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Supplementary Materials for

The extinct shark *Otodus megalodon* was a transoceanic superpredator: Inferences from 3D modeling

Jack A. Cooper *et al.*

Corresponding author: Catalina Pimiento, catalina.pimientohernandez@pim.uzh.ch;
John R. Hutchinson, jhutchinson@rvc.ac.uk.

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The PDF file includes:

Other Supplementary Material for this manuscript includes the following:

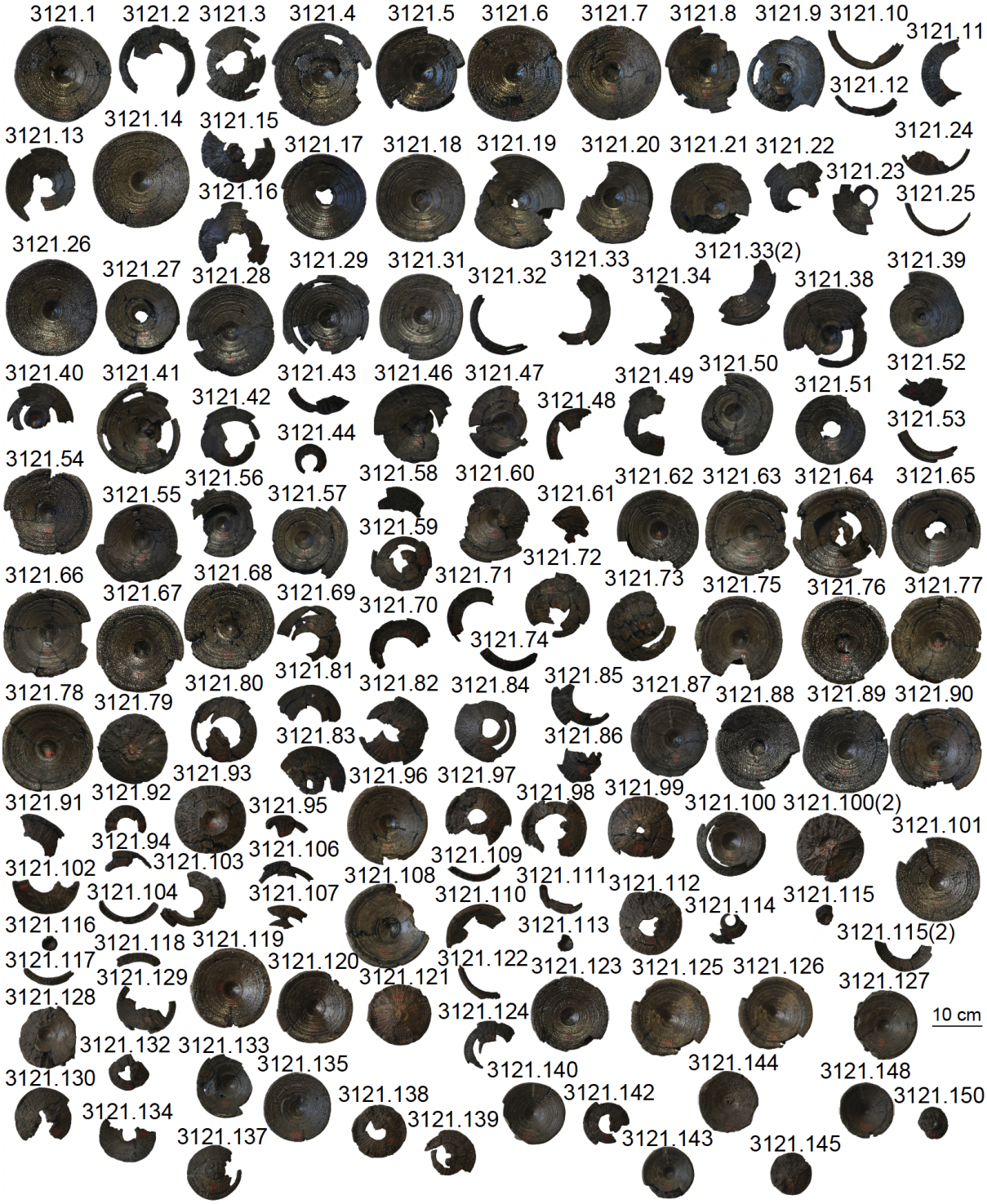

Figure S1. All 141 vertebral centra in the *Otodus megalodon* column (IRNSB P 9893). Labelling refers to position of the centra in the column, and the former labelling of the specimen (IRSNB 3121) (*7*). Centra labelled 30, 35-37, 45, 105, 131, 136, 141, 146, 147 and 149 are missing from the column and there are two centra labelled as 33, 100 and 115 (see main text).

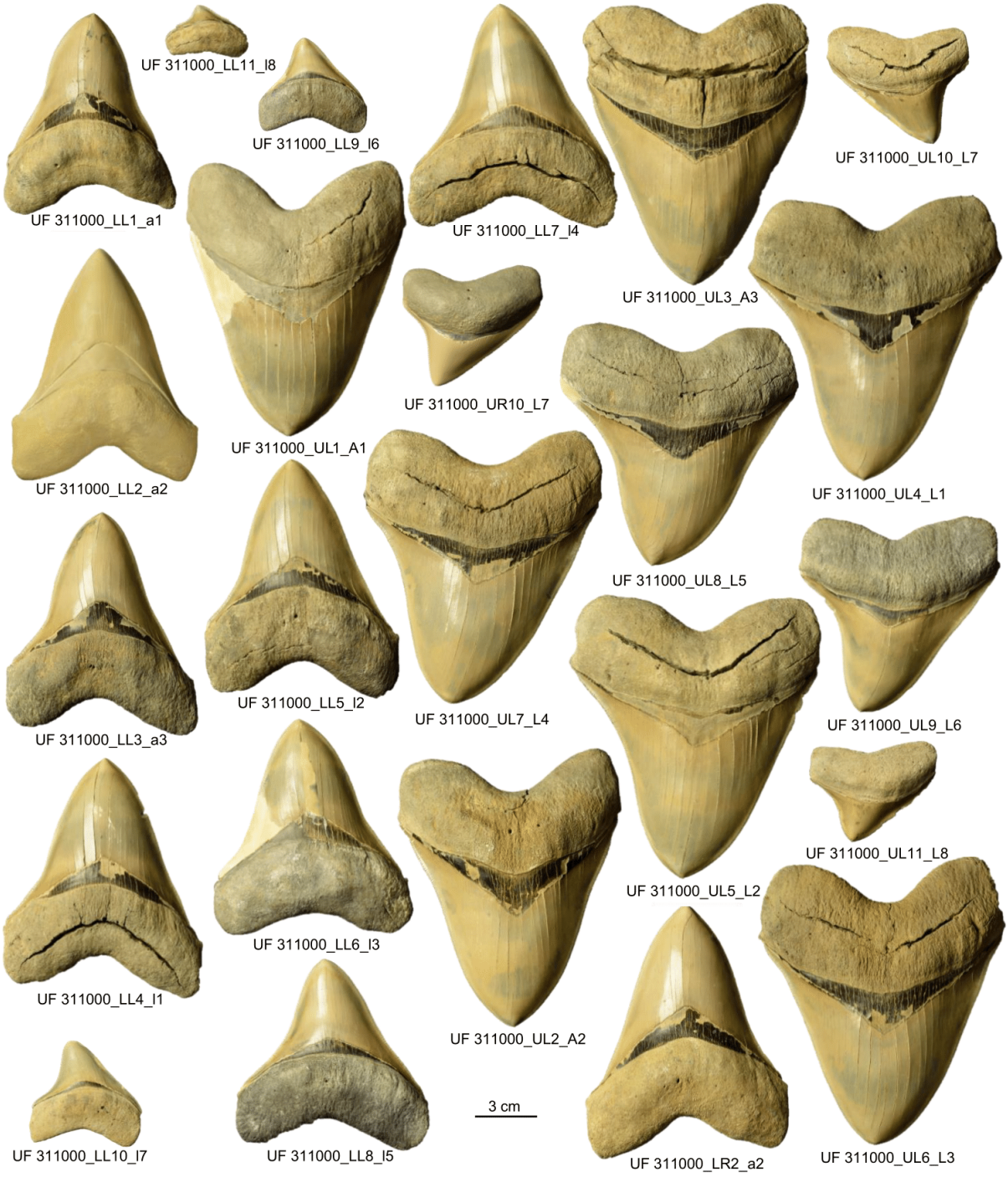

Figure S2. All *Otodus megalodon* teeth (n = 24) from specimen UF 311000, which formed the basis of our model's jaws. Labelling refers to specimen name, tooth position recorded by the Florida Museum of Natural History (LL = lower left; UL = upper left; LR = lower right; UR = upper right), and the tooth position following standard nomenclature, where A/a refers to anterior teeth and L/l represents lateral teeth. In the latter case, upper-case and lower-case letters indicate upper and lower teeth respectively. Photographs taken from the Florida Museum of Natural History online catalogue.

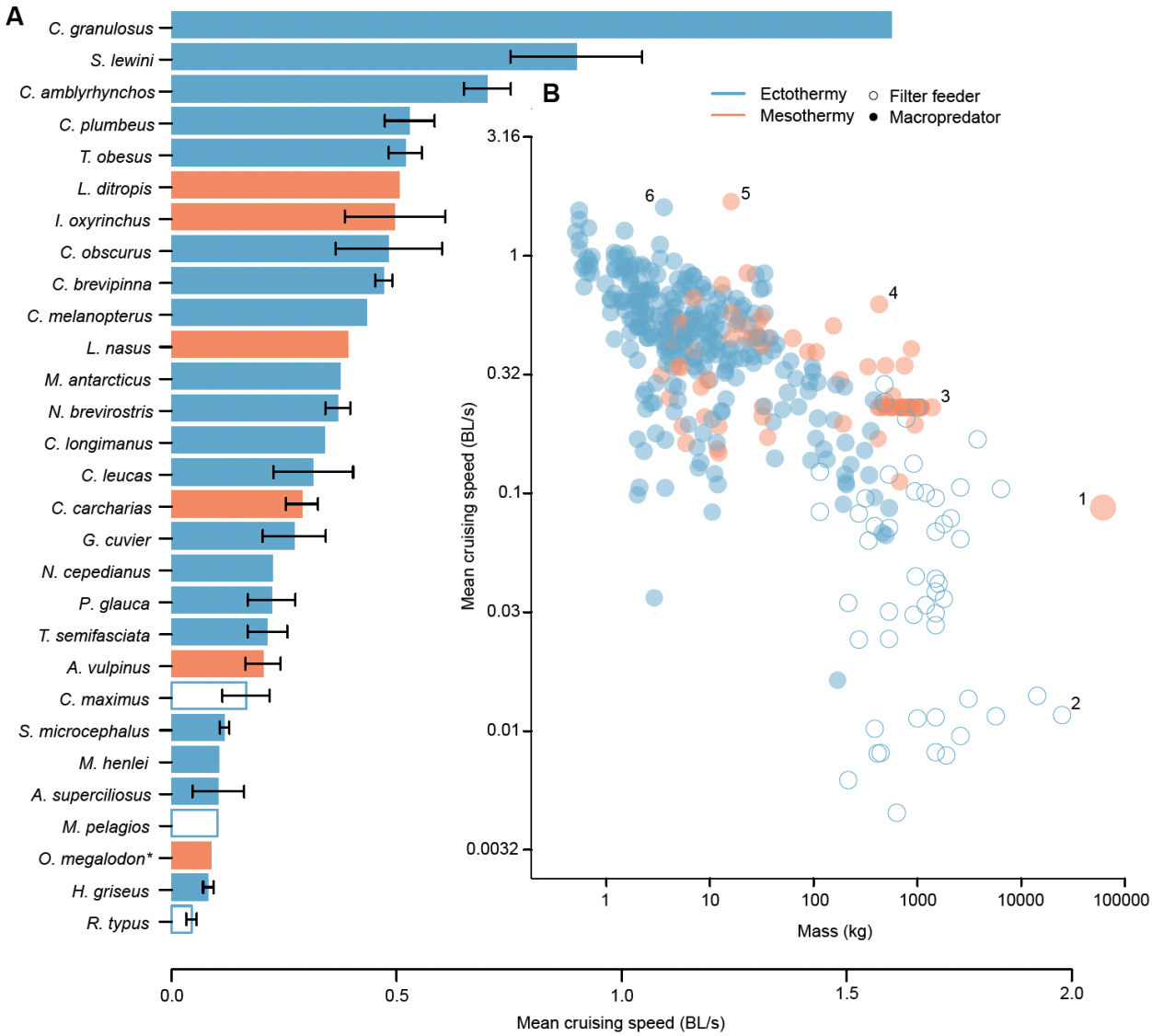

Figure S3. Shark mean relative cruising speeds. (**A**) Mean relative cruising speeds of all shark species from data S1 (n = 28 plus the model *Otodus megalodon*) with error bars drawn from multiple individuals per species. Species without error bars are those where only one individual is represented. An asterisk (*) indicates that *O. megalodon*'s speed estimate was made from equation 2 rather than from the mean of multiple speeds. (**B**) Mass and mean relative cruising speed of all individual sharks recorded in data S1 (n = 391 plus the model *O. megalodon*), plotted on a log scale. Numbered individuals are as follows: 1) the 15.9 m, 61,560 kg model individual of *Otodus megalodon*; 2) an 18 m, 24,800 kg individual of the whale shark (*Rhincodon typus*); 3) a 5.3 m, 1,382 kg great white shark (*Carcharodon carcharias*); 4) a 3.6 m, 427.5 kg *C. carcharias*; 5) a 1.1 m, 16 kg shortfin mako shark (*Isurus oxyrinchus*); and 6) a 0.15 m, 3.6 kg gulper shark (*Centrophorus granulosus*).

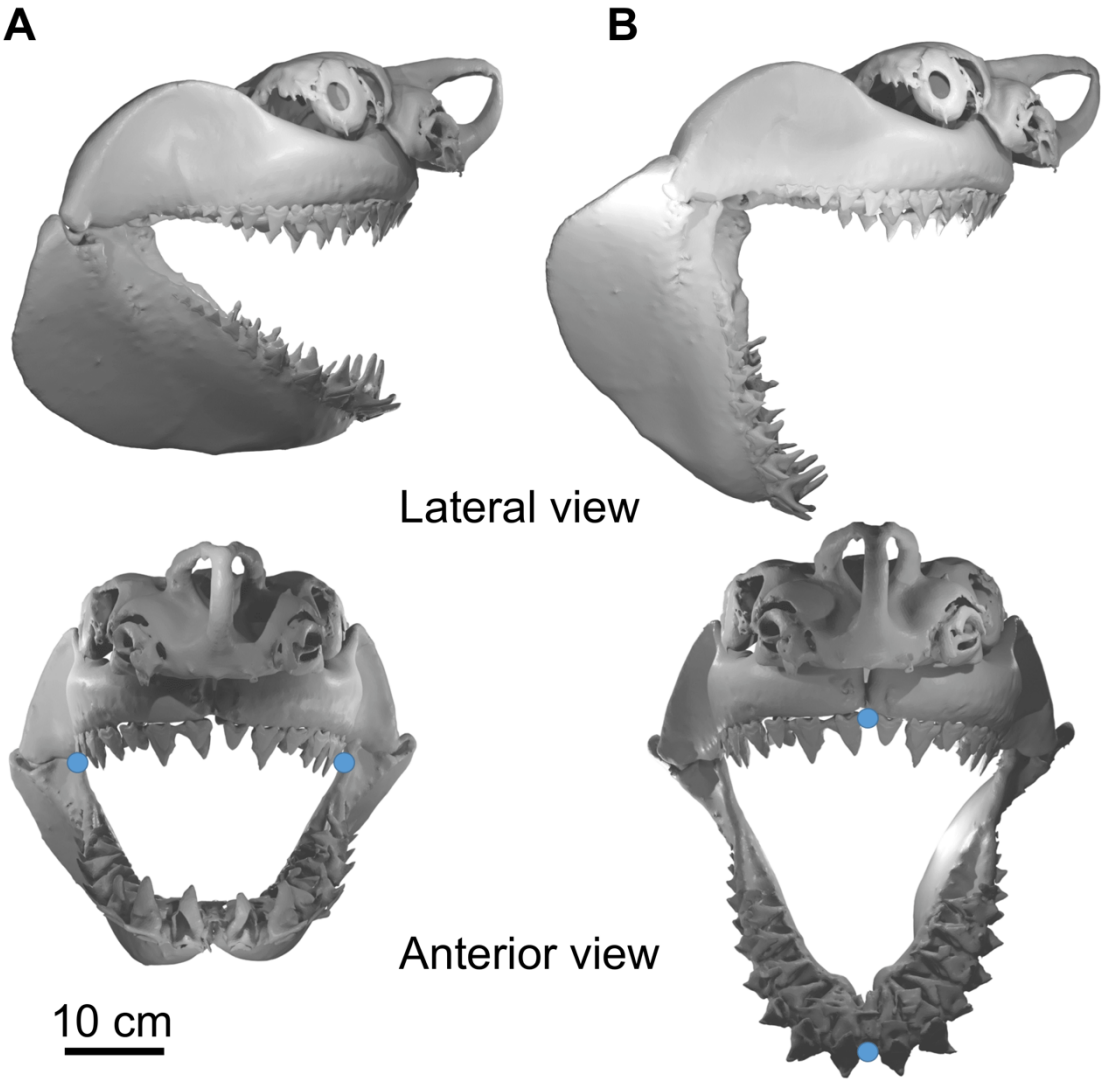

Figure S4. Gape angles used to estimate gape size of the *Otodus megalodon* model. This uses a *Carcharodon carcharias* chondrocranium containing the UF 311000 *O. megalodon* teeth at (**A**) 35º, and (**B**) 75º. The *C. carcharias* chondrocranium is scaled according to its original size here. Blue landmarks are used in the anterior views to denote the points between which (**A**) gape width and (**B**) height were measured.

Table S1. Summarised occurrence data of putative *Otodus megalodon* prey taxa. Abundance is categorised based on raw occurrences as: <10 = "Low"; 10-24 = "Medium"; ≥25 = "High". Daggers (†) denote extinct taxa. Data was downloaded from the Paleobiology Database (https://paleobiodb.org/). Max_ma and Min_ma represent the earliest and latest occurrence in the Paleobiology Database respectively.

Taxa	Occurrences	Abundance	Max_ma	Min_ma
Phocoena	3	Low	5.333	2.588
†Nanosiren	12	Medium	23.03	3.6
Stenella	10	Medium	7.246	2.588
†Xiphiacetus bossi	25	High	23.03	2.588
Tursiops	10	Medium	15.97	0.781
†Orcinus sp.	4	Low	15.97	0.781
†Piscobalaena nana	5	Low	13.82	5.333
†Carcharodon sp.	34	High	23.03	2.588
†Dioplotherium	15	Medium	23.03	3.6
†Metaxytherium	200	High	28.1	2.588
Pseudorca	5	Low	5.333	2.588
†Balaenoptera spp. (cortesii/bertae/davidsoni)	55	High	23.03	0.01
Globicephala	16	Medium	23.03	0.781
Delphinapterus	2	Low	15.97	0.781
†Dusisiren	20	Medium	15.97	3.6
†Hydrodamalis	27	High	11.62	2.588
Carcharodon carcharias	58	High	23.03	1.8
Orcinus orca	1	Low	5.333	3.6
Balaenoptera acutorostrata	10	Medium	23.03	2.588
Eschrichtius	1	Low	3.6	2.588
Eubalaena	11	Medium	23.03	2.588
Balaena	19	Medium	23.03	0.781
Megaptera novaeangliae	17	Medium	23.03	2.588

Table S2. Comparisons between body dimensions from a *Otodus megalodon* 2D model that accounts for multiple analogues (*15*) and those from the completed 3D model. The 19 body-part dimensions measured are as follows: Snout-eye distance (SE); snout-pectoral fin distance (SP); pectoral fin length (PecL) and width (PecW); snout-dorsal fin distance (SD): dorsal fin height (DH) and width (DW); dorsal tip-abdomen distance (DTA); dorsal posterior-abdomen distance (DPA); primary-secondary dorsal fin distance (DD); pectoral-pelvic fin distance (PP); pelvic fin length (PelL) and width (PelW); dorsal side-pelvic fin anterior distance (BPA); pelvic-anal fin distance (PA); secondary dorsal-anal fin distance (DA); dorsal-caudal fin distance (DC); fork height (FH) and tail height (TH). SE was measured using the *C. carcharias* chondrocranium CT scan (*71*) scaled to fit our model while all other measurements are taken from the completed model.

Variable	**Predicted (*15*)**		**Empirical**	
	Mean (cm)	Standard deviation (cm)	Model measurement (cm)	Fits mean ± SD? (Y/N)
SE	79.34	25.44	83.23	Y
SP	419.83	45.96	391.75	Y
PecL	307.07	76.88	301.03	Y
PecW	164.07	31.16	152.15	Y
SD	591.11	49.93	591.96	Y
DH	161.77	35.38	162.02	Y
DW	198.09	29.88	186.54	Y
DTA	451.12	55.51	447.76	Y
DPA	279.19	40.08	281.31	Y
DD	366.39	31.86	353.02	Y
PP	350.38	57.99	348.43	Y
PelL	73.24	18.13	74.83	Y
PelW	99.34	24.34	101.12	Y
BPA	195.11	19.41	194.71	Y
PA	143.37	31.86	158.74	Y
DA	95.58	15.93	96.56	Y
DC	804.9	46.84	831.09	Y
FH	43.5	4.84	43.14	Y
TH	383.68	69.47	355.66	Y

Table S3. Output of the geometric scaling model between body mass and cruising speed from Jacoby et al. (*33*). We independently re-collected and re-analysed the data from (*33*) to both replicate this model and perform our speed comparisons (see main text). Trophic level, temperature and habitat type, which are considered in the model, were gathered from the supplementary material of (*33*). Converting the intercept and mass coefficients to a power function generates the equation: $y = 0.266x^{0.082}$. Note that the exponent of 0.0823 falls within the CI range (0.053-0.249) and that this exponent was found to be 0.15 following correction for phylogeny (*33*). SE = standard error.

	Coefficients	**SE**	**T value**	**P value**
Intercept	-1.328	10.143	-0.131	0.898
Log mass	0.082	0.071	1.159	0.269
Log trophic level	-0.164	6.949	-0.024	0.982
Temperature – Mixed	-8.933	8.489	-1.052	0.313
Temperature – Warm	-4.447	3.582	-1.242	0.238
Habitat type – benthopelagic	0.794	0.516	1.538	0.15
Habitat type – demersal	-7.578	10.298	-0.736	0.476
Habitat type – pelagic-oceanic	0.79	10.51	0.075	0.941
Habitat type – reef-associated	16.728	13.157	1.271	0.228
lm(formula = log(Speed) ~ log(Mass) + log(Trophic level)*Temperature*Habitat type				
$F_{(13,12)} = 3.534$, $R^2 = 0.79$, $P = 0.018$				

Table S4. *C. carcharias* individuals dissected and analysed for stomach volume analysis.

Shark KZNSB-ID	Sex	Total length (cm)	Body mass (kg)	Stomach volume (L)
TRA15004	Male	196	67	7.49
RB15017	Male	263	156	10.86
RB15023	Female	255	126	12.2
MG15008	Female	271	188	18.45
GLN17003	Male	270	162	13
LEB17007	Female	220	106	12
RB17031	Female	224	105	18.55
BAL17003	Male	324	296	42
LEB18004	Female	310	282	31.8
SAL18004	Male	204	115	21.3
RB18037	Female	239	130	8.7
ZIN09016	Female	437	892	135

Table S5. Model outputs of the linear regression of body mass and stomach volume in *Carcharodon carcharias*. SE = Standard error; LCL = Lower limit of the 95% confidence interval; UCL = Upper limit of the 95% confidence interval. $R^2 = 0.97$.

	Coefficients	SE	LCL	UCL	t Stat	p-value
Intercept	-6.54	2.48	-12.07	-1.02	-2.64	0.02
Body mass	0.16	0.01	0.14	0.17	19.25	0.00

Table S6. Literature sources for body size and energy density of putative *Otodus megalodon* prey. Body mass estimates of each taxon are found in individual literature sources. Energy densities for marine mammal taxa come from estimates for different groups – specifically sirenians (1,257 kcal/kg), dolphins (3,052 kcal/kg), and baleen whales (7,314 kg/kcal) (*81*-*83*) – whereas the energy density for *Carcharodon carcharias* is based on the muscle energy density reported in (*42*). Extinct taxa are denoted by daggers (†).

Taxa	Group	Body mass reference	Energy density reference
Phocoena[a]	Dolphin	(*84*)	3,052 (*83*)
†*Nanosiren*[a]	Sirenian	(*85*)	1,257 (*82*)
Stenella[a]	Dolphin	(*86*)	3,052 (*83*)
†*Xiphiacetus bossi*[b]	Dolphin	(*87*)	3,052 (*83*)
Tursiops[a]	Dolphin	(*88*)	3,052 (*83*)
†*Orcinus* sp.[a]	Dolphin	(*87*)	3,052 (*83*)
†*Piscobalaena nana*[c,d]	Baleen whale	(*89*)	7,314 (*81*)
†*Carcharodon* sp.[e,f]	Shark	(*44*)	4,400 (*42*)
†*Dioplotherium*[a]	Sirenian	(*90*)	1,257 (*82*)
†*Metaxytherium*[a]	Sirenian	(*90*)	1,257 (*82*)
Pseudorca[a]	Dolphin	(*91*)	3,052 (*83*)
†*Balaenoptera* spp. (*cortesii/bertae/davidsoni*)[a]	Baleen whale	(*92*)	7,314 (*81*)
Globicephala[a]	Baleen whale	(*93*)	7,314 (*81*)
Delphinapterus[a]	Baleen whale	(*94*)	7,314 (*81*)
†*Dusisiren*[a]	Sirenian	(*90*)	1,257 (*82*)
†*Hydrodamalis*[a]	Sirenian	(*90*)	1,257 (*82*)
Carcharodon carcharias[f,g]	Shark	(*44*)	4,400 (*42*)
Orcinus orca[a,h]	Dolphin	(*95*)	3,052 (*83*)
Balaenoptera acutorostrata[a]	Baleen whale	(*92*)	7,314 (*81*)
Eschrichtius[a]	Baleen whale	(*96*)	7,314 (*81*)
Eubalaena[a]	Baleen whale	(*97*)	7,314 (*81*)
Balaena[a]	Baleen whale	(*98*)	7,314 (*81*)
Megaptera novaeangliae[a,i]	Baleen whale	(*99*)	7,314 (*81*)

[a]Genus-level taxa recorded in the Pliocene as reported in (*11*); [b]fossil evidence of *O. megalodon* bite mark (*20*); [c]fossil evidence of *O. megalodon* bite mark (*19*); [d]size estimated based on humerus, radius and ulna (*90*) and following (*100*); [e]size based on (*14*); [f]mass calculated from (*44*) (see Methods); [g]largest size based on (*23*, *101*); [h]largest male size (*95*); [i]fossil rib specimen potentially bitten by *O. megalodon* not identified to species-level; however, similar to *M. novaeangliae* (*18*).

Movie S1. Rotation videos of all model components (separate file).
Included model components are as follows: IRSNB P 9893, UF 311000, NSWDPI-WS2006/4 with *O. megalodon* teeth (UF 311000) attached, the South African full-body 3D scan of *C. carcharias*, the final *O. megalodon* model, and the visualised open gape models of 35° and 75° gape angles.

Data S1. Datasets assembled for this study (Dryad Data Repository).
Divided into two sheets. *Vertebral column*: Measurement data of IRSNB P 9893 vertebral centra. Preservation state of all vertebrae are labelled as follows: 0) fragmentary; 1) partial preservation; 2) near-complete. *Species comparisons*: Feeding strategy, thermoregulatory ability, body mass and cruising speed for 28 extant species and the *Otodus megalodon* model used in swim speed analysis.

Data S2. Blender file of the completed *Otodus megalodon* model (Dryad Data Repository).

Data S3. Blender file of the 3D scanned *Carcharodon carcharias* used to aid flesh reconstruction (Dryad Data Repository).

Data S4. Blender file of the recreated fossil specimen UF 311000 (Dryad Data Repository)

Data S5. Blender file of the recreated fossil specimen IRSNB P 9893 (Dryad Data Repository).

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