1	Supplementary Materials for
2	Discovery of giant magnetofossils within and outside of the Palaeocene-Eocene Thermal
3	Maximum in the North Atlantic
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13	This file presents more TEM and SEM images and statistics analyses of particle size (length and
14	width) distributions for all types of magnetofossils in this study, including:
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16	Figs. S1 to S12
17	Tables S1 to S5



Fig. S1. TEM images of small needles, bullets, and other conventional magnetofossil crystals within the studied sediment samples from IODP Sites U1403 and U1409. Red and green arrows indicate small needles and bullets, respectively. In this study, cuboctahedral (orange arrow) and elongated-prismatic magnetite (blue arrow) particles are defined to be other conventional magnetofossils.



Fig. S2. SEM images showing the presence of four types of giant magnetofossils before, during, and

26 after the PETM from IODP Hole 1409A. The four columns from left to right indicate spearheads (a, e,

i), spindles (b, f, j), needles (c, g, k), and giant bullets (d, h, l), respectively.



Fig. S3. SEM images for four types of giant magnetofossils before, during, and after the PETM from IODP Hole 1409C. The four columns from left to right indicate spearheads (a, e, i), spindles (b, j), needles (c, g, k), and giant bullets (d, h, l), respectively. A broken spearhead particle rather than a spindle is shown in (f), which may indicate the growth direction for spearheads.



Fig. S4. SEM images for four types of giant magnetofossils before, during, and after the PETM from
IODP Hole 1403B. The four columns from left to right indicate spearheads (a, e, i), spindles (b, f, j),
needles (c, g, k), and giant bullets (d, h, l), respectively.



41 Fig. S5. SEM images for spearheads without tails and with variable sizes of stalks.



Fig. S6. The normality test for crystal length of the seven defined groups of magnetite crystals using 44 Quantile-Quantile (QQ) plots, Shapiro-Wilk test, Kolmogorov-Smirnov test (Tables S1 and S2). 45 Normal length distributions for spearheads, spindles, and small needles are confirmed using QQ plots 46 and Shapiro–Wilk test (P > 0.05). Crystal length of needles and small bullets shows approximately 47 normal distributions. Bullets and other conventional magnetofossils indicate abnormal distributions. 48 The category for other conventional magnetofossils was tested using the Kolmogorov-Smirnov 49 method because the counts of particles are more than 3000, while others were tested using the Shapiro-50 Wilk method. 51



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Fig. S7. Examples of energy dispersive X-ray spectroscopy (EDS) results for all types of giant magnetofossils. (a) Giant bullet, (b) needle, (c) spearhead, and (d) spindle are analysed from SEM observations. C and Ca are from the carbonate materials surrounding the analysed particle, and Si are from silica wafer. (e) Giant bullet, (f) needle, (g) spearhead, and (h) conventional magnetofossils are analysed from TEM observations. C and Cu are from the TEM grid.



61 Fig. S8. Micromagnetic modelling results for different sizes of small needles. All modelled small

62 needles have single domain structures with a flower state at both ends.



Fig. S9. TEM or SEM images and magnetofossil cartoons showing the hypothetical crystal growth model for spearheads (a-c) and spindles (d-f). The pyramid-like structure of spearheads forms first (a), followed by the formation of the stalk (b) and tail (c) in the direction of crystal elongation. The morphology of spindles retains during crystal growth. The length of spindles continues to grow with negligible change in width (d-f).



Fig. S10. TEM images and magnetofossil cartoons showing the hypothetical crystal growth model for all needle-shaped (a-d) and bullet-shaped particles (e-h). Small needles have an isotropic growth pattern (a, b), while needles maintain a width of ~100 nm and mainly grow in length (c, d). All bulletshaped crystals appear to have similar length and width growth rates (e-g).



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Fig. S11. Statistical analysis of morphological data for four types of giant magnetite crystals in samples from the New Jersey (NJ) cores, IODP Sites U1409, and U1403. The 95% and 90% levels of confidence ellipse are indicated by the colored shadows and inner solid lines, respectively. Morphological data for the NJ core samples are from Schumann et al. (2008), Wang et al. (2015), and Wagner et al. (2021a).



Fig. S12. Crystal length distribution for spearheads, needles, and giant bullets at Sites U1409 (a-c) and U1403 (d-f). Orange (U1409) and blue (U1403) lines represent normality fitting curves. Results of ttest (g-i) for crystal length of giant magnetofossils at Sites U1409 and U1403 suggest that there is no difference in spearheads (P = 0.641 < 0.05), possibly minor differences in needles (P = 0.045 < 0.05), and giant bullets (P = 0.003 < 0.1).

Statistics	Spearhead			Spindle			Needle			Giant bullet		
	Length (nm) Width (nm) W/L		Length (nm)	Width (nm)	W/L	Length (nm)	Width (nm)	W/L	Length (nm)	Width (nm)	W/L	
Maximum	3531.8	1880.8	0.87	2857.8	696.6	0.30	2040.7	182.3	0.26	2603.6	937.8	0.57
Minimum	572.4	248.2	0.29	653.1	158.3	0.16	407.5	66.9	0.04	411.6	102.3	0.13
Median	1799.7	860.6	0.47	1918.1	403.1	0.20	805.6	100.2	0.12	875.2	302.4	0.36
Mean	1832.2	855.7	0.49	1899.8	395.6	0.21	846.5	100.6	0.13	897.5	318.5	0.36
σ	505.0	195.4	0.01	489.0	104.4	0.04	280.0	15.1	0.04	310.1	130.7	0.07
K-S test*	0.200	0.001	0.006	0.200	0.003	0.132	0.010	0	0.011	0	0	0.027
S-W test*	0.115	0	0	0.274	0.001	0.054	0	0	0.005	0	0	0.054
Counts	192	192	192	27	27	27	211	211	211	165	165	165

0 Table S1. Statistical results of grain sizes for the four types of giant magnetofossils at IODP Sites U1409 and U1403.

1 Note*: K-S test, Kolmogorov–Smirnov test; S-W test, Shapiro–Wilk test.

2 Table S2. Statistical results of grain sizes for small needles, bullets, and other conventional magnetofossils at

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IODP Sites U1409 and U1403.

	Sn	nall Noodle	`		Rullot		Other conventional			
Statiation					Duilet		magnetofossils			
Statistics	Length	Width	\\//I	Length	Width	\\//I	Length	Width	\\//	
	(nm)	(nm)	VV/L	(nm)	(nm)	VV/L	(nm)	(nm)	vv/L	
Maximum	397.3	101.6	0.30	399.6	192.1	0.78	299.3	284.1	1.00	
Minimum	83.8	23.2	0.10	35.1	14.0	0.16	16.7	8.7	0.30	
Median	274.8	60.5	0.24	105.0	37.3	0.36	53.5	45.7	0.89	
Mean	256.6	58.1	0.23	117.3	41.1	0.37	60.3	49.7	0.85	
σ	86.0	21.0	0.05	52.5	16.7	0.10	27.9	19.8	0.14	
K-S test	0.064	0.011	0.014	0	0	0	0	0	0	
S-W test	0.050	0.018	0.016	0	0	0	-	-	-	
Counts	64	64	64	738	738	738	7838	7838	7838	

Table S3. Micromagnetic modelling results for individual magnetite crystals.

Particle	Length (nm)	Width (nm)	Width/Length	Crystallographic direction	$M_{\rm rs}/M_{\rm s}$
Spearhead 1	2545.2	830.9	0.33	[110]	0.177
Spearhead 2	2147.8	1020.3	0.48	[110]	0.040
Spearhead 3	1779.2	840.7	0.47	[110]	0.028
Spearhead 4	1154.3	893.3	0.77	[110]	0.011
Spearhead 5	980.1	498.7	0.51	[110]	0.095
Spindle 1	2530.4	409.1	0.16	[111]	1.000
Spindle 2	2345.5	421.0	0.18	[111]	1.000
Spindle 3	1918.1	380.5	0.20	[111]	1.000
Spindle 4	1533.3	378.0	0.25	[111]	0.999
Spindle 5	908.2	182.2	0.20	[111]	1.000
Needle 1	1403.1	100.4	0.07	[111]	0.998
Needle 2	1191.0	138.7	0.12	[111]	0.945
Needle 3	805.6	99.1	0.12	[111]	0.996
Needle 4	575.0	69.8	0.12	[111]	0.998
Needle 5	489.0	104.8	0.21	[111]	0.992
Giant bullet 1	1347.7	495.0	0.37	[111]	0.040
Giant bullet 2	1157.3	293.3	0.25	[111]	0.129
Giant bullet 3	853.1	298.9	0.35	[111]	0.094
Giant bullet 4	539.4	301.5	0.56	[111]	0.060
Giant bullet 5	425.7	161.8	0.36	[111]	0.276
Small needle 1	327.6	60.6	0.19	[111]	0.998
Small needle 2	312.0	42.0	0.13	[111]	0.999
Small needle 3	215.1	43.8	0.20	[111]	0.999
Small needle 4	151.3	31.6	0.21	[111]	0.999
Small needle 5	145.3	36.4	0.25	[111]	0.999

7 <u>Table S4. Statistics analysis of length for giant magnetofossils at Sites U1409 and U1403.</u>

Statistics	ics Spearhead		Spindle		Nee	edle	Giant bullet	
(nm)	Site 1409	Site 1403	Site 1409	Site 1403	Site 1409	Site 1403	Site 1409	Site 1403
Minimum	792.2	572.4	653.1	908.2	409.8	407.5	422.5	411.6
Maximum	3307.7	3531.8	2857.8	2464.1	2040.7	1491.7	2603.6	1347.7
Median	1800.3	1786.4	1980.2	1791.2	880.0	757.6	905.5	848.0
Mean	1853.5	1818.5	1921.5	1856.5	892.6	814.2	963.9	821.5
σ	485.3	518.8	519.1	448.7	307.0	255.8	372.6	193.9
Counts	75	117	18	9	87	124	88	77

9 <u>Table S5. Statistics analysis of width for giant magnetofossils at Sites U1409 and U1403.</u>

Statistics	Spearhead		Spindle		Nee	edle	Giant bullet	
(nm)	Site 1409	Site 1403	Site 1409	Site 1403	Site 1409	Site 1403	Site 1409	Site 1403
Minimum	441.7	248.2	158.3	182.2	66.9	69.8	115.5	102.3
Maximum	1297.0	1880.8	696.6	478.7	182.3	138.7	937.8	495.0
Median	871.7	856.9	401.2	426.4	101.4	99.6	313.9	293.7
Mean	856.0	855.6	395.3	396.1	103.4	98.6	350.3	282.1
σ	171.1	210.2	112.6	92.0	19.3	10.9	159.2	73.1
Counts	75	117	18	9	87	124	88	77