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Palynological reconstruction of the Eocene marine palaeoenvironments in south of Western Siberia

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ABSTRACT. Analysis of quantitative distribution of the aquatic and continental palynomorphs from a marginal marine Eocene section drilled by the borehole No.011-BP (south-western Siberia) allows the reconstruction of the early through latest Eocene palaeoenvironmental settings of the southern part of West Siberian marine basin. Successive palynomoprh assemblages allow the recognition of 12 depositional cycles, attributed to third-order sea-level fluctuations. The palynological data indicate significant marine environmental changes characterizing the West Siberian Eocene, viz: 1) the absolute dominance of cosmopolitan dinoflagellate cysts in the middle Ypresian assemblages suggests a shallow water West Siberian marine basin in constant connection with northern and southern seas, with warm climate; 2) a late Ypresian regressive phase culminates in the temporary cessation of marine sedimentation spanning the early Lutetian; and 3) from latest Lutetian times onwards the south-east of the West Siberian marine basin became significantly shallower, indicating the development of brackish settings; 4) a strong influx of endemic taxa, combined with a high dominance of terrestrial palynomorphs suggest a shallow connection with adjacent basins during the Bartonian; the early Priabonian is characterized by the influx of freshwater in the southern part of the West Siberian Sea; while 5) a final transgression occurred in southern West Siberian Basin by the middle-late Priabonian (~35.5–34.8 Ma).

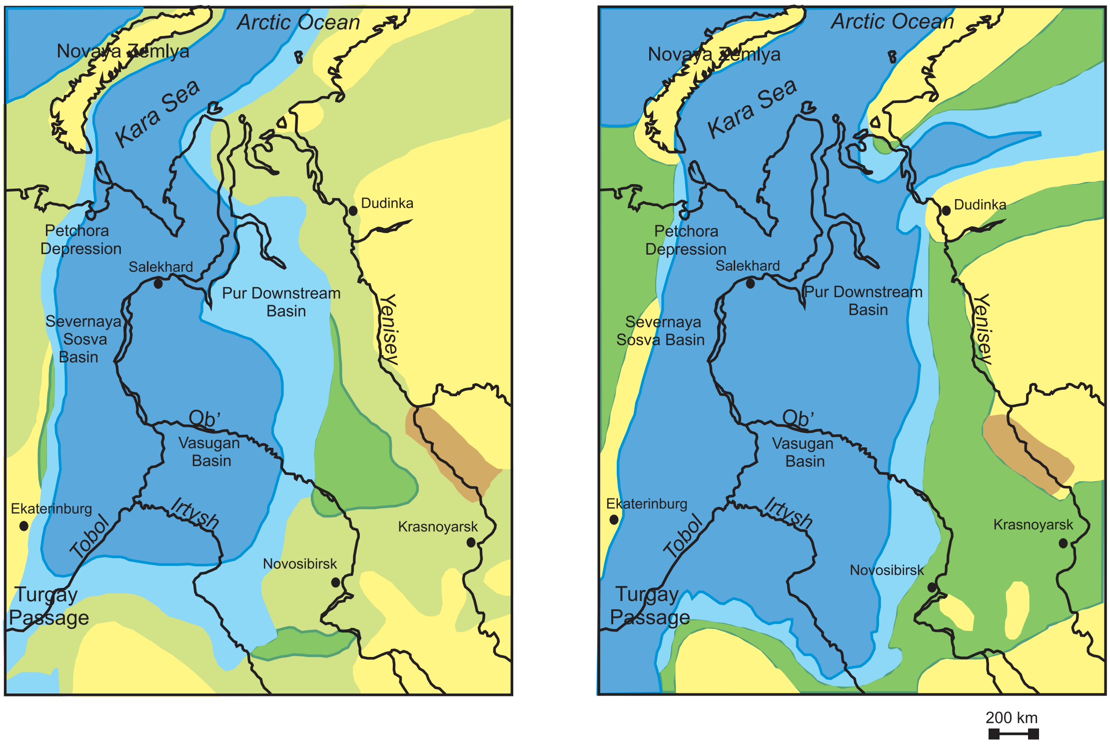
KEYWORDS: dinoflagellate cysts, palynomorphs, biosequence-stratigraphy, palaeosettings, Eocene, SW Siberia

INTRODUCTION

During the Palaeogene large seaways existed and disappeared in northern hemisphere, influencing somehow or other the climate change. Thus, during the Palaeocene-Eocene a vast epicontinental marine basin existed on the territory (up to 70% in Ypresian) of Western Siberia (Fig. 1; Shatsky 1978, Iakovleva 2000). Being connected or gradually disconnected to surrounding oceans, the West Siberian Sea, with its warm waters transport from the Tethys by the Turgay Strait to the north, was of importance for the evolution of the Arctic climate.

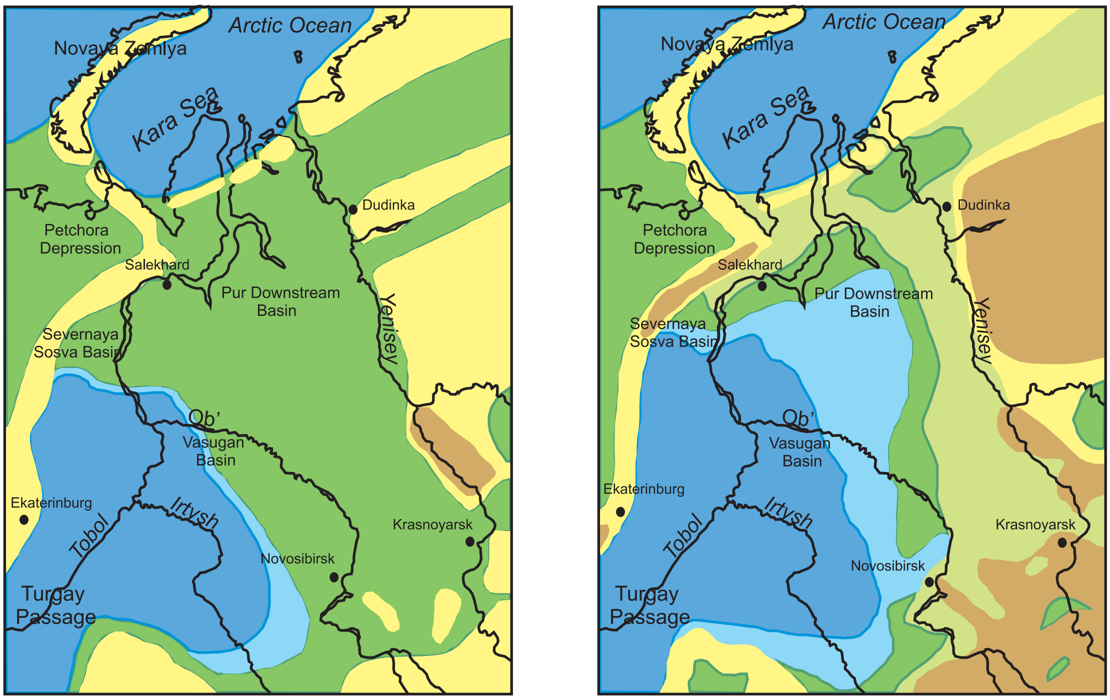
Dinoflagellate cysts are considered now to be an important proxy for understanding the Palaeogene palaeoceanography (Brinkhuis et al. 2003a, 2003b, Williams et al. 2004, Crouch & Brinkhuis 2005, Sluijs et al. 2005, Sluijs & Brinkhuis 2009). As far as age-indicative calcareous nannofossils are generally absent in non-calcareous West Siberian Palaeogene marine sediments, organic-walled dinoflagellate cysts become extremely useful for age-assessments and reconstructions of the Palaeogene environmental settings in this area (Kulkova 1987, Kulkova & Shatsky 1990, Iakovleva & Kulkova 2001, Akhmetiev et al. 2001, Iakovleva et al. 2001, Iakovleva & Kulkova 2003, Akhmetiev et al. 2004a, 2004b, Iakovleva 2008).

A recent dinoflagellate cyst study in the borehole No.011-BP (southern West Siberia; Iakovleva & Heilmann-Clausen 2010) has resulted in revised age-interpretation of



A. Latest Selandian-early Thanetian

B. Late Thanetian-Ypresian



C. Lutetian

D. Bartonian-Priabonian

🟦 - Sea, continental plate-forme

🟦 - Low, coastal plain, periodically flooded by sea

🟩 - Low, accumulative or lacustrine-accumulative plain

🟩 - Accumulative-denudative plain

🟨 - Plain-elevated plateau

🟫 - Low mountains

Fig. 1. Palaeogene palaeogeographic reconstruction of the West Siberian marine Basin (modified from Shatsky 1978 in Iakovleva 2000)

regional lithological formations; based on new updated dinoflagellate cyst data combined with palaeomagnetic signals an important regional hiatus (corresponding to lower Lutetian) was recognized; and the time of final interruption of marine sedimentation in southern part of West Siberian Basin during the late Priabonian (~34.8 Ma) is now suggested.

The purpose of the present study is to re-examine the Eocene record (dinoflagellate cysts, other aquatic and continental palynomorphs) from borehole No. 011-BP in the aim (1) to interpret the marginal marine palaeoenvironmental settings from early through latest Eocene in this section and (2) to provide new information on the Eocene evolution of the West Siberian Sea (i.e. timing and character of connections with the world's oceans).

MATERIAL AND METHODS

GENERAL INFORMATION AND LITHOLOGY

Borehole No. 11-BP is located 1.5 km north-east of the Achayir village, Irtysch shore, 35 km south of Omsk (Fig. 2) and is situated within the so-called Barabinskaya lithological zone (tectonically part of the Omsk Depression), which occupies the most part of the West Siberian plate (Akhmetiev et al. 2004a). The total depth of drilled borehole is 498.0 m. Marine Eocene deposits are present in this section up to 265.04 m and comprise sediments (from base to top) of the Upper Lulinvor and Tavda formations. The lithology of the borehole No.011-BP was described by Benyamovsky et al. (2002); from base to top there are (Figs 3, 4):

UPPER LULINVOR FORMATION

498.0–460.0 m – alternation of gaizy, grey and light-grey clays; a 5 centimetre layer of glauconitic sandstone occurs at 490.0 m; an interval of grey and light-grey gaizes is noted in the middle part (475.0–480.0 m), while a layer of silty, striped clay is observed at 470.0–471.4 m.

456.0–460.0 m – light, siliceous, sandy clays; the sand content increases upwards, and lenses of glauconitic fine-grained sand appear in upper part.

TAVDA FORMATION, OVER MEMBER

446.0–456.0 m – green-grey clayey, glauconitic, quartz-feldspar sands and siltstone; the lower boundary shows signs of erosion, with pebbles of the underlying siliceous clays occurring in the basal sand layer.

402.0–446.0 m – green, fat and homogenous clay, and, in some intervals, micaceous-silty clay with markasite spots.

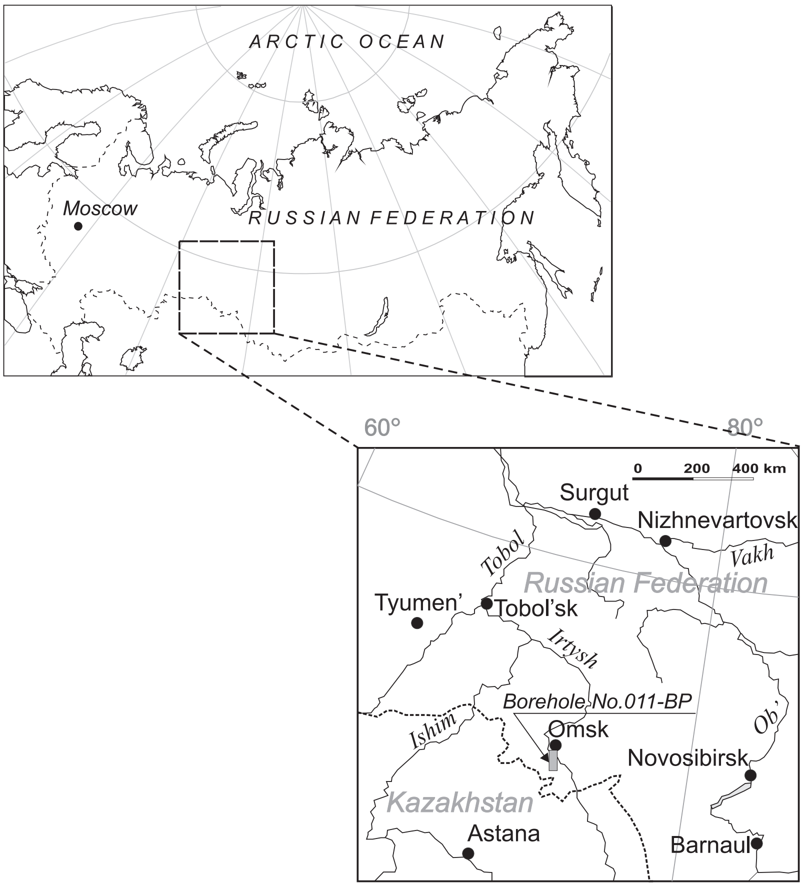


Fig. 2. Geographical location of the borehole No. 011-BP

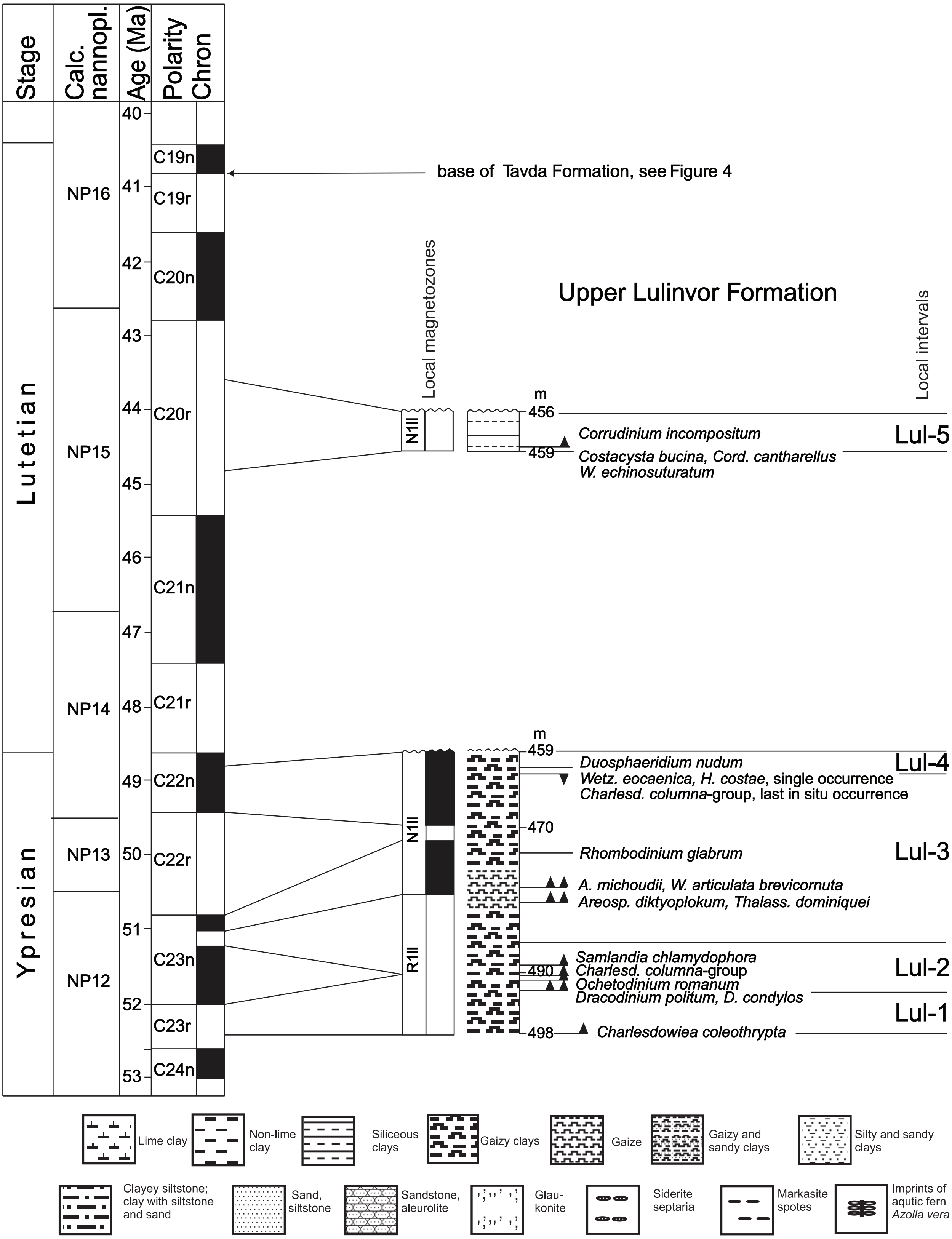


Fig. 3. Litho-, magneto- and biostratigraphy of the Upper Lulinvor Formation in the borehole No. 011-BP (after Iakovleva & Heilmann-Clausen 2010)

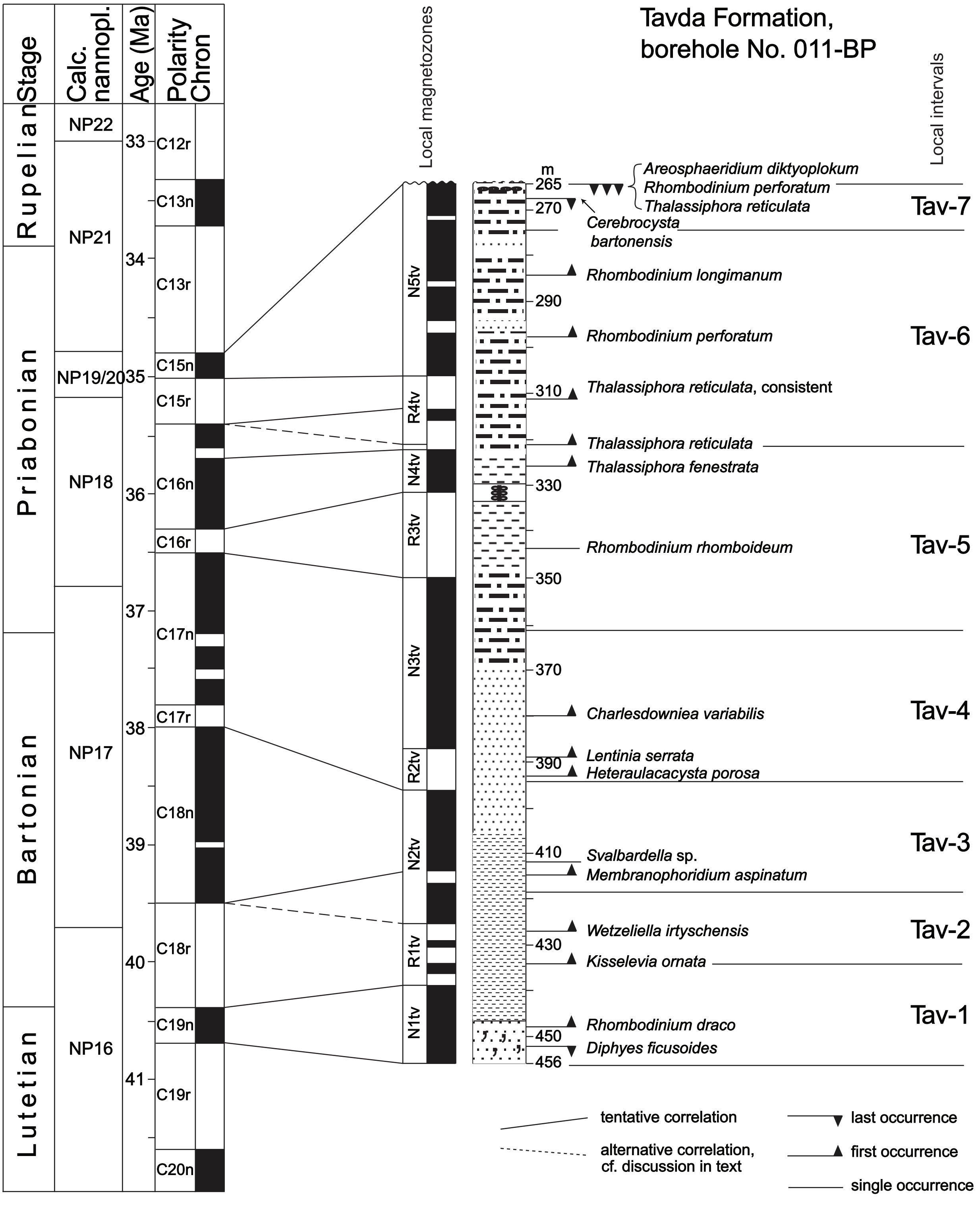


Fig. 4. Litho-, magneto- and biostratigraphy of the Tavda Formation in the borehole No. 011-BP (after Iakovleva & Heilmann-Clausen 2010)

TAVDA FORMATION, UPPER MEMBER

334.0–402.0 m – green-grey, mottled clays with numerous markasite spots and siderite concretions; a layer of fine-grained sand and siltstone is present in the interval of 362.0–362.5 m. Just above this layer occurs an alternation of clayey siltstone and silty clay with numerous markasite spots. Interval is terminated by an 11.4 m thick interval of light-grey clays.

330.0–334.0 m – clays with concretions of siderite and contains numerous imprints of the aquatic fern *Azolla vera* and small pelecypods.

265.0–330.0 m –alternating layers of clay and siltstone. Numerous markasite spots and rare siderite concretions are present. Clays from the uppermost part (266.3–272.2 m) are platy and fat, with numerous markasite spots. Near the top clays become gradually sandier.

Marine Tavda Formation is overlain by continental sediments (ash-coloured kaolinitic sands with a large amount of carbonised plant fragments and plant detritus) of the Isikul Formation, with a likely Oligocene age (Akhmetiev et al. 2004a).

PALYNOLOGICAL PREPARATION

For the present study seventy six samples were analysed palynologically. All samples were prepared in the Geological Institute, Moscow; the routine chemical preparation is described in Iakovleva & Heilmann-Clausen (2010).

The quantitative analysis of palynological samples was performed in 2 steps: (1) a minimum of 100–150 palynomorphs were counted, and grouped in 7 broad categories (viz: dinoflagellate cysts, terrestrial palynomorphs, acritarchs, miscellaneous algae, and aquatic ferns). Terrestrial palynomorphs, in their turn, were recognized in 3 large categories: (a) conifers (e.g. Pinaceae, Podocarpaceae and Taxodiaceae), (b) angiosperms and (c) spores. The group of aquatic ferns includes *Hydropteris indutus* and *Azolla vera* (*Azollites*-group). Then, (2) a minimum 150–250 (if possible) dinoflagellate cysts, acritarchs and other 'miscellaneous' algae were counted. Subsequently, remaining materials were scanned for rare taxa. Quantitative results are expressed as a percentage of the total count.

The present palaeoenvironmental reconstructions are mainly based on the procedures described in e.g. Brinkhuis 1994, Powell et al. 1996, Sluijs et al. 2005, Crouch & Brinkhuis 2005. Here, we grouped morphologically closely related dinoflagellate cyst taxa in 12 groups: (1) Wetzelielloideae, (2) *Deflandrea*, (3) *Phthanoperidinium*, (4) *Thalassiphora*; (5) *Cribroperidinium*, (6) *Areoligera*, (7) *Cordosphaeridium*, (8)

Table 1. Dinocyst-complexes of Tavda Formation and their palaeoenvironmental interpretation

Dinocyst complex	Taxa included	Paleoenvironmental interpretation	Bibliographical source
Wetzelielloids	all representatives of Wetzelielloideae	Coastal and neritic settings Shallow-water conditions with elevated nutrient availability	Stover et al. 1996 Brinkhuis et al. 1992
Deflandrea	*Deflandrea* spp. and *Alterbidinium*, *Senegalinium*, *Lentinia*, *Lejeunecysta*, *Palaeocystodinium*	Coastal and neritic settings Shallow-water conditions with elevated nutrient availability Inshore, possibly brackish eutrophic settings; abundant during high-productivity episodes; closely tied to an ancient deltaic setiing and organic-rich facies	Stover et al. 1996 Brinkhuis et al. 1992 Sluijs et al. 2005
Phthanoperidinium	all species of *Phthanoperidinium*	Relatively shallow marine settings; abundant during high-productivity episodes; closely tied to an ancient deltaic setting and organic-rich facies	Sluijs et al. 2005
Thalassiphora	all species of *Thalassiphora*	Productivity increase and/or cooling of surface waters	Vonhof et al. 2000
Areoligera	*Areoligera*, *Glaphyrocysta* related *Adnatosphaeridium*, *Membranophoridium*, tentatively *E. ursulae*, *Enneadocysta* and *Areosphaeridium*	Marginal marine, inner neritic settings, often associated with hydrodynamically high energetic environments	Powell et al. 1996
Cordosphaeridium	*Cordosphaeridium*, *Fibrocysta*, *Aran. araneosa*	Open marine, neritic settings	Powell et al. 1996
Operculodinium	all species of *Operculodinium*	Open marine, neritic settings	Brinkhuis 1994
Homotryblium	*Homotryblium*, *Dinopterigium*, *Lingulodinium*, *Heteraulacacysta*, *Pol. zoharyi*	Restricted marine to inner neritic settings with increased: lower salinity Preference for warm water settings	Brinkhuis 1994 Crouch & Brinkhuis 2005
Spiniferites	*Spiniferites*, *Achomosphaera*, *Spiniferella*, *Hafniasphaera*, *Hystrichostrogylon*, *Hystrichosphaeropsis*	Neritic to oceanic settings Stable salinity	Brinkhuis 1994 Lewis et al. 1999
Impagidinium	all species of *Impagidinium*	Oceanic environments	Brinkhuis 1994

Operculodinium, (9) *Homotryblium*, (10) *Spiniferites*, (11) *Impagidinium*, (12) others. Taxa included in these groups and their possible palaeoenvironmental relationships are displayed in Table 1.

AGE-ASSESMENTS

The age interpretation of marine sediments of borehole No. 011-BP is done by dinoflagellate cysts data (Iakovleva & Heilmann-Clausen, 2010) combined with previously published palaeomagnetic data (Gnibidenko in Akhmetiev et al. 2004a). The synthesis of dinoflagellate cyst age assessments and a tentative interpretation of the correlation between the local polarity zones and the global polarity chrons are present in Figures 3 and 4 and were discussed in previous biostratigraphic publication (Iakovleva & Heilmann-Clausen 2010). It has to be noted that despite calcareous nannofossils are absent in the present section, the ages of intervals are interpreted in terms of NP zones and used here as NP chronozones.

The dinoflagellate cyst assemblages from the Upper Lulinvor Formation demonstrated a close similarity to their North Sea Basin and Peri-Tethys counterparts (Bujak et al. 1980, Heilmann-Clausen & Costa 1989, Köthe 1990, De Coninck 1991, Mudge & Bujak 1994, Iakovleva et al. 2004). As a result, five major intervals (Lul-1 to Lul-5) characterized by key-dinoflagellate cyst events previously established in NW Europe have been identified within the Upper Lulinvor Formation (Fig. 3, Iakovleva & Heilmann-Clausen 2010). Sediments of the intervals Lul-1 to Lul-4 have been therefore attributed to middle-uppermost Ypresian (middle NP12-lowermost NP14, polarity chrons C23r-C22); and important hiatus corresponding to the lower Lutetian (chron C21) is recognized; and, finally the interval Lul-5 is attributed to the middle Lutetian (NP15, polarity chron C20).

The overlying Tavda Formation is characterized by dinoflagellate cyst assemblages of low diversity; additionally, some levels are dominated by endemic Siberian species. Nevertheless, several dinoflagellate cyst events used for correlation in NW Europe are present in sediments of borehole No. 011-BP; however, some of them seem to have delayed ranges in this section. As a result, only few dinoflagellate cyst events more or less synchronous with NW Europe permitted to make a tentative calibration of local magnetozones of the Tavda Formation with global palaeomagnetic time scale (Fig. 4; Iakovleva & Heilmann-Clausen 2010). Thus, the Tavda Formation was divided in the present section into seven intervals (Tav-1 to Tav-7) of characteristic dinoflagellate cyst assemblages and attributed to upper Lutetian-Priabonian (NP16-NP19/20; polarity chrons C19n-C15n). Based on the presence of key-species *Thalassiphora reticulata* and the normal polarity in the uppermost part of the Tavda Formation, the interruption of marine sedimentation in the south-eastern part of the West Siberian Basin took place during the late Priabonian (~34.8 Ma).

RESULTS

GENERAL ASPECTS

The taxonomical diversity of dinoflagellate cysts is presented in Table 2 and Figure 5. Quantitative distribution of dinocysts, acritarchs, terrestrial palynomorphs and aquatic ferns is presented in Figures 6 and 7, while the quantitative distribution of the dinoflagellate cyst groups is plotted in Figures 8 and 9.

In general, most samples from the Upper Lulinvor and Tavda formations revealed rich palynological assemblages; nearly all of them yielded dinoflagellate cysts. Totally, about 230 phytoplankton taxa have been recognized in the section (see Iakovleva & Heilmann-Clausen 2010). Nevertheless, the diversity of dinoflagellate cyst assemblages and the ratio between dinoflagellate cysts and other palynomorphs (pollen, spores, and aquatic fern massulae) differs markedly between two formations (Figs 5, 6, 7). Thus, rich and divers dinoflagellate cyst assemblages characterize all samples from the Upper Lulinvor Formation; most diversified Ypresian assemblage consists of 75 taxa. Dinoflagellate cysts are dominant in the interval of 498.0–470.8 m depth, while the interval from 469.7–460.0 m depth is characterized by the increase in the content of acritarchs and pollen grains, especially angiosperms. Dinoflagellate cyst assemblages which characterize the Lutetian part of the Upper Lulinvor Formation reveal a relative decrease in dinoflagellate cyst diversity and have common conifer and angiosperm remains.

The lowermost part of the Tavda Formation (~10 m) probably includes reworked material

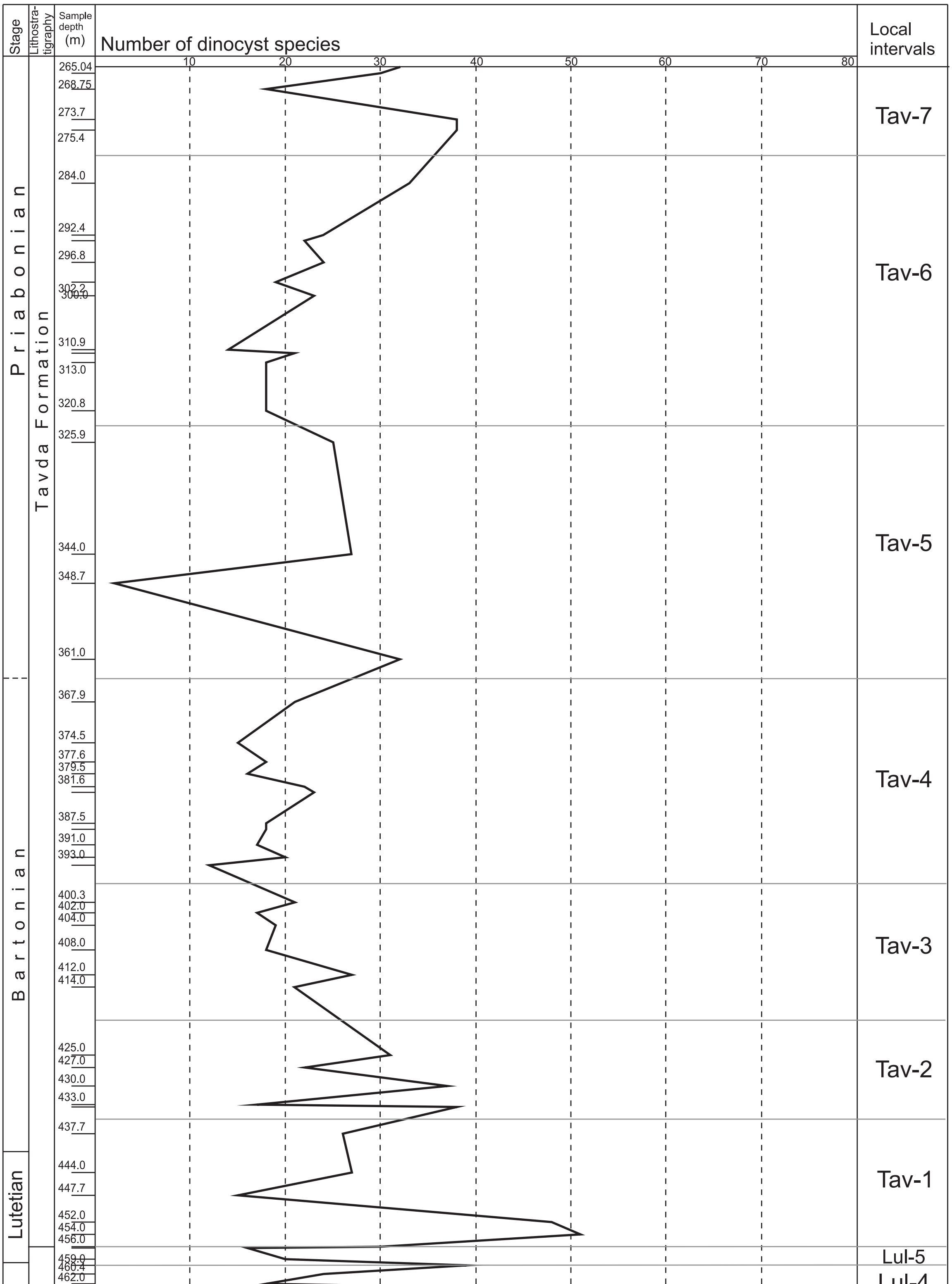


Fig. 5. Taxonomical diversity of dinocysts through the section of borehole No. 011-BP

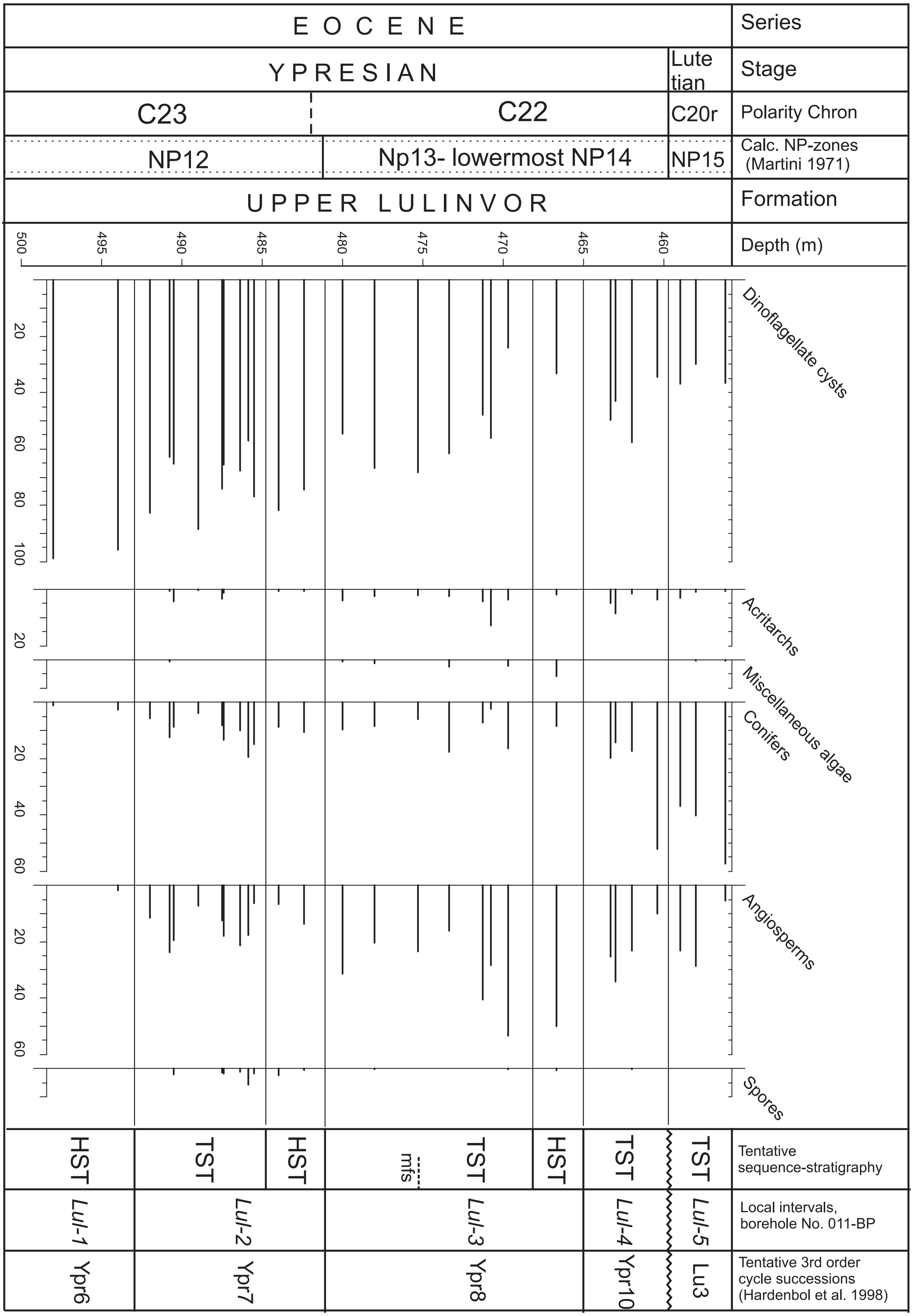


Fig. 6. Quantitative distribution of dinocysts, acritarchs and continental palynomoprhs in the Upper Lulinvor Formation of the borehole No. 011-BP

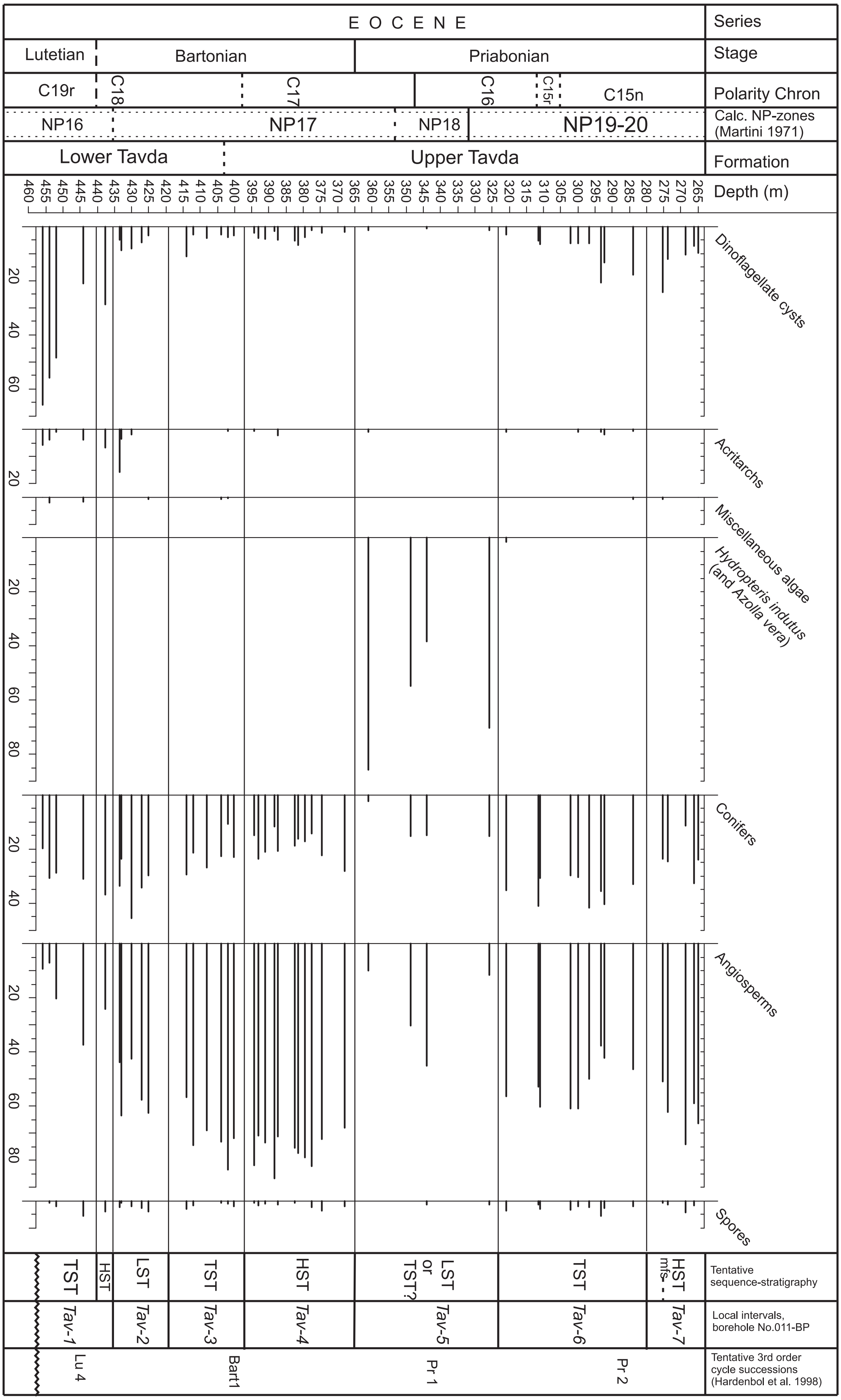


Fig. 7. Quantitative distribution of dinocysts, acritarchs and continental palynomoprhs in the Tavda Formation of the borehole No. 011-BP

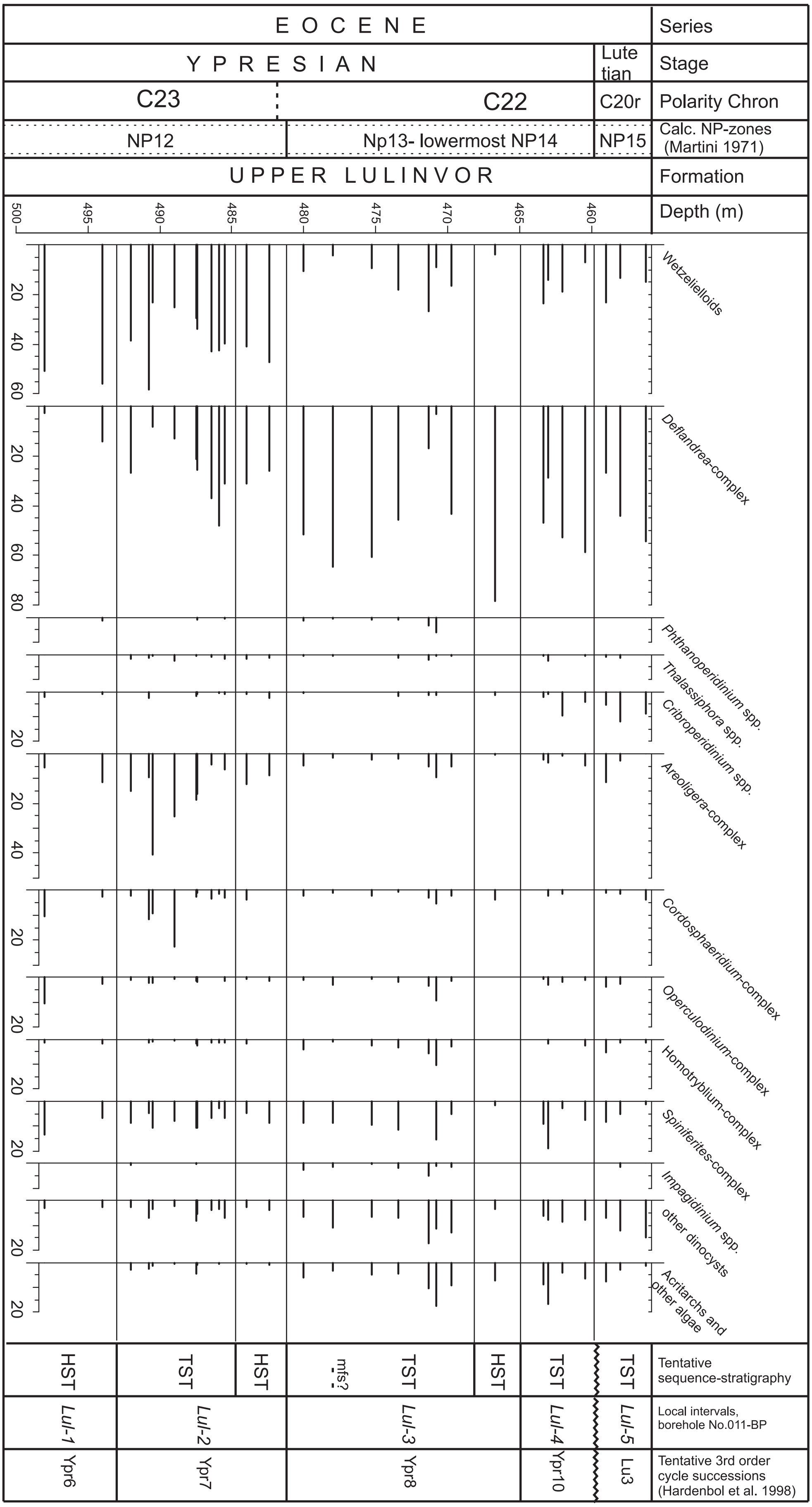


Fig. 8. Quantitative distribution of dinocyst-complexes in the Upper Lulinvor Formation of the borehole No. 011-BP

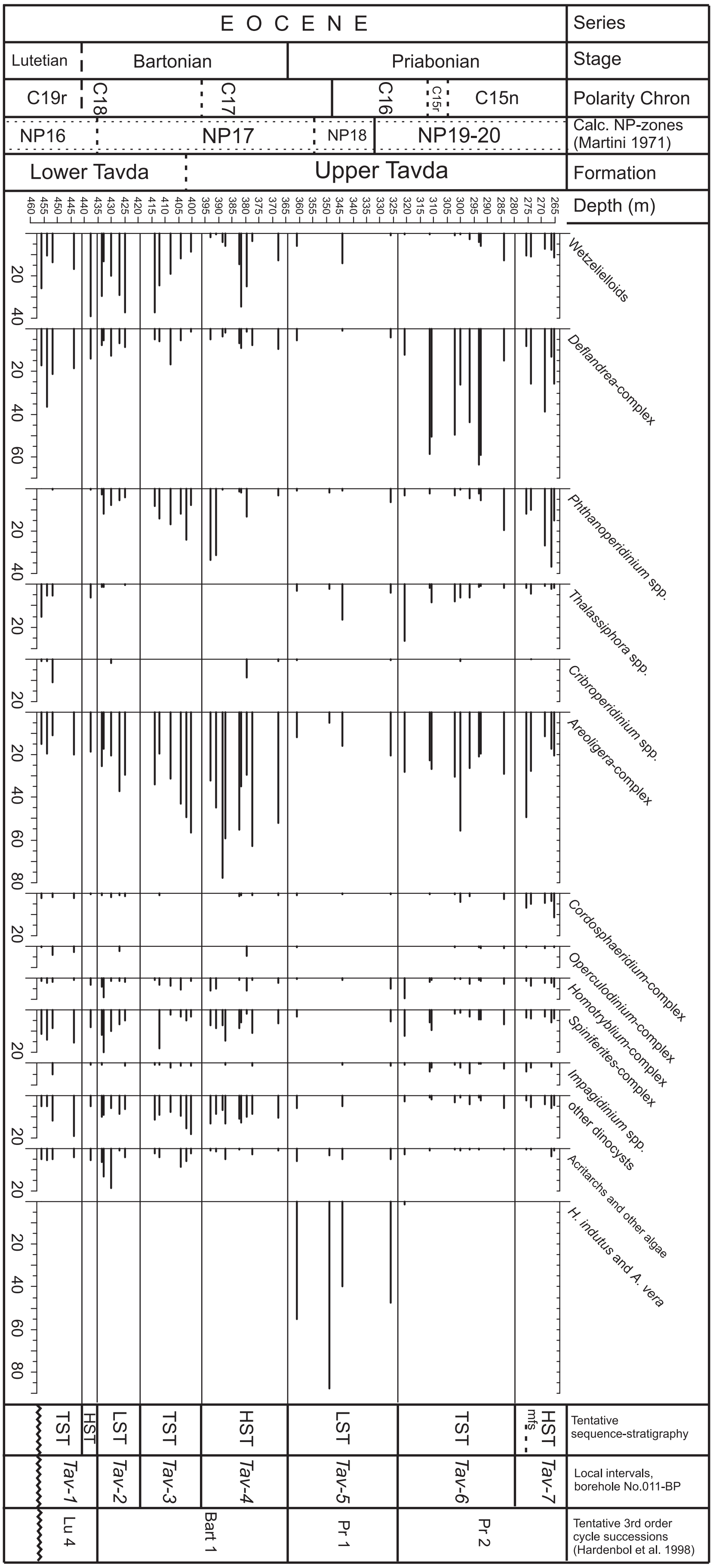


Fig. 9. Quantitative distribution of dinocyst-complexes in the Tavda Formation of the borehole No. 011-BP

Table 2. List of taxa

DINOFLAGELLATE CYSTS

Areosphaeridium diktyoplokum (Klump 1953) Eaton 1971
Areosphaeridium michoudii Bujak 1994
Cerebrocysta bartonensis Bujak in Bujak et al. 1980
Charlesdowniea coleothrypta (Williams & Downie 1966) Lentin & Vozzhennikova 1989
Charlesdowniea columna-group sensu Iakovleva & Heilmann-Clausen 2010
Charlesdowniea variabilis (Bujak in Bujak et al. 1980) Lentin & Vozzhennikova 1989
Cordosphaeridium cantharellus (Brosius 1963) Gocht 1969
Corrudinium incompositum (Drugg 1970) Stover & Evitt 1978
Costacysta bucina Heilmann-Clausen & Van Simayes 2005
Dracodinium condylos (Williams & Downie 1966) Costa & Downie 1979
Dracodinium politum Bujak in Bujak et al. 1980
Duosphaeridium nudum (Cookson 1965) Loeblich & Loeblich 1968
Heteraulacacysta porosa Bujak in Bujak et al. 1980
Hystrichosphaeropsis costae Bujak 1994
Kisselevia ornata Vozzhennikova 1967
Lentinia serrata Bujak in Bujak et al. 1980
Membranophoridium aspinatum Gerlach 1961
Ochetodinium romanum Damassa 1979
Rhombodinium longimanum Vozzhennikova 1967
Rhombodinium perforatum (Jan du Chêne & Châteauneuf 1975) Lentin & Williams 1977
Rhombodinium rhomboideum (Alberti 1961) Lentin & Williams 1973
Samlandia chlamydophora Eisenack 1954
Thalassiphora dominiquei Iakovleva & Heilmann-Clausen 2010
Thalassiphora fenestrata Liengjarern et al. 1980
Thalassiphora reticulata Morgenroth 1966
Wetzeliella articulata subsp. *bre vicornuta* Heilmann-Clausen & Costa 1989
Wetzeliella eocaenica Agelopoulus 1967
Wetzeliella irtyschensis Alberti 1961
Wilsonidium echinosuturatum (Wilson 1967) Lentin & Williams 1976

SPOROMORPHS

Azolla vera Nikitin 1959
Hydropteris indutus Kondinskaja 1966

from the underlying Lulinvor layers (see discussion in Iakovleva & Heilmann-Clausen 2010). This part of the formation is also characterized by the predominance of diversified dinoflagellate cysts. A significant change of palynological assemblages is observed at ~448.0 m depth, where the dominantly dinoflagellate cyst assemblages give way to the dominance of continental palynomoprhs, especially angiosperms; and impoverished assemblages of dinoflagellate cysts (maximum 38 species per sample and only up to 27% of the whole palynomoprh association) are typical for the whole Tavda Formation. Additionally, the interval between 361.0 and 325.0 m depth contains a strong increase (up to 88%) of the aquatic fern *Hydropteris indutus* (*Azollites*-group).

PALYNOMORPH SUCCESSIONS AND ENVIRONMENTAL INTERPRETATIONS

UPPER LULINVOR FORMATION

Five intervals with characteristic palynomorph assemblages are established in the Upper Lulinvor Formation in the borehole No. 011-BP from base to top (Figs 6, 8, 10):

1. The lowermost interval Lul-1 (498.0–494.0 m depth; FO[*] of *Charlesdowniea coleothrypta*, indirectly the early part of middle NP12, polarity chron C23r; ~52.2–52.1 Ma) is characterized by a high dominance of dinoflagellate cysts (almost 100%). Based on the absolute abundance of peridinioid Wetzelielloideae, combined with a virtual absence of acritarchs and very low content of terrestrial palynomorphs, this interval is interpreted to be deposited in coastal-neritic settings with elevated nutrient availability (probably lowered salinity; see Sluijs et al. 2005) and is tentatively attributed to a part of highstand system tract (HST). Combined with the age-assessment (~52.2–52.1 Ma), this part of the section should represent a part of the NW European third order cycle Ypresian 6 in Hardenbol et al. (1998), Figs 6, 8, 10.

2. The interval (Lul-2) between 492.0 and 480.0 m depth (FOs of *Dracodinium politum*, *Ochetodinium romanum*, *Charlesdowniea columna*-group, *Samlandia chlamydophora*; indirectly middle-upper part of NP12, uppermost C23r-C23n polarity chrons; ~52.1–51.0 Ma) revealed palynomorph associations which are still dominated by dinoflagellate cysts with a minor component of acritarchs and the pollen of conifers and angiosperms. Based on the high percentages of representatives of the peridinoid Wetzelielloideae and *Deflandrea*-group, this interval appears to represent coastal settings with possible lowered salinity and increased nutrient supply from land.

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[*] FO – first occurrence

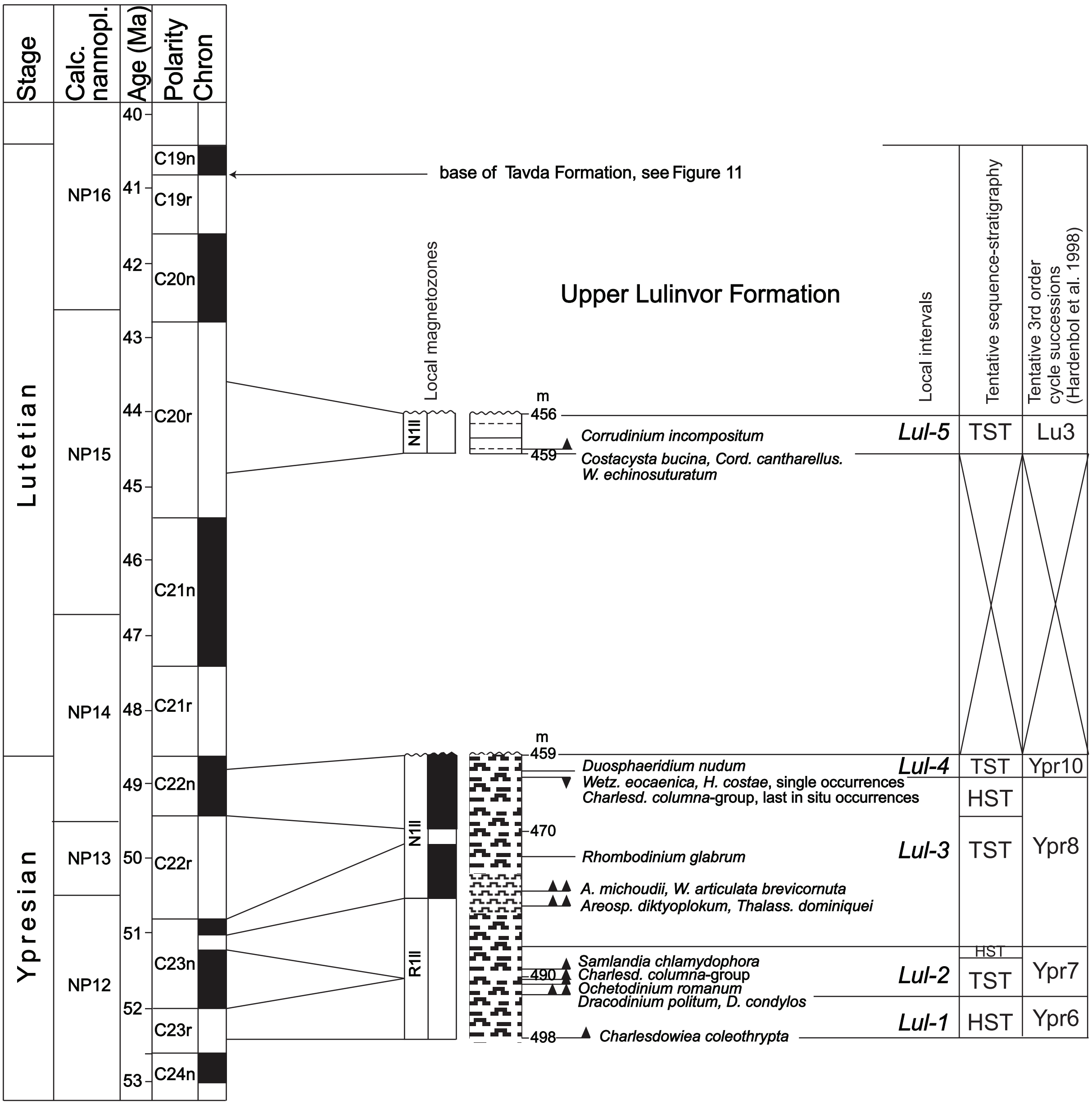

Fig. 10. Combined litho-, bio- and sequence-stratigraphy of the Upper Lulinvor Formation in the borehole No. 011-BP

The subsequent influx of the *Areoligera*-group (up to 40%), common *Cordosphaeridium,* and appearance of isolated open marine *Impagidinium* spp., the interval between 492.0 and 484.0 m is tentatively interpreted as a part of a transgressive systems tract (TST). The uppermost part of this succession (484.0–480.0 m) is marked by a decrease in percentages of the *Areoligera*-group, and by the disappearance of *Impagidinium* spp.; this is taken to indicate a part of a highstand systems tract (HST; see also Sluijs et al. 2005, Pröss & Brinkhuis 2005). Comparing with NW European third order sequences, this interval may represent a part of the Ypresian 7 cycle (Hardenbol et al. 1998), Figs 6, 8, 10.

3. The interval (Lul-3) between 480.0 and 463.0 m depth (FOs of *Areosphaeridium diktyoplokum*, *Areosphaeridium michoudii*, *Wetzeliella articulata* subsp. *brevicornuta*; indirectly uppermost NP12-NP13; polarity chron C22; ~51.0–49.2 Ma) is still characterized by an abundance of peridinioid cysts (dominantly *Deflandrea*-group), a significant decrease in the *Areoligera*-group, together with a minor increase in the *Spiniferites* and *Homotryblium*-groups, and a slight increase in *Impagidinium* numbers (up to 5%). The dominance of peridinioid cysts together with the increase in terrestrial palynomoprhs (primarily angiosperms, up to 50%), probably indicates an enhanced nutrient delivery from the coast and the

eutrophication of surface waters. A combined influx of *Impagidinium* spp. and a very slight increase in the *Spiniferites* and *Homotryblium* groups in the interval between 480.0 and 466.7 m are interpreted to be a part of a transgressive systems tract (TST), whereas the uppermost interval of 466.7–463.0 m, characterized by the absence of *Impagidinium* spp., the *Spiniferites* and *Homotryblium* groups and the absolute predominance of the *Deflandrea*-group (80%), is tentatively considered to represent a part of a highstand systems tract (HST). On the basis of maximal dinoflagellate cyst diversity the maximum flooding surface (m.f.s.) is tentatively placed at 478.0 m. The interval of 480.0–463.0 m is tentatively attributed to the Ypresian 8 succession from the NW Europe (Hardenbol et al. 1998), Figs 6, 8, 10.

4. The interval (Lul-4) between 463.0 and 459.0 m (FOs of *Hystrichosphaeropsis costae*, *Wetzeliella eocaenica*, *Duosphaeridium nudum*; indirectly earliest NP14, polarity chron C22n; ~49.4–48.7 Ma) yielded associations with approximately equal concentrations of dinoflagellate cysts and continental palynomorphs. High numbers of peridinioid *Deflandrea*-group and Wetzelielloideae, typical for the whole Upper Lulinvor Formation, persist during the terminal Ypresian phase and, combined with elevated content of terrestrial palynomorphs, again indicate coastal settings with delivery of nutrient supply from river mouths, and likely lowered salinities. However, subtle increases in the more open-marine *Spiniferites*-complex is taken to indicate a minor sea-level rise, and this interval is assigned to a transgressive systems tract, likely correlative to a part of Ypresian succession 10 as described from NW Europe (Hardenbol et al. 1998), Figs 6, 8, 10.

5. The uppermost interval (Lul-5) referred to the Upper Lulinvor Formation (presence of *Costacysta bucina*, *Cordosphaeridium cantharellus*, *Wilsonidium echinosuturatum*; indirectly NP15, chron C21; ~44.8–43.6 Ma) revealed dinoflagellate cyst associations characterized by the dominance of the *Deflandrea*-group and by increased numbers (up to 20%) of the *Spiniferites*-group. Combined with the elevated content of terrestrial palynomorphs (conifers), this is suggestive of coastal settings with probably normal salinity, but a rich nutrient supply from the land. The influx of the open-marine *Spiniferites*-group probably reflects a slight sea-level rise and this interval is therefore assigned to a transgressive systems tract (TST), tentatively correlated with the NW European Lutetian 3 sequence (Hardenbol et al. 1998), Figs 6, 8, 10.

TAVDA FORMATION

Seven intervals, characterized by significant dinocyst-events and/or palaeoecological changes have been revealed within the Tavda Formation from base to top (Figs 7, 9, 11).

1. The lowermost interval (Tav-1) between 456.0 and 433.4 m depth (FO of *Rombodinium draco* at 447.7 m; indirectly upper NP16, polarity chrons C19n-C18r; ~40.7–40.4 Ma) contains a number of probably reworked Ypresian-Lutetian species of the underlying Lulinvor Formation (456.0–447.7 m depth interval) as well as a clear lithological signs of an erosional unconformity (see Iakovleva & Heilmann-Clausen 2010) at the base of the Tavda Formation. Based on the combination of lithology and palynological associations, the interval between 456.0 and 437.7 m (abundant dinoflagellate cysts and conifers) is assigned to a part of a transgressive systems tract (TST). The overlying interval (437.7–433.4 m depth) is marked by a slight decrease in dinoflagellate cysts (only 30% of total palynomorphs) with the influx of peridinioids (especially Wetzelielloideae). This suggests an enhanced supply from land, and the interval may therefore correspond to a highstand systems tract (HST). Taking the tentative age into account (Late Lutetian), the whole interval from 456.0 to 433.4 m may be synchronous with parts of the NW European Lutetian Sequence 4 (Hardenbol et al. 1998); see Figs 7, 9, 11.

2. The interval (Tav-2) from 433.4 to 414.0 m depth (FOs of *Kisselevia ornata* and *Wetzeliella irtyschensis*; indirectly NP17, chron C18r-probably C18n.2n; ~40.4–39.5 Ma) is also marked by a significant decrease in marine palynomorphs (down to a maximum 15% of the total assemblage), a slight decrease in dinoflagellate cyst diversity, and a pronounced increase in terrestrial palynomorphs with dominance of angiosperms. Aquatic palynomorph assemblages are dominated by peridinioid cysts (primarily Wetzelielloideae, up to 40%), the *Areoligera* group (up to 40%) and common *Spiniferites* group (20–5%). High numbers of peridinioid cysts and the increase in terrestrial

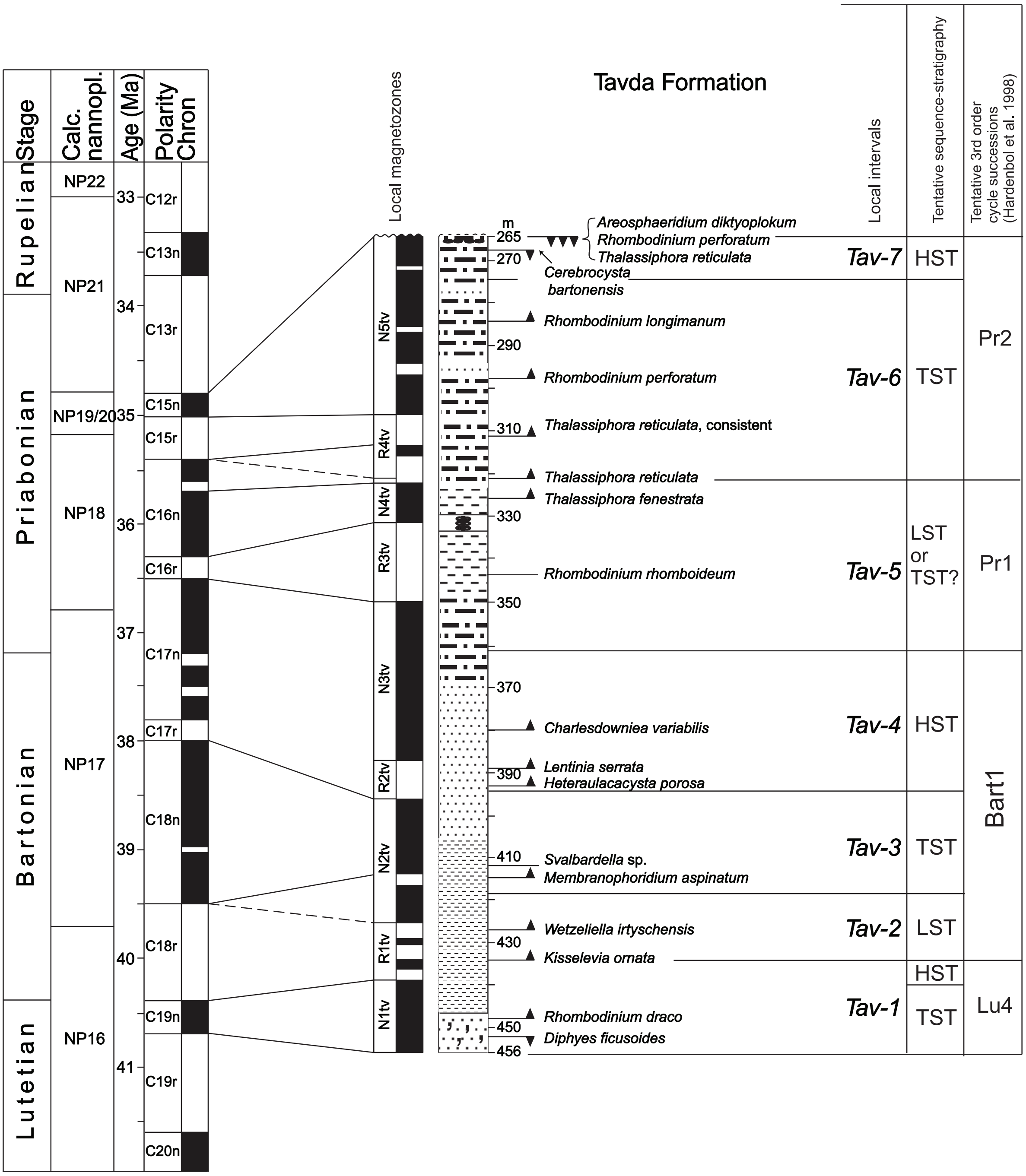

Fig. 11. Combined litho-, bio- and sequence-stratigraphy of the Tavda Formation in the borehole No. 011-BP

palynomorphs suggest that this interval represents coastal settings with delivery of nutrients from river mouths and lowered salinities; it is tentatively attributed to a highstand systems tract (HST), and tentatively correlated to part of the NW European Bartonian sequence 1 (Hardenbol et al. 1998); Figs 7, 9, 11.

3. Palynological associations from the interval (Tav-3) between 414.0 and 394.3 m depth (occurrences of *Membranophoridium aspinatum* and *Svalbardella* sp.; indirectly NP16, polarity chron C18n; ~39.5–38.0 Ma) are overwhelmingly dominated by terrestrial palynomorphs; dinoflagellate cysts represent only ~5% of the total assemblage. The aquatic palynomorphs are dominated by peridinioid cysts (Wetzelielloideae, *Phthanoperidinium*- and *Deflandrea*-groups; up to 60%) and the *Areoligera*-group (35–60%), members of *Spiniferites*-group are common at the base of this interval with a constant presence of sporadic *Impagidinium* spp. This slight increase of the *Spiniferites*-group at the base of this phase, combined with the consistent presence

of *Impagidinium* spp. reflects a transgressive pulse superimposed on a long term general shallowing of the basin. This part of the section is thus tentatively assigned to a TST, and correlated to part of NW European Bartonian 1 sequence (Hardenbol et al. 1998); Figs 7, 9, 11.

4. Palynological associations of the interval (Tav-4) between 394.3 and 361.0 m depth (FOs of *Heteraulacacysta porosa*, *Lentina serrata* and *Charlesdowniea variabilis*; tentatively C17 chron; ~38.0–36.9 Ma) are characterized by a very low numbers of marine palynomorphs (maximum 10% of the assemblage) and a very pronounced dominance of angiosperms (up to 85%). A peak of the *Areoligera*-group characterizes the dinoflagellate cyst associations; peridinioid cysts are also very common (~40%). The palynomorph assemblage therefore suggests high-energy marginal settings with nutrient supply from the land. This interval is tentatively interpreted to be a part of a HST, and correlated to part of NW European Bartonian 1 sequence (Hardenbol et al. 1998); Figs 7, 9, 11.

5. The interval (Tav-5) between 361.0 and 320.8 m depth (occurrence of *Thalassiphora fenestrata*; tentatively C16r-C16n,2n. chrons; ~36.9–35.7 Ma) revealed a very distinctive palynomorph assemblage marked by a bloom of aquatic fern *Hydropteris indutus* (with the concurrent presence of *Azolla vera*) and scanty dinoflagellate cysts (less than 3% of the assemblage). The acme of aquatic ferns reflects a significant influx of freshwaters probably in extremely brackish conditions during a low sea level or a transgressive trend; this implies to assign this interval to a lowstand systems tract, or, alternatively, a transgressive systems tract (TST), correlated to part of NW European Priabonian 1 third order cycle (Hardenbol et al. 1998); Figs 7, 9, 11.

6. The interval (Tav-6) from 320.8 to 275.4 m depth (FOs of *Thalassiphora reticulata* and *Rhombodinium longimanum*; tentatively chrons C16n.1r, C16n.1n and C15r or alternatively only C15r, ~35.7?–35.0 Ma) is marked by a clear palaeoenvironmental change: the aquatic fern *H. indutus* disappears, and dinoflagellate cysts become relatively more numerous (up to 25%), although continental palynomorphs continue to dominate the associations. Dinoflagellate cyst assemblages are dominated by the peridinioid *Deflandrea*- and *Phthanoperidinium*-groups and the *Areoligera*-group; the *Thalassiphora*-group is very common (30%) at the base of this interval; this suggests that this interval represents restricted, high-energy, marginally marine settings with a high delivery of nutrients from river mouths. Combined with a slight increase in numbers of *Homotryblium*- and *Spiniferites*-groups at the base of the interval, and sporadic presence of *Impagidinium* spp. (maximum 5%) in most of the samples, this implies to assign this interval to a part of a transgressive systems tract (TST), tentatively correlative to part of the NW European Priabonian 2 sequence (Hardenbol et al. 1998) The maximum flooding surface is tentatively placed at 275.4 m based on the highest percentage and diversity of marine palynomorphs (Figs 7, 9, 11).

7. Palynological associations from the uppermost marine interval (Tav-7) between 275.4 and 265.0 m depth (chron C15n, ~35.0–34.8 Ma) are dominated by terrestrial palynomorphs (primarily angiosperms). Dinoflagellate cysts only reach 10% of the total assemblage. Dinoflagellate cyst assemblages are dominated by peridinioid cysts (Wetzelielloideae, *Deflandrea*- and *Phthanoperidinium*-groups), common *Areoligera*-group and a slight increase in the *Cordosphaeridium*-group, again suggesting coastal settings with a continued nutrient supply from land. This interval is tentatively assigned to a part of a highstand systems tract (HST), correlative to part of the NW European Priabonian 2 sequence (Hardenbol et al. 1998); Figs 7, 9, 11.

DISCUSSION

Considerable differences in dinoflagellate cyst diversity and ratio dinocyst/pollen in the Upper Lulinvor and Tavda Formations clearly indicate significant environmental changes in the West Siberian marine Basin during the early, middle and late Eocene, elucidating the sea level history, and the connections between the West Siberian Sea and World Ocean during this time.

The dominance and high diversity of mid-latitude dinoflagellate cysts in the palynological assemblages of the middle Ypresian (~ 52.2–51.0 Ma), suggest a sustained connection between the West Siberian Sea and the North Sea Basin via the Peri-Tethys and Arctic Ocean during this time interval. Based on the palaeoecological characteristics of the palynomorph associations, shallow water conditions are suggested during the middle Ypresian in the south-eastern part of the West Siberian Sea.

The late and terminal Ypresian dinoflagellate cyst assemblages of the section No. 011-BP are equally similar to their counterparts from the North Sea Basin and Peri-Tethys realms: a succession of West European dinoflagellate cyst events (principally FOs of *Areosphaeridium diktyoplokum*, *Areosphaeridium michoudii*, *Wetzeliella articulata* subsp. *brevicornuta*, *Hystrichosphaeropsis costae*, *Wetzeliella eocaenica* and *Duosphaeridium nudum*, Iakovleva & Heilmann-Clausen 2010) has been revealed here, indicating the continuation of marine connection with the Peri-Tethys and North Sea Basin (~51.0–48.7 Ma). Noteworthy is, nevertheless, a relative decrease in the ratio dinocyst/pollen and dinoflagellate cyst diversity in the upper Ypresian assemblages and the absence of clearly early Lutetian deposits. These observations suggest the beginning of a weak regressive cycle (NW European third order cycles Ypresian 8 and 10), followed by stronger regression, culminating with the cessation of marine sedimentation coeval with deposition of the Lu1 and Lu2 cycles in NW Europe in the early Lutetian (NP14 interval; ~48.7–44.8 Ma). This last assumption is in accordance with the previously proposed idea of disconnection of the West Siberian Sea from the Arctic Ocean and its regression from north during the Lutetian (Iakovleva & Kulkova 2003). Indeed, it seems likely that the West Siberian Sea shallowed significantly during the Lutetian, and only its central and (at times, ~44.8–43.6 Ma) southern parts remained connected to the Turgay Strait. It can be noted here that a similar early Lutetian sea-level fall has been recently recognized from the Aktulagay outcrops, Kazakhstan, eastern Peri-Tethys area (Iakovleva et al. 2004).

According to new data, marine sedimentation became re-established by the end of the Lutetian (from ~40.7 Ma, lowermost Tavda Formation) in the south-eastern part of the West Siberian Sea. This suggestion is in accordance with previously published information from NW Siberia (Iakovleva 2000, Iakovleva & Kulkova 2003). However, in general, the Tavda Formation, characterized by ~inner-neritic, rather brackish conditions (in comparison with the Upper Lulinvor Formation), confirms the deterioration of marine connections with the World Ocean and a general slow regression of the West Siberian Sea during the late Bartonian-Priabonian. While the Ypresian and Lutetian dinoflagellate cyst associations of the Upper Lulinvor Formation are clearly cosmopolitan, the endemism increases toward the late middle and late Eocene. Thus, the Tavda Formation is marked by a strong influx of Siberian endemics, primarily *Kisselovia ornata* and *Wetzeliella irtyschensis,* which are very common in the Bartonian. This increase of the endemic flora, combined with very low ratio dinocyst/pollen and dinoflagellate cyst diversity within the middle part of the section, probably reflects a laboured and weak (sometimes interrupted) connection with other marine basins through the Turgay Strait (from ~40.4 Ma). According to present data, the strongest regression probably corresponds to the beginning of the Priabonian (tentatively ~36.9–35.7 Ma): during this time interval the south-eastern part of the West Siberian Sea was situated in extremely brackish conditions with important influx of freshwaters, which provoked the *Hydropteris indutus* bloom (*Azollites*-group). The last short and relatively slight sea-level rise characterizes late Priabonian (~35.0–34.8 Ma). This is supported by a relative increase in dinoflagellate cyst diversity and in dinocyst/pollen ratio. It is associated with the FO of *Thalassiphora reticulata* and *Rhombodinium longimanum* in the present section, and was previously observed also in the borehole No. 9 (Novosibirsk region, Akhmetiev et al. 2004a). Based on palaeomagnetic data (Gnibidenko 2006), suggesting the absence of sediments of Polarity Chronzone C13, the interruption of marine sedimentation in south of West Siberian Basin occurred during the late Priabonian, no later than 34.8 Ma.

CONCLUSIONS

The present study demonstrates the utility of detailed palynological analysis (dinoflagellate cysts, aquatic algae and continental palynomorphs) for interpretations of third-order sea-level fluctuations and palaeosetting reconstructions of the West Siberian marine Basin, characterized by non-calcareous siliclastic and terrigeneous sedimentation.

Successive palynomorph assemblages from borehole No. 011-BP allowed the recognition of

12 depositional cycles (respectively Lul-1 to Lul-5 and Tav-1 to Tav-7), attributed to third-order sea-level fluctuations. Analysis of quantitative distribution of dinocysts, aquatic and continental palynomorphs through the Eocene section indicates significant environmental changes characterising the West Siberian Eocene, viz:

a) The West Siberian marine basin was in constant marine communication with the Arctic Ocean and Peri-Tethys during the Ypresian (~52.2–48.7 Ma);

b) The first major sea level fall occurred during the early Lutetian (~48.7–44.8 Ma);

c) The next second-order transgression in Western Siberia corresponds to the latest Lutetian-early Bartonian; nevertheless, from Bartonian the West Siberian marine Basin lost connection with the Arctic Ocean, whereas its connection with the Tethyan realm (via the Turgay Strait) became limited or even sometimes interrupted; the second major sea level fall is tentatively recognized during the early Priabonian (~36.9–35.7 Ma);

d) The last and short second order transgression in Western Siberian marine basin occurred during the middle Priabonian (~35.0 Ma); whereas the last major sea level fall provoked the sea to definitively leave the Western Siberia during the late Priabonian, no later than 34.8 Ma.

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