Paleocene–Eocene warming and biotic response in the epicontinental West Siberian Sea

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ABSTRACT

We present a Paleocene–Eocene (ca. 60–52 Ma) sea-surface temperature record from sediments deposited in the epicontinental West Siberian Sea. TEX_{86} paleothermometry indicates long-term late Paleocene (~17 °C ca. 59 Ma) to early Eocene (26 °C at 52 Ma) sea-surface warming, consistent with trends previously observed for the Southern Ocean and deep oceans. Photic zone and seafloor anoxia developed as temperatures rose by 7 °C to ~27 °C during the Paleocene–Eocene Thermal Maximum (PETM). Based on paired palynological and TEX_{86} data, we suggest that the minimum temperature for the proliferation of Paleocene and early Eocene members of the dinoflagellate family Wetzelielloideae, which includes the PETM marker taxon *Apectodinium*, was ~20 °C.

INTRODUCTION

Southern Ocean surface and global deep-water temperatures rose by ~11 °C and 7 °C, respectively, between the late Paleocene, ca. 58 Ma, and the early Eocene Climatic Optimum, 52–50 Ma (Zachos et al., 2008; Bijl et al., 2009, 2013; Hollis et al., 2012). Superimposed on this long-term warming, several transient warming events or hyperthermals occurred, including the Paleocene–Eocene Thermal Maximum (PETM; ca. 56 Ma) and Eocene Thermal Maximum 2 (ETM2; ca. 54 Ma). These hyperthermals were associated with rapid and massive injections of ^{13}C-depleted carbon into the ocean-atmosphere system, based on pronounced negative carbon isotope excursions (CIEs) in sedimentary components (e.g., Dickens et al., 1995; Lourens et al., 2005).

Early Eocene global climate was ~15 °C warmer than at present based on data and models, with particularly warm polar regions and reduced meridional temperature gradients (e.g., Bijl et al., 2009; Huber and Caballero, 2011). Notably, the gradient changed during the early Paleogene as mid- and high-latitude regions cooled, and the limited information from the tropics shows only minor temperature change (Pearson et al., 2007; Bijl et al., 2009). Because of poor spatial coverage, however, the constraints on this gradient are limited. Critically, there is no record of long-term late Paleocene through early Eocene sea-surface temperature (SST) evolution for the Northern Hemisphere other than the Arctic Ocean (Integrated Ocean Drilling Program, IODP Expedition 302; Arctic Coring Expedition, ACEX; Sluijs et al., 2006, 2008, 2009).

Both the long-term warming and the hyperthermals were marked by poleward migrations of biota, notably recorded in the tropical and subtropical dinoflagellate cyst (dinocyst) genus *Apectodinium* (Crouch et al., 2001). However, there are few quantitative temperature constraints on plankton biogeography. Here we present organic geochemical and dinoflagellate cyst data from the southern part of the West Siberian Sea (Fig. 1) to document regional long-term temperature evolution in relation to plankton biogeography.

MATERIALS

Upper Paleocene sandstones in Well 10 near Omsk, southwestern Siberia, Russia (53°30′
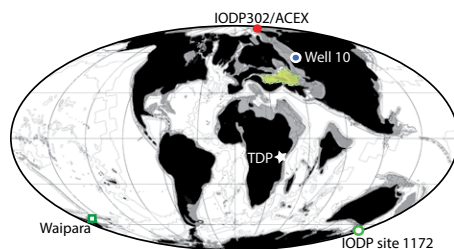

Figure 1. Paleogeographic map (55 Ma) showing site locations: Arctic Coring Expedition (ACEX) (Sluijs et al., 2006, 2008, 2009), West Siberian Sea (Well 10) (this study), Waipara, New Zealand (Hollis et al., 2012), Integrated Ocean Drilling Program (IODP) Site 1172 (Bijl et al., 2009, 2013; Sluijs et al., 2011), and Tanzania Drilling Project (TDP) (Pearson et al., 2007). Green shaded area represents the approximate extent of sapropel deposition during the Paleocene–Eocene Thermal Maximum (PETM) in epicontinental Eurasia (Radionova et al., 2003).

06.37″N, 73°31′35.57″E; paleolatitude ~58°N) are unconformably deposited on the Maastrichtian Gan'kino Formation 260.2 m below surface (mbs; Fig. 2). The Paleocene sandstones fine upward into mudstones and gaize, a sediment type rich in amorphous silica, indicating a gradual deepening of the basin. A glauconite-rich sandstone from 237.7 to 237 mbs separates the lower and upper part of the Lulinvor Formation. It underlies a sapropelitic bed, which may be correlative to similar lithological units in the northern Peri-Tethys shown to correspond to the maximum flooding surface of the PETM (Gavrilov et al., 2003; Radionova et al., 2003; Fig. 1). The upper part of the Lulinvor Formation consists mainly of siliceous silt and sandstones. The similarity of early Paleogene dinocyst assemblages in the epicontinental West Siberian Sea with those in the North Sea Basin (Heilmann-Clausen, 1985), Atlantic Ocean (Sluijs and Brinkhuis, 2009), and Tethys indicates that the West Siberian Sea was well connected to the global ocean (Iakovleva, 2011).

METHODS

We integrate existing dinocyst biostratigraphy (Iakovleva and Heilmann-Clausen, 2010; Iakovleva and Aleksandrova, 2013) and magnetic polarity reversals (Akhmet'ev et al., 2010) with new stable carbon isotope stratigraphy to optimize the age model in Well 10. We apply the organic molecular TEX_{86} (tetraether index of tetraethers consisting of 86 carbon atoms) temperature proxy (Schouten et al., 2002) to reconstruct temperature and use dinocyst assemblages as paleoenvironmental indicators.

We measured total organic carbon (TOC) and $\delta^{13}C_{TOC}$ on ~10 mg of homogenized and decalcified sample using a CNS (carbon-nitrogen-sulfur) analyzer (Fisons) coupled to an isotope ratio mass spectrometer (Finnigan MAT Delta Plus). For TEX_{86} analysis, ~10 g of sediment was extracted by a Dionex accelerated solvent extractor. Extracts were separated into polar and apolar fractions over an Al_2O_3 column. The apolar fractions of the sapropelitic bed and adjacent samples were scanned for isorenieratane by gas chromatography and gas chromatography mass spectrometry. Isoprenoid glycerol dibiphytanyl
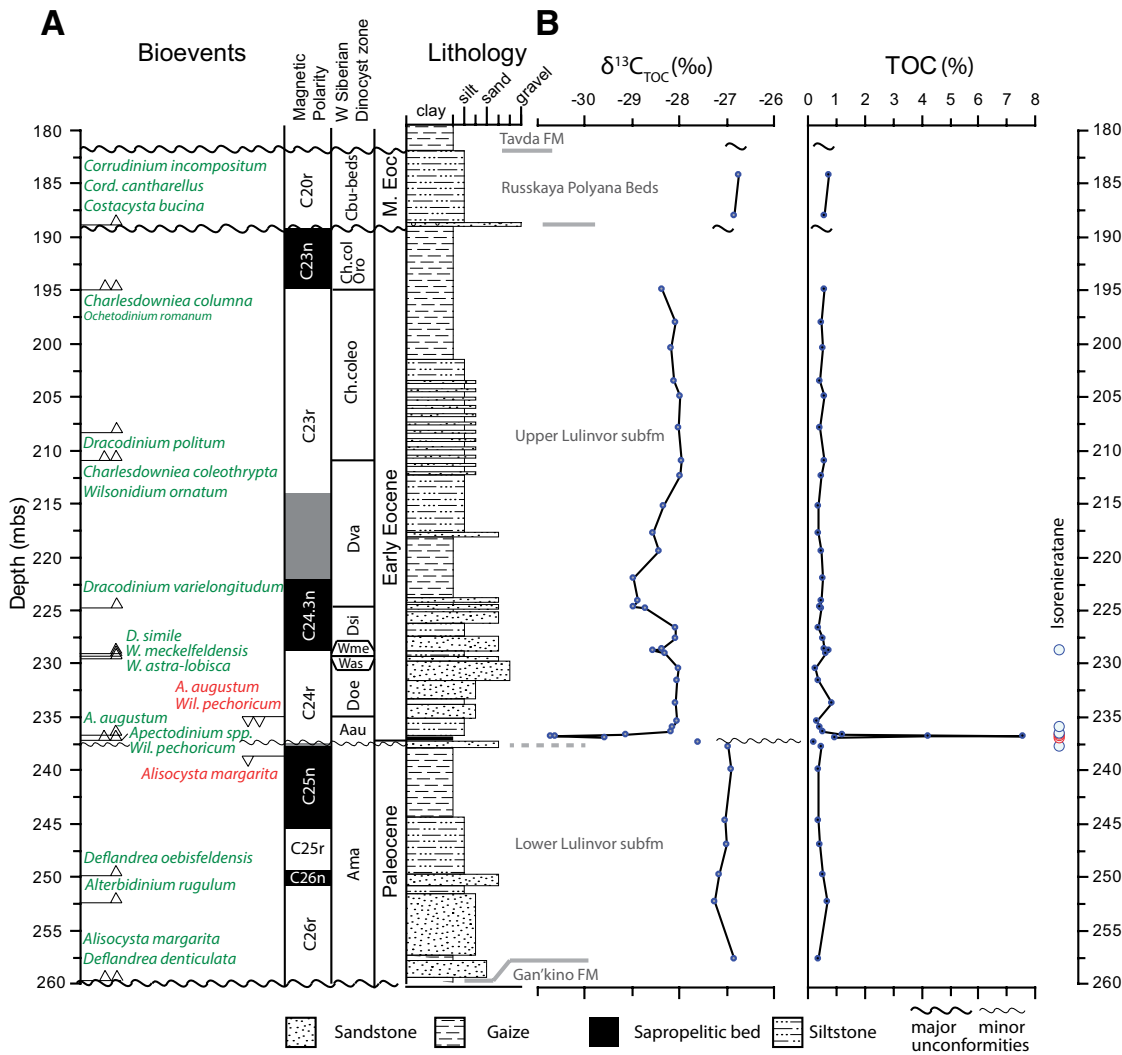
Figure 2. A: Lithological column of Well 10 and stratigraphic markers. Standard Wentworth grain-size classes are used. B: Stable carbon isotope ($\delta^{13}C_{TOC}$) and total organic carbon (TOC); circles indicate samples tested for isorenieratane (red—present, blue—absent). Depth is in meters below surface (mbs). FM—formation; M.—middle. West Siberian dinoflagellate cyst zonation follows Iakovleva and Aleksandrova (2013). Genus name abbreviations: A.—*Apectodinium*, Dr.—*Dracodinium*, Cord.—*Cordosphaeridium*, W.—*Wetzeliella*, Wil.—*Wilsonidium*. Dinozone abbreviations: Ama—*Alisocysta margarita*, Aau—*Apectodinium augustum*, Doe—*Deflandrea oebisfeldensis*, Was—*Wetzeliella astra*, Wme—*Wetzeliella meckelfeldensis*, Dsi—*Dracodinium simile*, Dva—*Dracodinium varielongitudum*, Ch.coleo—*Charlesdowniea coleothrypta*, Ch.colum—*Charlesdowniea columna*, Oro—*Ochetodinium romanum*, Cbu—*Costacysta bucina*.

glycerol tetraethers (GDGTs) and branched GDGTs in the polar fractions were measured on an Agilent 1100 high performance liquid chromatography mass spectrometer. We calculated SSTs using the most recent high-temperature (H) calibration, TEX_{86}^{H} which yields a calibration error of 2.5 °C (Kim et al., 2010; see the GSA Data Repository[1] for detailed methods and discussion concerning TEX_{86} calibrations and caveats).

Palynological processing included treatment with HCl (10%) for carbonate removal. Clay particles were dispersed with tetrasodium pyrophosphate ($Na_4P_2O_7 \cdot 10H_2O$, 10%) and decanted. Residues were centrifuged with heavy liquid (K_2CdI_4) and boiled with HF (10%) to remove heavy particles and silicates, respectively. We applied no exote spiking or sieving. At least 200 dinocysts were counted per sample where possible. Samples yielding <100 dinocysts were excluded from quantitative analyses.

RESULTS AND DISCUSSION

Stratigraphy

We apply the dinocyst zonation scheme for western Siberia (Iakovleva and Heilmann-Clausen, 2010; Iakovleva and Aleksandrova, 2013) to correlate recorded first (e.g., *Alisocysta margarita*, *Deflandrea denticulata*, *Charlesdowniea columna*) and last occurrences (e.g., *A. margarita*, *Apectodinium augustum*, *Wilsonidium pechoricum*), and the magnetic reversals of Iakovleva et al. (2012) to the Geomagnetic Polarity Time Scale (see the Data Repository) (Fig. 2). This indicates that the section spans the interval from ca. 60 Ma to 52 Ma. The combined occurrence of the dinocyst *Apectodinium augustum* and the 3.1‰ negative CIE from −27.6‰ to −30.7‰ indicates that the sapropelitic bed from 237 to 236.4 mbs represents the PETM (Fig. 2; e.g., Crouch et al., 2001, Schmitz et al., 2004). BIT (branched/isoprenoid tetraether) index values of ~0.05 indicate low terrestrial contributions to TOC (Hopmans et al., 2004) throughout this interval, excluding a major effect of varying organic matter sources on the recorded $\delta^{13}C_{TOC}$ shift.

The 70-cm-thick glauconite-rich unit separates the top of Chron 25n and the PETM and marks a ~1 m.y. hiatus or condensed interval associated with the unconformity between the lower and upper parts of the Lulinvor Formation.

Several first occurrences of Wetzelielliodeae, *Wetzeliella astra-lobisca*, *W. lunaris*, *W. meckelfeldensis*, and *Dracodinium simile* at ~228.8 mbs suggest an age close to that of ETM2. However, the absence of a CIE suggests a hiatus or insufficient sampling resolution. At 188.2 mbs, an erosional surface marks the boundary between the upper Lulinvor Formation and middle Eocene Russkaya Polyana beds (Akhmet'ev et al., 2010).

Anoxia During the PETM

We recorded the presence of isorenieratane and its derivatives within the PETM (Fig. 2). This provides evidence for the presence of photosynthetic green sulfur bacteria, which implies photic zone euxinia (e.g., Sinninghe Damsté et al., 1995). Concurrent high TOCwt% suggests that anoxia developed in the entire water column. However, given the partially benthic life cycle stage of cyst-forming dinoflagellates that
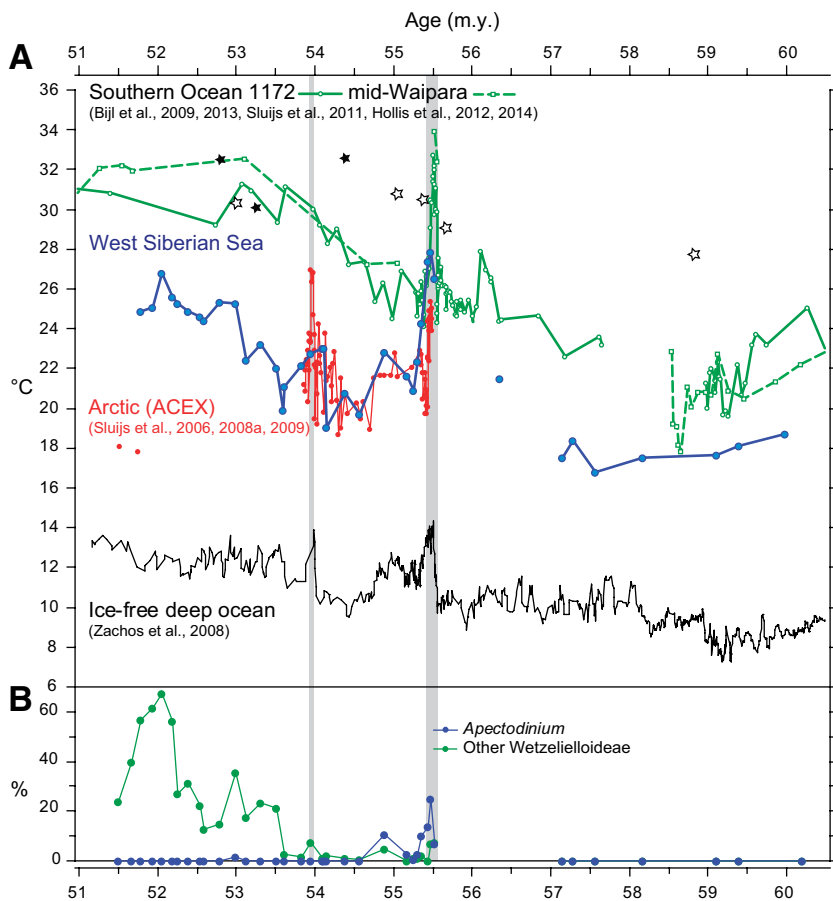
Figure 3. A: TEX$_{86}^{H}$ (see text) reconstructed temperatures. Geological time scale 2012 (Gradstein et al., 2012) (age in Ma). Ice-free temperatures represent 5-point moving average of the Zachos et al. (2008) benthic oxygen isotope stack. Gray bands mark positions of Paleocene–Eocene Thermal Maximum (ca. 55.5 Ma) and Eocene Thermal Maximum 2 (ca. 54 Ma; not recorded in Well 10, WSS [West Siberian Sea]). Closed stars (Tanzania) indicate TEX$_{86}^{H}$ data; open stars are maximum foraminifer δ^{18}O derived temperatures (Pearson et al., 2007). The TEX$_{86}^{H}$ calibration error is 2.5 °C. B: Relative abundances of *Apectodinium* (blue) and Wetzelielloideae (green) in Well 10.

requires oxygen, anoxia likely developed intermittently or seasonally.

Temperature Evolution

Regardless of the applied calibration (see the Data Repository), the TEX$_{86}$ temperature record at Well 10 closely resembles global deep-water temperature trends inferred from the benthic oxygen isotope stack (Zachos et al., 2008) and temperature evolution in the southwest high (Bijl et al., 2009, 2013) and mid-latitudes (Hollis et al., 2012) of the Pacific Ocean for the late Paleocene and early Eocene (ca. 60–52 Ma; Fig. 3A; Fig. DR2 in the Data Repository). Based on latest Paleocene and earliest Eocene temperatures (~21 °C), SSTs rose by ~7 °C during the PETM (Fig. 3A), consistent with several other mid-latitude sites, but somewhat greater than the global average (Dunkley Jones et al., 2013). TEX$_{86}^{H}$ (applied to all records for optimal comparison) shows ~10 °C of long-term warming in both the Northern and Southern Hemispheres. Rising atmospheric CO$_2$ concentrations may have

caused this warming; however, the only available tropical temperature record suggests stable temperatures throughout the early Eocene, thus challenging this hypothesis (Pearson et al., 2007).

Contrasting with general assumptions in the literature and Southern Hemisphere records (Bijl et al., 2009; Hollis et al., 2012), the Arctic Ocean and West Siberian Sea show stable temperatures or slight cooling between the PETM and ETM2. This is also apparent in various benthic oxygen isotope records (e.g., Zachos et al., 2008) and seems to mark a prolonged (0.8–0.9 m.y.) period of comparatively warm temperatures in the Northern Hemisphere SST records following the PETM. Northern Hemisphere–Southern Hemisphere temperature gradients were reestablished at ca. 54.3 Ma, and match the previously observed hemispheric asymmetry, as noted by Bijl et al. (2009).

It is remarkable that temperatures in the West Siberian Sea were nearly identical, in both trend and absolute values, to those in the Arctic Ocean during the earliest Eocene (55.5–54 Ma;

Fig. 3A), thus implying the absence of a gradient from 58°N to 85°N. Seasonal and depth biases in the TEX$_{86}$ proxy, as well as the impact of genetic differences between archaeal populations, are poorly understood and likely important in higher latitudes and stratified basins, respectively. However, if TEX$_{86}$ truthfully reflects mean annual SST, this implies that mechanisms must have acted that amplified warming in the Arctic Ocean (Sluijs et al., 2006) or cooled the West Siberian Sea.

SST Limitation of *Apectodinium* and other Wetzelielloideae

The oldest record of *Apectodinium* is close to the Danian-Selandian boundary in the Tethys Ocean (Guasti et al., 2005), and it has long been hypothesized to be a thermophilic genus (e.g., Bujak and Brinkhuis, 1998) that required a minimum temperature to thrive (Sluijs and Brinkhuis, 2009). If so, *Apectodinium* and its entire subfamily Wetzelielloideae would not be present below this SST threshold in Well 10 (Fig. 3). To test this hypothesis, we investigate the relation between SST and the Wetzelielloideae in Well 10 and the ACEX record (Sluijs et al., 2006, 2009; Fig. 4), the sites with the lowest TEX$_{86}$-derived SSTs for the studied time interval and therefore suitable to quantify a lower tolerance limit. We expect this relation to exhibit major scatter; alongside SST, salinity and nutrients were likely important for *Apectodinium* and Wetzelielloideae (Sluijs et al., 2006; Sluijs and Brinkhuis, 2009). Low-salinity–tolerant dinocysts (e.g., *Senegalinium*) were only minor components in West Siberian Sea assemblages during the PETM (see the Data Repository) and co-occur with Wetzelielloideae in the early Eocene, suggesting that low salinity was unlikely to be limiting. Moreover, we find that the correlation of Wetzelielloideae to SSTs is significant (p = 2.7 × 10^{-6}), whereas the correlation to the BIT is not (p = 0.015), which implies that temperature is here more important than terrestrial nutrient and freshwater input. Therefore, we can estimate the lower tolerance limit of Wetzelielloideae, including *Apectodinium* as
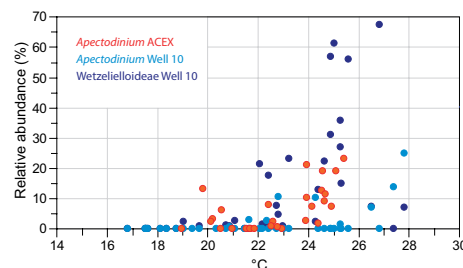

Figure 4. Relative concentrations of *Apectodinium* in Well 10 (light blue) and Arctic Coring Expedition (ACEX) (orange) and other Wetzelielloideae (Well 10—dark blue) plotted against reconstructed temperature. WSS—West Siberian Sea.

~20 ± 2.5 °C (Fig. 4), suggesting that this temperature was a minimum prerequisite for their proliferation in the Paleocene and early Eocene.

CONCLUSIONS

Upper Paleocene and lower Eocene sediments from the West Siberian Sea reveal 9 °C of long-term warming from 58 to 52 Ma and 7 °C of warming during the PETM, based on TEX_{86}^H. Absolute recorded temperatures are nearly identical to those recorded in the Arctic Ocean. Slight cooling occurred in the interval between the PETM and ETM2, consistent with Arctic surface and deep ocean trends. During the PETM, euxinia developed in the photic zone. We quantify the threshold minimum temperature for the proliferation of Paleocene and early Eocene Wetzelielloideae, an extinct dinocyst subfamily that also includes *Apectodinium*, at 20 °C.

REFERENCES CITED

Akhmet'ev, M.A., Zaporozhets, N.I., Iakovleva, A.I., Aleksandrova, G.N., Beniamovsky, V.N., Oreshkina, T.V., Gnibidenko, Z.N., and Dolya, Z.A., 2010, Comparative analysis of marine Paleogene sections and biota from west Siberia and the Arctic region: Stratigraphy and Geological Correlation, v. 18, p. 635–659, doi:10.1134/S0869593810060043.

Bijl, P.K., Schouten, S., Sluijs, A., Reichart, G.-J., Zachos, J.C., and Brinkhuis, H., 2009, Early Palaeogene temperature evolution of the southwest Pacific Ocean: Nature, v. 461, p. 776–779, doi:10.1038/nature08399.

Bijl, P.K., Sluijs, A., and Brinkhuis, H., 2013, A magneto- and chemostratigraphically calibrated dinoflagellate cyst zonation of the early Palaeogene South Pacific Ocean: Earth-Science Reviews, v. 124, p. 1–31, doi:10.1016/j.earscirev.2013.04.010.

Bujak, J.P., and Brinkhuis, H., 1998, Global warming and dinocyst changes across the Paleocene/Eocene Epoch boundary, *in* Aubry, M.-P., et al., eds., Late Paleocene–early Eocene biotic and climatic events in the marine and terrestrial records: New York, Columbia University Press, p. 277–295.

Crouch, E.M., Heilmann-Clausen, C., Brinkhuis, H., Morgans, H.E.G., Rogers, K.M., Egger, H., and Schmitz, B., 2001, Global dinoflagellate event associated with the late Paleocene thermal maximum: Geology, v. 29, p. 315–318, doi:10.1130/0091-7613(2001)029<0315:GDEAWT>2.0.CO;2.

Dickens, G.R., O'Neil, J.R., Rea, D.K., and Owen, R.M., 1995, Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene: Paleoceanography, v. 10, p. 965–971, doi:10.1029/95PA02087.

Dunkley Jones, T., Lunt, D.J., Schmidt, D.N., Ridgwell, A., Sluijs, A., Valdes, P., and Maslin, M., 2013, Climate model and proxy data constraints on ocean warming across the Paleocene-Eocene Thermal Maximum: Earth-Science Reviews, v. 125, p. 123–145, doi:10.1016/j.earscirev.2013.07.004.

Gavrilov, Y.O., Shcherbinina, E.A., and Oberhansli, H., 2003, Paleocene-Eocene boundary events in the northeastern Peri-Tethys, *in* Wing, S.L., et al., eds., Causes and consequences of globally warm climates in the early Paleogene: Geological Society of America Special Paper 369, p. 147–168, doi:10.1130/0-8137-2369-8.147.

Gradstein, F.M, et al., 2012, The Geologic Time Scale 2012: Boston, Elsevier, doi:10.1016/B978-0-444-59425-9.00004-4.

Guasti, E., Kouwenhoven, T.J., Brinkhuis, H., and Speijer, R.P., 2005, Paleocene sea-level and productivity changes at the southern Tethyan margin (El Kef, Tunisia): Marine Micropaleontology, v. 55, p. 1–17, doi:10.1016/j.marmicro.2005.01.001.

Heilmann-Clausen, C., 1985, Dinoflagellate stratigraphy of the uppermost Danian to Ypresian in the Viborg 1 borehole, central Jylland, Denmark: Danmarks Geologiske Undersøgelse, ser. A, v. 7, p. 1–69.

Hollis, C.J., et al., 2012, Early Paleogene temperature history of the Southwest Pacific Ocean: Reconciling proxies and models: Earth and Planetary Science Letters, v. 349–350, p. 53–66, doi:10.1016/j.epsl.2012.06.024.

Hopmans, E.C., Weijers, J.W.H., Schefuss, E., Herfort, L., Sinninghe Damsté, J.S., and Schouten, S., 2004, A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids: Earth and Planetary Science Letters, v. 224, p. 107–116, doi:10.1016/j.epsl.2004.05.012.

Huber, M., and Caballero, R., 2011, The early Eocene equable climate problem revisited: Climate of the Past, v. 7, p. 603–633, doi:10.5194/cp-7-603-2011.

Iakovleva, A.I., 2011, Palynological reconstruction of the Eocene marine palaeoenvironments in south of Western Siberia: Acta Palaeobotanica, v. 51, no. 2, p. 229–248.

Iakovleva, A.I., and Aleksandrova, G.N., 2013, To the question on dinocyst zonation of Paleocene-Eocene in western Siberia: Bulletin of Moscow Society of Naturalists Geological Series, v. 88, no. 1, p. 59–82.

Iakovleva, A.I., and Heilmann-Clausen, C., 2010, Eocene dinoflagellate cyst biostratigraphy of research borehole 011-BP, Omsk region, southwestern Siberia: Palynology, v. 34, p. 195–232, doi:10.1080/01916121003629974.

Iakovleva, A.I., Aleksandrova, G.N., and Gnibidenko, Z.N., 2012, Updating of Paleogene Lulinvor Formation age in southern western Siberia by palynological and paleomagnetic data: Moscow Society of Naturalists Geological Series Bulletin, v. 87, no. 3, p. 53–87.

Kim, J.-H., van der Meer, J., Schouten, S., Helmke, P., Willmott, V., Sangiorgi, F., Koc, N., Hopmans, E.C., and Sinninghe Damsté, J.S., 2010, New indices and calibrations derived from the distribution of crenarchaeal isoprenoid tetraether lipids: Implications for past sea surface temperature reconstructions: Geochimica et Cosmochimica Acta, v. 74, p. 4639–4654, doi:10.1016/j.gca.2010.05.027.

Lourens, L.J., Sluijs, A., Kroon, D., Zachos, J.C., Thomas, E., Rohl, U., Bowles, J., and Raffi, I., 2005, Astronomical pacing of late Palaeocene to early Eocene global warming events: Nature, v. 435, p. 1083–1087, doi:10.1038/nature03814.

Pearson, P.N., van Dongen, B.E., Nicholas, C.J., Pancost, R.D., Schouten, S., Singano, J.M., and Wade, B.S., 2007, Stable warm tropical climate through the Eocene Epoch: Geology, v. 35, p. 211–214, doi:10.1130/G23175A.1.

Radionova, E.P., Beniamovksy, V.N., Iakovleva, A.I., Muzylov, N.G., Oreshkina, T.V., Shcherbinina, E.A., and Kozlova, G.E., 2003, Early Paleogene transgressions: Stratigraphical and sedimentological evidence from the northern Peri-Tethys, *in* Wing, S.L., et al., eds., Causes and consequences of globally warm climates in the early Paleogene: Geological Society of America Special Paper 369, p. 239–261, doi:10.1130/0-8137-2369-8.239.

Schmitz, B., Peucker-Ehrenbrink, B., Heilmann-Clausen, C., Aberg, G., Asaro, F., and Lee, C.-T.A., 2004, Basaltic explosive volcanism, but no comet impact, at the Paleocene-Eocene boundary: High-resolution chemical and isotopic records from Egypt, Spain and Denmark: Earth and Planetary Science Letters, v. 225, p. 1–17, doi:10.1016/j.epsl.2004.06.017.

Schouten, S., Hopmans, E.C., Schefuss, E., and Sinninghe Damsté, J.S., 2002, Distributional variations in marine crenarchaeotal membrane lipids: A new tool for reconstructing ancient sea water temperatures?: Earth and Planetary Science Letters, v. 204, p. 265–274, doi:10.1016/S0012-821X(02)00979-2.

Sinninghe Damsté, J.S., Köster, J., Baas, M., Koopmans, M.P., van Kaam-Peters, H.M.E., Geenevasen, J.A.J., and Kruk, C., 1995, Cyclisation and aromatisation of carotenoids during sediment diagenesis: Journal of the Chemical Society, Chemical Communications, p. 187–188, doi:10.1039/c39950000187.

Sluijs, A., and Brinkhuis, H., 2009, A dynamic climate and ecosystem state during the Paleocene-Eocene Thermal Maximum: Inferences from dinoflagellate cyst assemblages on the New Jersey Shelf: Biogeosciences, v. 6, p. 1755–1781, doi:10.5194/bg-6-1755-2009.

Sluijs, A., et al., 2006, Subtropical Arctic Ocean temperatures during the Palaeocene/Eocene thermal maximum: Nature, v. 441, p. 610–613, doi:10.1038/nature04668.

Sluijs, A., Rohl, U., Schouten, S., Brumsack, H.-J., Sangiorgi, F., Sinninghe Damsté, J.S., and Brinkhuis, H., 2008, Arctic late Paleocene–early Eocene paleoenvironments with special emphasis on the Paleocene-Eocene thermal maximum (Lomonosov Ridge, Integrated Ocean Drilling Program Expedition 302): Paleoceanography, v. 23, p. 1–17, doi:10.1029/2007PA001495.

Sluijs, A., Schouten, S., Donders, T.H., Schoon, P.L., Rohl, U., Reichart, G.-J., Sangiorgi, F., Kim, J.-H., and Sinninghe Damsté, J.S., 2009, Warm and wet conditions in the Arctic region during Eocene Thermal Maximum 2: Nature Geoscience, v. 2, p. 777–780, doi:10.1038/ngeo668.

Sluijs, A., Bijl, P.K., Schouten, S., Röhl, U., Reichart, G.-J., and Brinkhuis, H., 2011, Southern Ocean warming and hydrological change during the Paleocene–Eocene thermal maximum: Climate of the Past, v. 7, p. 47–61, doi:10.5194/cp-7-47-2011.

Zachos, J.C., Dickens, G.R., and Zeebe, R.E., 2008, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics: Nature, v. 451, p. 279–283, doi:10.1038/nature06588.

Geology

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