

Nordic *Nummulites*: An unusual occurrence of *Nummulites planulatus* from Jyske Rev, Danish North Sea

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ABSTRACT: Small reticulate *Nummulites* are found across the Eocene shallow marine deposits of the Paris Basin, Belgium, as far north as northern Germany and southern United Kingdom. Only two isolated instances of *Nummulites* at higher latitudes than this are known, from the Rockall bank and Wyville-Thomson ridge in the north Atlantic, and no *Nummulites* have been reported from the Nordic North Sea Basin – until now. Here *Nummulites planulatus* is described within a glacial erratic dredged from Jyske Rev in the Danish North Sea of likely Ypresian age. Whilst the specimen is not *in situ*, it indicates that populations of *Nummulites* were living further north in the North Sea region than previously known. This range expansion may have been facilitated by the hyperthermal events of the early Eocene.

Keywords: Eocene, hyperthermal, range expansion, invasive species, foraminifera, Denmark

INTRODUCTION

The genus *Nummulites* is probably the most well-known and recognised of the Paleogene larger foraminifera, occurring globally in warm-water shallow marine deposits. Within the Eocene, in particular, it reaches both exceptionally large sizes and occurs in huge numbers in rocks of the Neotethys. Modern relatives of *Nummulites* (e.g., *Operculina* (*Assilina*), *Heterostegina*, *Paleonummulites*) show a global distribution limited by the 15°C winter sea surface temperature isotherm (Langer and Hottinger 2000). However, warmer global temperatures during the Eocene meant that geographic ranges of taxa were expanded, allowing larger foraminifera to live at higher latitudes than found today. Whilst *Nummulites* are most common in lower palaeolatitude deposits such as around the modern day Mediterranean, a number of species (including but not limited to *N. rockallensis*, *N. planulatus*, *N. aquitanicus*, *N. laevigatus*, *N. variolarius*, *N. prestwichianus*, and *N. rectus*) are known to occur across northern Europe (e.g., Drooger et al. 1971; Schaub 1981; King et al. 2016).

Over the last ~100 years a number of detailed studies have focussed on the distribution, evolution and biostratigraphic use of these northern European forms (e.g., Curry 1937; Drooger et al. 1971; Blondeau 1972; King et al. 2016). More recently it has been found that the *Nummulites* of North West Europe include some of the best-preserved examples in the world (Cotton et al. 2020) and as such are being included in an increasing number of geochemical studies (Purton and Brasier 1999; Evans et al. 2018; Martens et al. 2022). The northern European *Nummulites* are generally small (although *N. laevigatus* can reach several centimetres), radiate taxa. Temporally, the northern European *Nummulites* discontinuously span the lower Ypresian (*N. rockallensis*) to the uppermost Priabonian or possibly lowermost Rupelian (*N. germanicus*), but their discontinuous nature and the general issues of shallow water biostratigraphy make correlations challenging (e.g. Cotton et al. 2021). Moorkens (1988) developed a biozonation for Belgium, although it is not widely used. More recently, King et al. (2016) correlated taxon ranges to the Shallow Benthic Zones (SBZ) of Serra-Kiel et al.

(1998) and nannoplankton (NP) Zones to provide a more robust regional framework. Geographically, the northern European *Nummulites* are found within the Paris and Dieppe Basins in France, the Hampshire and London Basins in the south of the UK, Belgium and southern Netherlands and northwest Germany (Curry 1937; Jarzeva et al. 1968; Drooger et al. 1971; King et al. 2016). Two isolated occurrences further north have been reported. Hinte and Wong (1975) described a new species, *Nummulites rockallensis*, from Rockall Plateau, North Atlantic (57°20.17'N; 15°32.97'W) and Stoker et al. (1988) recorded *N. rockallensis* from a borehole on the Wyville-Thomson ridge (59°34.9'N; 6°32.5'W). However, until now there have been no documented occurrences of *Nummulites* in the Nordic region.

Natural History Museum Denmark collection number NHMD876053/DK1162 is a rock sample collected in Esbjerg Havn in a rock pile, after being dredged from Jyske Rev in the Danish North Sea and was deposited in the collections as containing Elphidiidae cf. *Elphidiella* sp. Here I have re-identified the foraminifera in the sample as *Nummulites planulatus* (de Lamarck 1804) and propose that it may be the first example of *Nummulites* from the Nordic region. Although not *in-situ*, their occurrence in a glacial erratic indicates general southward transport, suggesting that during particularly warm intervals *Nummulites* may have extended to even higher latitudes than previously thought.

GEOLOGICAL SETTING

Jyske Rev in the North Sea is a submarine high at with a present day depth of ~25–30 m situated at approximately 57°N, 07.7° E (Jensen et al. 2011). The sediment comprises of tens of meters of Quaternary sands and gravels overlaying Miocene sands and clay, Danian Limestone and in some areas Cretaceous chalk (Jensen et al. 2011). The region is known for glacial erratics eroded from nearby deposits from onshore Denmark during the last glaciation, often containing fossil material of Paleogene, Neogene or Ordovician age (e.g., Myrvold et al. 2018). However, this is the first time *Nummulites* have been recorded from the deposit.



TEXT-FIGURE 1

Location map showing the dredging area, Jyske Rev, and Esbjerg havn where the specimen was collected, on the west coast of Denmark.

The Eocene of onshore Denmark is relatively thin and comprises of the Ølst, Fur, Rosnæs, Lillebælt and Søvind marl formations. With the exception of the Fur formation these are largely a series of clays, claystones and marls (King et al. 2016). The Fur formation is an argillaceous diatomite, with a large number of volcanic ash beds, and laterally grades into the Ølst formation (King et al. 2016). The onshore sediments cumulatively represent bathyal to outer neritic environments. Off-shore in the North Sea Viking and Central Grabens the Eocene is represented by the Balder (earliest Ypresian) and Horder (early Ypresian to Rupelian) formations, these are outer neritic to bathyal claystones with interbedded, laterally discontinuous sand units (King et al. 2016). The sand units in both formations occur mainly in the Viking Graben and northern area of the Central Graben, and have been emplaced by deep water flows. Though publications address the microfossils and smaller foraminifera present in the Eocene of Denmark, no larger foraminifera are mentioned (e.g., King 1994; Schmitz et al. 1996; Laursen and Andersen 1997).

MATERIALS AND METHODS

The sample was recovered in Esbjerg harbour by Mette Hofstedt in a rock pile dredged from Jyske Rev off the west coast of Denmark (text-fig. 1). The material consists of two pieces of nummulitic sandstone approximately 9 x 7.5 x 2 cm and 6 x 4 x 1 cm respectively. The sandstone is overall well indurated and largely composed of *Nummulites* and quartz grains, with small oyster and pecten-type bivalve fragments. The *Nummulites* have a sugary outer texture and cannot easily be removed from the rock. However, in a number of small pockets less well consolidated examples are seen, with clear outer morphology pre-

served, and can be removed from the rock surface with a mounted needle.

Seven individual specimens were successfully removed. External images were taken using an Olympus camera microscope for diameter and thickness measurements and a record of external ornamentation. Specimens were mounted in Lakeside 70 cement and hand-ground on fine sand paper to produce equatorial thin sections. Equatorial sections were imaged using a Leica camera microscope and software. Standard measurements following Schaub (1981) were taken as shown in Cotton et al. (2015; figure 2), including proloculus height and width, deuteroconch height and successive whorl radii. Number of chambers per whorl were counted. Taxonomy follows Schaub (1981) and Blondeau (1972). Preservation of the removed specimens is poor to moderate. All show infilling of at least the innermost whorl, though in two of the specimens the outer whorl has not been infilled.

SYSTEMATIC DESCRIPTION

Order Foraminifera d'Orbigny 1826

Suborder Rotaliina Delage and Herouard 1896

Superfamily Nummulitacea de Blainville 1827

Family Nummulitidae de Blainville 1827

Genus *Nummulites* Lamarck 1801

Nummulites planulatus (de Lamarck 1804)

Plate 1a–f; table 1

Lenticulites planulata, de LAMARCK 1804, p. 187.–D'ARCHIAC and HAIME 1853, p. 142, pl. IX, figs. 5–10

Nummulites planulatus Lamarck.–DOUVILLÉ 1919, p. 46, fig 5; pl. IV, figs. 1–12.–SCHAUB 1966, p. 367, fig. 6: k, l, o, p; fig 8; pl. III, figs. 1–15.–BLONDEAU 1973, p. 123; pl. III, fig. 1–11; pl. IV, figs. 1–3.–SCHAUB 1981, p. 159; figs. 98–99; pl. 57, figs. 1–9, 11–15, 18, tableau 7, figs. f–g.

Material: A total of seven individuals in equatorial section were studied from the rock sample. Along with observations of external morphology from individuals still within the rock and three loose specimens which were left unsectioned. All specimens have been deposited within the Danekræ collection, in the Palaeontological collections of the Natural History Museum Denmark, Copenhagen. Collections number NHMD876053/DK1162, individuals labelled A–J.

Description: All measured and visible specimens are A forms. Tests are involute flattened to lenticular with diameter up to 2407 µm and thickness up to 675 µm, and a mean D/T of 3.25, although in some specimens edges of the test were slightly damaged or had attached sediment grains increasing error. Septal filaments are radiate to slightly sinusoidal in smaller specimens meeting centrally with an almost central plug. In larger specimens septal filaments are meandriform. No granules are present, trabeculae are visible in some specimens (plate 1d). In equatorial section the spire is relatively regular, increasing slightly from the second whorl (see plate 1a–c), with a maximum of three complete whorls. The spiral laminae are relatively thin. Chambers are approximately 2x taller than wide, and up to ~3x taller than wide in the outer whorls. Septa are relatively straight with a steep backbend where they meet the spiral wall. Number of chambers per whorl increases from a mean of 9 in the first, 20 in the second and 27 in the third whorl. The proloculus has a mean height (P1) of 230 µm and mean width (P2) of 308 µm, both excluding chamber walls. Full measurements are given in table 1.

TABLE 1

Measurements in microns, measurements follow those of Schaub (1981) and shown in the figure of Cotton et al., (2015). D= diameter of test; T= maximum thickness of test; P_w = horizontal width of proloculus, excluding chamber wall; P_h =height of proloculus in direction whorl radii are measured; W1-3 = radius of whorl measured through the deuterioconch; C1-3 = number of chambers in the respective whorls.

SPECIMEN	D	T	D/T	P_w	P_h	P_w/P_h	D	W1	W2	W3	C1	C2	C3
A	-	-	-	300	213	256.5	103	606	1098	1786	9	19	27
B	1412	310	4.6	333	241	287	156	658	-	-	10	-	-
C	1411	596	2.4	-	-	-	-	-	-	-	-	-	-
D	3767	1166	3.2	315	269	292	145	781	1394	2030	9	21	29
E	-	-	-	249	187	218	128	648	1210	-	9	20	27
F	1649	456	3.6	-	-	-	-	-	-	-	-	-	-
G	1945	661	2.9	305	220	262.5	118	618	-	-	-	-	-
H	1314	525	2.5	324	220	272	143	755	-	-	9	-	-
I	2407	675	3.6	332	265	298.5	157	720	1182	-	9	20	-
J	1186	-	-	-	-	-	-	-	-	-	-	-	-
MEAN	1886	627	3.3	308	231	270	136	685	1221	1908	9	20	28

Biostratigraphy: *Nummulites planulatus* has a Ypresian age: NP11 to 12 and SBZ 8 to 10 (King et al. 1996; Serra-Kiel et al. 1998).

Remarks: All measured and surface specimens appear likely the same species, suggesting the population is either monospecific or highly dominated by a single species. The most northerly occurring *Nummulites* species known is *Nummulites rockallensis*, however the specimens described here show clear differences in morphology to *N. rockallensis*. Notably *N. rockallensis* is near evolute and highly flattened (Hinte and Wong 1975), in contrast to the involute specimens described here.

The proloculus size, number of chambers and overall spiral and chamber morphology closely match the descriptions of Blondeau (1972) and Schaub (1981). *Nummulites planulatus* as described by Blondeau (1972) has a proloculus of 250–350 μ m, comparable with our P2 measurements. The largest difference between the Jyske Rev specimens and those described in Blondeau (1972) is the diameter to thickness ratio: Blondeau's measurements result in a D/T of 1.5 to 1.8 whereas the Jyske Rev specimens described here have a higher mean D/T of 3.25, indicating flatter tests. This in part may be due to difficulties removing matrix from the outside of some tests and sediment may have slightly obscured the edge of the test when measuring thickness. However, this would likely result in only minor changes to the thickness of some specimens. Larger foraminifera including *Nummulites* have been shown to exhibit environmental plasticity, forming thinner, flatter tests in lower light environments and vice versa (Hallock et al. 1986; Eder et al. 2018). Schaub (1981) described test morphology as flat to lenticular indicating variation in D/T ratio. The diameter of A forms in Schaub's description is 1.5–5 mm, encompassing the size of the Jyske Rev specimens, although they are at the lower end of the range. Schaub additionally noted variation in the spiral whorl between populations.

Distribution: *Nummulites planulatus* has a wide distribution and is found across UK, Belgium, France, Spain, Switzerland, Northern Italy, Turkey, former USSR, Armenia, Algeria, Egypt, Somalia, Mozambique, India, Madagascar (Blondeau 1972; Schaub 1981).

DISCUSSION

Quaternary sediments, including ice derived cobbles and sands, as well as fossil material are common in the Jyske Rev region of

the North Sea (e.g., Jensen et al. 2011; Myrvold et al. 2018). Though not *in situ*, this suggests that the fragment containing the *N. planulatus*, was also transported to this location by ice, from an unknown locality further to the north or northeast. Therefore *Nummulites* may not have only extended their geographic range northwards in the western Atlantic (Hinte and Wong 1975; Stoker et al. 1988), but also within the North Sea/Nordic regions. The previous absence of which Hinte and Wong (1975) after their discovery of *N. rockallensis* commented on being “surprising”.

It has been recognised that the occurrences of northern European *Nummulites* (e.g., UK, Paris Basin, Belgium, and North Germany) correlate with warm periods of the Paleogene and Neogene (Adams et al. 1990; King et al. 2016; Prazeres and Renema 2018) and Hinte and Wong (1975) propose a proto-Gulf stream enabled occurrences on Rockall Bank. The sediments containing *N. rockallensis* were initially assigned a late Paleocene age (Laughton et al. 1972; Hinte and Wong 1975) but have been since revised to early Eocene (Morton et al. 1983; Stoker et al. 1988). Though we lack independent dates for our specimens, *N. planulatus* is a well-known and well-documented species throughout the Tethyan region and known to have a Ypresian age. All three of these highest latitude occurrences therefore are within the early Eocene.

The early Eocene was a dynamic interval of Earth's climate history. An overall warming trend is punctuated by a series of rapid hyperthermals (ETM 2 and 3), followed by the Early Eocene Climatic Optimum (EECO) (Westerhold et al. 2020). These sudden intervals of warming could have therefore allowed the migration and expansion of *Nummulites* taxa into previously less habitable regions. Modern larger foraminifera show a global distribution limited by the 15°C winter sea surface temperature isotherm within this the modern nummulitids have a distribution limited 18.5 to 25 °C global isotherm depending on species (Langer and Hottinger 2000; Förderer et al. 2018). Model data suggest sea surface temperatures near Denmark of 12–16°C warmer than today during the EECO (Lunt et al. 2021) and even in the coolest part of the Paleogene, Tex₈₆ values from the Kysing-4 core in northern Denmark indicates temperatures of ~28 °C in the Priabonian to 16°C in the Oligocene (Sliwinska et al. 2019). Large areas of northern Europe therefore became potentially habitable to *Nummulites* during these extreme warming events, should other conditions (e.g. light, substrate) prove favorable.

CONCLUSION

Here for the first time, *Nummulites planulatus* is described from the Danish North Sea. Though *not in situ* this sample opens the possibility that *Nummulites* may have had an even more expansive range than previously thought during periods of global warming, and limited populations may have lived in the Nordic region during the early Eocene. By introducing this possibility, there is hope that additional unexpected occurrences may be recognised. As modern global warming continues, expansion and migrations of warm water taxa are becoming increasingly common (e.g., Titelboim et al. 2019; Yasuhara and Deutsch 2022). Therefore understanding the response of taxa in to rapid climate change in the geological record is key to helping predict potential future changes.

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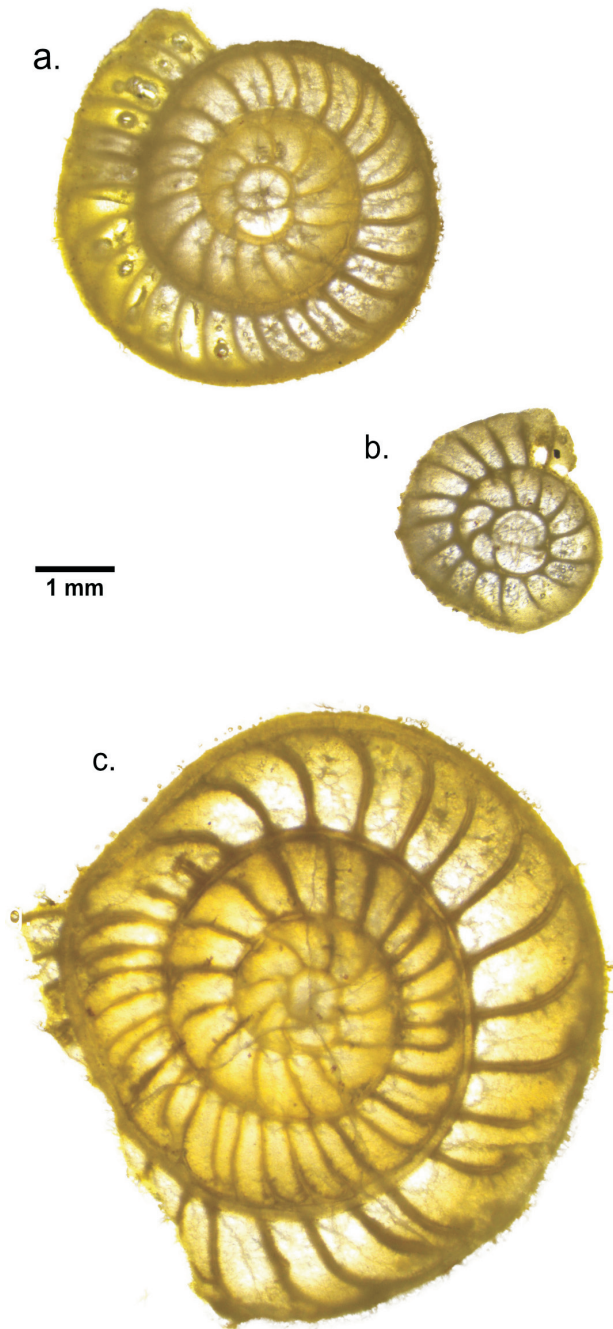
REFERENCES

- ADAMS, C. G., LEE, D. E. and ROSEN, B. R., 1990. Conflicting isotopic and biotic evidence for tropical sea-surface temperatures during the Tertiary. *Palaeogeography Palaeoclimatology Palaeoecology*, 77: 289–313.
- BLONDEAU, A., 1972. *Les Nummulites*. Paris: Vuibert, 254 pp.
- COTTON, L. J., EVANS, D. and BEAVINGTON-PENNEY, S. J., 2020. The high magnesium calcite origin of nummulitid foraminifera and implications for the identification of calcite diagenesis. *Palaios*, 35: 421–431.
- COTTON, L. J., PEARSON, P. N. and RENEMA, W., 2015. A new Eocene lineage of reticulate *Nummulites* (Foraminifera) from Kilwa district, Tanzania; a place for *Nummulites ptukhiani*? *Journal of Systematic Palaeontology*, 14: 569–579.
- COTTON, L., RIVERO-CUESTA, L., FRANCESCHETTI, G., MONECHI, S., IAKOVLEVA, A., ALEGRET, L., DINARES-TURELL, J., HOOKER, J., KING, C., FLUEGEMAN, R. and YAGER, S., 2021. Reassessing the Bartonian unit stratotype at Alum Bay (Isle of Wight, UK): an integrated approach. *Newsletters on Stratigraphy*, 54: 17–42.
- CURRY, D., 1937. The English Bartonian *Nummulites*. *Proceedings of the Geologists' Association*, 48: 229–246.
- DROOGER, C. W., MARKS, P., PAPP, A. and BIK, T. A., 1971. Smaller radiate *Nummulites* of northwestern Europe. *Utrecht Micropaleontological Bulletins*, 5:1–138.
- EDER, W., HOHENEGGER, J. and BRIGUGLIO, A., 2018. Test flattening in the larger foraminifer *Heterostegina depressa*: predicting bathymetry from axial sections. *Paleobiology*, 44: 76–88.
- EVANS, D., SAGOO, N., RENEMA, W., COTTON, L. J., MÜLLER, W., TODD, J. A., SARASWATI, P. K., STASSEN, P., ZIEGLER, M., PEARSON, P. N. and VALDES, P. J., 2018. Eocene greenhouse climate revealed by coupled clumped isotope-Mg/Ca thermometry. *Proceedings of the National Academy of Sciences*, 115: 1174–1179.
- FÖRDERER, M., RÖDDER, D. and LANGER, M. R., 2018. Patterns of species richness and the center of diversity in modern Indo-Pacific larger foraminifera. *Scientific Reports*, 8: 8189.
- HALLOCK, P., FORWARD, L. B. and HANSEN, H. J., 1986. Influence of environment on the test shape of *Amphistegina*. *Journal of Foraminiferal Research*, 16: 224–231.
- HINTE, J. E. V. and WONG, T. E., 1975. *Nummulites rockallensis* n. sp. from the upper Paleocene of Rockall Plateau (North Atlantic). *Journal of Foraminiferal Research*, 5: 90–101.
- JARZEVA, M. V., LOTSCH, D. and NEMKOV, G. I., 1968. Zur Nummuliten fauna des mittleren und höheren Eozäns der Deutschen Demokratischen Republik. *Geologie*, 17: 418–459.
- JENSEN, J. B., BORRE, S., LETH, J. O., AL-HAMDANI, Z. and ADDINGTON, L. G., 2011. Mapping of raw materials and habitats in the Danish sector of the North Sea. *Geological Survey of Denmark and Greenland Bulletin*, 23: 33–36.
- KING, C., 1994. Eocene microfaunas of the Harreborehole (north Jylland, Denmark). *Aarhus Geoscience*, 1: 73–80.

TEXT-FIGURE 2

Nummulites planulatus

- a-c equatorial sections of individuals from NHMD 876053 specimens I, B and D respectively.
- d close up of external surface of *Nummulites planulatus* showing septal traces and trabeculae.
- e some of the more well-preserved individuals in a small cavity in the sample.
- f example of possible B form still within matrix.



- KING, C., GALE, S. A. and BARRY, T. L., 2016. *A revised correlation of Tertiary rocks in the British Isles and adjacent areas of NW Europe*. London: Geological Society of London, 724 pp.
- LANGER, M. R. and HOTTINGER, L., 2000. Biogeography of selected larger foraminifera. *Micropaleontology*, 46: 105–126.
- LAUGHTON, A. S., 1972. The southern Labrador Sea – a key to the Mesozoic and early Tertiary evolution of the North Atlantic. *Initial Reports of the Deep Sea Drilling Project*, 12: 1155–1179.
- LAURSEN, G. V. and ANDERSEN, S. B., 1997. A Late Palaeocene–Early Eocene benthic foraminiferal record from Bovlstrup, Denmark, showing a remarkable agglutinated fauna. *Journal of Micropalaeontology*, 16: 19–29.
- LUNT, D.J., BRAGG, F., CHAN, W. L., HUTCHINSON, D. K., LADANT, J.B., MOROZOVA, P., NIEZGODZKI, I., STEINIG, S., ZHANG, Z., ZHU, J. and ABE-OUCHI, A., 2021. DeepMIP: Model intercomparison of early Eocene climatic optimum (EECO) large-scale climate features and comparison with proxy data. *Climate of the Past*, 17: 203–227.
- MARTENS, L., STASSEN, P., STEURBAUT, E. and SPEIJER, R. P., 2022. Assessing *Nummulites* geochemistry as a proxy for early Eocene palaeotemperature evolution in the North Sea Basin. *Journal of the Geological Society*, 179: jgs2021-102.
- MOORKENS, T., 1988. Belgium. Larger foraminifera. In: Vinken, R., Ed., The northwest Europe Tertiary basin: results of the IGCP project no. 124. *Geologisches Jahrbuch*, A100: 188–190.
- MORTON, A. C., BACKMAN, J. and HARLAND, R., 1983. A reassessment of the stratigraphy of DSDP hole 117A, Rockall Plateau: Implications for the Paleocene-Eocene boundary in NW Europe. *Newsletters on Stratigraphy*, 12: 104–111.
- MYRVOLD, K. S., MILAN, J. and RASMUSSEN, J. A., 2018. Two new finds of turtle remains from the Danian and Selandian (Paleocene) deposits of Denmark with evidence of predation by crocodilians and sharks. *Bulletin of the Geological Society of Denmark*, 66: 211–218.
- PRAZERES, M. and RENEMA, W., 2019. Evolutionary significance of the microbial assemblages of large benthic foraminifera. *Biological Reviews*, 94: 828–848.
- PURTON, L. M. and BRASIER, M. D., 1999. Giant protist *Nummulites* and its Eocene environment: Life span and habitat insights from $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data from *Nummulites* and *Venericardia*, Hampshire basin, UK. *Geology*, 27: 711–714.
- SCHAUB, H., 1981. *Nummulites* et Assilines de la Téthys Paléogène. Taxonomie, phylogénèse et biostratigraphie. *Schweizerische Paläontologische Abhandlungen*, v. 104–106: 1–236.
- SCHMITZ, B., HEILMANN-CLAUSEN, C., KING, C., STEURBAUT, E., ANDREASSON, F. P., CORFIELD, R. M. and CARTLIDGE, J. E., 1996. Stable isotope and biotic evolution in the North Sea during the early Eocene: the Albæk Hoved section, Denmark. *Geological Society, London, Special Publications*, 101: 275–306.
- SERRA-KIEL, J., HOTTINGER, L., CAUS, E., DROBNE, K., FERRANDEZ, C., JAUHRI, A.K., LESS, G., PAVLOVEC, R., PIGNATTI, J., SAMSO, J.M., SCHAUB, H., SIREL, E., STROUGO, A., TAMBAREAU, Y., TOSQUELLA, J. and ZAKREVSKEYA, E., 1998. Larger foraminiferal biostratigraphy of the Tethyan Paleocene and Eocene. *Bulletin de la Société Géologique de France*, 169: 281–299.
- ŚLIWIŃSKA, K. K., THOMSEN, E., SCHOUTEN, S., SCHOON, P. L. and HEILMANN-CLAUSEN, C., 2019. Climate- and gateway-driven cooling of Late Eocene to earliest Oligocene sea surface temperatures in the North Sea Basin. *Scientific Reports*, 9: 4458.
- STOKER, M. S., MORTON, A. C., EVANS, D., HUGHES, M. J., HARLAND, R. and GRAHAM, D. K., 1988. Early Tertiary basalts and tuffaceous sandstones from the Hebrides shelf and Wyville-Thomson Ridge, NE Atlantic. *Geological Society London Special Publications*, 39: 271–282.
- TITELBOIM, D., ALMOGI-LABIN, A., HERUT, B., KUCERA, M., ASCKENAZI-POLIVODA, S. and ABRAMOVICH, S., 2019. Thermal tolerance and range expansion of invasive foraminifera under climate changes. *Scientific Reports*, 9: 1–5.
- WESTERHOLD, T., MARWAN, N., DRURY, A. J., LIEBRAND, D., AGNINI, C., ANAGNOSTOU, E., BARNET, J. S., BOHATY, S. M., DE VLEESCHOUWER, D., FLORINDO, F. and FREDERICH, T., 2020. An astronomically dated record of Earth's climate and its predictability over the last 66 million years. *Science*, 369: 1383–1387.
- YASUHARA, M. and DEUTSCH, C. A., 2022. Paleobiology provides glimpses of future ocean. *Science*, 375: 25–26.