Supplementary Information

Subtropical Arctic Ocean temperatures during the Palaeocene-Eocene thermal maximum. Appy Sluijs, Stefan Schouten, Mark Pagani, Martijn Woltering, Henk Brinkhuis, Jaap S. Sinninghe Damsté, Gerald R. Dickens, Matthew Huber, Gert-Jan Reichart, Ruediger Stein, Jens Matthiessen, Lucas J. Lourens, Nikolai Pedentchouk, Jan Backman, Kathryn Moran and the Expedition Scientists

Relative stratigraphic position of Core 31X

The stratigraphic position of the 55 cm recovered section of Core 302-4A-31X relative to Cores 30X and 32X is uncertain (Fig. 2). It may be located anywhere in the interval between 384.54 and 388 meters composite depth (mcd). For illustration purposes, we have placed this core 1m lower than indicated in ref. 1.

Description and calibration of TEX_{86}'

Originally TEX_{86} values were calculated as described in ref. 2 and converted to sea surface temperature (SST). However, the glycerol dialkyl glycerol tetraether (GDGT) lipid containing three cyclopentane rings (GDGT-3), almost always the least abundant GDGT lipid in marine sediments, was unusually high in Core 302-4A-32X (Fig. S-2A). Since terrestrial organic matter also contains isoprenoid GDGT lipids with cyclopentane rings[3] (and Weijers, J Schouten, S., Sinninghe Damsté, J.S., unpublished results), it is likely that the high terrestrial input in this section has disturbed the aquatic signal. The high abundance of GDGT-3 resulted in unusually high TEX_{86} values in Core 32X. To circumvent this problem, TEX_{86}' was devised which has the same definition as TEX_{86} except that isomer GDGT-3 was removed from the denominator[2]. The TEX_{86}' was determined for 104 marine surface sediments and found to correlate very well with annual mean SST: $TEX_{86}' = 0.016 \times SST + 0.20$ with $R^2 = 0.93$ (Fig S-2B). This equation was used to convert TEX'_{86} into SST. Sediments from Cores 30X and 31X show a normal marine tetraether lipid distribution, i.e., showing a very minor peak at GDGT-3, resulting in the TEX_{86}' values only slightly different from TEX_{86} values (Fig SI-2C). Interestingly, the top part of Core 30X, which shows a large terrestrial influence (Fig. 2), shows again a relatively large offset between TEX_{86}' and TEX_{86}, evidencing a larger contribution of the GDGT-3. This is consistent with a terrestrially-derived contribution to the GDGT-3 peak.

Which temperature does TEX_{86}' indicate in the Arctic Ocean?

TEX_{86} and TEX_{86}' are calibrated by core top analysis to mean annual mean SST. This empirical relation is not the same as a causal relationship. Several studies have shown that the cell number of crenarchaeota in the water column strongly depends on the season[4]. In most studies a negative correlation has been observed between the cell abundance of crenarchaeota and phytoplankton, likely because they compete for the nutrient ammonia. As crenarchaeota are chemoautotrophic organisms[5] and thus not directly depend on light it is likely that crenarchaeota predominantly thrived during times of low cell abundances of phytoplankton and low light intensities, i.e. in the Arctic winter. However, for the crenarchaeotal signal to reach the sediment floor a significant sedimentation flux is needed. In the present day ocean significant organic carbon fluxes are observed during periods of high phytoplanktonic productivity because an active food web leads to grazing and feacal pellet packaging[6,7]. In agreement with this we recently recorded the highest fluxes of crenarchaeotal lipids in the Arabian Sea coinciding with the periods of high productivity, despite that their relative abundance was lower in these periods (Wuchter C., Schouten S., Wakeham, S.G. and Sinninghe Damsté, J.S., unpublished results). In the Eocene Arctic Ocean the bulk of the signal will be derived from those periods with highest biological productivity, which at this high latitude must be the summer months. Hence we refined our interpretation of the TEX_{86}' estimates by suggesting that its signal in the Eocen Arctic Ocean, although calibrated to globally-derived annual mean SSTs, may record the, on average, higher summer SSTs due to the flux-dependency of the signal.

Preservation of the organic matter used in this study

Water column anoxia, in this paper indicated by the laminated sediments and the presense of isoreneratene derivatives, will lead to an improved preservation of certain organic compounds[8]. Below, we discuss the preservation of the different types of organic matter used in this paper and conclude that selective preservation did not affect our proxy records.

The presence of isorenieratene derivatives has been frequently used to detect anoxia extending up into the photic zone of the water column during the Phanerozoic[9,10], including late Pliocene sapropel formation in the eastern Mediterranean[11]. These compounds are derived from photosynthetic green sulfur bacteria which require both light and free sulfide (i.e. euxinic conditions) to thrive. In the particular, these organisms are found in lakes and marine settings where the water column is euxinic such as the present day Black Sea[12]. Accordingly, the presence of isorenieratene derivatives in ACEX Cores 30X and 31X indicates that euxinic conditions prevailed in the photic zone in the Arctic ocean during the PETM. These compounds preserve quite well, even when the water column is re-oxygenated and sediments are inhabited by benthic organisms[13]. Therefore we exclude selective preservation as possible bias on the presence/absence pattern of these compounds. Moreover, well preserved palynomorphs and substantial organic matter concentrations (~2% TOC) outside the laminated interval with isorenieratene derivatives, indicates that no severe organic matter degradation occurred. In this respect, we also exclude a bias on the terrestrial vs. marine palynomorph ratio, since it has recently been shown that preferential preservation of terrestrial palynomorphs only occurs in well-oxygenated bottom water settings[14].

The terrestrial and marine compounds used in the BIT index represent structurally very similar compounds[15]. It has been shown that the relative distribution of the different isomers of glycerol dialkyl glycerol tetraethers (GDGTs) is independent of the oxygen concentration in the water column[16]. Thus, the absolute amounts of GDGTs may have increased within the laminated interval, but their relative distribution, i.e. the BIT index, has remained unaffected.

Bottom water anoxia at the PETM

Organic linings of benthic foraminifera are common through the latest Palaeocene and earliest Eocene except during the photic zone euxinia, indicated by isorenieratane (Fig. S-3A). Sediments from the latter interval are laminated (Fig. S-3B), which implies that no bioturbation occurred after deposition of the sediments and that bottom waters were anoxic. Despite a large scatter % TOC is on average ~1.3% higher during the PETM compared to the latest Palaeocene. Unfortunately, due to the core recovery problems and potential changes in siliciclastic sediment supply related to the transgression there is relatively poor grip on sediment accumulation rates across the studied interval. However, some of the enhanced % TOC may be due to increased nutrient supply by rivers, resulting in higher phytoplankton production and, under anoxic bottom water conditions, high organic matter accumulation.

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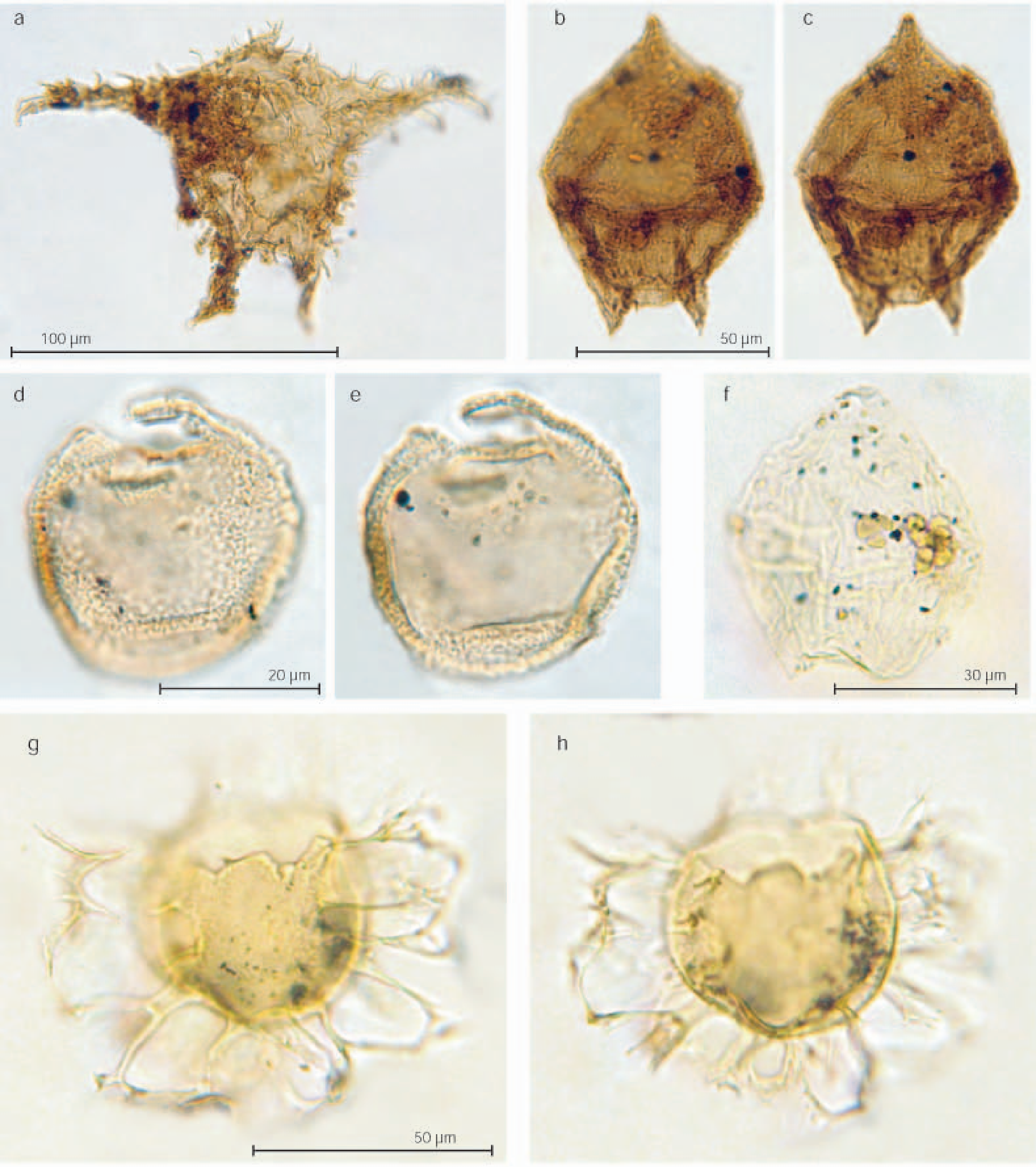
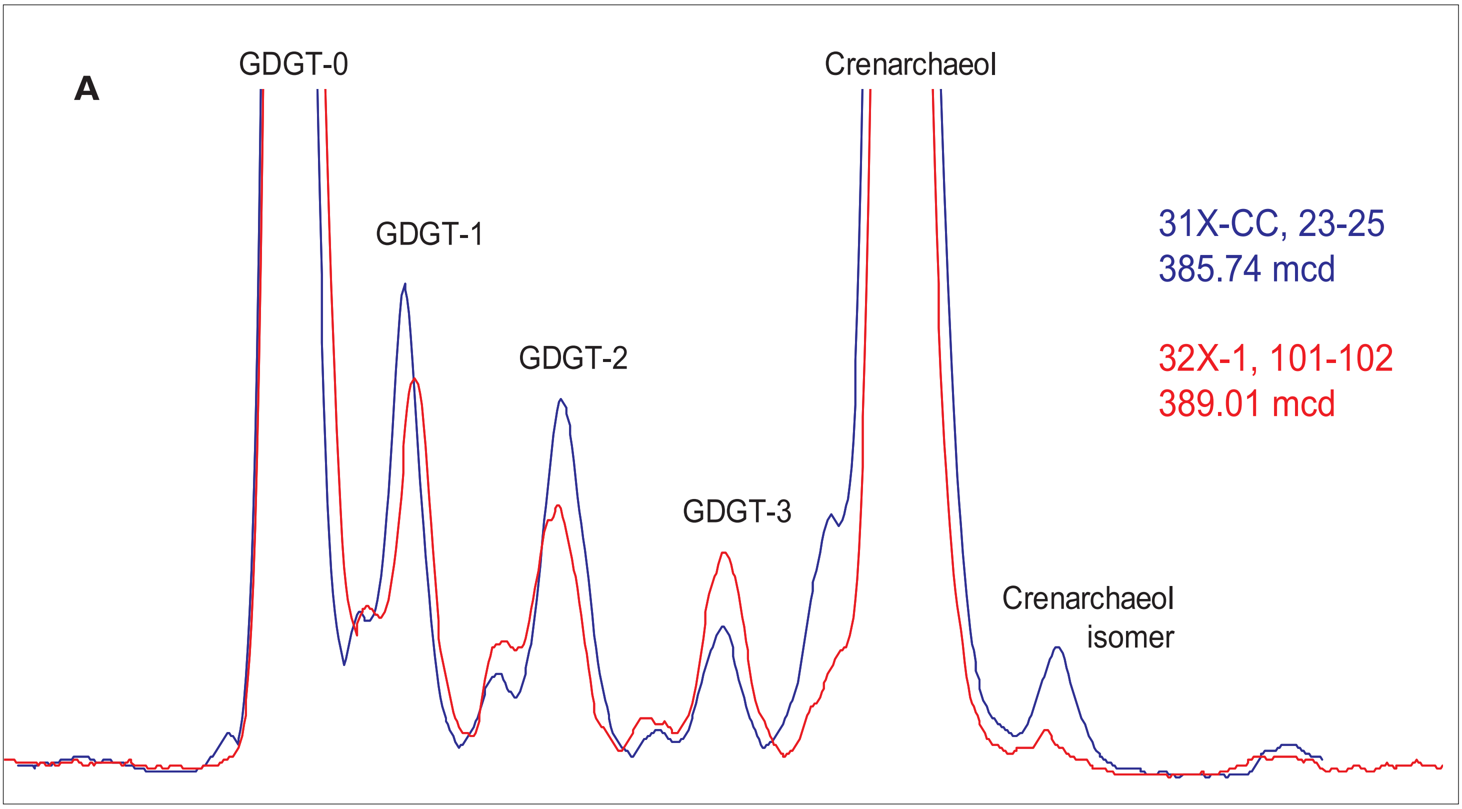
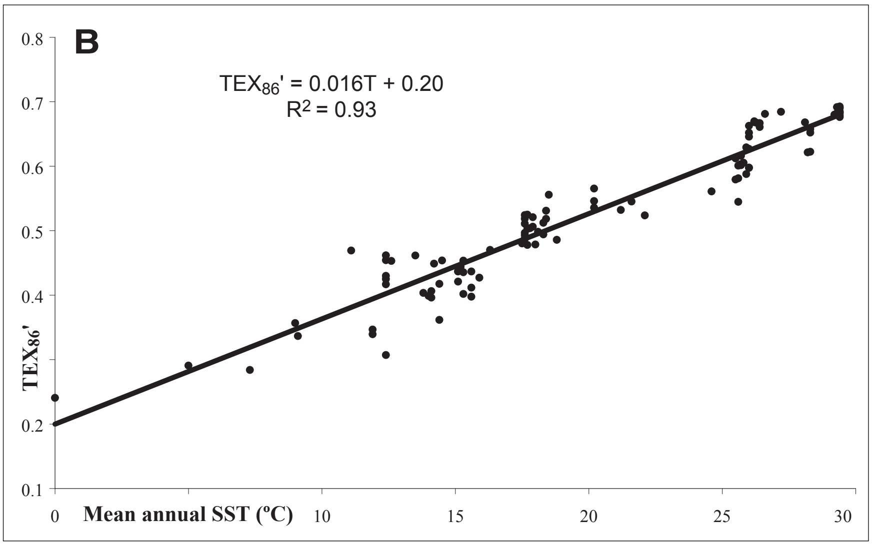


Fig. S-1.
Light microscope photos of dominant dinocyst taxa across the PETM of IODP Hole 302-4A. **a**. *Apectodinium augustum* (302-4A-30X, 101-103 cm; Slide 1, England Finder Coordinates S32-1); **b, c**. *Cerodinium wardenense* (302-4A-30X-3, 81-83 cm; Slide 1, F37-0); **d, e**. *Membranosphaera* spp. (302-4A-30X-1, 141-143 cm; Slide 1, L31-3); **f**. *Senegalinium* spp. (302-4A-30X-3, 101-103 cm; Slide 1, L37-3); **g, h**. *Glaphyrocysta* spp. (302-4A-30X-1, 141-143 cm; Slide 1, J43-4).





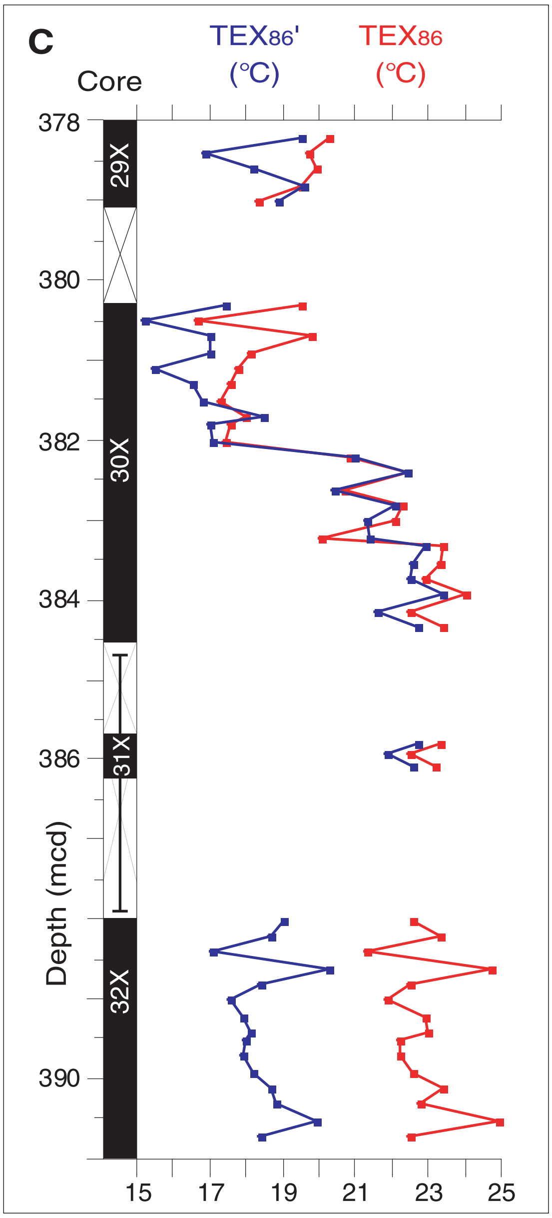


Figure S-2. TEX86' calibration **A)** HPLC/MS base peak chromatograms showing the chrenarchaeotal membrane lipid distribution of samples from Cores 31X and 32X. **B)** Calibration of TEX86' to mean annual sea surface temperature. **C)** Comparison between TEX86' and TEX86 across the PETM of Site 302-4A.

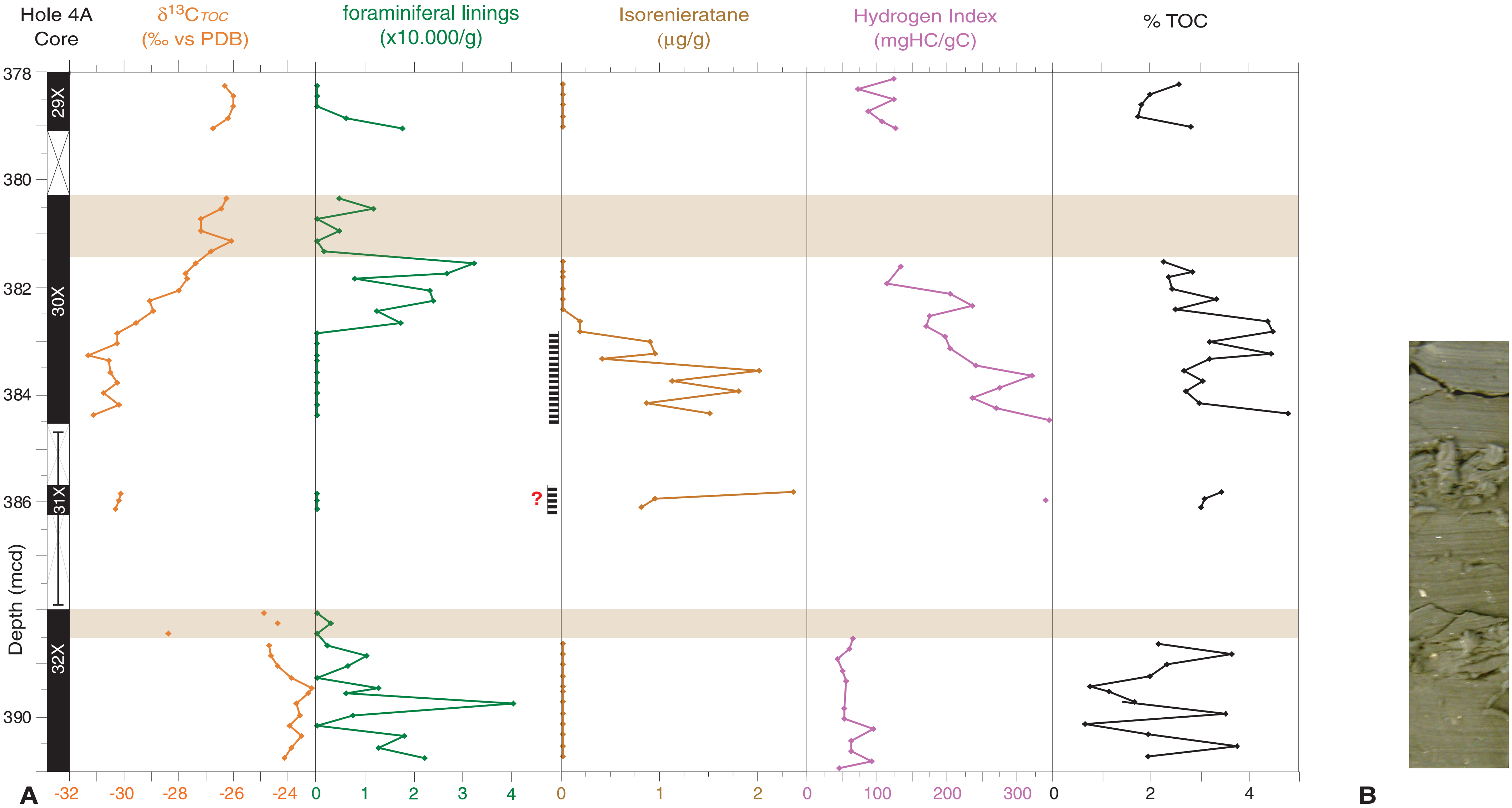


Figure S-3. Additional indicators for water column euxinia and terrestrial influence. **A)** Isorenieratane and foraminifer lining distribution through the latest Palaeocene - earliest Eocene. Laminated interval indicated by stripes. Laminae are unclear in Core 31X due to drilling disturbance. The hydrogen index shows a substantial increase during the PETM, consistent with increased auquatic versus terrestrial organic matter. Despite significante scatter, average % Total Organic Carbon (TOC) increases by ~1% at the PETM. **B)** Core picture (interval 302-4A-30X-3, 123-129 cm) showing laminations.

Expedition	Site	Hole	Core	type	sec	t (cm)	b (cm)	depth (mcd)	*Apectodinium spp.*	*Areoligera/Glaphyrocysta* cpx	*Caligodinium aceras*	*Cerodinium/Deflandrea* cpx	*Cordosphaeridium* cpx	*Senegalinium* spp.	*Spiniferites* cpx	*Membranosphaera* cpx	*Polysphaeridium* cpx	Others	n dinocysts	% *Apectodinium* spp.	% *Areoligera/Glaphyrocysta* cpx	% *Caligodinium aceras*	% *Cerodinium/Deflandrea* cpx	% *Cordosphaeridium* cpx	% *Senegalinium* spp.	% *Spiniferites* cpx	% *Membranosphaera* cpx	% *Polysphaeridium* cpx	% Others	% low salinity tolerant dinocysts	Foraminifer linings per gram	Angiosperms	Spores	Gymnosperms	n terr. Palmorphs	% Angiosperms	% Spores	% Gymnosperms	number of marine palynomorphs	% marine palynomorphs	% terrestrial palynomorphs
302	4	A	29	X	1	41	43	378.21	0	50	0	4	0	63	31	44	0	17	209	0	24	0	2	0	30	15	21	0	8	36	0	141	175	327	643	22	27	51	274	30	70
302	4	A	29	X	1	61	63	378.41																								129	52	94	275	47	19	34	12	4	96
302	4	A	29	X	1	81	83	378.61	1	56	0	25	0	58	10	37	1	19	207	0	27	0	12	0	28	5	18	0	9	45	0	137	176	165	478	29	37	35	244	34	66
302	4	A	29	X	1	101	103	378.81	0	1	0	17	0	94	57	33	1	15	218	0	0	0	8	0	43	26	15	0	7	55	6.E+03	282	206	215	703	40	29	31	316	31	69
302	4	A	29	X	CC	1	3	379.01	0	2	4	35	0	92	23	36	1	8	201	0	1	2	17	0	46	11	18	0	4	66	2.E+04	503	300	1527	2330	22	13	66	263	10	90
302	4	A	30	X	1	1	3	380.31																								77	101	94	272	28	37	35	67	20	80
302	4	A	30	X	1	21	23	380.51																								89	127	57	273	33	47	21	32	10	90
302	4	A	30	X	1	41	43	380.71																								91	124	114	329	28	38	35	27	7	93
302	4	A	30	X	1	61	63	380.91																								100	113	98	311	32	36	32	11	3	97
302	4	A	30	X	1	81	83	381.11																								102	78	106	286	36	27	37	7	2	98
302	4	A	30	X	1	101	103	381.31	0	0	2	10	0	71	57	49	0	10	200	0	0	1	5	0	36	29	24	0	5	43	1.E+03	159	176	100	435	37	40	23	219	12	88
302	4	A	30	X	1	121	123	381.51	16	2	1	10	2	29	20	35	1	5	122	13	2	1	8	2	23	16	29	1	4	40	5.E+04	411	326	576	1313	31	25	44	201	13	87
302	4	A	30	X	1	141	143	381.71	13	0	1	29	0	27	47	80	0	18	215	6	0	0	13	0	13	22	37	0	8	30	3.E+04	267	362	491	1120	24	32	44	253	18	82
302	4	A	30	X	2	1	3	381.82	7	0	2	18	0	13	29	124	1	8	201	3	0	1	9	0	7	14	62	1	4	17	8.E+03	300	344	421	1065	28	32	40	230	18	82
302	4	A	30	X	2	21	23	382.02	5	1	0	25	0	40	41	93	0	5	210	2	0	0	12	0	19	20	44	0	2	33	2.E+04	345	796	296	1437	24	55	21	261	15	85
302	4	A	30	X	2	41	43	382.22	5	3	16	45	0	15	50	59	14	11	218	2	1	7	21	0	7	23	27	6	5	37	2.E+04	116	67	106	289	40	23	37	255	47	53
302	4	A	30	X	2	61	63	382.42	4	1	8	15	1	27	58	82	7	12	215	2	0	4	7	0	13	27	38	3	6	25	1.E+04	101	70	131	302	33	23	43	291	49	51
302	4	A	30	X	2	81	83	382.62	2	3	10	72	0	35	50	21	0	14	207	1	2	5	35	0	17	24	10	0	7	58	2.E+04	244	60	83	387	63	16	21	216	32	68
302	4	A	30	X	2	101	103	382.82	6	4	1	121	5	50	27	3	0	5	222	3	2	0	55	2	23	12	1	0	2	81	0	70	20	47	137	51	15	34	256	65	35
302	4	A	30	X	2	121	123	383.02	15	6	0	97	1	44	26	5	1	8	203	7	3	0	48	0	22	13	2	0	4	79	0	122	25	56	203	60	12	28	238	54	46
302	4	A	30	X	2	141	143	383.22	17	0	0	73	0	35	3	81	0	2	211	8	0	0	35	0	17	1	38	0	1	56	0	129	22	17	168	77	13	10	231	58	42
302	4	A	30	X	3	1	3	383.34	18	1	1	138	2	37	9	31	6	4	247	7	0	0	56	1	15	4	13	2	2	80	0	68	14	25	107	64	13	23	264	71	29
302	4	A	30	X	3	21	23	383.54	30	0	0	132	1	19	4	49	2	2	239	13	0	0	55	0	8	2	21	1	1	74	0	74	8	13	95	78	8	14	269	74	26
302	4	A	30	X	3	41	43	383.74	20	1	1	151	1	22	3	17	1	6	223	9	0	0	68	0	10	1	8	0	3	88	0	13	3	6	22	59	14	27	232	91	9
302	4	A	30	X	3	61	63	383.94	52	0	0	51	0	54	3	55	0	10	225	23	0	0	23	0	24	1	24	0	4	64	0	92	12	3	107	86	11	3	251	70	30
302	4	A	30	X	3	81	83	384.14	48	2	0	104	1	52	1	15	0	5	228	21	1	0	46	0	23	0	7	0	2	89	0	72	19	21	112	64	17	19	250	69	31
302	4	A	30	X	3	101	103	384.34	26	2	0	83	0	98	6	10	0	5	230	11	1	0	36	0	43	3	4	0	2	91	0	51	9	8	68	75	13	12	244	78	22
302	4	A	31	X	CC	10	12	385.80	49	3	0	143	1	30	13	16	0	2	257	19	1	0	56	0	12	5	6	0	1	84	0	71	15	97	183	39	8	53	290	61	39
302	4	A	31	X	CC	23	25	385.93	29	0	0	140	0	43	1	61	4	5	283	10	0	0	49	0	15	0	22	1	2	75	0	81	4	9	94	86	4	10	297	76	24
302	4	A	31	X	CC	40	42	386.10	47	1	0	156	0	29	2	11	0	1	247	19	0	0	63	0	12	1	4	0	0	93	0	40	0	4	44	91	0	9	256	85	15
302	4	A	32	X	1	1	3	388.01	24	5	2	92	0	7	10	0	0	5	145	17	3	2	63	0	5	7	0	0	3	85	0	40	34	150	224	18	15	67	175	44	56
302	4	A	32	X	1	21	23	388.21	6	0	0	93	0	11	19	0	2	0	130	4	0	0	71	0	9	14	0	1	0	85	0	54	66	165	285	19	23	58	142	33	67
302	4	A	32	X	1	41	43	388.41	82	0	0	43	0	4	7	0	2	0	137	60	0	0	31	0	3	5	0	1	0	87	0	3	9	4	16	20	60	20	144	89	11
302	4	A	32	X	1	61	63	388.61																								181	45	95	321	56	14	30	19	6	94
302	4	A	32	X	1	81	83	388.81	0	0	1	84	0	71	19	30	0	10	215	0	0	0	39	0	33	9	14	0	5	76	1.E+04	96	87	78	261	37	33	30	348	57	43
302	4	A	32	X	1	101	103	389.01																								34	23	20	77	44	30	26	7	8	92
302	4	A	32	X	1	121	123	389.21																								43	29	19	91	47	32	21	2	2	98
302	4	A	32	X	1	141	143	389.41																								42	22	20	84	50	26	24	8	9	91
302	4	A	32	X	2	1	3	389.51																								49	27	32	108	45	25	30	20	16	84
302	4	A	32	X	2	21	23	389.71																								55	33	24	112	49	29	21	17	13	87
302	4	A	32	X	2	41	43	389.91	0	0	0	55	0	105	27	13	1	5	206	0	0	0	27	0	51	13	6	0	2	80	7.E+03	260	154	228	642	40	24	36	295	31	69
302	4	A	32	X	2	61	63	390.11																								66	21	23	110	60	19	21	3	3	97
302	4	A	32	X	2	81	83	390.31	0	0	0	71	0	65	44	20	0	4	204	0	0	0	35	0	32	22	10	0	2	68	2.E+04	323	233	324	880	37	26	37	340	28	72
302	4	A	32	X	2	101	103	390.51																								56	35	23	114	49	31	20	9	7	93
302	4	A	32	X	2	121	123	390.71																								22	25	50	97	23	26	52	22	18	82

Table S-1. Summarized palynological results across the PETM of IODP Hole 4A. Core 31X has been shifted down 1 meter relative to ref. SI-1 (see Supplementary Information text). Green bars indicate intervals affected by drilling disturbance. Low salinity tolerant dinocyst percentages are normalised to the sum of all dinocysts minus the species with unknown salinity tolerance. The latter group is 10% on average.