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THE PALEOGENE HISTORY OF THE WESTERN SIBERIAN SEAWAY – A CONNECTION OF THE PERI-TETHYS TO THE ARCTIC OCEAN

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KEYWORDS

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ABSTRACT

During the Paleocene and Eocene the extratropical Central Eurasia was the main seaway link of the contiguous south to north seaway system connecting the Tethys and Arctic oceans. The seaway extended from North Pakistan and India to North Siberia through a system of inland seas and straits and acted as a kind of heat transfer to the Arctic during this time. Before the emergence of the latitudinal Alpine-Himalayan orogenic belt, the Tethys and its marginal seas to the north formed a continuous shelf area. The closest linkage of the water masses and exchange of biota between the Tethys and the Arctic ocean existed during the Thanetian and Ypresian. Latest Paleocene - Early Eocene heat transfer developed both by water- and atmospheric currents at the mid- latitudes of Central and Eastern Eurasia. From the end of the Paleocene or earliest Eocene onwards this system was complicated by latitudinally oriented straits that ensured the connection of the Northern Peri-Tethys with the Atlantic through the North Sea basin. The combination of two sea systems controlled the climatic history of the Central Asia regions from the Late Paleocene until the Late Eocene. During the Bartonian and Priabonian the West Siberian inland sea was isolated completely from the Arctic Basin during the last phase of marine sedimentation. It was connected with the Turan sea through the Turgai strait. Azolla beds accumulated periodically during eustatic sea level lowstands in fresh-water surface waters, and in dysoxic bottom waters inhabited stunted benthos during the Bartonian – earliest Late Eocene. During the Late Eocene eustatic rise of sea level the input of saline water from the Peri-Tethys increased and the West Siberian basin became normally marine again. The monsoonal subtropical climate during Ypresian – Early Lutetian was transformed to subtropical seasonal with semi-arid features during the Late Lutetian – Early Priabonian, up to subtropical to warm-temperate with alternations of humid and arid phases in the Late Priabonian.

1. INTRODUCTION

Subsequent to the closure of the Western Interior Basin along the Cordilleras in Maastrichtian times there existed only one epicontinental north-south trending seaway in the northern hemisphere in Eurasia. This Paleogene seaway in northern Central Eurasia extended for 5000 km from the Tethys in southern Asia to the Arctic basin in the North. This system of marine straits primarily controlled surface and bottom water currents and played a decisive role in organisms life, specially dispersion and migrations of plankton and benthic organisms. This meridional seaway also served as a boundary between the main palynological provinces: the *Normapolles* and the *Aquilapollenites* realms (Zaklinskaya, 1977). Biotic and abiotic events were largely similar in the West Siberian and the Arctic regions in the Paleocene and Eocene (Akhmetiev et al., 2010).

During investigations carried out on the Lomonosov Ridge (Backman et al., 2006) several peculiar features in the marine succession, biota and events were found. The first anomalous event was an increase in the surface water temperatures in the polar areas up to 20ºC and more which was associated with the global warming episode at the Paleocene-Eocene Thermal Maximum (PETM). The second anomalous event recognized was the mass occurrence of the aquatic fern *Azolla*, which indicates a desalination of the surface waters at the Early-Middle Eocene transition (Akhmetiev et al., 2010) The study of palynomorphs (dinocysts, pollen grains, and spores) from the marine Paleogene sediments of West Siberian Plate, which were deposited under conditions similar to the Arctic Basin, allows these events to be at least partly interpreted in a paleogeographic context. In Western Siberia these sediments were studied both in boreholes and outcrops (Akhmetiev et al., 2010).

The aim of this paper is to demonstrate that (1) the PETM sequences were deposited in the same environmental setting in both regions; (2) the PETM events were related to heat transfer from the Tethys by oceanic and atmospheric currents from tropical regions to the Arctic Basin through a seaway system, the Western Siberian seaway within Central Asia; (3) *Azolla* beds were forming in line with a common scenario in those inland basins that were partly isolated from the open ocean and (4) these Paleogene events in the Arctic were controlled by processes that took place in the West Siberian realm.

Recently new information on the composition of marine Paleogene sediments and biota including Azolla beds was obtained from two wells in the Russkaya Polyana area in the marginal part of the Omsk trough (southern part of West Siberian

Plate). We largely use the lithostratigraphic units of the West Siberian marine Paleogene sections, which are defined in the Unified Stratigraphical Chart approved by the Interdepartmental Stratigraphic Commission of Russia in 2001 (Unified, 2001).

2. Results

2.1 Communications of the Paleogene Turan and West Siberian seas with open oceans

The existence of a meridional seaway system between the Arctic and the Tethys oceans in western Asia started in the Late Cretaceous (Naidin, 2007). It was interrupted at the Cretaceous/Paleogene boundary and resumed from the Middle Danian to the Lutetian. From the Eocene onwards, this system was complicated by latitudinal straits that connected marginal and inner seas of the Northern Peri-Tethys with the Atlantic Ocean. From the Middle Eocene onwards, as the Indian Plate collided with Asia, planktonic biota dispersed northward to the Turgai strait and farther, to the West Siberian sea, from the marginal Turan sea only. The cold-water benthic fauna of the West Siberian sea was more endemic (Akhmetiev and Beniamovskii, 2006; Akhmetiev et al., 2010).

In contrast to the earlier concept of continuous marine sedimentation on the West Siberian Plate in the Paleogene (Shatskii, 1978) recent studies have revealed several breaks associated with block movements of the basement and eustatic variations. There exists also evidence of partial erosion of sediments during changes of depositional systems such as the appearance of redeposited palynomorphs (Classopollis, Aquilapollenites etc.) in the basal members of younger units. These breaks resulted in attenuation or, conversely, enhancement of the effect of open water masses located north and south of the Western Siberian sea on the seaway currents and the sedimentation in the inland seas.

The largest eustatic transgressions occurred in the Ypresian, especially the Early Ypresian. They also occurred in the Middle Lutetian, in the Late Bartonian and at the end of the Priabonian. The Ypresian and Lutetian transgressions came from opposite directions, i.e. the Ypresian transgression from the south and the Lutetian transgression from the northwest.

Oceanic currents were also associated with transgression directions. The southern and eastern districts of the West Siberian Plate were influenced by the warm-water southern current running northward along the eastern edge of the plate through the Turgai strait. Wet and warm climates due to this large warm-water current favored the formation of bauxites, e.g. on the right bank of Yenisei River (Leipzig et al., 1976). Highly thermophilic assemblages of different microplanktonic groups were found near the southern boundary of the West Siberian plate, as well as palynological assemblages with a great taxonomic richness of thermophilic plant pollen (Akhmetiev et al., 2004a, b).

The clayey-siliceous Lyulinvor Formation formed in the area of the south-eastern plate exposed to currents from the Tethys during the Early Paleogene. A cold current from the Arctic, running southwards along the western edges of the plate resulted in the accumulation of "opoka" (gaizes = siliceous sandstones) in the Paleocene and diatoms in the Early-Middle Eocene (Serov and Irbit formations).

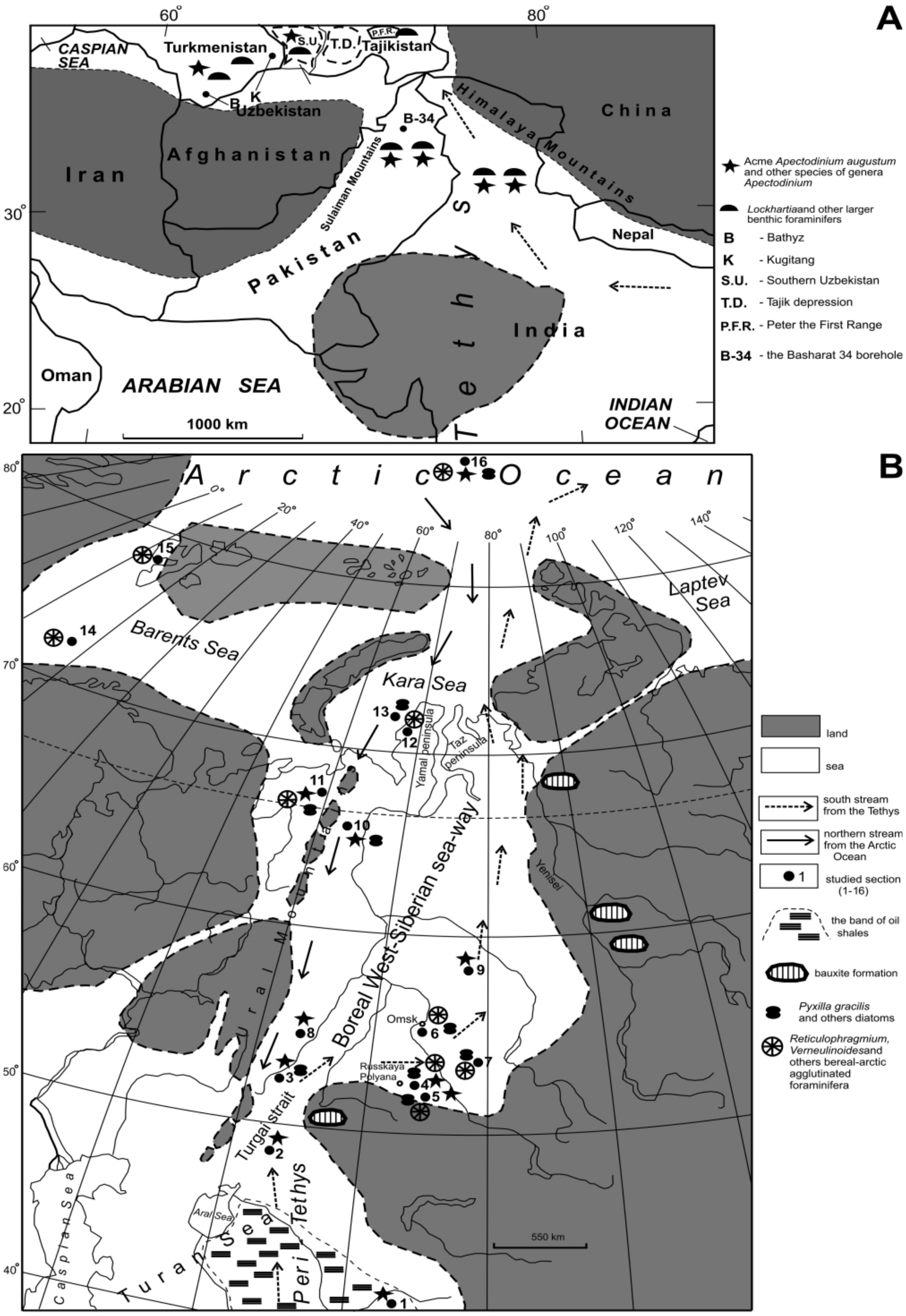
The Tavda Formation formed at the final stage of the marine sedimentation during the Bartonian and Priabonian. During deposition of the Tavda Formation the West Siberian inland sea was entirely separated from Arctic basin and opened only to the Turan sea through the Turgai strait. In the northern Yamal-Taz structure-facies zone of the platform, except for its southern margin, the Tavda Formation was replaced by continental sands.

The sea retreated from the West Siberian Plate and Turgai trough at the Eocene/Oligocene boundary as a result of a global regression. This event followed the short but widespread Late Priabonian transgression, which in turn, followed the long high-amplitude regression, lasting from Late Bartonian to the first half of the Priabonian during the formation of the boundary beds with Azolla dividing the lower and upper parts of the Tavda Formations.

2.2 The Paleocene and Early Eocene stable meridional sea system of Central Eurasia connecting the Tethys and Arctic basins

During the Early Paleogene the maximum development of marine transgressions occurred in the mid-latitudes of Central Eurasia. The area of the West Siberian Plate covered by sea reached its maximum, above 60%. The warmer areas of the Turan Sea, the Turgai strait, and the gulfs in middle Asia and Afghanistan also reached their maximum extent during the Early Eocene.

Conditions during the biosphere crisis at the Paleocene/Eocene boundary (PETM) are of particular interest. The temperature of the surface layers of the globe reached the highest value in the entire Cenozoic (Akhmetiev, 2004; Sluijs, 2006). The highest mean annual temperatures in circumpolar regions can be judged from the discovery of palm leaves and pollen (Alaska, Koryakia, and Kamchatka), leaves and reproductive organs of Myrtaceae, Magnoliaceae, Loranthaceae, Lauraceae, and Altingiaceae (Kharaulakh Range, the lower reaches of the Lena River, and interfluve of the Yana and Indigirka Rivers; Akhmetiev, 2010; Akhmetiev et al., 2010). At the same time, thermophilic planktonic foraminifera and organic-walled phytoplankton spread to the southern and eastern areas of the West Siberian Plate. It is known that the biosphere crisis of the PETM was reflected in the compositions of benthic faunas, some groups of non-carbonate microplankton of the open ocean and epeiric water basins, large terrestrial mammals, and higher terrestrial plants (Speijer et al., 1997). The crisis was marked by negative excursions in carbon isotope composition ($\delta^{13}C$) to 2–4‰ or even more and oxygen isotope composition ($\delta^{18}O$). However, this biosphere crisis, unlike some other Phanerozoic ones, was not determined by a preceding glaciation, geomagnetic inversion, or impact events (Akhme-


A
60°
80°
30°
20°
CASPIAN SEA
Turkmenistan
S.U.
T.D.
P.F.R.
Tajikistan
B
K
Uzbekistan
Afghanistan
Iran
China
B-34
Sulaiman Mountains
Himalaya Mountains
Nepal
Pakistan
Tethys
India
Oman
ARABIAN SEA
INDIAN OCEAN
1000 km
★ Acme *Apectodinium augustum* and other species of genera *Apectodinium*
Lockhartia and other larger benthic foraminifers
B - Bathyz
K - Kugitang
S.U. - Southern Uzbekistan
T.D. - Tajik depression
P.F.R. - Peter the First Range
B-34 - the Basharat 34 borehole
B
Arctic Ocean
0°
20°
40°
60°
80°
100°
120°
140°
80°
70°
60°
50°
40°
Barents Sea
Laptev Sea
Kara Sea
Yamal peninsula
Taz peninsula
Yenisei
Ural Mountains
Boreal West-Siberian sea-way
Omsk
Russkaya Polyana
Turgai strait
Aral Sea
Caspian Sea
Turan Sea
Peri Tethys
550 km
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
land
sea
south stream from the Tethys
northern stream from the Arctic Ocean
● 1 studied section (1-16)
the band of oil shales
bauxite formation
Pyxilla gracilis and others diatoms
Reticulophragmium, Verneulinoides and others bereal-arctic agglutinated foraminifera

tiev et al., 2008). According to the concept of Akhmetiev et al. (2011) and Akhmetiev (2012),appreciable burial of Corg and δ^{13}C took place mainly on continental and inland sea shelves (e.g. Romankevich, 1976; Solov'ev, 2002); followed by global warming allowing heat transfer from the tropic zone to high latitudes. An attempt to prove the possibility of efficient heat transfer by the Central Asian meridional system directly from the Tethys to the Arctic is presented. It is based on the homogeneity of shelf sedimentation and on the fact that terminal Paleocene and Early Eocene sediments north and south of the recent Alpine–Himalayan orogenic belt are highly similar in composition and thickness. Another piece of evidence is provided by signs of the uniformity of not only planktonic but also some groups of benthic biota in Peri-Tethyan sections of the North Afghanistan Platform and Tajik Trough with the Tethyan biota in sections of the Sulaiman Mountains, Salt Range, and West Himalayas.

New palinspastic and tectonic reconstructions, including those for the Paleocene–Eocene boundary interval, provide better grounds for discussions of heat transfer from the tropical belt to high latitudes during these times. We used Scotese's (2002) model with paleogeographic modifications which forms the basis for the construction of the International Tectonic Map of the World (IUGS International Union of Geological Sciences; Fig. 1). The model is different from those previously constructed for the end of the Cretaceous (Gordon, 1973; Naidin, 2007) (Fig. 2) but has inherited some of its features, including the high pressure zone, which is located, as in the Early Eocene, in the Arctic sector of the Northern Hemisphere (Parrish and Curtis, 1982). For reference, a chart of ocean currents proposed for the Maastrichtian (Naidin, 2007), is presented in Figure 2b.

We present this model for comparison, as the Late Cretaceous trade winds (lower latitudes) had the same directions as during the Early Paleogene and had the same branching currents: one east-west and the other to the north (towards the Turgai Strait; see Gordon, 1973; for more details see Akhmetiev et al., 2004; Akhmetiev, 2007, 2011). This model clearly shows shelf areas between ancient blocks, which link the Tethys and marginal basins. In accordance with this model, the existence of an independent northern branch of the trade drift from the Tethys through its marginal seas to the Turgai Strait, the West Siberian epeiric sea, and farther to the Arctic Basin is substantiated.

Figure 1: Paleogeographical scheme of the central part of Eurasia in the Late Paleocene – Early Eocene times. A – Distribution of *Apectodinium* and *Lockhartia* acme on both sides of the latitudinal Alpine-Himalayan mountain belt (Edwards, 1992; Bugrova, 1997; Bugrova and Starshinin, 2012 (in press); Scotese, 2002; Zakrevskaya, 2011 with author's supplements). B – Bathyz, K – Kugitang, S.U. – Southern Uzbekistan, T.D. – Tajik Depression, P.F.R. – Peter the First Range, B-34 – the Basharat 34 borehole. B – The meridional seaway system between Tethys and Arctic on the base of paleogeographical maps of Central Eurasia and studied marine sections in the Tethys, Peri-Tethys, Turgai strait, West Siberian basin and Polar Arctic (using maps by Benyamovskiy, 2007; Akhmetiev and Benyamovskiy, 2010 with author's supplements). Studied sections (1-16): 1– Kurpai (Tajik depression), 2 - BHs 85 and BHs 96 (southern part of Turgai strait), 3 – Sokolovski quarry (north of Turgai strait); 4-10: sections in West Siberian basin: 4 – BH8, 5 – BH10, 6 – BH11, 7 – BH9, 8 – Pershino, 9 – BH4, 10 – BH19 Ust' Man'ya; 11– BH228 (Polar part Ural Mountains); 12 – BH - Kharasaway (Yamal peninsula), 13 – BH157 (Kara Sea), 14 – BH7119/7-1 (Torsk Formation - western part of Barents Sea) (Nagy et al., 2000), 15 – Firkanten and Basilika and Grumantbyen Formations (Spitsbergen Central Basin) (Nagy et al., 2000), 16 – Polar BH2 and BH4.

Marine Paleogene deposits that formed in the zone of northern trade drifts of the Tethys directed westward are now exposed in fault wedges in a narrow band of no less than 1500 km in the West Himalayas. This band runs from Nepal to the west through the Himachal Pradesh and Jammu and Kashmir states to Pakistan. Just before the collision, the whole area between the Hindustan block and the southern margin of Asia belonged to the contiguous Tethys seaway(s). Mainly carbonate–terrigenous and, less often, reef sediments accumulated there in the Late Paleocene and Early Eocene (Loyal and Gupta, 1990; Saxena, 1983). During transgressions, the sea ingressed deep into the South-Asian margin. In consideration of Lower Paleogene strata formed in the eastern trade drift zone of the Tethys, the Subathu Formation (type section near Simla city, Himachal Pradesh, Saxena, 1983; Edwards, 1992; Kothe, 1988) can be traced to the Jammu and Kashmir state and farther to Pakistan (Loyal and Gupta, 1990; Mirza and Sheikh, 2006). A rich dinoflagellate assemblage has been described which is also present in the Neogene Shivalik Group, Himalayan foredeep (Saxena, 1983). The formation appears as a transgressive–regressive assemblage of shelf sediments 100–150 m in thickness, formed by Upper Paleocene limestones and Eocene marls and clays. In Pakistan, Lower Paleogene deposits, similar to the Subathu Formation in composition and laterally replacing it, occur within the Salt Range, the Sulaiman Mountains, and in regions bordering Eastern Afghanistan (Edwards, 1992). In sections of the Salt Range (Nammal Pass and Nammal Dam), the Upper Paleocene is represented again by carbonate sediments, and the Lower Eocene, by clays and marls, with a composite thickness of ~ 225 m. It is subdivided (from the base) into the Hangu Formation of sandstones and clays with rare dinoflagellates, including *Adnatosphaeridium multispinosum*, and the Lockhart Formation (limestones). The uppermost Paleocene Patala Formation consists of marls with limestone interbeds with a clayey terminal member representing the PETM interval. The overlying Lower Eocene Nammal Formation consists of clays and marls with rare limestone interbeds (Edwards, 1992). The Late Paleocene and Early Eocene planktonic foraminifera and nannoplankton assemblages have the same taxonomic composition as in the northern parts of Indian Ocean, and the coeval assemblages of Middle Asia and southern Kazakhstan (Krasheninnikov and Basov, 2007). Thus, all these sections belong to the same Tethyan realm.

Dinoflagellates and large benthic foraminifera show also strong similarities pointing to connected water masses during the Paleogene. Edwards (1992) studied dinoflagellates from three Upper Paleocene–Lower Eocene sections of the Salt Range

(Fig. 1), and Kothe (1988) from coeval assemblages in the Sulaiman Mountains and near Kohat. It should be noted that these dinoflagellate assemblages are similar in composition to coeval assemblages in West Siberia. In addition to the characteristic taxa of the PETM, such as *Apectodinium augustum*, *A. paniculatum*, etc., present in terminal Paleocene beds in West Siberia, two samples from the Patala and Nammal Formations of the Nammal Dam section contain species occurring in West Siberia (Letters P and N indicate the occurrence in the Patala and Nammal Formations, respectively.): *Diphyes colligerum* (P), *Adnatosphaeridium multispinosum* (P, N), *Apectodinium paniculatum* (P), *A. homomorphum* (P), *Cordosphaeridium gracile* (P), *Polysphaeridium subtile* (P, N), *Muratodinium fibrianum* (P, N), *Cribroperidinium giuseppei* (P), *Hafniasphaera septata* (P), *Melitasphaeridium pseudocurvatum* (P, N), and *Homotryblium tenuispinosum* (P, N). In addition, genera common to West Siberian ones and not identified to species level were found: *Spiniferites* spp., *Operculodinium* spp., *Achillodinium* sp., *Lejeunecysta* sp., and *Wetzeliella* sp. The range of the PETM event, containing up to 20 taxa, was the richest. *Areoligera* sp. and *Wetzeliella astra* were found in the section of the Basharat 34 borehole. The latter had been found in the lower part of the Lyulinvor Formation in West Siberia (Kul'kova, 1994). *Thalassiphora pelagica* was found in marls of the Patala Formation. The overall number of taxa from sections of the Upper Paleocene and Lower Eocene common to the Salt Range and West Siberia is no less than one-half of all taxa found in the Salt Range hitherto (Kul'kova and Zaporozhets in Akhmetiev, 2004a, b; Iakovleva and Heilmann-Clausen, 2010). Simultaneously with Early Paleogene phytoplankton, assemblages of large foraminifers were studied in the Salt Range and other regions at the Pakistan–Afghanistan border (Weiss, 1993). The presence of numerous Rotaliida, including *Lockhartia* (described in the type section of the Upper Paleocene Lockhart Formation in the Salt Range); *Miscellanea*, *Discocyclina*, *Ranikothalia*, and *Kathinia* exhibit little difference between the Salt Range assemblage and assemblages found in the Tajik depression, Peter the First Range, and southern and southeastern Turkmenistan (Fig. 1). As reported by Zakrevskaya (2011), Bugrova and Starshinin (2012, in press), *Lockhartia* occurs in sections of the Shikergin Formation in the Peter the First Range together with the genera *Kathinia*, *Rotalia*, and *Ranikothalia*, common also in shallow-water Lower Paleogene deposits in Eastern Afghanistan, Pakistan, Northwestern India, and Saudi Arabia. *Miscellanea*, *Nummulites* and *Lockhartia luppovi* have been found in Middle–Upper Paleocene limestones of the Bukhara regional stage of Tajikistan. The last is also present in Bathyz, Kugitang, and Southern Uzbekistan (Bugrova, 1997).

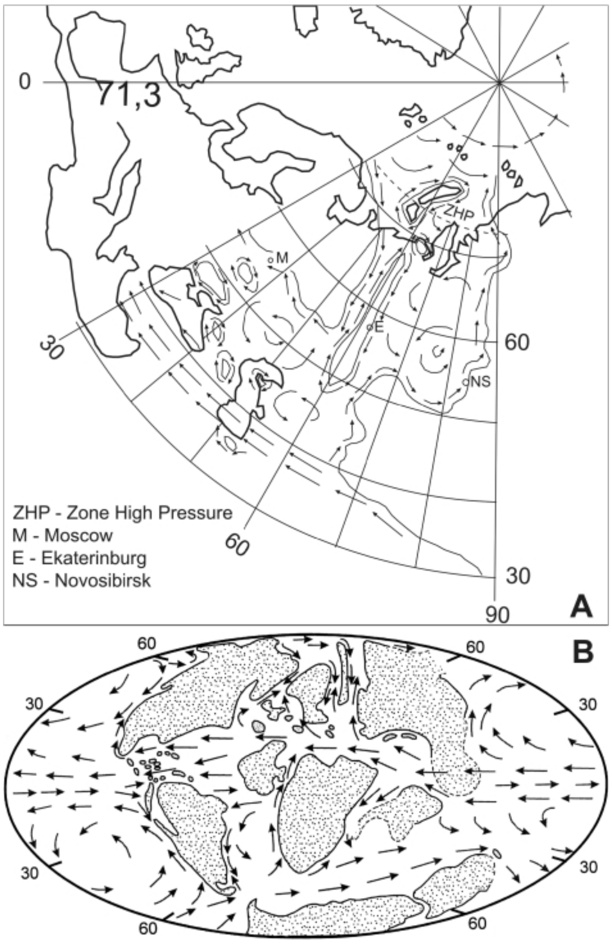


Figure 2: Schematic models of surface oceanic circulation from Maastrichtian to the Paleocene-Eocene transition: A – according to. Naidin (2007) and B – according to Gordon (1973).

The age of the Middle Asian localities is confirmed by the presence of planktonic and small benthic foraminifers and nannoplankton. It clearly points to the absence of barriers in the dispersal of the Tethyan fauna of Northern Pakistan and India through meridional passes to marginal basins of the Northern Peri-Tethys, to the warmest southern parts of Peri-Tethyan water areas. This fact agrees with the hypothesis put forward by Davidzon et al. (1982) that the Tajik depression together with adjacent regions of Southern Afghanistan was a vast shallow water gulf of the tropical Tethys Ocean. To the north, the basin was connected with shelf seas in present Uzbekistan and southern Turkmenia. The benthic fauna, characteristic of cooler waters, was rapidly losing its typically Tethyan components and gave way to Arctic ones to the north. At the same time, warm-water plankton assemblages, inhabiting the photic zone, moved north with the warm surface current from the Tethys.

Scarce works published by Indian and Pakistan specialists in recent years (Mirza and Sheikh, 2006; Sarma, 2006) supplement earlier data on the structure of the narrow northern band of the Tethyan shelf until its final disappearance in the upper Eocene. Assemblages of large foraminifers, resembling western ones and containing Late Paleocene and Early Eocene *Lockhartia*, *Assilina*, and *Ranikothalia*, also occur to the east of West Himalayas (Shivalik Hills). They have been found in the Assam–Arakan Basin behind the outlet from the narrow collision shelf zone of the Northern Tethys to its open area.

The data on the distribution of Early Paleogene planktonic and large foraminifers in Upper Indian shelf basins (Weiss, 1993, Plate 3, Fig. 12) allow a clearer view of the extent of the most intense biotic exchange between the Hindustan and

Middle Asia Basins. In the Indian Ocean, they are confined to the second half of the Thanetian–Early Ypresian interval (*Morozovella velascoensis*, *Acarinina acarinata* and *Morozovella subbotinae* Zones, Krasheninnikov and Basov, 2007). The presence of *Lockhartia* spp., *Assilina leimeriei*, *Ass. pustulosa*, *Nummulites globosus*, etc. (Weiss, 1993; Zakrevskaya, 2011; Bugrova and Starshinin, 2011) confirms the same level of biotic exchange with regard to large foraminifers (zones SBZ4-SBZ8). It matches the time of the maximum development of the Early Paleogene transgression and the temperature maximum during PETM. We reconstruct pathways of the Tethyan biota via the Mediterranean and the Crimea–Caucasus region. According to the adopted palinspastic reconstruction, the Tethys was divided into northern and southern branches in the Salt Range region until the end of the Early Eocene at which time the Indian-Eurasian plate collision led to restriction and eventual termination of the circulation of Tethyan water between Eurasia and the Indian Plate. The supply of Tethyan water and heat transport completely ceased at the beginning of the Middle Eocene, after the completion of the Early Eocene warming. As the northern branch of the Tethys contracted to the size of a sea strait north of Hindustan, the velocity of the trade drift must have increased owing to piling of water masses. Surface water temperature at sites near the origin of present day northern trade winds is no more than +25°C, and it rises to +26-27°C as the currents move into the tropics from east to west. It is reasonable to infer that during the PETM the temperature of the northward trade drift at its bifurcation was no less than +27°C. The temperature of surface water in the south of the Turan Sea, where Tethyan warm water was transported, was about the same. The sandy intercalations regularly found at the top of the clayey beds are associated with a stronger trade drift activity (Loyal and Gupta, 1990). In the Early Eocene, as the shelf strait between the Indian Plate and Eurasia was constantly shrinking, water current velocity increased. Higher water current velocities in the Turgai Strait in the Eocene were deduced by Lipman (1965) from the morphology of radiolarian tests.

The predominantly carbonate composition of the Upper Paleocene deposits and fine terrigenous clayey composition of the Lower Eocene in Northern India and Pakistan is similar to Middle Asia basins, i.e. the Bukhara and Suzak regional stages. Clayey Lower Eocene sediments occur in all depressions of the Turan Sea basin from its southern margin (Central Karakum Desert, Bathyz, and the Alai depression) to the Aral region and the Turgai depression. As mentioned above, the proportion of the finely terrigenous component in sediments was elevated during Early Eocene warm periods, including the PETM, affecting especially dinoflagellates (e.g. Hollis et al., 2005; Akhmetiev et al., 2004a, b; Iakovleva and Heilmann-Clausen, 2010).

Two boreholes were drilled in the axial part (BH9 and 11), and two (BH8 and 10), in the southern part of the Omsk Depression in the Russkaya Polyana region (Figs. 1, 3). Core samples from BH8 (Lutetian–Priabonian) and BH10 (Thanetian–Lutetian) were studied in more detail. The first break in the Ypresian–Lutetian transition is associated with the beginning of a reduction in the meridional marine communication system, and the second transformation, with the completion of the reduction of the epeiric West Siberian Sea to a vast bay of the Turan Sea, Northern Peri-Tethys.

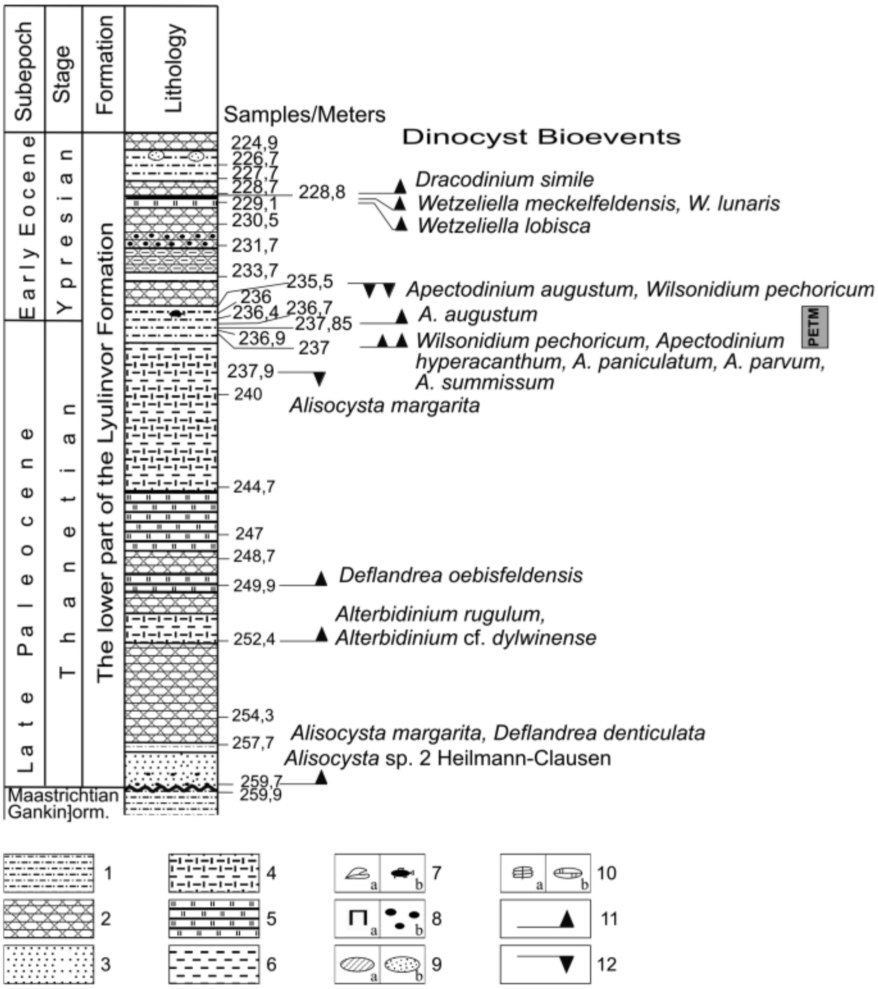


Figure 3: Well BH10. The section of the lower part of the Lyulinvor Formation (with PETM) and dinocyst events. Legend (also figs. 4 and 6): 1 – siltstone; 2 – sandstone; 3 – sand; 4 – siliceous clay; 5 – gaizes (opoka), 6 – clay, 7a – remains of molluscs, 7b – fish remains, 8a – pyrits, 8b – gravel, pebble; 9a – marcasite inclusions; 9b – silty inclusions, films; 10a – *Azolla* macroremains; 10b – siderite inclusions, concretions; 11 – first occurence levels of taxa; 12 – last occurence levels of taxa.

The thickness of the Lyulinvor Formation s. str. in BH10 is about 70 m. The lower part of the Lyulinvor Formation (259.7–237 m; Fig. 3) contains greensands, sandstones, opokas, and a member of silts with sapropelic clay interbeds associated with the PETM. The presence of *Alisocysta margarita* and *Deflandrea denticulata* supports assigment of the pre-sapropelic part to the Thanetian. The PETM horizon (237–233.7 m) is drawn at the appearance of the type species of the *Apectodinium augustum* zone and of *Wilsonidium pechricum*, *A. paniculatum*, and *A. sammissum*.

The upper part of the Lyulinvor Formation replaces the lower Lyulinvor Formation (sand–opoka beginning with the *Dracodinium varielongitudum* Zone) in BH10. It is formed by alternating sandstone and clay members. Deposits of all regional zones are recognized in the Thanetian–Ypresian transition interval and in the Lower–Middle Ypresian. They are characterized by *Areoligera/Glaphyrocysta*, *Wetzeliella astra*, *W. lobisca*, *W. meckelfeldensis*, *Dracodinium simile*, *D. varielongitudum*, *Charlesdowneia coleothrypta*, *Dracodinium politum*, and *Ch. columna* (Akhmetiev et al., 2010). A benthic foraminiferal assemblage with *Saccammina grzybowski–Nothia robusta* was found in the lower part of the Lyulinvor Formation section of BH10 and *Reophax sunfusiformis–Nothia excelsa* in the upper part of the Lyulinvor Formation (Fig. 4). Information on Lower Eocene diatoms, silicoflagellates, and radiolarians is presented in Akhmetiev et al. (2010). They assign the Ypresian diatom assemblage from the top of the Lyulinvor section in BH10 to the *Pyxilla gracilis* Zone.

Radiolarians of the upper part of the Lyulinvor Formation in BH10 include *Apocrunum* cf. *A. subbotinae* starting at 219.5 m (Kozlova, personal communication). This species is often found together with an assemblage of Ypresian planktonic foraminifers in the *Morozovella subbotinae* Zone. The *Heliodiscus lentis* Zone is recognized in the upper part of the formation in the same range as the *Pyxilla gracilis* diatom Zone (212.7–189 m). X-ray fluorescence analysis indicated an increase in minor and trace element contents, probably related to the warming and development of marine transgression, when large amounts detrital matter derived from the nearby land (Akhmetiev, 2011).

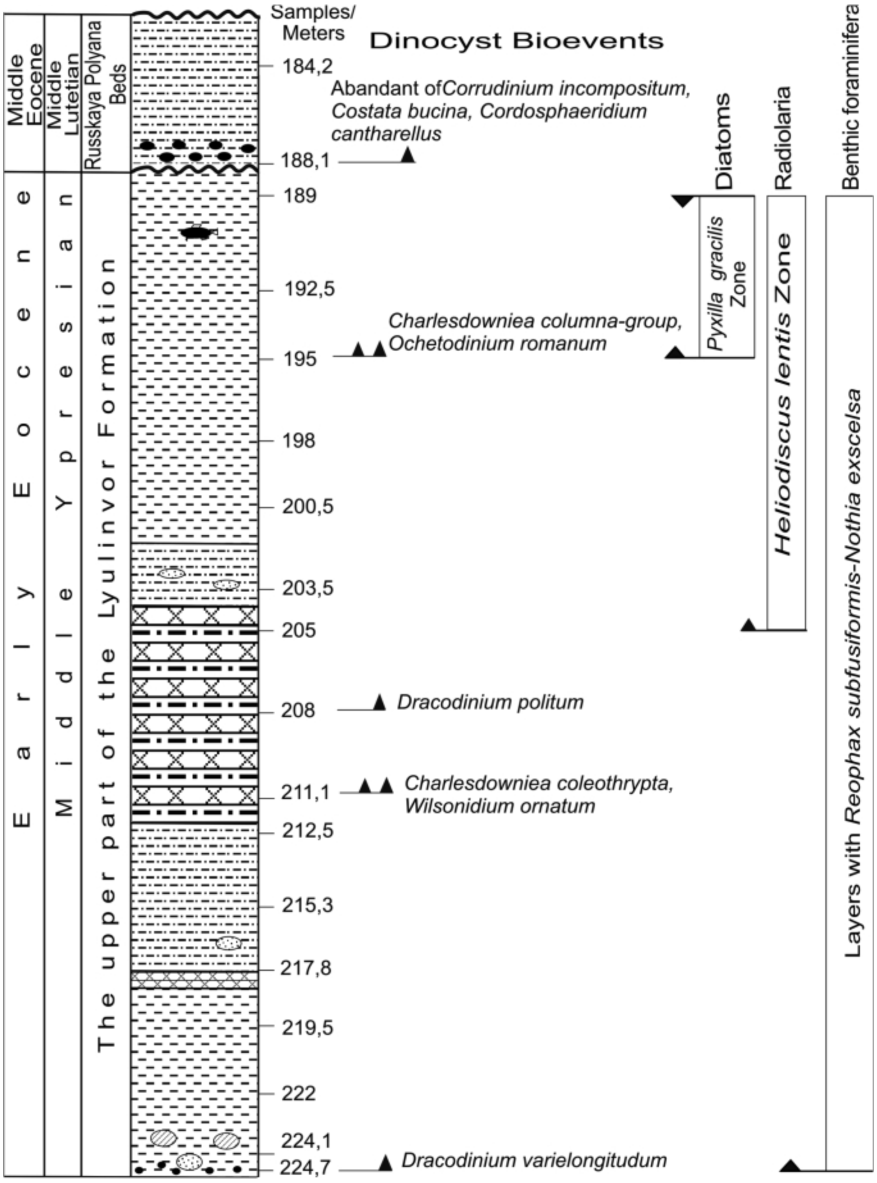


Figure 4: Well BH10. The section of the upper part of the Lyulinvor Formation, overlying PETM interval, and Russkaya Polyanskaya beds, overlying the upper part of the Lyulinvor Formation with a break (Akhmetiev et al., 2010).

2.3 The Lutetian phase of the transformation of the Tethys – Arctic meridional marine communication to an estuary system

The transition from direct marine meridional communication between the Arctic and Tethys to complete isolation of the West Siberian inland sea from the Arctic occurred in the Lutetian. Regional breaks marking its beginning and completion are recorded in both tops of formations of the transitional phase. These breaks are biostratigraphically proven in BH8 and BH10. Siliceous microbiota (radiolarians, diatoms and sponge spicules) do not pass from the underlying Lyulinvor Formation s.str. to the transitional phase sections. The upper boundary is also clearly proven lithologically and biostratigraphically. In addition to *Thalassiphora elongata*, which appears in the Lutetian, endemic dinoflagellates confirming the isolation of the West Siberia sea appear beginning at the bottom of the Tavda Formation such as *Kisselevia ornata*, *Wetzeliella irtyschensis*, Deposits of the transitional phase are designated as the Russkaya Polyana beds (Akhmetiev et al., 2010).

The Russkaya Polyana beds have different thicknesses in the wells. In BH 10; they are penetrated in the interval 188.2–182.0 m. They include only a Middle Lutetian transgressive member, which contains a dinoflagellate assemblage of *Costacysta bucina*, *Cordosphaeridium cantharella*, *Wilsonidium echinosuturatum* and dominated by *Corrudinium incompositum* (Fig.4). In BH9, in the axial part of the Omsk Depression, a unit containing a Lower Lutetian *Wetzeliella articulata–Systematophora placacantha* dinoflagellate assemblage has been found at the bottom of the Russkaya Polyana beds. It overlies the lower part of the Lutetian section in the depression. This fact confirms a significant gap at the bottom of the Russkaya Polyana beds in BH10, which falls in the Early and, partly, Middle Lutetian. The section of the Russkaya Polyana beds in BH8 is more complete. As in BH10, the upper member formed during the Middle Lutetian transgression. A basal member of darker Tavda clays occurs with a benthic foraminifer assemblage (Akhmetiev et al., 2010). The richest dinoflagellate assemblage, up to 40 species, with the characteristic Middle Lutetian species *Costacysta bucina*, is confined to the middle of the section. It corresponds to the acme of the Middle Lutetian transgression. All samples studied are dominated by cavate cysts of the genera *Deflandrea*, *Wetzeliella*, *Kisselevia*, *Charlesdowniea*, *Cerodinium*, and the proximate *Phthanoperidinium*. The predominance of these dinoflagellate genera indirectly points to the beginning of current rearrangement, because they are more typical of semiclosed rather than open sea systems (Akhmetiev et al., 2011, 2012). The fact that most samples are dominated by *Charlesdowniea coleothrypta* and *Ch. coleothrypta rotundata*, zonal species of the Lutetian deposits in the Paris Basin, Crimea–Caucasus region of the southern East European craton, and West Siberia, unambiguously indicates that the Russkaya Polyana beds belong to the Lutetian. The endemic West Siberian species *Thalassiphora elongata*

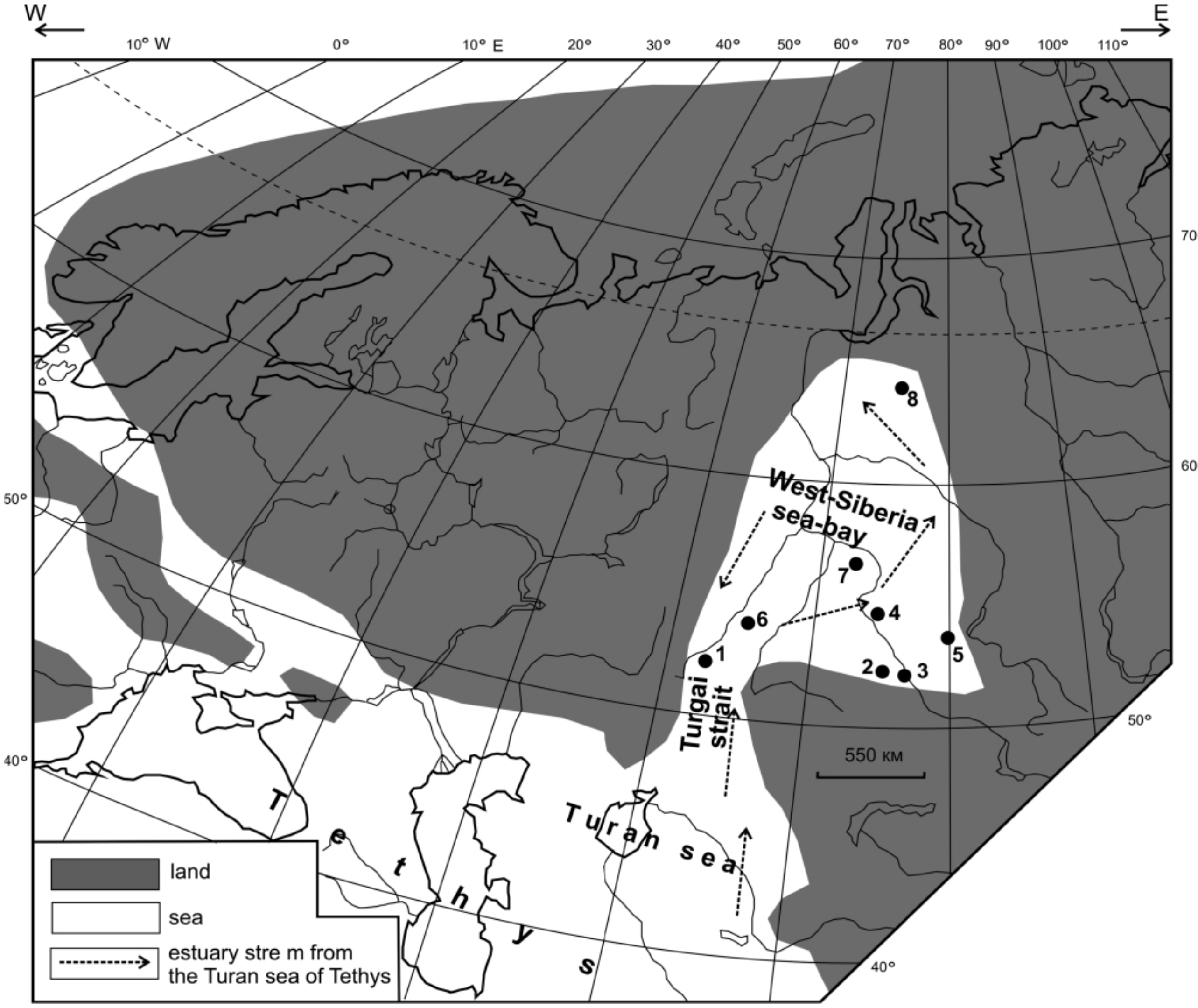


Figure 5: Bartonian-Priabonian West-Siberian semi-closed basin (using maps by Benyamovskiy, 2007, and Akhmetiev and Benyamovskiy, 2010, with author's supplements). 1-8: studied sections: 1 – Sokolovski quarry (north of Turgai strait); 2-8: sections in West Siberian sea-bay: 2 – BH8, 3 – BH10, 4 – BH11, 5 – BH9, 6 – BH36, 9 – BH32.

and the index species of the first half of the Bartonian, *Rhombodinium draco*, appear in the upper part of member 3.

A specific feature of the spore-and-pollen spectra of Lutetian deposits is the notable predominance of angiosperm pollen in the transgressive part of the transition strata. The proportions of *Pinus*, *Keteleeria*, and Taxodiaceae among conifers increase. Angiosperm pollen are represented by Fagaceae, including *Castanopsis*, and Juglandaceae. The richness of taxa currently inhabiting summer humid subtropics and the southern temperate belt of East Asia is high: Hamamelidaceae (Hamamelis, Corylopsis, Fothergilla), and Liquidambar, Loranthaceae, Myricaceae, Moraceae, Sapindaceae, and Araliaceae. Occasional grains of Palmae pollen are constantly found. The assemblage is similar to the Lutetian regional West Siberian *Castanea crenataeformis–Castanopsis pseudocingulum–Platycaryapollis* spp. assemblage, which has also been found in boreholes in southeastern West Siberia (Kuz'mina et al., 2003). The subtropical summer humid monsoon climate, formed during the maximum Late Ypresian transgression, persisted in the Lutetian. In the middle Lutetian, with the development of seaward facies, it was warm and humid. *Castanopsis* species, Araliaceae and Lauraceae constitute a significant proportion (Karasor flora in the Irtysh region, dominated by *Castanopsis* and floras of Mugodzhary and Emba region (Makulbekov, 1972; Akhmetiev, 2010). The belt of subtropical humid floras is traced to the west to Volhynia and the Kievan Dnieper region.

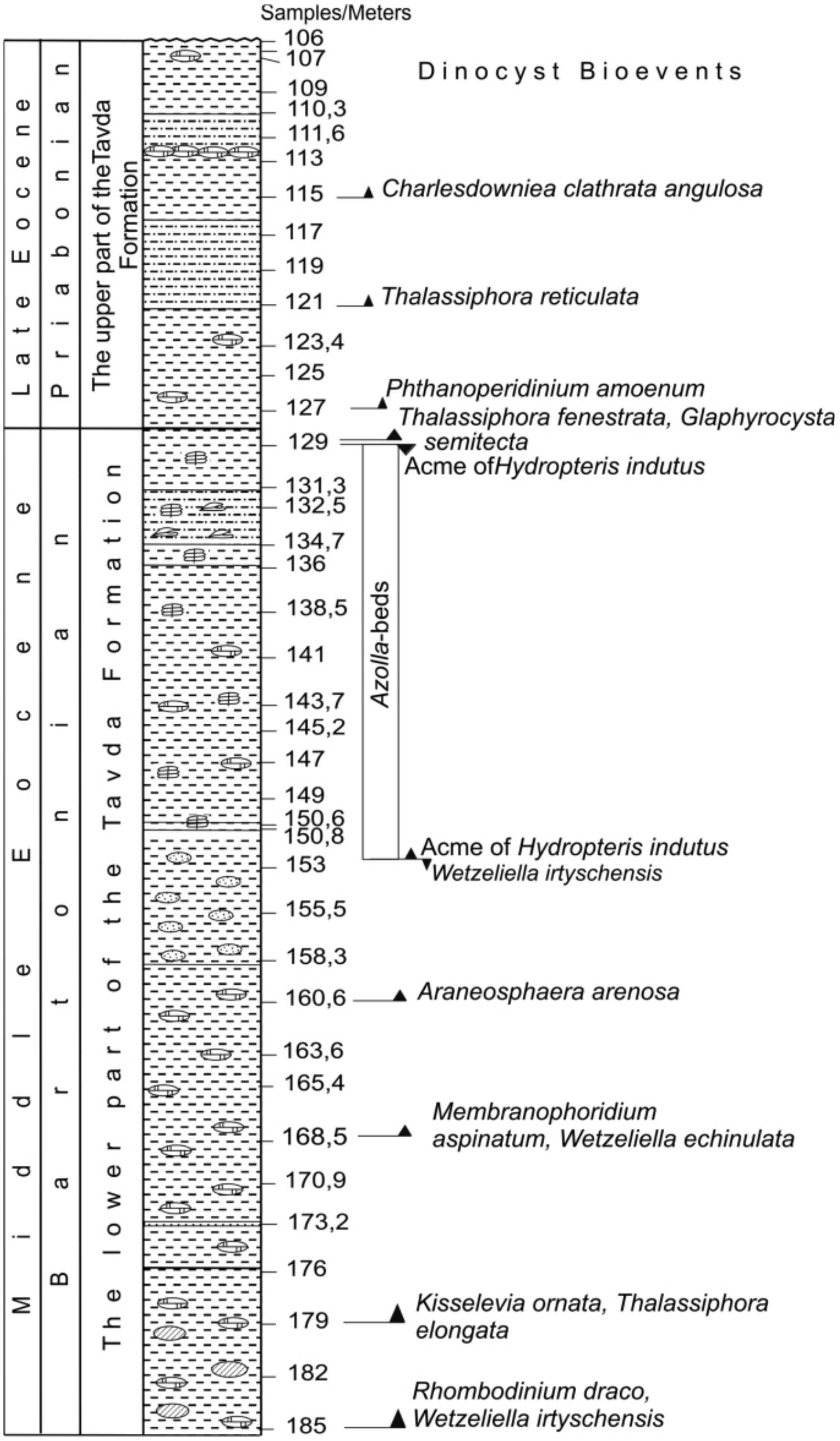


Figure 6: Section of the Tavda Formation (Bartonian-Priabonian) based on data of BH8.

2.4 The Bartonian – Priabonian history of the West Siberian sea open to the Turan sea

The third, final phase of the development of the West Siberian epeiric sea falls into the Bartonian–Priabonian transition (Tavda age) (Figs. 5, 6). The sea was isolated from the Arctic Basin, and the only communication with the World Ocean was through the Turan sea and the Turgai strait. The rearrangement of sea currents was completed, and an estuarine type of circulation was established. This caused desalination of the surface water. With an extreme fall of the sea level, the influx of fresh water from the drainage area exceeded the influx of saline marine water from the south. This resulted in water column differentiation to form a fresh-water surface water layer and anoxia in the bottom layers. In episodes of sea-level high stands, the West Siberian sea became fully saline again. The traces of the maximum desalination of the photic zone are *Azolla* mats. The first large-scale appearance of *Azolla* mega and microspores in spore-and-pollen spectra is taken to be the boundary between the lower and upper parts of the Tavda Formation. The existence of *Azolla* beds in the transition phase between the Bartonian and Priabonian lasted c. 1.5–2 myr. The sea became fully marine again only in the end of the Tavda age. The salinity recovery was interrupted again by a new global regression at the Eocene/Oligocene boundary, when not only the West Siberian Sea but also the Turgai Strait became land.

The lower part of the Tavda Formation begins with the *Rhombodinium draco* (*Areosphaeridium diktyoplokum–Rhombodinium draco*) Zone of the regional dinoflagellate zonal scale (Akhmetiev et al., 2001a, b; Kul'kova, 1994; Vasil'eva, 1990; Volkova et al., 2002). In BH8, the lower marker bed of coarse sandstones, traced in many seismic profiles and taken to be the formation bottom, is missing. Endemic dinoflagellate taxa appear at different levels of the lower part of the Tavda Formation: *Wetzeliella irtyschensis* appears as low as the basal bed and is present up to the base of the *Azolla* beds. *Kisselevia ornata* appears 6 m above the bottom of the formation. The Bartonian age of the lower part of the Tavda Formation is confirmed by the presence of characteristic pollen of the Kuma horizon in North Caucasus: *Quercus gracilis*, *Q. graciliformis*, *Castanea crenataeformis*, *Castanopsis pseudocingulum*, and *Rhoipites porrectus*. The amount of conifer pollen is reduced.

The upper part of the Tavda Formation includes two major members. The lower member, known as the *Azolla* beds, consists of alternating light and dark thin layers of clays and silts with small siderite nodules, dispersed plant debris, and prints of Azolla shoots. There are two interbeds of shell deposits consisting of bivalves *Culltelus*, *Nucula*, and *Arctica* (S.V. Popov, personal communication). Judging from the presence of *Araneosphaera araneosa* in the clays underlying the *Azolla* beds, the latter are still of Bartonian age. The upper member, devoid of *Azollae*, is formed by alternating clays with and without siderite nodules, formed under normal marine salinity.

The reduction of marine exchange with the Turan Sea and progressive isolation with the "approach" to the *Azolla* beds are confirmed by progressive reduction in the diversity of dinoflagellates, appearance of cavate (*Deflandrea* and *Wetzeliella*) and thin-walled (*Hystrichokolpoma* and *Batiacasphaera*) cysts, and an elevated proportion of prasinophytes. *Azolla* are represented by shoots with attached sori and by two macro- and microspore species, including *Hydropteris indutus*. The beds are characterized by two spore-and-pollen assemblages, whose boundary is 2 m above the bottom of the *Azolla* member. The older assemblage with *Castanopsis* pollen is the continuation of the Lower Tavda one. Its distinctive feature is the reduced amount of conifer pollen, whereas xerophytic oaks are predominant. This is typical of the warming phase and aridification of the Late Bartonian. The presence of Juglandaceae, Hamamelidaceae, and Altingiaceae pollen and occasional pollen grains of palms, Araliaceae, *Magnolia*, and *Engelhardia* confirms the thermophilic nature of the assemblage. Li-

Age, Ma	Phase	Lithostratigraphic unit
Rupelian 23,8		Isiulkul Formation, sands, silts Regression
Priabonian 33,9 Bartonina 37,2	Third phase: establishment of semi-closed (estuary-like) system of seawater circulation West Siberian sea isolated from the Arctic ocean with preservation of the communication with marginal seas of the Peri-Tethys	Formation of the *Azolla* beds due to periodic desalination of surface waters Formation of the clays of the lower part of the Tavda Formation in the marine basin of normal salinity. Basal gritstones (Horizon "T") Regression
Lutetian 40,4	Second phase: rearrangement of the Tethys-Arctic marine meridional system opened to the Peri-Tethys	Formation of clayey, poorly siliceous Russkaya Polyana beds with variable salinity and current circulation Regression
Ypresian 48,6 Thanetian 55,8	First phase: development of a stable marine meridional system linking Tethys to Arctic basin	Formation of silica accumulation: siliceous clays, silts and sandstones of the upper part of the Lyulinvor Formation Formation of sandstones, gaize-like silstones and clayey-siliceous members of the lower part of the Lyulinvor Formation Sapropel horizon (PETM) Regression Formation of glauconitic sandstones and gaizes of the lower part of the Lyulinvor Formation

Table 1: Main stages of the geologic and paleogeographic history of the West Siberian sea in the Paleogene according to data from sections BH8 and BH10 from the Omsk depression.

mited water supply is indicated by findings of *Ephedra* and Chenopodiaceae pollen. Occasional cells of conjugates of the primitive order Mesotaeniales were found in spore-and-pollen macerates. Small *Cribrononion* ex gr. *rischtanicum* (benthic foraminifera), first described in the Isfara Formation, Middle Asia, were found in anoxic clay interbeds with dispersed sulfides (Akhmetiev et al., 2004a).

The accumulation of the lower part of the *Azolla* beds was synchronous with the dispersal of small-leaved subxerophytic floras in the middle latitudes of Central Eurasia. The belt of these floras ran from Central Europe (Tyrol) to Ukraine, the Southern Urals (Baky) southern West Siberia, and finally, to the Pavlodar Irtysh region (Makulbekov, 1972; Akhmetiev, 2010).

In the upper portion of the *Azolla* beds, the amount of conifer pollen increases, except for pine and Taxodiaceae. The greater amount of spruce and tsuga pollen reflects the cooling and migration of aridity that began in the Priabonian. The above-*Azolla* member formed at restored marine salinity, which is evident from the notable increase in the proportion of dinoflagellates in palynomorph spectra, to 40% or even more. These dinoflagellate assemblages include several tens of species. The type Priabonian species *Charlesdowniea clathrata angulosa* occurred beginning at a depth 115 m and up the section. The top of the Tavda Formation is eroded.

3. CONCLUSIONS

Three major phases in the Paleocene and Eocene geological and paleogeographic history of Central Eurasia are delineated (see Table 1).

1) The Late Paleocene – Early Eocene phase, characterized by direct water exchange between the Arctic ocean and the Tethys through the meridional system of straits and Turan and West Siberian inland seas.
2) The Lutetian phase of the transformation of the Tethys-Arctic meridional communication system to a semi-closed system of estuary type opened to Tethys only.
3) The Bartonian-Priabonian phase of the Western Siberian basin connected only with the Turan Sea.

Transition from one phase to another was accompanied by sedimentation breaks and gaps, and rearrangements of ocean currents. The global warming at the Paleocene/Eocene boundary (PETM) was associated with large scale heat transfer from tropical to high latitudes by marine currents and wind systems over the Eurasian continent during the maximum transgression in the Eocene. With increasing isolation of the West Siberian Sea in the second half of the Eocene, the role of endemic biota progressively increased. The formation of Azolla beds in the inland basin accompanied its desalination at the Bartonian/Priabonian boundary and the Early Priabonian, at times of low eustatic sea-level, when the supply of fresh water from land exceeded the supply of marine water from the Peri-Tethys.

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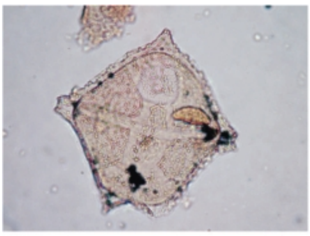
PLATE 1:
(Numbers refer to borehole number/sample depth in m, scale bar 20 µm.)
FIGURE 1: *Kisselevia ornata* Vozzh.; 8/182
FIGURE 2-3: *Wetzeliella irtyshensis* Alb. 8/182
FIGURE 4: *Charlesdowniea clathrata angulosa* (Chateaneuff et Gr.-Cav.); 8/109;
FIGURE 5: *Wetzeliella articulata* Eis.; 8/102
Charlesdowniea crassiramosa (Williams and Downie) Lentin et Vozzh.;
FIGURE 6: 8/185
FIGURE 7: *Araneosphaera araneosa* Eaton; 8/155,5
FIGURE 8: *Deflandrea phosphoritica* Eis., 8/131,3
FIGURE 9: *Membranophoridium aspinatum* Gerlach; 8/109
FIGURE 10: *Areosphaeridium diktyoplokum* (Klump) Eaton; 8/109
FIGURE 11: *Phthanoperidinium* sp.; 8/131.3
FIGURE 12: *Selenopemphix nephroides* Benedek; 8/155.5
FIGURE 13: *Selenopemphix selenoides* Benedek; 8/155,5
FIGURE 14: *Lejeunecysta* sp.; 8/155.5
FIGURE 15-16: *Lejeunecysta* spp; 8/131.3
FIGURE 17: *Thalassiphora microperforata* Helm.-Claus et Simaeys: 8/109
FIGURE 18-19: *Thalassiphora elongata* Vassil. 8/176
FIGURE 20: *Thalassiphora turgaica* sp.n. (Akhmetiev, in press) 8/168,5
FIGURE 21: *Thalassiphora* sp.; 8/131.3
FIGURE 22: *Hapsocysta* sp.; 8/155.5
FIGURE 23-24: *Azolla* sp. fragments of massula with glochidia; 8/143,7; 8/131.3
FIGURE 25: Fragment of microspore, 8/143.7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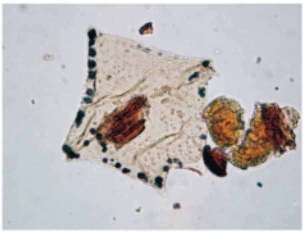
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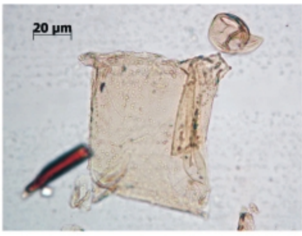

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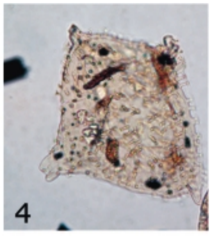
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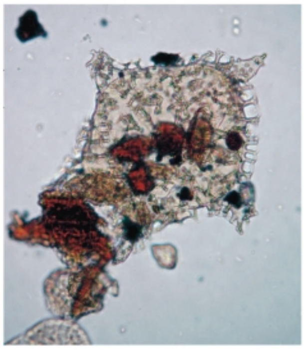
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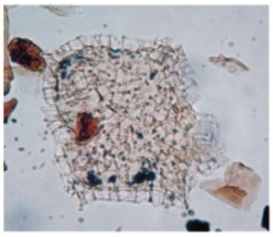
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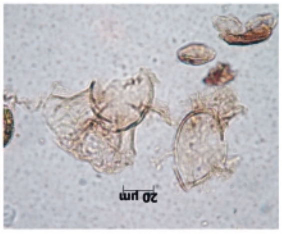

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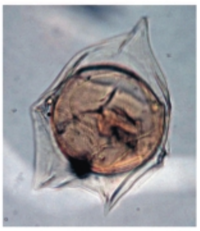
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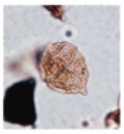
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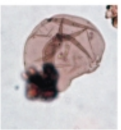
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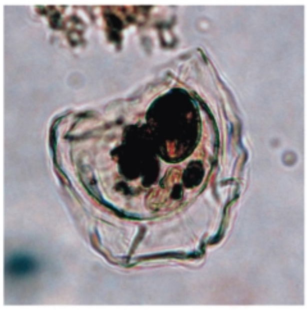
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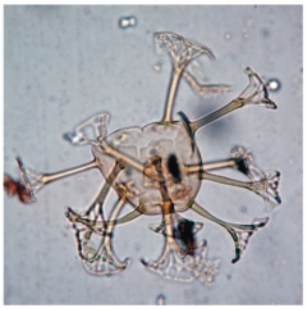
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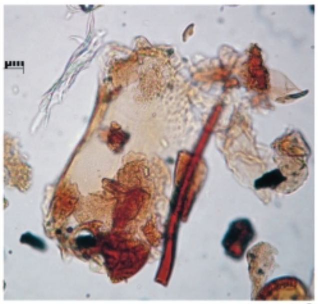
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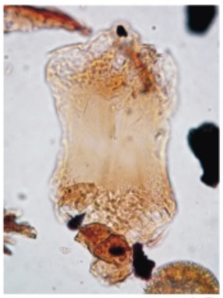
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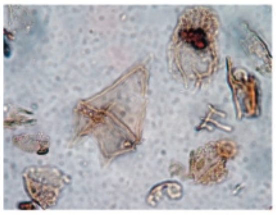
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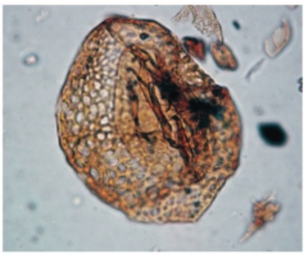
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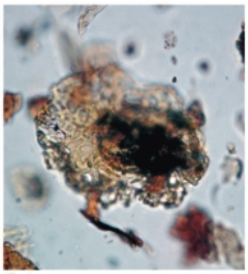
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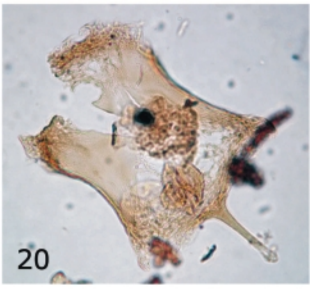
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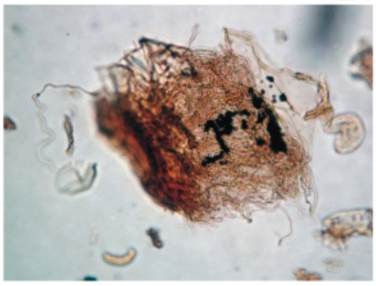
20 µm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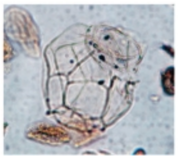
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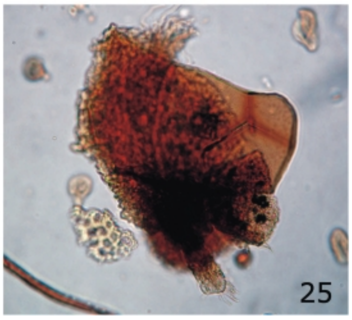
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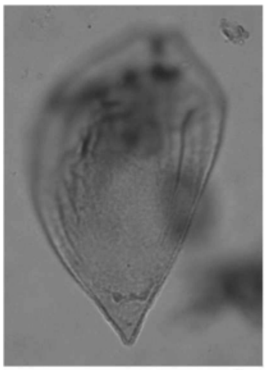
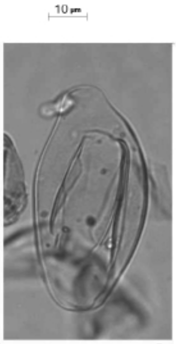
PLATE 2:

Azolla megasori, macro- and microspores and cellular envelops of conjugates (Saccodendrophyceae, Chlorophyta). The upper part of the Tavda Formation (BH8). Scale bar in figures 1-4 – 10 µm; in figures 5, 6 – 50 µm; scale in figures 7, 8 1mm

FIGURE 1-2: Conjugates (Saccodendrophyceae), cellular envelopes: 1a and 1b – depth. 150 m, 2 – depth. 145 m
FIGURE 3-4: *Hydropteris* spp; microspores, depth. 149;
FIGURE 5: Fragment massula with glochidia, depth. 150;
FIGURE 6: Accumulation of microspores (*Hydropteris indutus* Kandinsky; depth. 149;
FIGURE 7-8: *Azolla vera* Krysht. (shoots), depth. 131,5; 7 – with sori, 8 – sterile.


1a


1б



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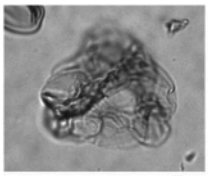
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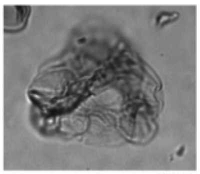
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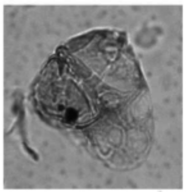
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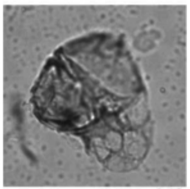
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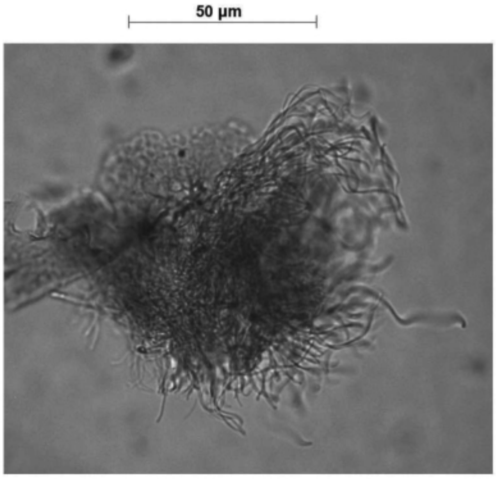

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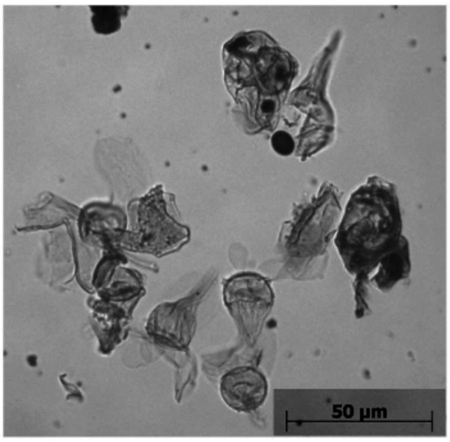

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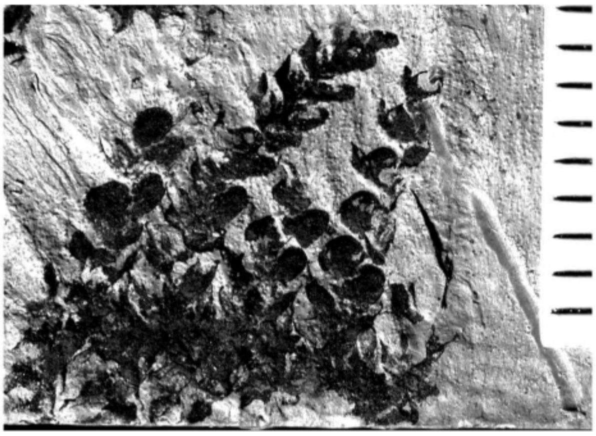
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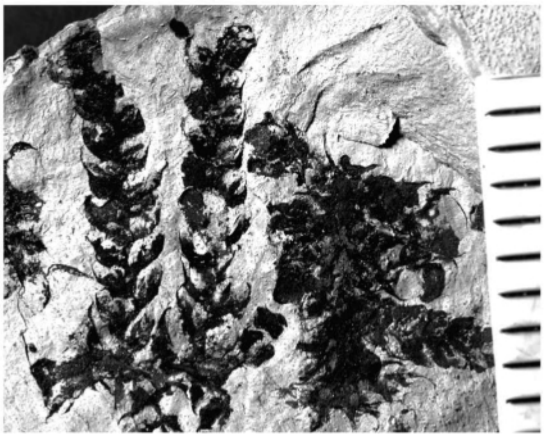
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