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Global and regional palaeoclimate records from the Paleogene and Neogene: selected examples from the Polish Lowland

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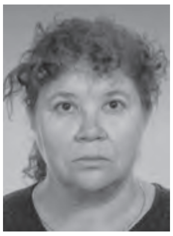

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A b s t r a c t. Global climate changes during the Paleogene and Neogene have been recorded in sedimentary strata in many regions of the world, as well as in the Polish Lowlands, where there are characteristic deposits containing plant and animal fossils. Records of global climatic events have been recognized in strata from the Cretaceous/Paleocene boundary, the Eocene, which includes an amber-bearing association, and also the Oligocene, Miocene and Pliocene. A climatic transition is seen in the flora at the Eocene/Oligocene boundary, marking the beginning of a vegetational pattern similar to the modern one. Cyclic sequences including rich lignite seams also provide clearly palaeoclimate records within the middle Miocene. During the upper Miocene and Pliocene, there was a distinct cooling trend, reaching its maximum during the Pleistocene glaciations.

Keywords: *climate changes, global events, Paleogene, Neogene, Polish Lowland*

INTRODUCTION

The climate change we are currently experiencing is not a new phenomenon, much less an exceptional one. Climate change been observed by several generations for ~150 years and has also been documented in form of meteorological measurement results using instrumental methods. Due to the high dynamics of these changes that have been observed since the beginning of the industrial era, scientists are analysing the impact of the anthropogenic factor on global warming. Climate changes have been also recorded in ancient strata. In this paper we describe natural factors of global and regional climate change in the Paleogene and Neogene.

Each kind of sedimentary rock has been formed in specific environmental and climate conditions. Salts, gypsum, lignite or glacial deposits indicate the conditions working during they were formed. The assemblages of animal and plant fossils often preserved in sedimentary rocks provide more detailed information about the characteristics of the climate, by comparing these with the climatic requirements of contemporary ecosystems. Factors stimulating climate changes include global phenomena, mountain-building movements, continental drift, earthquakes, volcanism, ocean currents, the release of methane clathrates accumulated on the ocean floor, as well as orbital processes (sunspots, Milankovitch cycles, *etc.*). Climate change also affected the evolution of organic world, including the great faunal and floral extinctions. Using the selected example of strata formed during the Paleogene and Neogene on the Polish Lowland, we trace the evidence of significant climatic changes that occurred from 66 to 2.6 million years ago.

Climate changes in the Paleogene and Neogene have their record in marine and terrestrial strata in the Polish Lowlands. Not all global climatic events have been recorded in these deposits, depending on the palaeogeography of this area and erosion that interrupted the record of these events.

GLOBAL CLIMATE CHANGES

In the Paleogene and Neogene, climate change was clearly expressed and well-documented all over the world (Alvarez *et al.*, 1980; Keller *et al.*, 2003; Morgan *et al.*, 2022) including in the Polish Lowland (Słodkowska, Kasiński, 2016). Climate changes and a great extinction were most likely caused by a global catastrophic event, a meteorite impact, at the boundary of the Cretaceous and Paleocene (Alvarez *et al.*, 1980). Circa 75% of animal taxa were exterminated. At the boundary of the Mesozoic and Cenozoic eras (Cretaceous-Paleocene), the meteorite that hit the Yucatan Peninsula caused global changes in environmental conditions (Morgan *et al.*, 2022). Many fauna groups did not survive this cosmic catastrophe, including the (non-avian) dinosaurs, ammonites, belemnites, planktonic foraminifera. The organic world was reborn into a different pattern, and other animal groups began to gain importance, taking over niches occupied in the Mesozoic by large reptiles (MacLeod *et al.*, 1997). The lava flows on the Deccan Plate were probably also of great importance for climate changes (Schoene *et al.*, 2021). Due to the long-lasting dust from the volcanic eruptions, insolation weakened and climate cooled. There are few places in Poland with a preserved record of this climatic event. In the profiles from Nasiłów and Kamienny Dół, the Cretaceous-Paleocene boundary is marked by a hardground surface (Żarski *et al.*, 1998; Remin *et al.*, 2021; Machalski *et al.*, 2022). However, no iridium layer was found in this succession, that might be a residue of a cosmic catastrophe. The iridium layer is clearly visible at many sites of the K/Pc boundary (Keller *et al.*, 2003), also in Europe (Fig. 1).

During the later part of the Paleocene, in the Thanetian, the climate warmed, as indicated by the presence of thermophilic foraminifera in strata of this age (Odrzywolska-Bieńkowa, Pożaryska, 1981; Aze *et al.*, 2014). The area of Poland at that time was land, and sedimention of this age occurred locally, as in the lignites forming the VII Odra lignite seam, which formed in warm and humid climate con-

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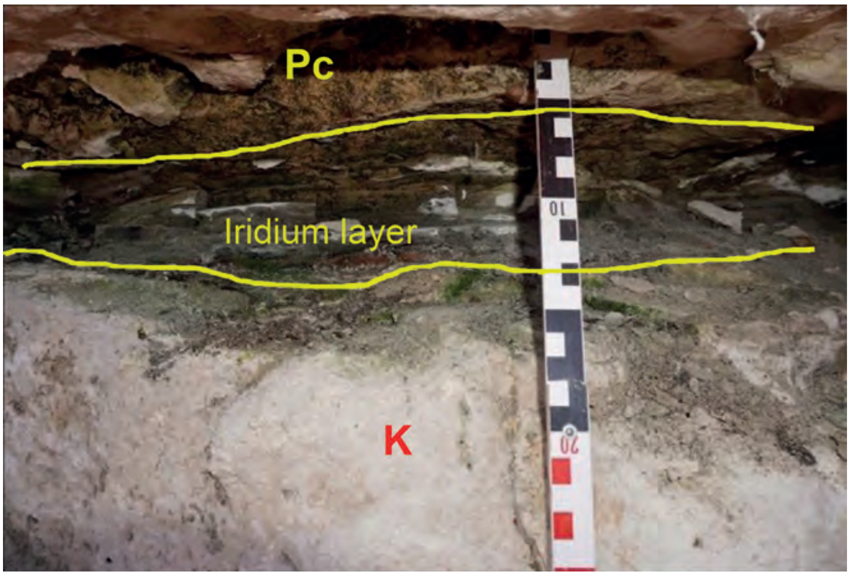

Fig. 1. Detailed view of the K/Pc boundary layer at Stevns Klint, Sjaelland Island, Denmark. Photo by: A. Kupisz

ditions (Grabowska, 1983). The Paleocene-Eocene Thermal Maximum (PETM) at 56 Ma is another global event. It was of relatively brief duration (170 thousand years), and was caused by geotectonic factors, plate collision and breakup of the Gondwana and Laurasia continents, as well as the release of CH_4 and CO_2 clathrates into the oceans and then into the atmosphere (Tierney *et al.*, 2022). Temperatures reached extremally high values. The temperature of the world ocean waters increased by 6°C, the surface waters of the Arctic reaching 24°C (Inglis *et al.*, 2020; Tierney *et al.*, 2022). The higher temperatures allowed to the expansion of thermophilic plant and animal species into circumpolar zones. At that time, the area of Poland probably was mostly dry land, because no marine fossil record of the thermal maximum has been found so far.

In the area of the Polish Lowland, there is an incomplete record of another global event, the Early Eocene Climatic Optimum (EECO) 52–50 Ma, which was characterized by high temperatures with the mean estimate being around 27.0°C, and a lack of clear climate zones (Słodkowska *et al.*, 2013; Inglis *et al.*, 2020). The Eocene climatic optimum was of such significance that it influenced the palaeontological record, that became dominated by species of microfauna and marine phytoplankton characteristic of tropical and subtropical waters. The peak of development and the largest territorial range in higher latitudes was reached by thermophilic dinocysts of the genus *Apectodinium* (Fig. 2), in the *Apectodinium* acme (Bujak, Brinkhuis, 1998).

In western and central Poland, a thermophilic foraminiferal community appeared, including *Nummulites orbignyi, N. germanicus, Spiroloculina grateloupi* and *Pararotthalia lithothamnica* (Odrzywolska-Bieńkowa, Pożaryska, 1981). In the earlier phase of the optimum, lush vegetation developed on land, that was tropical to subtropical in nature then, at the end of the Eocene, subtropical to warm-temperate. Rainforests prevailed up to 45°N latitude, and in the polar regions, forests with cypresses and *Sequoia* grew (Jahren, 2007).

Eocene warming stimulated the development of forests and their considerable species diversity. The rich mixed forests covering the continental areas included cypresses, sequoias, cedars, palms, magnolias, tulip trees, acacias, walnut trees, beeches, oaks, elms, Araliaceae, Rosaceae, as well as pines, hemlocks and *Cathaya* (Krajewska, Kohlman-Adamska, 2003). In the Northern Hemisphere the climatic conditions prevailing on the continental areas resulted in the occurrence of thermophilic, multi-species amber-bearing forests in the early Eocene, the resin of which gave rise to rich amber deposits (Kramarska *et al.*, 2008; Kasiński, 2016). The resin of these trees was delivered to marine basins and in the seawater it transformed into amber. Rich deposits of amber that formed then occur today on in marine deposits on the Sambian Peninsula (Katinas, 1971; Kasiński *et al.*, 2020), in the Chłapowo region (Grabowska, 1987), and in the northern Lublin region and in Volhynia (Kasiński, 2016; Fig. 3).

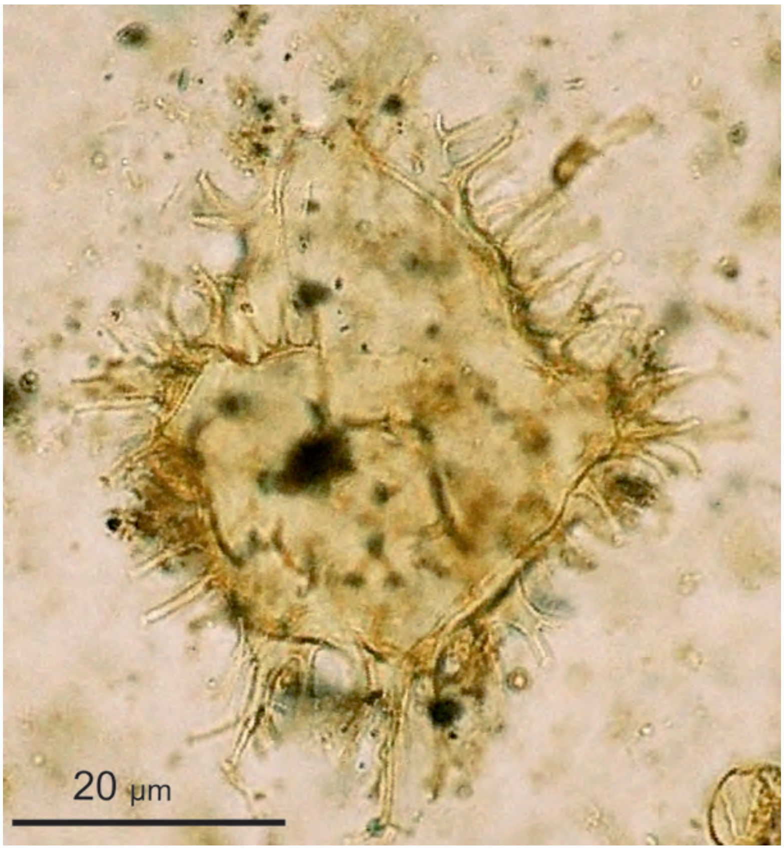

Fig. 2. *Apectodinium hyperacanthum* from the Yantarny P-1 borehole, Sambian Peninsula (Kasiński *et al.*, 2020)

The beginning of the cooling trend was connected with decrease in atmospheric CO_2 content from 3500 to 650 ppm dated to 49 Ma (Inglis *et al.*, 2020). One of its causes was the massive development of the aquatic fern of the genus *Azolla*, which reached the peak of its development in the waters of the polar zone at high latitudes. This plant sequestered significant amounts of the carbon from the atmosphere that had been responsible for the greenhouse effect in the early Eocene. With the decrease in atmospheric CO_2 concentration, increasingly rapid cooling took place (Neville *et al.*, 2019).

In the Eocene, the northern boundary of the rainforest zone moved southwards, and on extensive land areas there was a drying and associated thinning of forests. The place of evergreens was taken by deciduous forests that lost their leaves seasonally. In Poland, lower Eocene deposits have a very limited range. The Middle Eocene warming, of the Middle Eocene Climatic Optimun (MECO) at 40 Ma may be associated with the formation of the VI Tanowo lignite seam in NW Poland (Grabowska, 1983). In these deposits, pollen taxa from the extinct polyphyletic Normapolles group and thermophilic trees from the families Fagaeae: Fagoideae and Castaneoideae and Platanaceae, and Sapotaceae, Juglandaceae, etc. played an important role. Marine lower Eocene deposits containing marine phytoplankton representing the Ypresian, appear locally in the area of NE Poland and on the Sambian Peninsula (Kasiński *et al.*, 2020). The end of the Eocene and beginning of the Oligocene at 34 Ma played an important role in a high-level global climatic event. The cause of this event was the reconstruction of the land and sea system, which resulted in global climate changes, including the glaciation of Antarctica. At that time, there was a transition from a greenhouse world (without ice sheets) to a icehouse, colder, glaciated world with permanent ice sheets at southern pole and partial at northern one (Fig. 4 and Table 1).

This event is also called the Eocene Oligocene Transition (EOT), the formation of the circum-Antarctic ocean current led to the thermal isolation of Antarctica and its glaciation (Scher *et al.*, 2011). Following that transition, evidence of the beginning of plant zonation and seasonality has been recorded. The old tropical plant world came to an end, many species becoming extinct. In the middle latitudes, the dominant evergreen forests were replaced by forests with trees losing their leaves in winter. The Oligocene was a time of the dominance of vegetation similar to the present one. Small climatic fluctuations have been noted, related to the brief disappearance of the Antarctic ice sheet at 26 Ma. Cycles of glaciation and deglaciation repeated several times between 23 and 18 Ma. In the early Miocene there was further Antarctic ice growth during the Oligocene Miocene Transition (OMT) 23 Ma (Fig. 4 and Table 1).

In the Polish Lowlands, numerous lignite deposits were formed under favourable climatic conditions. Stable conditions of suitable temperature and humidity prevailed for over 11 million years, from the Oligocene to the Miocene (Kasiński, Słodkowska, 2016). The beginning of the lignite-forming cycle took place during the early Oligocene, when the V Czempin seam formed, and in the early Miocene the IV Dąbrowa seam. This lignite formation reached its greatest intensity in the middle Miocene, when the III Ścinawa, II Lusatian and I Konin lignite seams formed (Słodkowska, 1998; Kasiński *et al.*, 2010). Reconstruction of the zonal variability of peat-forming vegetation in the Miocene peatlands is shown in Figure 5.

This was probably related to the Middle Miocene Climatic Optimum (MMCO) at 17–14 Ma. At that time, the CO_2 content in the atmosphere increased to 500 ppm, as a result of the partial recession of the ice sheets in Antarctica, 17–13.8 Ma, ice-free conditions prevailed (Steinthorsdottir *et al.*, 2021). Geotectonic phenomena – the gradual uplift of the Alps and Carpathians arc – created an orographic barrier that hindered the inflow of moist and warm air masses from the south. This phenomenon is known as the Middle Miocene Climatic Transition (MMCT) at 14 Ma (Quaijtaal, 2017). Thus, there was a decline in lignite formation, as the climate became colder and drier (Fig. 4 and Table 1). Another cooling caused the glaciation of the East Antarctic Ice Sheet (EAIS) 13.8 Ma BP. Subsequently, the first traces of glaciation were recorded in the Northern Hemisphere and both poles became covered with ice (Mudelsee *et al.*, 2014). In the foreland of the rising Carpathian orogen, in the shrinking and drying Paratethys Sea, rock salt and gypsum were formed, in the Badenian Salinity Crisis (BSC) (Fig. 4 and Table 1). The effects of this can be observed in strata in the area of the Carpathian Foredeep (De Leeuw *et al.*, 2010). The subsequent drop in temperature and humidity changed plant communities, with thinner and less extensive forest cover, and the dominance of vegetation in open unforested habitats, such as steppes, savanna and prairie. Vegetation

Fig. 3. Reconstruction of an Eocene amber forest: **A** – Museum of Amber Inclusions, University of Gdańsk, **B** – Museum of Amber, Królewiec. Photo by: B. Słodkowska

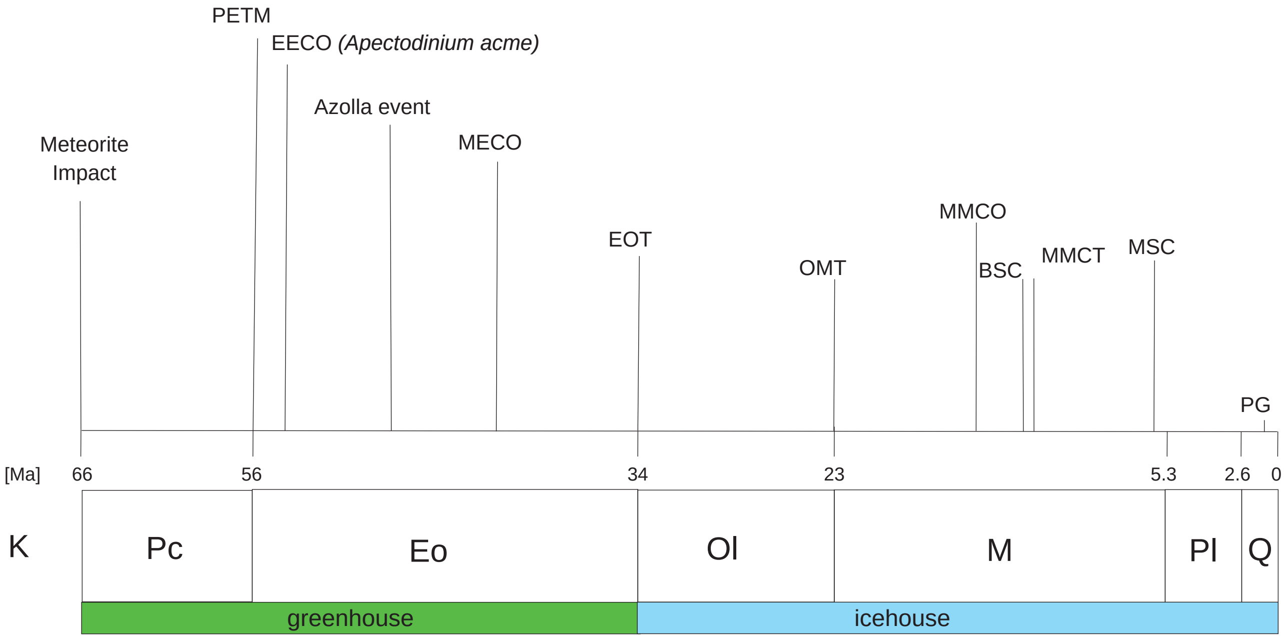

Fig. 4. Global climatic events: **PETM** – Paleocene Eocene Thermal Maximum, **EECO** – Early Eocene Climatic Optimum, **MECO** – Middle Eocene Climatic Optimum, **EOT** – Eocene Oligocene Transition, **OMT** – Oligocene Miocene Transition, **MMCO** – Middle Miocene Climatic Optimum, **BSC** – Badenian Salinity Crisis, **MMCT** – Middle Miocene Climatic Transition, **MSC** – Messinian Salinity Crisis, **PG** – Pleistocene Glaciations

with the ability to fix CO_2 using C4 photosynthesis adapted to these types of conditions (Osborne, 2008). At that time (6–8 Ma BP) there was an expansion of grasses (Table 1).

The Messinian Salinity Crisis (MSC) (5.93–5.33 Ma BP) was one of the most important climatic events at the end of Miocene. Increased evaporation resulted in the formation of salt deposits. This was caused by the closure of the connection between the Atlantic Ocean and the Mediterranean Sea, what was probably related to the pressure of the African plate on the European one (Fig. 6). The erosional base decreased significantly, and very deep river valleys were cut into the bottom of today's Mediterranean Sea (Krijgsman *et al.*, 2018, 2024; Fig. 4 and Table 1).

The Messinian crisis in Poland may be echoed by desert coatings in the upper Miocene strata of the Lublin Upland and Roztocze (Maruszczak, 2001). The Pliocene epoch was a time of gradual cooling and drying of the climate, when glaciers appeared in the Arctic, NE Asia, Alaska and Greenland. Plants adapted to the reduced CO_2 content, and open plant communities prevailed. Fluvial facies dominated the Polish Lowlands (Kasiński, Słodkowska, 2024). This type of sedimentation prevailed for over 4 million years until the older, preglacial Quaternary, when at around 0.9 Ma there was a transgression of the Pleistocene ice sheets (Fig. 4 and Table 1).

CAUSES OF CLIMATE CHANGE

Climate changes recorded in Paleogene and Neogene have a natural origin, and geotectonic and orbital factors were responsible for their occurrence. Geotectonic factors included continental drift, volcanism (emission of greenhouse gases and volcanic ash), earthquakes, mountain uplift, changes in the position of land and seas, tectonic reconstruction affecting the circulation of ocean currents, closing of circumpolar corridors, the advance of Africa to the N (onto Europe), the collision of the Indian subcontinent with

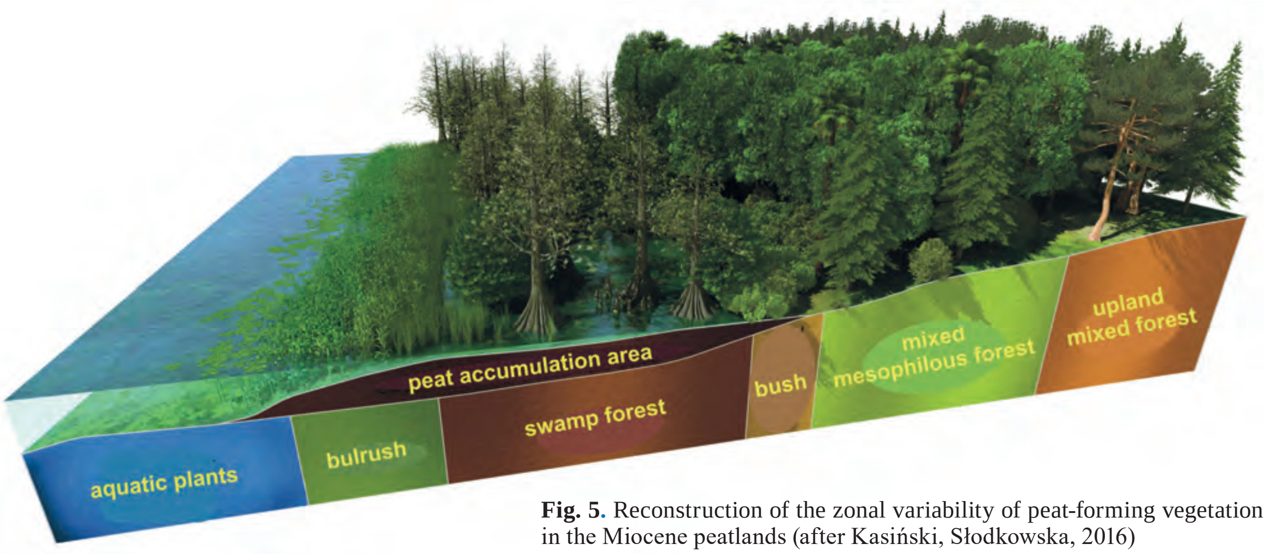

Fig. 5. Reconstruction of the zonal variability of peat-forming vegetation in the Miocene peatlands (after Kasiński, Słodkowska, 2016)

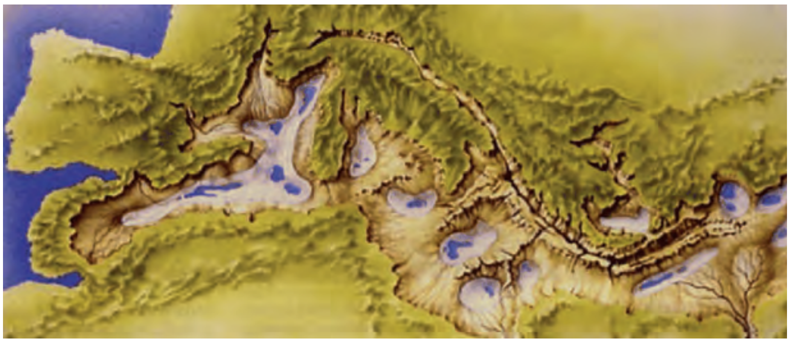

Fig. 6. The Mediterranean region in the late Miocene (Messinian Salinity Crisis), where there was a 1500 m sea-level drop (Hsü *et al.*, 1973)

the Deccan plate – the uplift of the Himalayas, closing of the Isthmus of Panama, and the release of CH_4 and CO_2 from methane clathrates. Orbital (astronomical) factors included changes in the position of the Earth's orbit, the tilt of the Earth's axis, eccentricity and precession, solar activity (changes in radiation intensity, albedo).

CONCLUSION

Research into the palaeoclimate of the Paleogene and Neogene is carried out by using proxy data including palaeontological, palynological, dendrological, isotopic geochemistry methods and observations of sea-level changes, so their resolution is not very high. Global climatic events have been recorded based on changes in the oxygen isotope ^{18}O values contained in benthic foraminifera tests (Zachos *et al.*, 2001; Miller *et al.*, 2020). These values have been compiled into palaeoclimate curves and their extremes clearly indicate episodes related to climate change (Słodkowska, Kasiński, 2016). Climatic events in the Polish Lowlands have been documented using palaeontological and sedimentological methods. The main role is played by palynological studies, commonly conducted in Paleogene and Neogene strata. The lack of record of some global climatic events in the Polish Lowlands profiles is most often caused by palaeogeographic reasons or erosion. To date, no isotopic studies have been performed on Paleogene marine strata; in combination with palaeontological methods, this would greatly improve the resolution of climatostratigraphic dating.

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Tab. 1. The major climatic events in the Paleogene and Neogene and their natural causes

Climatic event	Climat changes	Reason/evidence
Meteorite impact (K/Pc boundary)	cooling, mass extinction	space-derived catastrophe
PETM	warming	geotectonic, release of methane clathrates, disintegration of Gondwana and Laurasia, increase of CO_2 content
EECO	warming	geotectonic, *Apectodinium* acme
Azolla event	cooling	decrease of CO_2 content
MECO	warming	geotectonic, collision of India with Eurasia, volcanism
EOT	cooling, end of the greenhouse period	geotectonic, palaeogeographic reconstruction, Antarctic glaciation
OMT	cooling, minor glaciation of Antarctica	geotectonic, glacioeustatic sea-level change
MMCO	warming	volcanism, orbital eccentricity, deglaciation of Antarctica,
BSC	warming, evaporation	geotectonic, evolution of Carpathian orogen
MMCT	cooling	geotectonic, glacioeustatic sea-level change
C4	cooling	CO_2 fixing
MSC	warming, evaporation	geotectonic, closure of the connection between Atlantic Ocean and Mediterranean Sea
Pliocene	cooling, glaciation of both poles	geotectonic, deep ocean circulation changes
PG	cooling, cyclic Pleistocene glaciations	orbital

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