovae*, are restricted to Unit C. *Neoeponides karsteni* is represented by a single specimen from the top of Unit C (56.0m).

Comparison with the North Sea Basin composite zonation

Microfaunal zonations for the Cenozoic of the North Sea Basin based on benthic and planktonic foraminiferids (and diatoms), were introduced by King (1983) and upgraded by King (1989) (NSA, NSB and NSP Zones). These have now been fully revised and integrated into a single zonation (designated NS zones), calibrated in detail to the standard biostratigraphic scales (King, in press). The majority of the events defining zones or subzones were originally identified only in the North Sea Basin, and were assumed to largely reflect environmental changes consequent on opening/closing of oceanic connections and sea-level fluctuations, due to eustatic sea-level fluctuations or tectonic events, which would not necessarily be identifiable in other areas. However a closely similar series of events can be identified in the Early Eocene at Aktulagay. Precise synchrony of comparable events between these areas cannot be confirmed, but at least approximate synchrony is indicated in all cases by calibration with other biostratigraphic schemes.

The influx of *Subbotina* in the upper part of Unit A2 corresponds to a similar influx in the North Sea Basin (Zone NS16) (e.g. Schmitz et al. 1996). In both areas the influx begins in highest NP11 and ends within lowest NP12. Its occurrence elsewhere in Peri-Tethys is probable, but is so far undocumented.

The brief influx (major increase in abundance) of *Nuttallides truempyi* in the highest part of Unit A2 and the lowest part of Unit A3 corresponds to a similar event in bathyal environments in the North Sea Basin (e.g. Schmitz et al. 1996) (Subzone NS17b).

The LO of *Bulimina mitgarziana* (in the upper part of Unit B1 at Aktulagay) defines the base of Subzone NS18b in the North Sea Basin. This distinctive species was originally recorded from the North Sea Basin as *Bulimina* sp. A (King 1983, 1989; Schmitz et al. 1996), as it could not be confidently assigned to any described species, but comparison with near-topotype specimens of *B. mitgarziana* has confirmed their identity. *Bulimina*

		Caucasus-Crimea			eastern PreCaspian area (based on Naidin, Beniamovskii & Kopaevich 1994)		
LUT.				PF11	Acarinina bullbrooki	BF8	Hopkinsina bykovae - Uvigerina striata
YPIRESIAN	NP14	<i>Acarinina bullbrooki</i>		PF11	Acarinina bullbrooki	BF8	Hopkinsina bykovae - Uvigerina striata
	NP13	<i>Globorotalia aragonensis</i>	PF10		<i>Globigerina turgida-Globorotalia aragonensis</i>	BF7	<i>Heterolepa kasahstanica</i>
	NP12	<i>Globorotalia subbotinae</i>	PF9		<i>Globigerina pseudeocaena-Globorotalia lensiformis</i>	BF6	<i>Pseudogaudryina pseudonavarroana-Bulimina mitgarziana</i>
	NP11		PF8		<i>Globorotalia subbotinae</i>	BF5	<i>Bifarina millepunctata</i>
	NP10					BF4	<i>Pseudogaudryina externa</i>

TEXT-FIGURE 18

Planktonic and benthic foraminiferid zonations previously applied to the eastern Pre-Caspian area. The *G. aragonensis* Zone was formerly the *G. crassaformis* Zone.

mitgarziana has been recorded widely in outer neritic-upper bathyal environments in the Peritethys (including NW Kazakhstan and central Uzbekistan) and in the Caucasus. Where calibrated elsewhere in this area with nannofossil zones (e.g. Oberhansli and Beniamovskiy 2000) it has a short range from upper Zone NP12 to lower Zone NP13, as at Aktulagay. The HO of *B. mitgarziana* defines the top of Subzone NS18b. The HO of *Cancris plana* corresponds to this event, both at Aktulagay and in the North Sea Basin (where originally differentiated as *Cancris* sp. A: King 1983, King 1989, Schmitz et al. 1996). This species (kindly identified for us by V. Benyamovsky, Russian Academy of Sciences, Moscow, Russia) also was originally described from the Peri-Tethys and adjacent areas.

An influx of *Pseudohastigerina* characterizes the base of Zone NS20 in the North Sea Basin. This event appears to correlate with the influx of *Pseudohastigerina* within Unit C2 at Aktulagay.

These correlations, similar correlations based on dinoflagellate cysts and nannofossils cited above, and their significance, will be discussed further in a later publication.

OSTRACODS

Ostracods are represented consistently and often commonly through much of the section, although with much lower abundance than the benthic foraminiferids. Diversity is moderate, on average 10-15 taxa per sample (text-fig. 17). A total of ~ 40 taxa are represented. As for the benthic foraminiferids, many taxa have been described in the Russian-language literature, but it is clear that the majority of the taxa represented are probably identical or closely related to taxa of the same age in western Europe. *Acanthocythereis spiniferrima*, *Cytherella londinensis*, *Cytheropteron brimptoni*, *Krithe londinensis* and *Trachycy-*

leberidea prestwichiana occur through most of the section. Other features of the assemblage are as follows (text-fig. 19):

Unit A1

Ostracods are almost absent in Unit A1.

Units A2 and A3

Ostracods occur commonly from the base of Unit A2. Several taxa are restricted to Units A2 and A3, including *Bairdoppilata* sp., *Pterygocythere cf. hilli* and '*Trachyleberis*'*bowerbankiana*. The LO of *Echinocythereis* sp. is at 3.7m and the LO of *Eopaijenborchella* gr. *eocaenica* a is at ~ 5.6m. Both taxa occur consistently and often commonly through the overlying Ypresian section.

Unit B

There is an abrupt decrease in diversity at the base of Unit B1. Ostracods are rare in B1, entirely absent in some samples. Diversity and abundance return to previous levels at the base of Unit B2.

The LO of *Eopaijenborchella* gr. *aspera* is at the base of Unit B2. The LO of consistent *Cytheridea newburyensis* is in the upper part of B2.

Unit C

There is no significant change in the ostracod assemblage at the base of Unit C. *Eopaijenborchella* gr. *aspera* and *Cytheridea newburyensis* are common.

PTEROPODS

Very poorly preserved, specifically indeterminate pteropods occur sporadically through Units A, B1 and C. A single well-preserved limonite mould was recorded from Unit B1. In Unit B2 pteropods are relatively common (up to 10 specimens per 100 gram of sediment), preserved as partially crushed limonitic

TABLE 1

Distribution of sharks and rays in the Aktulagay section, with numbers of specimens collected. For collection levels see text-fig. 20. Asterisks indicate specimens seen in other collections, with level inferred by their preservation.

Species	Level	0	1	2	3	4	5	6
<i>Hexanchus agassizi</i> Cappetta 1976				2	1		1	
<i>Xiphodolamia ensis</i> (Woodward 1889)			32	28	20	11	17	2
<i>Carcharias</i> sp.		2	3	1	1			
<i>Striatolamia striata</i> (Winkler 1874)		2						
<i>Anomotodon</i> sp.		2						1
<i>Hypotodus verticalis</i> (Agassiz 1843)			1			1		
<i>Jaekelotodus</i> sp. *			2*	1				
<i>Cretalamna</i> sp.			8	4			1	
<i>Isurolamna affinis</i> (Leriche 1905)			6	2	1	1		
<i>Otodus (Otodus) obliquus</i> Agassiz 1843	5	22	17					
<i>Otodus (Carcharocles) aksuaticus</i> (Menner 1928)				16	11			
<i>Otodus (C.) auriculatus</i> (Blainville 1818)						13	4	
<i>Trigonotodus tusbaericus</i> Kozlov 1999 *			2*					
<i>Parotodus pavlovi</i> (Menner 1928)	1	12	7	3	1	2	1	
<i>Macrorhizodus nolfi</i> Zhelezko 1990			3		2	6	8	
<i>Alopias</i> or <i>Usakias</i> sp. *			1*					
<i>Physogaleus secundus</i> (Winkler 1874)			12	4		2	1	1
" <i>Myliobatis</i> " <i>raouxi</i> Arambourg 1952			8	5	2	1		

moulds, and have also been recovered as crushed 'chalky' aragonitic shells by surface collecting. They include *Limacina* spp., *Camptoceratops priscus* and *Creseidae*. These are apparently the first records of Early Eocene pteropods from Kazakhstan (text-fig. 19). The identifiable records and their biostratigraphic significance are summarised here.

Pteropod zonation

A pteropod zonation for the Eocene to Pliocene of the North Sea Basin was introduced by Janssen and King (1988). This reinforced the conclusions of the pioneer study by Curry (1965) that many pteropod taxa are short-ranging and have a wide geographic distribution. Further studies have confirmed these characteristics and enabled this zonation to be extended to other areas (e.g. Cahuzac and Janssen 2010). Some Eocene zones can be recognised in Uzbekistan (Janssen, King and Steurbaut 2011), and are here applied to the Aktulagay section. Pteropod identifications were verified by A. W. Janssen (Netherlands Centre for Biodiversity, Palaeontology Department, Leiden), and the specimens are in their collections (registered as RGM 570.579–570.592). Only small samples were available for this study; it is probable that analysis of larger samples would extend and enhance the limited data presented here.

Unit B1

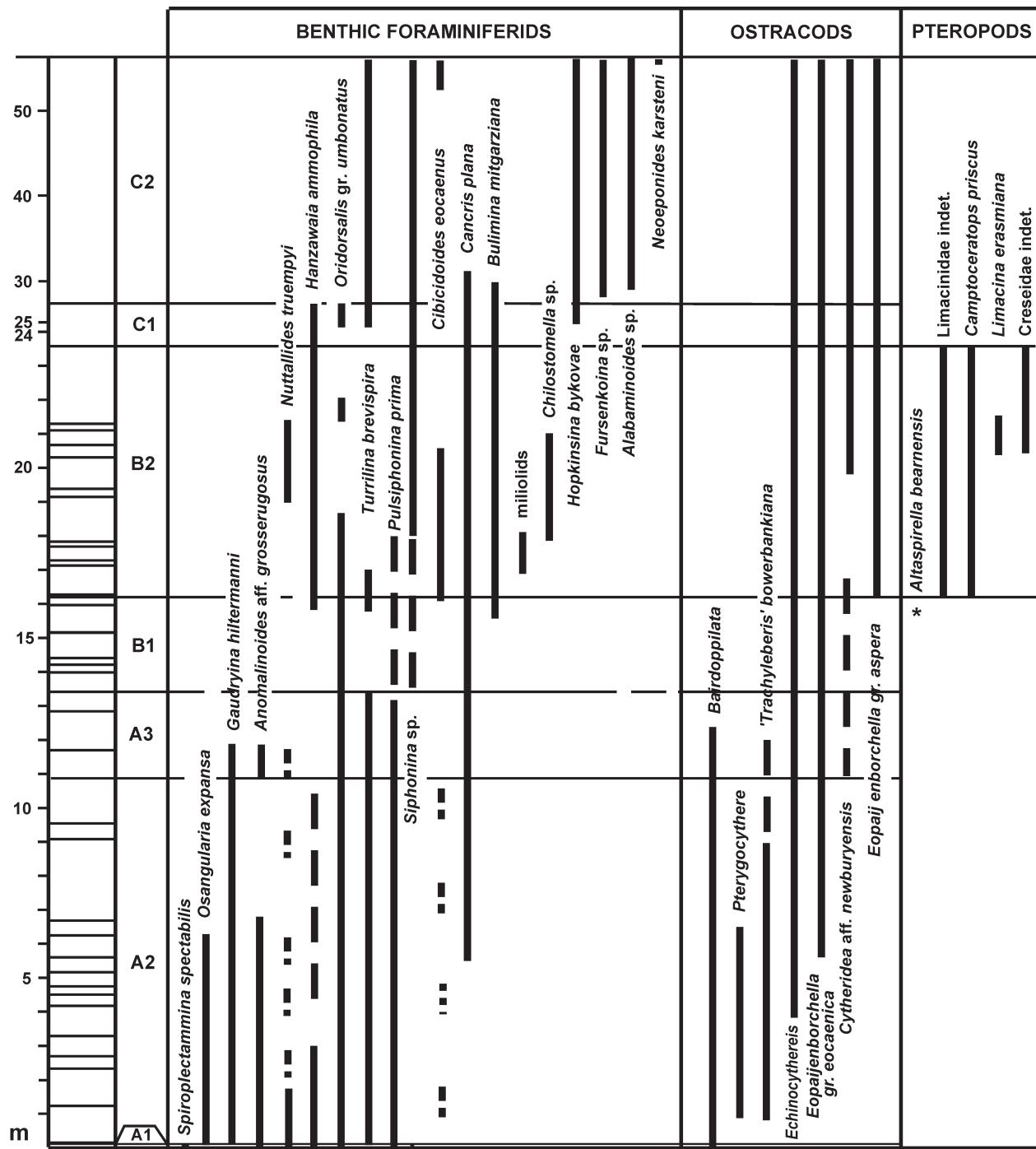
A single specimen of *Altaspirella bearnensis* is recorded near the top of Unit B1 (~15.95m), in upper NP12. *A. bearnensis* was originally described from the Ypresian of Gan (Aquitaine Basin) (Curry 1982; Cahuzac and Janssen 2010) (upper Zone NP12/lower NP13; Steurbaut and Sztrákos 2002), in Pteropod Zone 9. It was subsequently recorded from the London Clay

Formation of the London Basin. Here it occurs commonly in a thin interval in the lower part of Division E (middle NP12) (Cahuzac and Janssen 2010; unpublished data), in the upper part of Pteropod Zone 8.

Unit B2

Camptoceratops priscus ranges throughout Unit B2. The LO of *Camptoceratops* defines the base of Pteropod Zone 9, and the top of this zone has recently been redefined at the HO of *Camptoceratops* (Janssen, King and Steurbaut 2011). *Camptoceratops* is a very short-ranging genus, widespread in the southern North Sea Basin, also recorded in the Aquitaine Basin, the USA Gulf Coast (Cahuzac and Janssen 2010) and in Uzbekistan (Janssen, King and Steurbaut 2011), within upper Zone NP12 and lower Zone NP13. This is consistent with its range at Aktulagay.

Poorly preserved pteropods of the family *Creseidae* are recorded through the upper part of Unit B2 (20.25m–23.50m); they are abundant at ~20.9m. These cannot be definitely identified at generic level, but the only Early Eocene genus of *Creseidae* so far known is *Euchilotheca*. The LO of *Euchilotheca* was calibrated by Janssen and King (1988) with the base of Pteropod Zone 9, but in the North Sea Basin it is within Zone NP13, consistently at a higher level than the LO of *Camptoceratops*. In the North Sea Basin the ranges of these taxa overlap within Zone NP13. This overlap is also represented in the Aquitaine Basin (Cahuzac and Janssen 2010) within Zones NP12/NP13, and in Uzbekistan (Janssen, King and Steurbaut 2011) in Zone NP13, and is also represented at Aktulagay. Janssen and King (1988, p. 359) and King (1990) suggested that



TEXT-FIGURE 19
Ranges of selected benthic foraminiferids, ostracods and pteropods.

Pteropod Zone 9 could eventually be subdivided, and the additional data confirm this. Pteropod Zone 9 is therefore here formally subdivided into Subzones 9a and 9b. The base of Subzone 9b is defined at the LO of *Euchilotheeca*; Subzone 9b corresponds to the ‘overlap interval’ of *Campioceratops* and *Euchilotheeca*. Thus at Aktulagay Subzone 9a is represented in the lower half of Unit B2, and Subzone 9b probably in the upper half (text-figs 20, 23).

Limacina erasmiana is recorded at 20.37m and 21.50m. This species has only recently been described, from the North Sea Basin and Uzbekistan (Janssen, King and Steurbaut 2011). All calibrated records are from Zone NP13.

Unit C

Pteropods are much rarer and very poorly preserved in Unit C. Single specimens of low-spired Limacinidae, too poorly pre-

served to identify specifically, occur at several levels within Unit C2.

SHARKS AND RAYS

Well-preserved shark teeth occur commonly *ex situ* on the surface of the outcrop. Only a few were collected *in situ*, and bulk sampling and processing of the sediments was not practicable. Although teeth occur at almost all levels, they appear to be most frequent at six levels in Units B1 and B2. For field-collecting purposes these were designated Levels 1 to 6. Their relationship with the measured section is shown in text-fig. 20. Level 0 equates to the light-coloured marls of Unit A. Surface-collected teeth may clearly have been displaced downslope, but the clear differences in the *Otodus* assemblages from different levels (Table 1) indicate that they can be regarded as essentially *in-situ* faunas. Previous records of sharks from this section are cited by Zhelezko and Kozlov (1999).

The shark fauna is highly unusual in being dominated by large lamniform sharks. The only exceptions are a sixgill shark (*Hexanchus*), the carcharhiniform shark *Physogaleus* and a myliobatid ray. These three taxa are common in silty clay deposits of similar age such as the mid-Ypresian London Clay Formation (Caser 1966). No purely benthic species of rays or sharks were encountered, including the usually very common shark *Abdounia*. Although the possibility of this being a collecting artefact exists, it is more likely that dysoxic/anoxic bottom conditions discouraged small bottom-feeding sharks and rays, as well as their prey. Dental plates of the myliobatid "Myliobatis" *raouxi* bear a series of longitudinally direct striae, and have not been observed having the wear facets more typical of bottom-feeding rays (text-fig. 21: 16–18). It is likely that this species was a mid-water suction feeder or planktivore, not restricted to hard-shelled benthic prey as for typical myliobatids.

The most noticeable feature of the shark assemblage is its domination by *Xiphodolamia* and members of the *Otodus* lineage, which together account for two thirds of the specimens collected. *Xiphodolamia* is usually encountered in moderately deep high-productivity environments. It possesses very specialised dentition (Admet et al. 2009). As the tooth crowns rarely display wear facets, its preferred diet was probably composed of soft-bodied organisms such as cephalopods. *Otodus* was however an apex predator, and had a sufficiently robust dentition to tackle a variety of large prey.

It has been accepted that the lineage formally known as *Carcharocles* (or erroneously *Carcharodon*) was derived from *Otodus* by the acquisition of a serrated cutting edges on the teeth (Caser 1960; Zhelezko and Kozlov 1999, pls 25–27). The degree of serration of the tooth crowns of *Otodus* collected in successive levels at Aktulagay increases progressively from typically unserrated *Otodus* (*Otodus*) *obliquus* to fully serrated *Otodus* (*Carcharocles*) *auriculatus* (text-figs 20, 22). Those from Level 1 are unserrated and are referred to *Otodus* (*Otodus*) *obliquus*. Those from Level 2 could reasonably be referred to either *O.* (*O.*) *obliquus* or *O.* (*C.*) *aksuaticus*, but because some show very faint serration they are referred to *O.* (*C.*) *aksuaticus*. Those from levels 3 to 5 have fine serrae consistent with *Otodus* (*Carcharocles*) *aksuaticus*. Teeth from Level 6 possess fairly heavy and more regular serrae and are referred to *O.* (*C.*) *auriculatus*, although in this species the lateral cusps are typically more crenulated. This has been partially documented in other areas (Caser 1950) but this is the first time it has been ob-

served in a single well-dated continuous section, and is of obvious biostratigraphic importance. At Aktulagay the transition from the species *O. obliquus* (Thanetian to mid Ypresian) to *O. aksuaticus* takes place within the highest part of Zone NP12, and the transition from *O. aksuaticus* to *O. auriculatus* is within the lowest part of Zone NP13. Zhelezko and Kozlov (1999, p. 184, fig. 32) placed the lowest 9 m of the Ypresian section at Aktulagay in their Zone E8 (*Otodus aksuaticus* Zone).

The holotype of *O. aksuaticus* is from near the Aksuat well, on the Embi river ~ 50 km south of Aktulagay. The figured teeth from Aksuat (Menner 1928, pl. 11, figs 8–11) include a range of degrees of serration, and are most likely to have come from more than one stratigraphic level. The presumed holotype (Menner 1928, pl. 11, fig. 8) displays a degree of serration comparable with teeth found in levels 4 and 5 at Aktulagay.

In conclusion, the shark and ray fauna in Unit B indicates a moderately deep-water, high productivity open water environment with little or no benthos. The precise levels from which the assemblages originate are however difficult to identify. The collecting levels however correspond closely to the light brown 'shaly' clays (text-fig. 20), strongly suggesting that they originate from these units. This is substantiated by the dominance of the high-productivity *Xiphodolamia* and the absence of benthic taxa (see below).

OTHER FOSSIL GROUPS

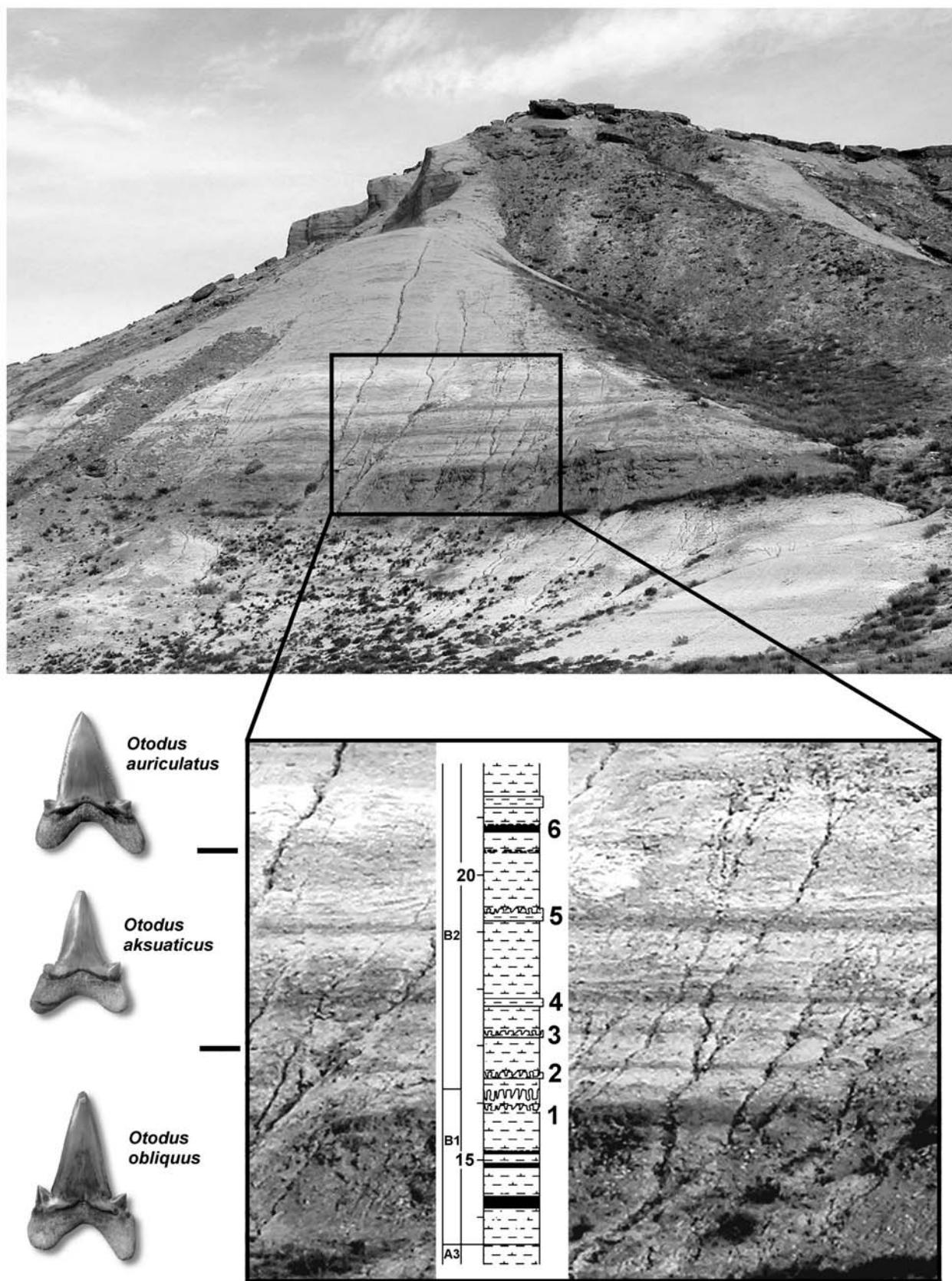
Aragonitic shells of benthic molluscs are represented only by dispersed compressed limonitic moulds, except in Unit A3 and the marly clays of Unit B2, where poorly preserved partly decalcified 'chalky' shells are present at some levels. These include common corbulid bivalves and a volutid gastropod. A venericardiid mould was seen in Unit D2. A single limonitic mould of the nautiloid *Aturia* was found on the surface of Unit B2 (text-fig. 21V).

Echinoid debris occurs consistently throughout Units A, B and C; ophiuroid and holothuroid debris is more restricted in distribution. The bryozoan *Dittosaria* occurs in one sample in Unit C. The problematic microfossil *Voorthuyseniella* occurs in several samples from Unit B2. Poorly preserved limonitic casts of radiolaria are frequent at the base of Unit D2. Fish debris (bones and scales) is present at many levels in the micropaleontological samples processed. Numerous disarticulated teleost (bony fish) remains, principally vertebrae, teeth and fin spines, are also visible on the surface of the outcrop. Some vertebrae collected exceed 4 cm in length, indicating a fish more than 2 m in length.

BIOSTRATIGRAPHIC SUMMARY

The detailed calibration between multiple biostratigraphic schemes which has been possible in the Aktulagay section serves as a template for the better integration and interpretation of Ypresian biostratigraphy, particularly in northern mid-latitude areas, including the North Sea Basin. The biostratigraphic results are summarised in text-fig. 23. Key features are as follows:

Unit A1: Subzone Zone NP10b; probably *D. oebrisfeldensis* acme interval. This is apparently the first section in which a diagnostic nannofossil assemblage has been recorded from the *D. oebrisfeldensis* acme interval. The former presence in the area of lowest Ypresian sediments (corresponding to the PETM) is indicated by reworked nannofossils in the base of Unit A2. A hiatus



TEXT-FIGURE 20

Levels from which shark and ray teeth were collected (levels 1-6, see Table 1), calibrated to the succession in Unit B. The intervals with successive *Otodus* species are indicated.

between Units A1 and A2 is indicated by the absence of upper Zone NP10 and the corresponding *W. astra* and *W. meckelfeldensis* dinocyst Zones, and by the intense reworking of nannofossils at the base of Unit A2.

Unit A2: Zone NP11 and lower Zone NP12; *D. simile*, *E. ursulae* and *D. varielongitudum* Zones.

Interpretation of the age of the basal sample is complicated by intense reworking. However, the few specimens of *Tribrachiatus orthostylus* (see above) indicate Zone NP11. The identification of almost all the nannofossil subzones identified in the much more expanded succession in the North Sea Basin indicates that there are no significant hiatuses in this interval.

Unit A3: NP12; *D. varielongitudum* Zone and basal *C. coleothypta* Zone.

Unit B1: Upper Zone NP12; *C. coleothypta* Zone. A minor hiatus between Units A3 and B1 may be indicated by the absence of nannofossil Subzone IV (or this interval may be too condensed at Aktulagay to be differentiated).

Unit B2: Upper Zone NP12–lower Zone NP13; *C. coleothypta* and *A. diktyoplakum* Zones.

The base of B2 is a deeply interburrowed omission surface. This corresponds to a significant break in the nannofossil succession, and a coincidence of the LO of *Ochetodinium romanum* and *Samlandia chlamydophora*, as noted above, indicating a hiatus with a duration of ~ 55 ky.

Unit C1: Zone NP13; *A. diktyoplakum* Zone. There is no evidence for a hiatus at the base of Unit C.

Unit C2: Zone NP13 and basal Zone NP14; *A. dictyoplakum* and basal *W.eocenica* [*D. pachydermum*] Zones. The

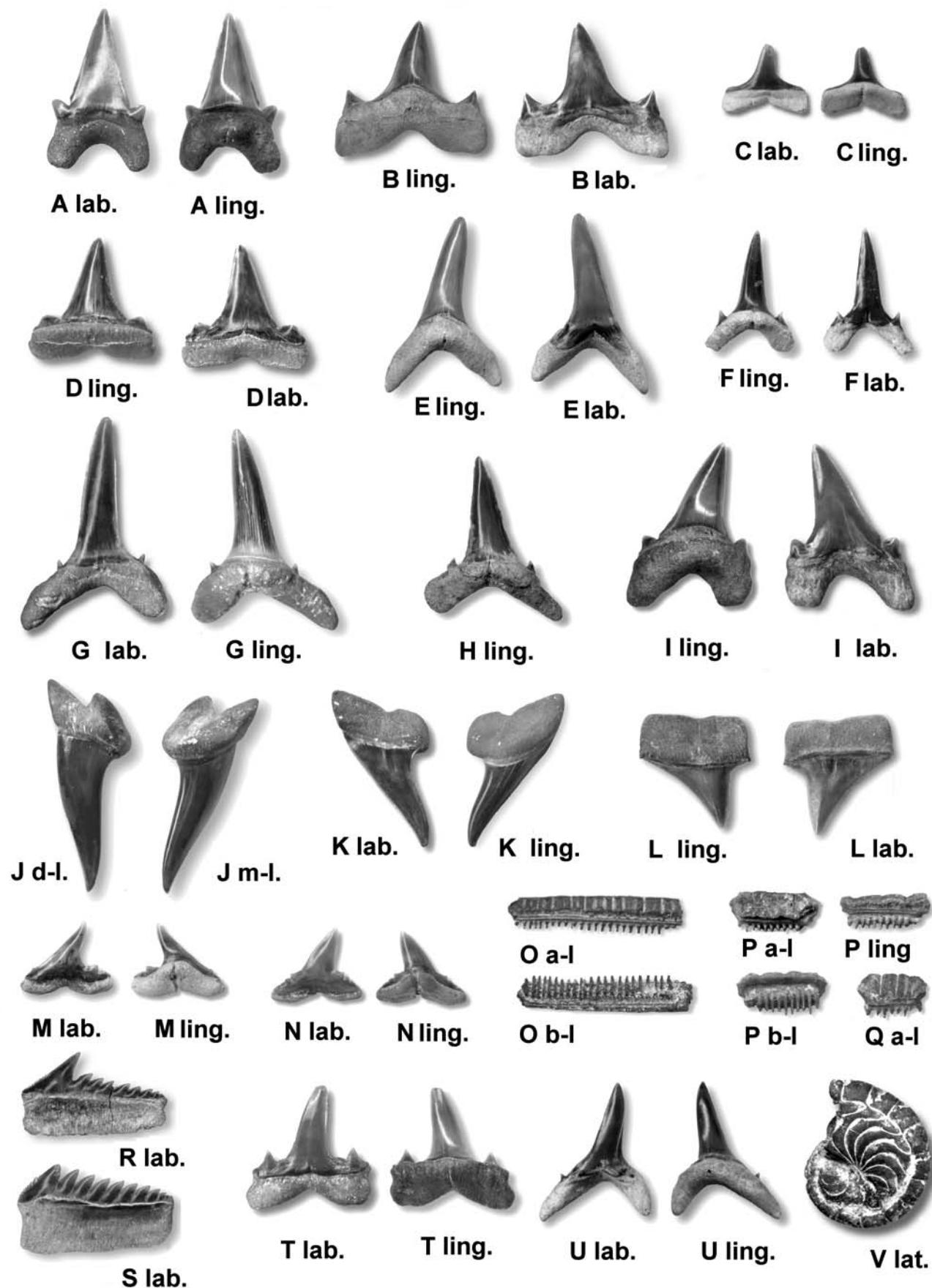
TEXT-FIGURE 21

Shark and ray teeth and nautiloid from Unit B (Aktulagay Formation) at Aktulagay.

Abbreviations: baso-labial view: lab. labial view; ling, lingual view; d-l, disto-labial view; m-l, mesio-lingual view; a-l, apico-lingual view; b-l, baso-labial view; lat, lateral view.

All the specimens in Text-Figures 21 and 22 are been deposited in the collections of the Natural History Museum, London, UK (NHMUK), whose registration numbers are cited.

- 1a,1b *Cretalamna* sp. (NHMUK P.73011), ?left first upper anterior tooth; level 1; ×1.5.
- 2a,2b *Cretalamna* sp. (NHMUK P.73012), right lower lateral tooth; level 1; ×1.5.
- 3a,3b *Anomotodon* sp. (NHMUK P.73013), right upper lateral tooth; level 0; ×2.0.
- 4a,4b *Macrorhizodus nolfi* (NHMUK P.73014), left upper lateral tooth; level 1; ×1.5.
- 5a,5b *Macrorhizodus nolfi* (NHMUK P.73015), right second upper anterior tooth; level 1; x1.5.
- 6a,6b *Carcharias* sp. (NHMUK P.73016), right third lower anterior tooth; level 2; x2.0.
- 7a,7b *Striatolamia macrota* (NHMUK P.73017), left, third lower anterior tooth; level 1; ×1.5.
- 8 *Hypotodus verticalis* (NHMUK P.73018), left second upper anterior tooth; level 1; ×1.5.
- 9a,9b *Parotodus pavlovi* (NHMUK P.73019), ? right second lower anterior tooth; level 1; ×1.5.
- 10a,10b *Xiphodolamia ensis* (NHMUK P.73020), right first lower anterior tooth level 1; ×1.5.
- 11a,11b *Xiphodolamia ensis* (NHMUK P.73021), ? left first upper lateral tooth; level 1; ×1.5.
- 12a,12b *Xiphodolamia ensis* (NHMUK Px.73022), lateral tooth; level 1; ×1.5.
- 13a,13b *Physogaleus secundus* (NHMUK P.73023), ? left lower anterior tooth; level 1; ×2.0.
- 14a,14b *Physogaleus secundus* (NHMUK P.73024), ? Right anterior tooth; level 1; ×2.0.
- 15a,15b “*Myliobatis*” *raouxi* (NHMUK P.73025), incomplete median tooth row; level 1; ×2.0.
- 16a-c “*Myliobatis*” *raouxi* (NHMUK P.73026), ? first lateral tooth row; level 1; ×2.0.
- 17 “*Myliobatis*” *raouxi* (NHMUK P.73027), ? second lateral tooth row; level 1; ×2.0.
- 18 *Hexanchus agassizi* (NHMUK P.73028), left lower antero-lateral tooth of mature male; level 1; ×2.0.
- 19 *Hexanchus agassizi* (NHMUK P.73029), left lower antero-lateral tooth of mature female; level 1; ×2.0.
- 20a,20b *Isurolamna affinis* (NHMUK P.73030), left lower lateral tooth; level 1; ×2.0.
- 21a,21b *Isurolamna affinis* (NHMUK P.73031), right ? second upper tooth; level 1; ×2.0.
- 22 *Aturia* sp : internal mould in limonite (NHMUK PAL CN127), level 1; ×2.0.



Ypresian/Lutetian boundary is now formally defined in the Gorrondatxe section (NW Spain) at the meter 167.85 level of the Gorrondatxe section in a dark marly level where the nannofossil Blackites inflatus has its LO (base of Subzone NP14b) (Molina et al. 2011). The top of Unit C2 is therefore within the latest Ypresian.

Unit D: There is a major hiatus at the base of Unit D, corresponding approximately to the Lutetian (~ 7 myr, on the scale of Luterbacher et al. 2004). The dinocyst assemblage at the base of Unit D indicates a latest Lutetian or early Bartonian age.

DEPOSITIONAL ENVIRONMENTS

The overall regional context of the Aktulagay section (text-figs 2, 3, 6) indicates a predominantly mid- to outer neritic environment. The nearest land area in the Early Eocene was probably the SE end of the Urals fold belt, c. 200km to the E/NE, interpreted as either an island or a prolongation of the East European Platform (compare text-figs 2 and 3). Regional paleogeographic interpretations (text-fig. 3) also indicate that neritic to upper bathyal water depths extended a long distance from the presumed coastline. This implies a ramp-type setting with a very low depositional gradient. Sediments in the lower part of the section are hemipelagic, becoming dominantly clastic in the upper part. Palynomorphs and palynofacies indicate a fully marine environment throughout, with very limited terrestrial influx in Unit A, increasing at higher levels. The open-marine *Spiniferites* group is predominant in Units A2, A3 and B (text-fig. 13). The nannofossil associations also point to fully marine environments, although episodically interrupted by shifts to more near-shore/hypsosaline depositional conditions. These probable shallowing events are evidenced by higher frequencies or blooms of *Micrantholithus* (in the lowest part of Unit A2 and in the lower half of unit B1 respectively) or by the high numbers of *Pontosphaera* spp. (between 15% and 23%) (base of Unit B2 onward). A slight reduction in paleosalinity may have occurred within the middle of B2 (top Zone NP12–base Zone NP 13), as shown by the increase of *Braarudosphaera bigelowii* (up to 5%).

The relatively high proportions of planktonic foraminiferids indicate open access to oceanic circulation at almost all levels (except in Unit A1), and on the basis of the results of Gibson (1989) and Nigam and Henriques (1992) would indicate depths of > 100 m almost throughout the section. The highest proportions (= 90%) suggest depths of > 200 m (upper bathyal). The planktonic foraminiferids are predominantly taxa interpreted as characteristic of shallow mixed-layer environments (*Acarinina*, *Pseudohastigerina* and *Planorotalites*) (Pearson et al. 2006) (although no isotopic data is available for the *Pseudohastigerina* species represented here). Intervals with high proportions of *Pseudohastigerina* correlate well with relatively low proportions of planktonic foraminiferids (text-fig.

17), suggesting that they represent the shallowest water depths. The exception is the thermocline and sub-thermocline dweller *Subbotina*, which comprises up to 50% of the assemblage through Units A2 and A3, probably indicating the greatest water depths in the section. The major *Subbotina* influx in the upper part of Unit A3 (to $> 90\%$ of the planktonic assemblage) however is not reflected by any other indicators of significantly increased water depth; this is discussed below. The corresponding *Subbotina* influx in the North Sea Basin has similar characteristics. The rarity of *Morozovella* and the absence of angular-chambered *Acarinina*, both warm-water taxa (Pearson et al. 2006), is characteristic of this area generally, and may reflect proximity to the Turgay Strait, which forms a connection to the Arctic Ocean (text-fig. 3).

The benthic foraminiferid assemblage in most intervals is comparable to the outer neritic ‘Midway-type’ assemblage of the Paleocene, interpreted as indicating water depths of 50–200m (Van Morkhoven, Berggren and Edwards 1986), with taxa such as *Lenticulina* spp., large nodosariids, *Loxostomoides applinae*, *Osangularia expansa*, large buliminids, *Alabamina*, *Anomalinoides nobilis* and *A. acutus*. Taxa with their shallowest common occurrence in outer neritic environments include *Gaudryina hiltermanni*, *Hanzawaia ammophila* and *Turrilina brevispira* (Van Morkhoven, Berggren and Edwards 1986; unpublished data). However some characteristically bathyal taxa, including *Aragonina aragonensis* and *Nuttalides truempyi*, are common at some levels, probably indicating water depths of > 200 m. These features are consistent with the conclusions based on planktonic foraminiferids. Upper depth limits for specific taxa cited by Van Morkhoven, Berggren and Edwards (1986) are however not always in agreement with later studies (e.g. see comments in Molina et al. 2006), and cannot be applied in all contexts. Detailed analysis of the benthic foraminiferid assemblages and their environmental implications will be published elsewhere.

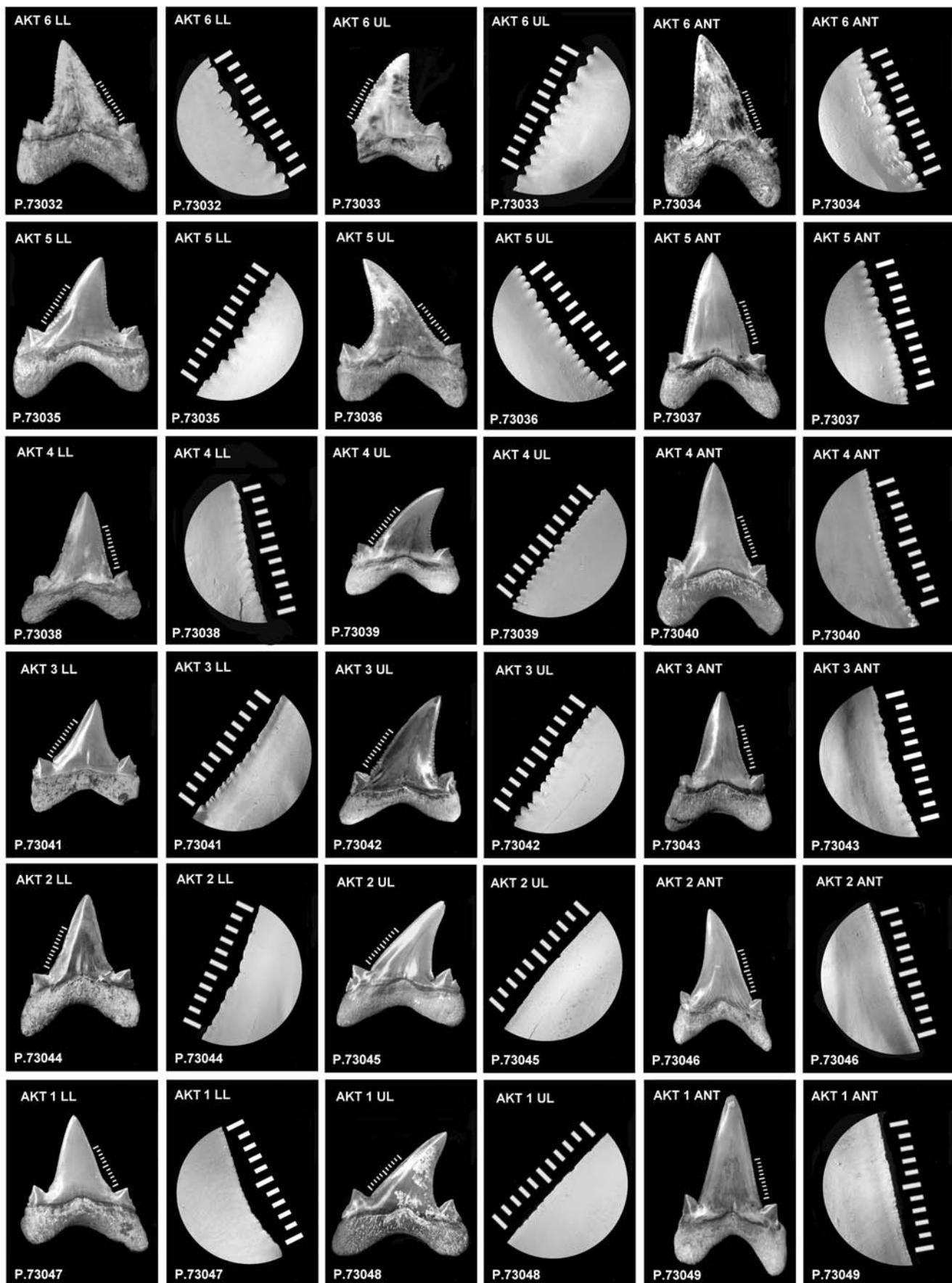
DEPOSITIONAL SEQUENCES

Identification of the key surfaces and trends comprising a sequence stratigraphic model is a difficult task in mid/outer neritic contexts in which sedimentation rates are low and terrestrial input is limited. Only major environmental shifts are likely to be reflected in this relatively distal environment. Adequate sequence stratigraphic analysis in such a context requires calibration to more proximal environments in the same area, in which sea-level fluctuations may be reflected by significant facies shifts. This is not currently possible in the Pre-Caspian area, as only limited information is available on more proximal sections. The interpretation here is based on the following criteria:

1. Relative pelagic/clastic ratios reflect relative water depths. This is supported by the general regional southward (distal) trend from dominantly clastic to dominantly carbonate facies (text-figs 2, 6).

TEXT-FIGURE 22

Teeth of the *Otodus* lineage from Unit B (Aktulagay Formation) at Aktulagay. From each collecting level (1–6), anterior (ANT), upper lateral (UL) and lower lateral (LL) teeth are figured. A progressive increase in the degree of serration occurs between levels 1 and 6.



2. Abrupt lithological shifts accompanied by decrease in water depth, deduced from lithological and/or paleontological criteria, indicate sequence boundaries. Highest proportions of planktonic foraminiferids probably indicate a maximum flooding surface (MFS).

3. Progressively decreasing proportions of planktonic foraminiferids or increasing proportions of shallow-water planktonic or benthic foraminiferids indicate highstand systems tracts.

These factors, together with sedimentological criteria discussed below, are used to construct a tentative sequence stratigraphy (text-fig. 24).

Unit A1

This interval is characterised by high proportions of *Spiniferites*, low-diversity benthic foraminiferids and ostracods, low proportions of planktonic foraminiferids, but relatively high proportions of ‘deep-water’ non-calcareous agglutinating foraminiferids. The benthic foraminiferids are characterised by common *Nuttallides truempyi*. The benthic foraminiferids suggest a deeper and somewhat more restricted environment than overlying units, probably upper bathyal. The surprisingly low proportion of planktonic foraminiferids may indicate limited access to oceanic watermasses. At this time, relatively restricted environments are characteristic of many non-oceanic areas in northern mid-latitudes (e.g. the North Sea Basin), in both shallow- and deep-water environments, probably reflecting low eustatic sea levels, with deep-water areas probably reflecting tectonically-controlled basinal subsidence.

Units A2 and A3

A hiatus between Units A1 and A2 is identified biostratigraphically. This hiatus, together with concentration of phosphate at the base of Unit A2, associated with high proportions of reworked nannofossils, indicates that this probably represents a sequence boundary. The major increase in the proportion of planktonic foraminiferids, with reworking of Thanetian sediments, indicates that this coincides with a transgressive surface. Both nannofossils and dinocysts indicate deepening within the lower part of A2. The highest proportion of planktonic foraminiferids in the Ypresian section (94 %) is ~0.5m above the base of A2. Upper bathyal water depths seem probable, but this is at variance with the relatively high proportions of *Micrantholithus* and the dominance of *Areoligera* at similar levels. Foraminiferid assemblages indicate outer neritic-upper bathyal depths through Unit A2. Progressively decreasing proportions of *Areoligera* up to ~7m (text-fig. 13) suggest deepening. The maximum flooding surface (MFS) is tentatively taken at ~7m, based on this and on a major influx of *Spiniferites* at this level (~80 % of the dinocyst assemblage; text-fig. 13). This is supported by a progressive but irregular decrease in the proportion of planktonic foraminiferids from about this level. Comparison with the benthic foraminiferid and ostracod assemblages in the coeval London Clay Formation of southern England (unpublished data), which has a number of taxa in common with Aktulagay, also indicates shallowing from a similar level, with deeper-water taxa (*Osangularia expansa*, *Nuttallides truempyi*, *Pterygocythere*) occurring more consistently and commonly in the lower part, and shallower-water taxa including the ostracod *Cytheridea* appearing at higher levels. A progressive increase in *Planorotalites*, associated with a *Chiloguembelina* influx in A3, are also indicators of shallowing in the upper part of this interval (in Unit A3).

The *Subbotina* influx in the upper part of Unit A2 interrupts this trend. *Subbotina* is characteristically a thermocline and sub-thermocline dweller, and this influx could be interpreted as an increase in water depth, but such an interpretation is not reflected by changes in other parameters. The overall proportion of planktonic foraminiferids actually falls within this interval, and there is no corresponding change in the benthic microfauna. The correlative *Subbotina* influx in the North Sea Basin is represented similarly in bathyal, outer neritic and even (although in very low numbers) in inner neritic environments (unpublished data). Its explanation is still unclear, but most probably reflects a water-mass shift.

The stacked parasequences bounded by omission surfaces in Units A2 and A3 (text-figs 10, 11) may represent Milankovitch-type cyclicity. Eleven omission surfaces are represented in NP11 (approximately 1.1 myr; Luterbacher et al. 2004); this suggests a good fit to the 100,000 year eccentricity cycle. It is notable that a similar number of parasequences (9) are represented in the coeval interval of the London Clay Formation in the Hampshire Basin (North Sea Basin) (King 1991b). This raises the possibility of potential intercontinental correlation at parasequence level. This will be explored in a future publication.

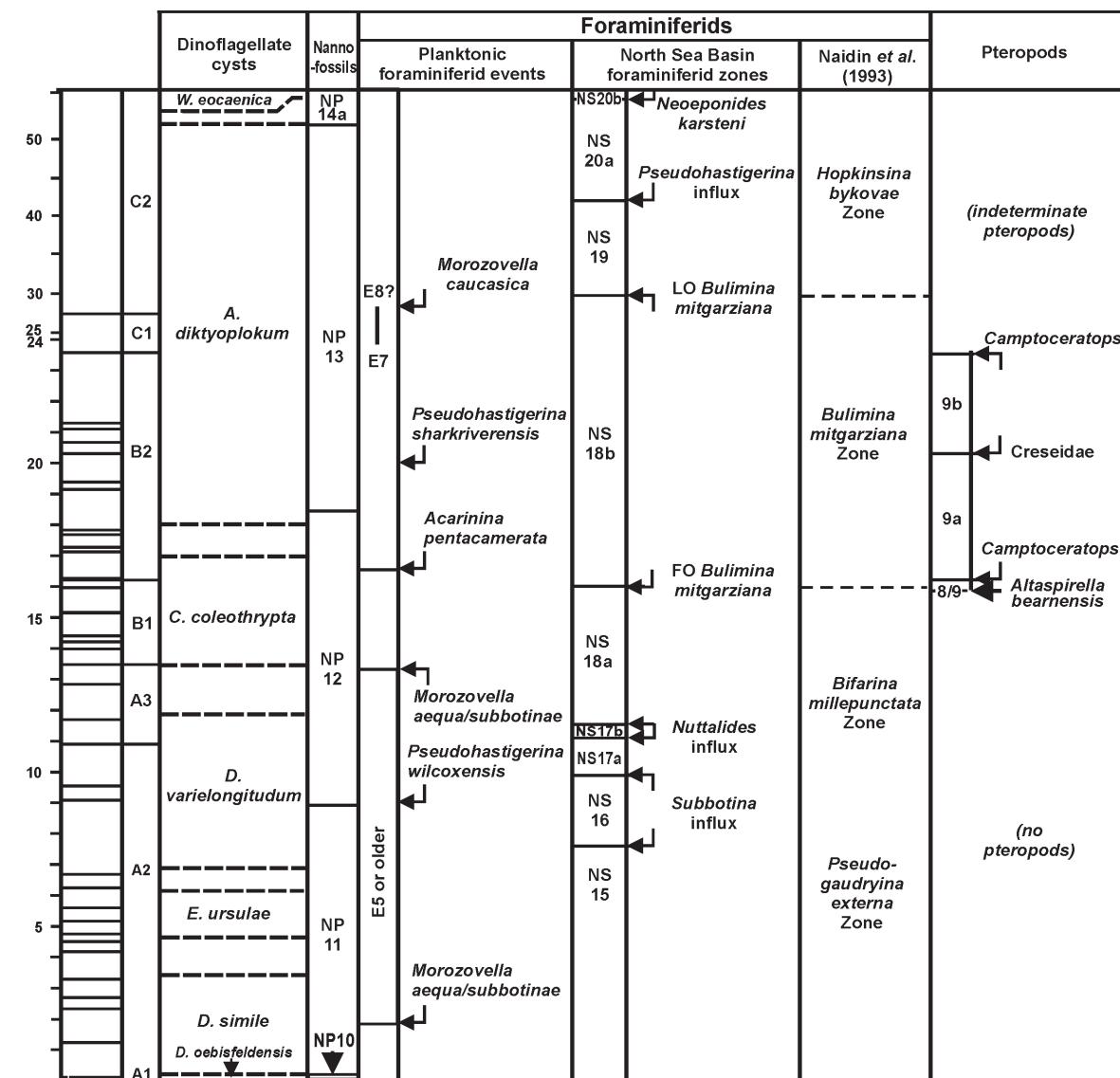
Unit B1

There is an abrupt lithological break at the base of B1, marked by the change from hemipelagic sediments to interbedded clay and marly clay with several sapropelic clay beds. The first sapropelic bed is at the base of B1. Across the A3/B1 boundary (excluding this non-calcareous sapropelic clay) there are relatively high proportions of planktonic foraminiferids, but benthic foraminiferid and ostracod diversity and abundance falls dramatically, continuing at low levels throughout B1 (text-fig. 17). Nannofossil productivity also decreases abruptly, and assemblages suggest shallowing. This indicates that the base of B1 represents a sequence boundary. Relatively high proportions of the *Areoligera*-complex, the *Homotryblium*-complex and wetzelelloids in the middle of B1 (text-fig. 13), and the influx of *Polysphaeridium zoharyi* also suggest significant shallowing.

The significance of the ‘shaly’ clay units and the sapropelic clay units (here and in B2) is discussed below.

Unit B2

The base of Unit B2 is defined at a prominent, deeply interburrowed omission surface. This corresponds to a significant hiatus (~55 ky). It is associated with the re-appearance of carbonate-rich sediments, an increase in nannofossil productivity and an increase in benthic foraminiferid diversity to levels similar to those of Unit A. This boundary is interpreted as a combined sequence boundary and transgressive surface. There is an influx of miliolids in the lower part of Unit B2. The MFS is tentatively placed at ~21.0m, at a peak in the relative proportions of planktonic foraminiferids. Above this, progressive shallowing is suggested by an upward increase in the proportion of *Pseudohastigerina* and the appearance of *Cytheridea aff. newburyensis*. Overall, depths appear slightly shallower than for Unit A: some of the presumed deeper-water taxa occurring in Units A2 and A3 are absent, and there is a relatively high proportion of coastal nannofossils.



TEXT-FIGURE 23
Integrated biostratigraphy.

Unit C

An abrupt lithological shift at the base of Unit C is marked by a sharp decrease in carbonate content and the incoming for the first time of significant proportions of silt-grade quartz. This boundary is apparently not marked by an omission surface, and no hiatus has been biostratigraphically detected. Many diffuse very thin laminae and layers of coarse silt/very fine sand in Unit C, partly reworked by bioturbation, are interpreted as storm-generated units, indicating deposition above storm wave-base (SWB). These features indicate an abrupt decrease in water depths compared with underlying intervals. The base of Unit C is therefore interpreted as a sequence boundary. It marks a major increase in sedimentation rates. This cannot be precisely quantified, due to imprecision in dating the boundary, but is estimated as from ~6m/myr in the underlying interval to a minimum of 15m/myr (probably > 20m/myr). The base of Unit C also corresponds approximately to a major influx of

Eatonicysta ursulae. Its significance is uncertain, but it clearly reflects a somewhat specialised environment.

Unit C is characterised by the consistent occurrence of relatively shallow-water ostracods (*Cytheridea*, *Echinocythereis* and *Eopaijenborchella*) and the foraminiferid *Alabaminoides*, a shallow-water indicator in the London Clay Formation. All these characteristics indicate shallower environments than below, but the proportion of planktonic foraminiferids is relatively high, only decreasing significantly in the upper part.

The lower part of Unit C (Unit C1) is tentatively interpreted as a LST, based on the indications of a shift to a more proximal setting. The base of Unit C2, marked by a decrease in grain-size, is tentatively interpreted as a transgressive surface. Above ~40m, a decrease in the proportion of planktonic foraminiferids is associated with a marked increase in relative proportions of *Pseudohastigerina*. This is interpreted as due to shallowing; the

lowest proportion of planktonic foraminiferids in the entire section (34%) is in the topmost sample in Unit C (at 56.0m), associated with the first incoming of sand-grade quartz. These features are interpreted as due to shallowing in the upper part of the HST. The increase in *Chiasmolithus* spp. (from < 1% to 5–10%), a cool-water taxon, starting around 6m above the base of Unit C2, may result from a marked reduction in sea surface paleotemperature, and may indicate the end of the Early Eocene Climatic Optimum (EECO) (e.g. Zachos, Dickens and Zeebe 2008) (~ 49–52 Ma).

LOW-OXYGEN FACIES

Brown ‘shaly’ clay units

Six units of this lithofacies are represented in Unit B, between 0.05m and 0.22m thick (text-fig. 12). They are sharp-based, without interburrowing; their top surface is also sharply defined, but in most cases is penetrated by burrows from the marly clays above. As in the case of the sapropelic clay units (see below), they occur as ‘intrusions’ into the otherwise well-oxygenated ‘normal marine’ succession, with no evidence for a regular cyclic context. Their characteristics (absence of bioturbation, fissility (but apparently not lamination), probable higher organic carbon content than the adjacent clays, fish debris and very fine plant debris) indicate deposition in a dysoxic or anoxic environment. It is probable that the shark and ray faunas collected *ex situ* are from these units, as discussed above; these confirm a poorly or non-oxygenated sea floor environment. The dominance by *Xiphodolamia*, a very unusual feature in shark faunas, indicates a high-productivity environment. This is supported by the record of rare and poorly preserved diatoms, generally represented by hollow moulds.

These units appear to represent influxes of a high-productivity watermass into this area. Non-calcareous facies with siliceous radiolaria and diatoms, including diatomites, are characteristic of the Ypresian of the northern Turgay Strait and West Siberian Basin (e.g. Radionova et al. 2003). These form part of an extensive high-latitude area with high levels of biogenic silica, which continues across the Arctic Ocean and into the North Atlantic (e.g. Radionova and Khoklova 2000; Expedition 302 Scientists 2006). The ‘shaly clay’ facies is here interpreted as reflecting episodic intrusion of this ‘Arctic’ high-productivity watermass into the ‘normal’ well-oxygenated Peri-Tethys. The controls on this feature are unclear; interpretation is difficult due to the lack of data in other environmental contexts in this area. Probably climatic and/or eustatic/tectonic controls are involved. Further investigation is needed. It may be significant that these episodes are within approximately the same interval as the sapropelic clay units, although without any obvious relationship to them (text-fig. 12).

Sapropelic clay units

The sapropelic clay beds in Units B1 and B2 are representatives of a group of late Ypresian sapropelic units which are present widely in the Peri-Tethys realm. They have been studied most intensively in the Kheu River section, Pre-Caucasus (e.g. Gavrilov et al. 1997; Akhmetiev and Zaporozhets 1996; Gavrilov, Shcherbinina and Muylöv 2000, Oberhänsli and Beniamovskii 2000; Shcherbinina and Gavrilov 2006; Shcherbinina 2008), but occur also in Crimea, the Caucasus, the Pre-Caspian area, NW Uzbekistan and Tadzhikistan (Muylöv, Benyamovsky and Tabachnikova 1989; Gavrilov and Muylöv 1991; Muylöv 1994; Stupin 2008).

Eight sapropelic units are identified at Aktulagay, four in B1 and four in B2; eight units are also represented in the Kheu River section. At Aktulagay the sapropels in B2 have been significantly disrupted by bioturbation, in some cases preserved only as streaks and lenses in marly clay. Here, as elsewhere, they occur within upper NP12 and lower NP13. In the Kheu River section the NP12/NP13 boundary is at the top of the sixth sapropel from the base (Oberhänsli and Beniamovskii 2000, fig. 2); at Aktulagay it is ~ 1–1.5m above the sixth sapropel. Allowing for differing sampling levels, this appears to confirm a precise correspondence between the sapropels at these sites. At Aktulagay the sapropels are non-calcareous, probably due to secondary decalcification, but elsewhere they contain calcareous microfossils and nannofossils. The palynofacies of a sample from one of these sapropels (at c. 14.7m) is highly dominated by marine amorphous organic matter (AOM); apart from this mainly dinocysts and a smaller amount of pollen are noteworthy.

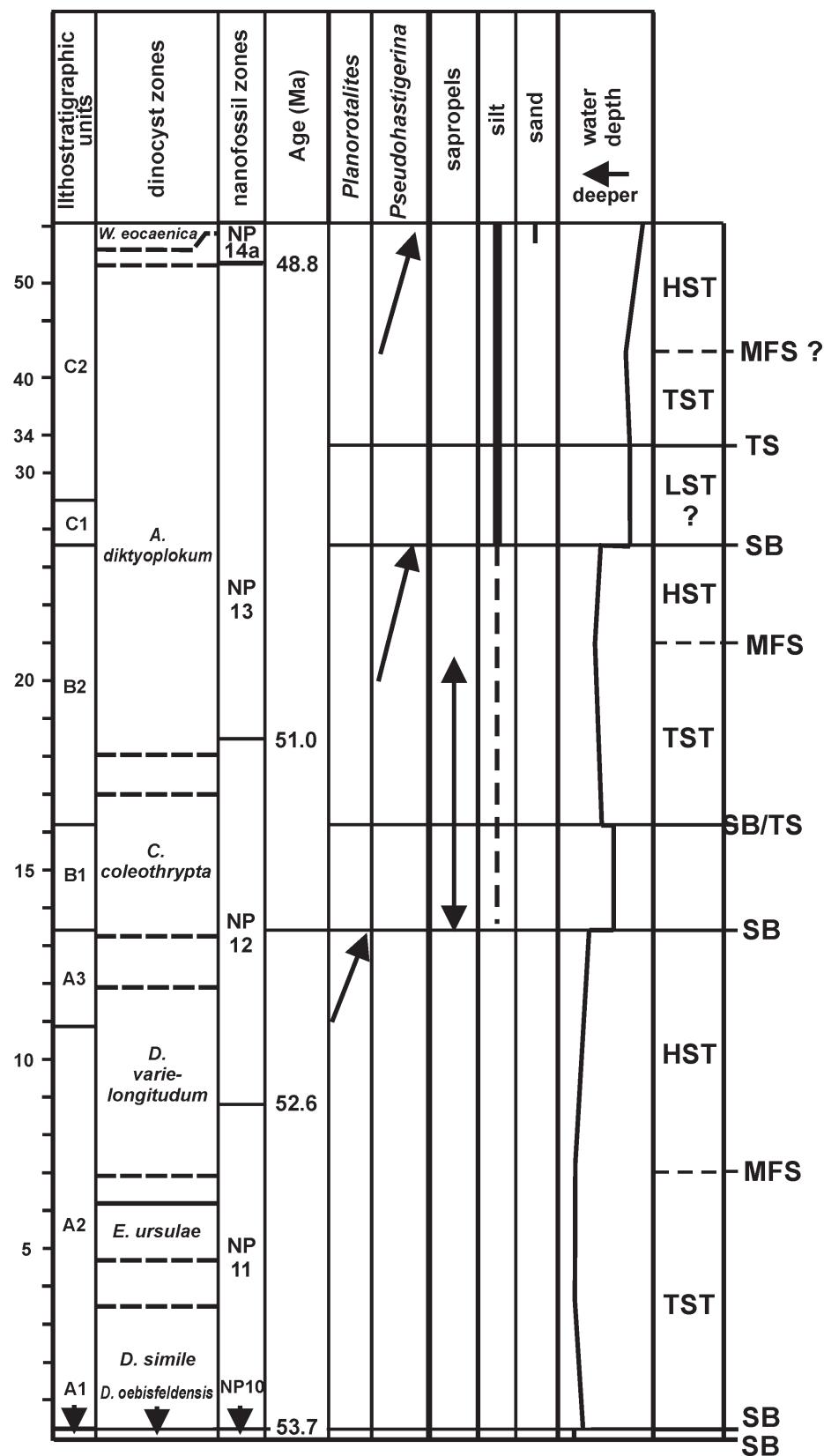
These sapropels have been interpreted as formed in episodic dysoxic environments, due to restricted water circulation, nutrient influxes or increased precipitation (see references cited above). The occurrence of benthic foraminiferid assemblages in the Kheu River section and elsewhere, although of low diversity, indicates that full anoxia was not achieved. The hydrogen index (HI) in the Kheu River section indicates that the carbon is derived largely from a terrestrial source (Shcherbinina and Gavrilov 2006). There the sapropels are associated with negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ excursions. Similar features are represented in organic-rich units, including sapropels, related to hyper-thermal episodes (including the PETM) at other levels in the Eocene and Paleocene (e.g. Bornemann et al. 2009; Luciani et al. 2010; Sprong et al. 2011).

Shcherbinina and Gavrilov (2006) noted an influx of reworked nannofossils immediately preceding the earliest sapropelic unit, interpreted as indicating a regressive event. This is consistent with the evidence from Aktulagay, where the earliest sapropelic unit, at the base of Unit B1, marks an abrupt environmental shift interpreted as a sequence boundary. Here the sapropelic units are within an interval tentatively interpreted as representing a LST followed by a TST. They terminate at a level interpreted as a MFS (text-fig. 24; see above).

An explanation for these units based solely on the paleogeography and depositional environments of the Peri-Tethys is not viable, as apparently identical sapropels are represented in the same stratigraphic interval (upper NP12-lower NP13) in deep-water environments in Denmark (Heilmann-Clausen, Nielsen and Gersner 1985) and in other areas of the North Sea Basin (C. King, unpublished data). This, together with their stratigraphic position within the EECO (early Eocene Climatic Optimum) enhances their interpretation as climatically-controlled events; this aspect will be discussed in a future publication.

RELATIONSHIP WITH THE NORTH SEA BASIN SUCCESSION

The strong biostratigraphic parallels between the Aktulagay section and the North Sea Basin involve not only planktonic groups (mainly nannofossils and dinoflagellate cysts, with aspects of the planktonic foraminiferid assemblages), but also benthic foraminiferids. Indirect links at higher or lower latitudes (through the Arctic Ocean via the Turgay Strait or through



TEXT-FIGURE 24

Depositional sequences. HST: Highstand systems tract. LST: Lowstand systems tract. MFS: Maximum flooding surface. TS: transgressive surface. TST: Transgressive sequence tract. SB: sequence boundary. Age of nannofossil zone boundaries is based on Luterbacher et al. (2004). Progressive upward increase in proportions of shallow-water planktonic foraminiferids is shown by arrows.

Tethys and the North Atlantic) seem unlikely to account for these similarities. In the case of the Arctic Ocean, its semi-isolation in the latest Ypresian, with lowered salinity and absence of the key dinoflagellate cysts (Brinkhuis et al. 2006), entirely negates this possibility. A particularly remarkable feature is the synchronous occurrence of the short-ranging benthic foraminiferids *Bulimina mitgarziana* and *Cancris plana*. These are widespread in Peri-Tethys but are apparently documented elsewhere only in the North Sea Basin (*Bulimina* sp. A and *Cansris* sp. A of King 1981, 1989). These are relatively deep-water taxa, in the North Sea Basin restricted mainly to probable upper and mid-bathyal environments, although also occurring in probable outer neritic settings at Aktulagay. These features imply a relatively direct deep-water connection between these areas, as already noted by Iakovleva et al. (2004). This is contrary to most previous paleogeographic models (text-fig. 3), but the evidence from Aktulagay was incorporated into a recent Ypresian paleogeographic interpretation (Knox et al. 2010). This topic will be fully addressed in a future publication.

CONCLUSIONS

This first detailed study of a Lower Eocene section in Peri-Tethys has documented an almost complete mid-and upper Ypresian succession. Dinocyst, nannofossil and foraminiferid zones and datums previously recognised in the North Sea Basin have been identified. This enables detailed correlation between these areas, and also more accurate calibration of events in these groups than has previously been possible. Other biostratigraphic aspects include the recognition of pteropod zones, and the first continuous and well-calibrated documentation of the evolution of the shark *Otodus* (*Otodus*) into *Otodus* (*Carcharocles*).

Depositional environments ranging from mid-neritic to upper bathyal are differentiated, although sharp delimitation is not possible. There is an overall upward shallowing trend through the section; five depositional sequences are tentatively delimited, although in the relatively distal environments, and without adequate information from more proximal areas, details are uncertain. The initiation of sapropelic units in the late Ypresian appears to correspond to a fall in sea-level and to be terminated by a maximum flooding surface. The close correspondence between the biostratigraphic events at Aktulagay and in the North Sea Basin is strong evidence for direct marine connection between these areas.

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