



Supplementary Materials for

Performance trade-offs define a fundamental dental dichotomy in mammals

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Science **393**, 265 (2026)
DOI: 10.1126/science.aee3453

The PDF file includes:

Materials and Methods
Supplementary Text
Figs. S1 to S17
Tables S1 to S4
References

Other Supplementary Material for this manuscript includes the following:

Movies S1 to S8
Data S1 to S4

Materials and Methods

Material provenance

All the specimens analyzed in this study (both fossils and extant) are cataloged and across 30 institutions: Muséum National d'Histoire Naturelle (65 specimens); The Field Museum of Natural History (39); American Museum of Natural History (25); Royal Belgian Institute of Natural Sciences (22); Université de Liège (18); Naturhistoriska riksmuseet (13); Yale Peabody Museum and Smithsonian National Museum of Natural History (8 each); Natural History Museum, Ditsong National Museum of Natural History Collection, Musée des Confluences, and University of Wyoming (5 each); Royal Museum for Central Africa, Uppsala Universitet, and Idaho Museum of Natural History (4 each); Natural History Museum of Los Angeles County (3); University of California Los Angeles, Museo Nacional de Ciencias Naturales, and University of Florida (2 each). The remaining institutions each contributed a single specimen: Anatomical Museum of Valladolid University, Institute of Vertebrate Paleontology and Paleoanthropology, Lyon 1 University, Ohio University, Museum für Naturkunde, Museum of Vertebrate Zoology, University of Kansas Natural History Museum, Museum of Comparative Zoology, Staatliches Museum für Naturkunde Stuttgart, Museu de Ciències Naturals de Barcelona, and Macedonian Museum of Natural History. A complete list of the specimen used along with their metadata can be found in **Data S1**; specimen numbers can be found in column H (Specimen_number) and the institution hosting the specimen can be found in column I (Institution). For specimens downloaded from 3D databases, relevant links can be found in column N (Model Ref), and most of those published 3D models have been previously employed in various studies which will state scanning parameters if not available on the associated 3D database (49–57).

Shape acquisition

We analyzed a total of 250 teeth (each representing one species), comprising 106 Feliformia (69 extant, 37 extinct), 111 Caniformia (62 extant, 49 extinct), 29 ‘creodonts’ and 4 Miacidae, utilizing various scanning techniques (see Excel file in **Data S1** for detailed specimen list and scan origins). Not all specimens were scanned for the current project, and sharing restrictions apply to some; however, all meshes that can be publicly released are available on: <https://www.morphosource.org/projects/000792218> (Project ID 000792218); and many of the other specimens are already available in various MorphoSource projects (cf Excel file in **Data S1**). The lower carnassial constitutes a particularly suitable model system because it integrates both slicing and crushing functions within a single tooth, whereas these functions are more spatially partitioned in the upper dentition (11). Moreover, upper and lower dentitions are expected to evolve in functional coordination to maintain occlusion (29, 58, 59), significant decoupling would likely result in malocclusion and reduced fitness. Our sample encompasses a broad diversity of body sizes and dietary adaptations; however, pinnipeds were excluded due to their derived dental specializations, including evolutionary tendencies toward secondary homodonty, which could distort the morphospace. Additionally, to ensure that our interpretations of shape were not biased by dental wear, teeth exhibiting signs of wear were excluded from the analysis. Whereas the influence of wear on dental efficiency is certainly of interest (see previous discussion in (60)) it is currently out of scope of the present study. Only permanent teeth were sampled. For canivoramorphans, we exclusively sampled the m1 but for taxa bearing multiple carnassials we selected the most specialized tooth, e.g. m3 for Hyaenodonta, sometimes called ‘principal carnassial’ (see (11, 29)). Due to the relative difficulty to find pristinely preserved fossil teeth, to

maximize our sampling effort we focused on obtaining one specimen per species rather than performing species average. Teeth were landmarked using a semi-automated high-density 3D geometric morphometric protocol modified from (61, 62) using the Morpho package (63). A subset of 12 fixed landmarks was initially placed using Landmark Editor (IDAV, Davis, California, USA). Eight landmarks (Points 1 to 8) were positioned along the base of the crown at the enamel-cement junction to ensure that subsequent pseudo-landmarks did not extend below the enamel line. Four additional landmarks were placed on the crown: the apex of the protoconid (Point 9), the apex of the paraconid (Point 10), and the apex of the metaconid (Point 11). The final landmark (Point 12) was positioned at the geometric center of the talonid basin. In hypercarnivorous taxa exhibiting cusp reduction, adjustments were made to maintain topological consistency. In taxa lacking a distinct metaconid, Point 11 was positioned halfway between Points 9 and 10 along the crest connecting the protoconid and paraconid. In taxa with a highly reduced or absent talonid basin, Point 12 was placed on the distal edge of the tooth, halfway between Point 5 (one of the basal landmarks) and Point 9. A template was then created in Meshlab (semi-ellipsoid) with 12 landmarks corresponding to these fixed points (**Fig. S1A**). Subsequently, 2,000 pseudo-landmarks were automatically generated on the template and applied to each tooth using the fixed landmarks as reference points. Finally, we performed a Procrustes superimposition using the *gpgen* function of the ‘geomorph’ package (64). To quantify the primary axes of morphological variation, we conducted a principal components analysis (PCA) using the *gm.prcomp* function of the ‘geomorph’ package. Morphological disparity between Feliformia and Caniformia was assessed using the dispRity package (65) estimating disparity as a bootstrapped sum of variances with 1,000 iterations.

Tooth modelling and processing

We selected a subset of 45 teeth and four theoretical shapes (approximately 25% of our shape dataset; see **Fig. S1A** and **Fig. S2A** for an annotated plot of selected taxa) to span the morphological variation observed in carnivorous mammals for mechanical testing, following previous studies (66). Sampling naturally occurring morphologies, rather than a grid of theoretical shapes, has been shown to produce accurate surfaces (67). The shape of a tooth results from millions of years of evolution, and analyzing actual morphologies allows for a direct understanding of adaptive strategies rather than hypothetical ones that may not be viable in nature. Naturally occurring morphologies are also directly linked to specific ecological niches and behaviors, making them critical for studying evolutionary pathways, constraints, and patterns. Whereas theoretical morphologies can provide insights into unoccupied regions of morphospace, their representation depends on sampling strategies, which can introduce biases. In contrast, naturally occurring forms represent an empirical dataset unaffected by sampling density. However, theoretical shape can also inform us as of why some shapes potentially never evolved, so we supplemented our dataset with four theoretical tooth shapes to better understand less densely occupied regions of the morphospace (see **Fig. S2**). The taxa used as templates for morphing these theoretical shapes were selected based on their proximity to the target form, minimizing excessive deformation during the morphing process. Morphing from the mean shape produced low-quality meshes with self-intersections and non-manifold faces which made those impossible to print without further, subjective modifications (see **Fig. S2A** for a graphical representation of the theoretical shape included in the simulations and the taxa used for the morphing process).

Each chosen tooth model was subjected to biomechanical analyses to quantify slicing and crushing performance. Models were processed in GeoMagic Wrap (3D Systems, Rock Hill, South Carolina, USA) following a standardized pipeline developed by Perez Ramos et al. 2023 (68). First, the ‘reduce noise’ tool was applied using the ‘prismatic shape (aggressive)’ parameter with one iteration. Next, the remesh tool was used, followed by another round of ‘reduce noise’ with the same settings. The refine tool was applied four times with two iterations, followed by a final round of ‘reduce noise.’ To integrate the teeth into the mechanical testing setup, solid models of the Mark-10 G1097 upper anvil for bend fixture bases were downloaded from the Mark-10 official website (<https://mark-10.com/products/grips-attachments/compression-push-bend/bend-fixtures/#tab-4>). The teeth were aligned to the support using the N-point alignment method in GeoMagic, with three points placed on the ventral border of the tooth and three on the top of the support following (68). Tooth orientation was adjusted to ensure the cusps were as vertical as possible. The crown was then cut at the gum line, fused with the support, and the intersection was closed. To remove size-related effects, all teeth were scaled to a 3 cm mesiodistal length.

Resin models were printed using an ELEGOO Saturn printer (ELEGOO, Shenzhen, China) with using a translucent ELEGOO Standard Photopolymer resin (see **Table S1** for resin properties). Models were rinsed in 100% ethanol and cured in a UV chamber for 25 minutes. To simulate the presence of a hard, brittle enamel layer, each printed tooth was coated with a professional-grade ceramic spray coating containing SiO₂ (silicon dioxide) and TiO₂ (titanium dioxide) following Pérez Ramos et al. (68) who previously investigated dental masticatory efficiency and its evolutionary variation across the phylogeny of Ursidae.

Finally, each resin model was mounted onto a Mark-10 ESM1500 electromechanical testing frame (Mark-10, New York, USA) (**Fig. S1B**). Three parameters were recorded during the analyses using MESURgauge Plus software (Mark-10, New York (NY), USA): force (N), time (s), and displacement (mm).

Crushing simulations

The CT scan of the femur of a Grant's gazelle (*Nanger granti*, AMNH-Mammals-M-85153) was downloaded from MorphoSource (Media ID 000421632), segmented, and a section of the shaft was isolated in GeoMagic Wrap (3D Systems, Rock Hill (SC), USA). The Grant's gazelle was chosen as it represents a relatively average ruminant morphology and therefore a good example of prey bone. These femur sections were then 3D-printed using SimuBone® Bone Modeling Filament (3DXTech, Grand Rapids (MI), USA) on an UltiMaker S5 printer (Ultimaker, Utrecht, Netherlands). SimuBone® is specifically designed for producing realistic bone models for clinical applications, serving as an alternative to cadaveric bone in surgical simulations and patient-specific preoperative planning. Although relatively new on the market, a recent comparative study has validated it as a viable alternative to human cadaveric samples for surgical simulations, offering the closest anatomical accuracy and dissection experience currently available (69). Whereas we did not directly compare SimuBone to actual bone in our own tests, we used it within a comparative framework to evaluate the relative crushing abilities of teeth against a material that approximates the structural properties and complexity of natural hard tissue, rather than attempting to replicate real-world bone-crushing conditions. Whereas bone-like properties may not accurately reflect the biological requirements of all crushing-specialized taxa (e.g., herbivorous taxa such as the giant

panda), it is not possible to identify a single element or material representative of all crushing-based diets. Each bone section was printed using a ‘Grid’ infill pattern with a density of 25%, a layer height of 0.15 mm, and a line width of 0.15 mm (see **Table S2** for further printing parameters and **Fig. S3** for a graphical representation of infill pattern). Infill density ranging from 25 to 35% were shown to produce similar pattern to actual bone during drilling test (70). However, although the ‘gyroid’ infill pattern yielded the most bone-like response in these tests, its high variability across the printing plate made it less practical for batch-printing consistent bone sections. All tooth models were mounted on the Mark-10 ESM1500 testing frame and brought into contact with the bone section using a 10 N preload. Simulations were performed at a constant speed of 1 mm/sec, following the protocol of (71). Analyses were terminated when either the load reached 2000 N, or that the bone section or the tooth fractured. Whereas fracture patterns are certainly of interest, they have been addressed extensively in previous studies on dental fracture mechanics (e.g. 13–15) and are not the focus of the present study. To ensure standardized starting conditions for the crushing simulations, if a specimen fractured during its first test, we reprinted the tooth and repeated the three slicing simulations before proceeding with a second crushing attempt.

Each crushing simulation was repeated three times, and the following data were collected (see **Fig. S4A** for a graphical representation of the variables measured):

- **Breakage load (N)**: Maximum load measured on a load vs displacement curve
- **Breakage Load (mm)**: Distance measured at the maximum load measured on a load vs displacement curve
- **Slope**: Slope of the linear/elastic portion of the load vs displacement curve
- **Tooth damage**: Scale to quantify damages visible on the tooth
 - 0 = tooth was not damaged in the process,
 - 1 = a cusp was slightly altered but the tooth remained functional for further analyses,
 - 2 = tooth lost its integrity
- **Bone damage**: Scale to quantify damages visible on the bone
 - 0 = no damages visible on the bone,
 - 1 = only indentation visible,
 - 2 = the bone lost its integrity (fractures visible)
 - 3 = the bone broke in two pieces during the analysis

Each specimen underwent three trials. For continuous variables (Breakage load, Breakage displacement, and Slope), the mean of the three repetitions was computed. To assess cumulative tooth damage across trials, the three individual tooth damage scores were summed, yielding a range from 0 (no damage) to 6 (complete breakage in all trials). Similarly, bone damage scores were summed across trials, ranging from 0 (no damage) to 9 (complete fracture in all trials). Because Breakage load, Breakage displacement, and Slope could indicate either poor (tooth breakage) or good (bone breakage) crushing performance, these values required adjustment. To account for this, we developed an adjustment factor (AF) to refine the influence of trials based on damage distribution:

$$Ajusting\ factor\ (AF) = \frac{Bone\ damage}{(Bone\ damage + tooth\ damage + 1)}$$

where Bone damage (0–9) and Tooth damage (0–6) represent cumulative scores, and the +1 in the denominator prevents division by zero when both values are 0. If the tooth was severely damaged (Tooth damage $\rightarrow$ 6) whereas the bone remained intact (Bone damage $\rightarrow$ 0), the AF was low, reducing the impact of that trial. On the other hand, if the tooth remained undamaged (Tooth damage $\rightarrow$ 0) whereas the bone sustained severe damage (Bone damage $\rightarrow$ 9), the AF was high (approaching 0.9), amplifying the contribution of that trial. When both bone and tooth exhibited minor damage, the AF was intermediate, down-weighting trials where the tooth sustained some damage. Continuous variables (Breakage load, distance to breakage load and slope elastic) were all multiplied by AF, then their variation was normalized between 0 and 1 in R to prevent large variation ranges from influencing the morphological landscapes. Only these adjusted and normalized values were used to generate the functional landscapes based on crushing simulations.

Slicing simulations

Three different medical-grade gelatins with variable material properties from Humimic Medical (Humimic Medical, Greenville, USA) were used for the simulations, see **Table S3** for gelatin properties). Medical-grade gelatin, also known as ballistic gel, is commonly employed by medical professionals and researchers for simulations, phantom imaging, and training due to its realistic tissue-mimicking properties. Each gelatin type replicates a specific tissue type, such as deep or superficial muscle, skin, fat, or particular organs. Recently, medical gelatin was used in (60, 66) to assess stabbing efficiency in Tasmanian devil canines and sabertooth felids. Each gelatin type was first cast in a 40-cavity square silicone mold, forming cuboids measuring $3 \times 3 \times 1.5$ cm. These cuboids were then sliced in half using a stainless-steel wire cutting tool to create thinner cuboids of $3 \times 3 \times 0.75$ cm. For the experiments, gelatin layers were stacked in the following order, from top to bottom: Gelatin #0, Gelatin #2, and Gelatin #1, resulting in a total stack size of $3 \times 3 \times 2.25$ cm (**Fig. S1B**). The densest gelatin was placed on the top layer to enhance the discrimination of tooth shapes that are more or less efficient at penetrating soft tissues. During simulations, teeth were placed in direct contact with the top gelatin layer. A constant speed of 1 mm/sec was maintained, and the maximum load was set at 500 N to prevent tooth breakage. Each test was repeated three times, and performance variables were recorded for each trial. To compare tooth shapes, various metrics were measured (See **Fig. S4B** for a graphical representation):

- **Maximum force (N):** The peak force exerted before initial contact between the tooth and the gelatin (marked by a sudden increase on the load axis).
- **Puncture length (mm):** The maximum length of each puncture marks across the three gelatin layers. For the bottom two layers, a puncture mark was only considered valid if it extended through the entire upper layers. If no puncture was observed in a given layer, its maximum length was recorded as 0. The length measured in each layer were then summed.

Each simulation was repeated three times per specimen, and the mean values were used to summarize the results. As with the crushing simulations, all variables were normalized between 0 and 1 in R to prevent range discrepancies from influencing the performance landscapes. The maximum force variable was inverted to reflect that lower forces indicate greater efficiency. This approach yielded a total of five normalized performance variables (two for the slicing tests, and three for the crushing tests) where a value of 1 represents the highest efficiency.

Performance surfaces

We assessed functional optimality by integrating functional outputs with high-density 3D geometric morphometric (HD3DGM) data in a weighted landscape using the Morphoscape package (74) following previous studies (75, 76).

For each functional trait measured, values were standardized by scaling them between 0 and 1, with 1 representing the most efficient value for a given trait. These standardized functional traits were then mapped onto the morphospace using a Kriging algorithm. First, we generated seven individual performance surfaces by interpolating each of the nine functional variables (three crushing and four slicing) using the *krige_surf* function (Fig. S5). Whereas the Kriging algorithm produced relatively ‘rugose’ interpolations across the space, it does not impose assumptions regarding the number or shape of performance peaks, making it particularly useful for exploratory analyses. Next, we computed combined landscape (W) as the summation of all four performance variables for the slicing aspect (F_n) and three performance variables for the crushing aspect, each weighted by its relative contribution to total fitness (W_n), with weights ranging from 0 to 1. These weights were automatically calculated using the *generate_weights* function applied to the *kr_surf* object. The final weighted landscape was then generated using the *calc_all_lscps* function. Optimal weights were determined by testing all possible weight combinations across 176,851 potential landscapes for slicing data and 125,751 for crushing data, see **Table S4** for optimal weights obtained. To combine slicing and crushing data into a single landscape, we used two approaches: the first by submitting all the slicing and crushing variables into a single landscape and by using the same process as before to compute weight, and the second using *calc_lscp_Pareto* to obtain Pareto optimality. The Pareto approaches allowed us to test whether some lineage of carnivorous mammals evolved along optimal functional trajectories in the morphospace, maintaining a given ‘optimal’ performance level even though the slicing and crushing output themselves might change, see (77, 78) for more details about the Pareto method. However, as *calc_lscp_Pareto* can only compute the tradeoff between two traits we had to combine all the crushing and all the slicing variables. To do so, we extracted the weight of each performance variable from the separate landscapes and created combined slicing and crushing variables by summing each performance variable's value, multiplied by its optimal weight. This process yielded new composite variables, where the influence of each performance variable was weighed according to its optimal contribution to functional efficiency. For instance, the slicing variable was obtained as follows:

$$\text{Combined variable slicing} = \text{Max.force} * \text{Weight}_{\text{Max.force}} + \text{Puncture L} * \text{Weight}_{\text{Puncture L}}$$

The landscape resulting from the Pareto approach with our combined variables is virtually similar to that obtained by submitting all of our variables to the Morphoscape package but allowed us to compute the Pareto front of optimality.

Whereas some authors have used actual prey/food items for mechanical testing in the past (79) we preferred the use of gelatin for the slicing aspect and a 3D printed structure for the crushing aspect to maximize replicability.

Digital image correlation

Preliminary tests revealed that teeth with similar overall shapes could exhibit markedly different mechanical behaviors. Notably, some highly derived, hypercarnivorous bicuspid teeth performed poorly in crushing simulations, showing significant structural damage in every trial, whereas others endured the tests with minimal or no damage. To investigate the biomechanical basis of these differences, we selected a subset of four bicuspid teeth with varying morphologies, particularly focusing on the development of the carnassial notch. The subset included *Dinailurictis bonali* (pronounced carnassial notch; withstood crushing), *Panthera leo* (minimal notch; withstood crushing), *Smilodon fatalis* and *Oriensmilus liupanensis* (no visible notch; both failed the crushing tests) (**Fig. S6**). Our hypothesis here was that the carnassial notch might help dissipate stress and strain during a crushing test. To test this hypothesis, we employed a Dantec two-camera Digital Image Correlation (DIC) system (Dantec, Inc.) to measure real-time surface strain and displacement during mechanical testing. The DIC system, a high-resolution, video-based tool, tracks deformation on a speckled surface. Each tooth was coated with a high-contrast black-and-white speckle pattern using spray paint (**Fig. S6**).

To replicate conditions from the initial crushing experiments, each tooth first underwent three slicing tests (maximum 500 N) prior to a single crushing test where the tooth was put in contact with the bone using a 10N preload, followed by the crushing test with a maximum of 2000N during which DIC data were collected. The two DIC cameras were positioned at approximately 25 degree angles and calibrated using a checkerboard pattern, achieving a triangulation error (global residuum) of approximately 0.5 pixels. To optimize strain capture, the crushing tests were conducted at a slower speed (30 mm/min), with data recorded at 10 Hz to match the acquisition rate of the Mark-10 force measurement system. A virtual strain gauge was placed in the region of the carnassial notch on each tooth to quantify true effective strain (Von Mises) and displacement (Total Displacement with Rigid Body Motion Removed) through time. Videos are available as **Movie S1-S8**, screenshots for each specimen at different times are available as **Fig. S6** and plots showing the evolution of strain and displacement in the carnassial notch through time are available as **Fig S7**.

Those digital correlation tests confirmed that the carnassial notch appears to serve a function to dissipate stress on the tooth during the crushing simulations. Indeed, in *Dinailurictis bonali*, whereas the displacement measured in the notch is the highest of the dataset (**Fig. S7**), the total true strain increases faster but remains lower than in other taxa (**Fig. S7**). The notch helps create a region of low stress between the two cusps, whereas in other taxa (e.g. *Oriensmilus liupanensis*) the two regions of high stress on each cusp are quickly connected, resulting in the fracture of the tooth.

Phylogeny

To investigate potential rate variation in carnassial biomechanical evolution, we used BayesTraits to fit a variable rates model (based on Brownian Motion) to the trait data and phylogeny using reversible-jump Markov Chain Monte Carlo (80). This analysis either scales branches or entire clades (applying some scalar to all branches within the clade). More branches scaled indicate greater support for rate heterogeneity across the tree within the tested trait. We ran the chain for 1,000,000,000 generations with a burn in of 10,000,000 and calculated the marginal likelihood for

each model with a steppingstone sampler using 512 stones and ran for 1,000,000 generations. For these analyses, we used the species-level tree of all known extant and extinct species of placental carnivorous mammals recently published by (81) as a fixed topology (i.e., assuming that this topology is the true topology explaining the variation in these taxa). The position of Amphicyonidae was adjusted at the base of Caniformia following (82). Two taxa from our mechanical dataset were absent from Faurby et al.'s tree: the amphicyonid *Cynodictis longirostris* and the nimravid *Oriensmilus liupanensis*. However, some closely related taxa were present, so we replaced 'Cynodictis lacustris' in the original tree by 'Cynodictis longirostris' and modified the FAD and LAD according to (83). Then we replaced *Sansonsmilus palmidens* with *Oriensmilus liupanensis* being the most closely related taxa in the tree and adjusted the FAD and LAD accordingly (84, 85). Those modifications were performed in Mesquite (86) and the tree was then imported in R using the *read.tree* function of the 'ape' package (87).

We also fitted multivariate Brownian Motion with multiple variance-covariance matrices to model a regime shift in feliforms and Carnivoramorphan, or a change in the correlation structure between different traits within a certain clade, using a custom C++ script (e.g., (88)). However, for these five traits, the model did not appear to be identifiable. Potentially more experimental data or a coupling of experimental and morphometric data may help investigate whether the relationship between carnassial slicing and cutting changes in certain clades.

Finally, we computed the phylogenetic signal (Blomberg's K , (89) and Pagel's λ , (90) using the *phylosig* function of the 'phytools' package (91) and inferred the ancestral states at each node under Brownian Motion using the 'phylopars' R package, both in R v4.4.1 (92). All trees were plotted using the 'ggtree' package (93) with silhouettes from PhyloPic (Fig. S8-11).

Supplementary Text

Potential limitations and new research avenues

Our model system, the carnivorous mammals, is well-suited to this type of analysis, given that adaptation to carnivory generally limits lateral jaw movement, making our vertical testing set-up a reasonable approximation of natural function. However, it is important to note that some taxa from our dataset and more particularly those lying in the high PC1/lowPC2 region of the morphospace bearing more flat teeth may rely more heavily on horizontal grinding, which our experiments did not capture. Several methodological approximations should be acknowledged. Variability in dental material properties that would be present in the teeth produced by variation of enamel thickness and structure (e.g. Hunter-Schreger bands (94)) was not incorporated. Furthermore, our study focused exclusively on the m1, although some taxa may primarily use other teeth for crushing (e.g., p4 in hyenas). Nevertheless, hyenas still performed very well in our tests, indicating that a robust m1 remains critical for taxa adapted to durophagy.

Some species in our dataset, particularly certain late-diverging Hyaenodonta (e.g., the genus *Hyaenodon*), possess multiple carnassialized teeth. However, their molars remain morphologically variable. These differences may influence the performance and efficiency observed in specific biting scenarios when considering the complete tooth row, including all tooth positions contributing to occlusal function. By focusing our analyses on a single tooth position (e.g., m3 in

hyaenodonts), not all potential occlusal aspects are captured. Other tooth positions may provide additional functional contributions to overall chewing performance in species with multiple functional cheek teeth. This also highlights the potential for future studies incorporating additional tooth positions.

Our study design focused on the lower carnassial, which functionally interacts with the upper dentition (primarily P4, with additional crushing input from M1). Whereas the m1 integrates slicing and crushing functions within a single element, these antagonistic functions are more spatially distributed in the upper dentition (11). Upper and lower teeth are also expected to evolve in parallel to preserve occlusal congruence (29, 58, 59), the opposite would lead to malocclusion and potentially reduced fitness. Nevertheless, a study explicitly examining the interaction between upper and lower carnassials using a similar experimental pipeline would provide a more comprehensive understanding of whole-tooth-row performance. Previous work has investigated interactions between simplified cutting blades of different morphologies (95), but such analyses have not yet been conducted using anatomically realistic dental elements.

We selected a bone-modelling filament for the crushing analyses, which may not be biologically appropriate for all crushing-specialist taxa (e.g., the giant panda, sea otter). However, given the remarkable dietary diversity observed among carnivorans, it is not possible to identify a single object that would be ecologically relevant for the entire dataset. Future studies could further explore crushing specializations using different object geometries and material properties, and by more explicitly incorporating body size effects. For example, some taxa that performed well in our crushing tests (e.g., the Asian palm civet) have small body masses and are unlikely to process large bones in natural settings, meaning that an experimental pipeline more specific to those small taxa could reveal additional nuances in their crushing adaptations.

For consistency, the bone section was always positioned in the carnassial notch, as hypercarnivorous bicuspid teeth often lack a functional talonid. However, this configuration may not accurately reflect feeding mechanics in more omnivorous taxa like canids, potentially explaining their moderate crushing performance. Despite these limitations, this experimental framework provides a foundation for further studies on form-function relationships in evolutionary morphology.

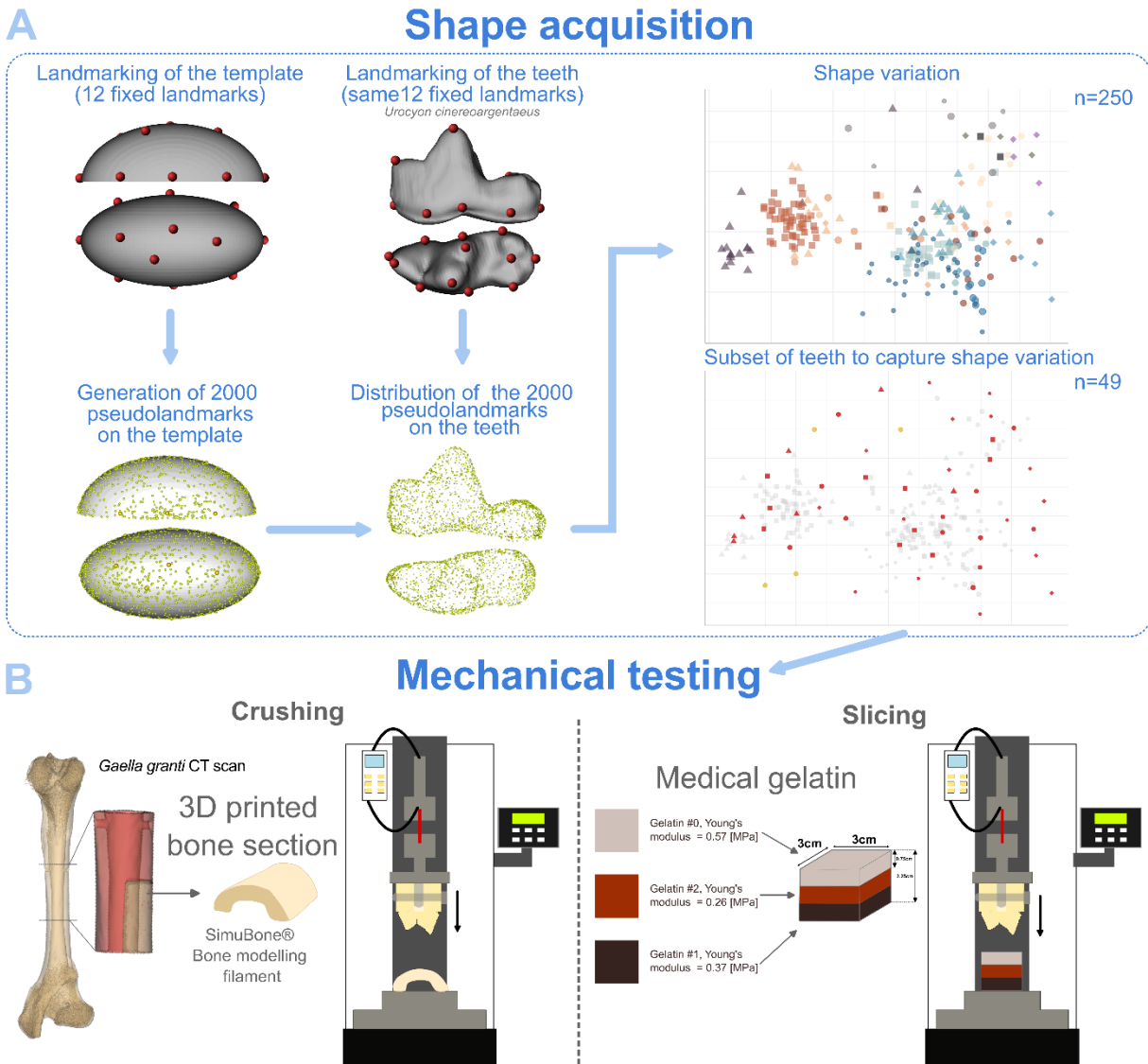


Fig. S1.

Figure exemplifying the workflow developed for the present study. **(A)** Shape acquisition starting with the landmarking of a template and all the specimens using a defined number of fixed landmarks, followed by the generation of pseudo-landmarks on the template applied automatically on every single specimen by means of the fixed landmarks. Semi-automated protocol based on Fischer et al (2022) (61). **(B)** Acquisition of experimentally based functional data using a bone modelling filament for the crushing aspect and medical gelatin for the slicing aspect (see other studies using medical gelatin to quantify tooth efficiency (60, 66). Assembly of tooth models on the Mark-10 support based on (68).

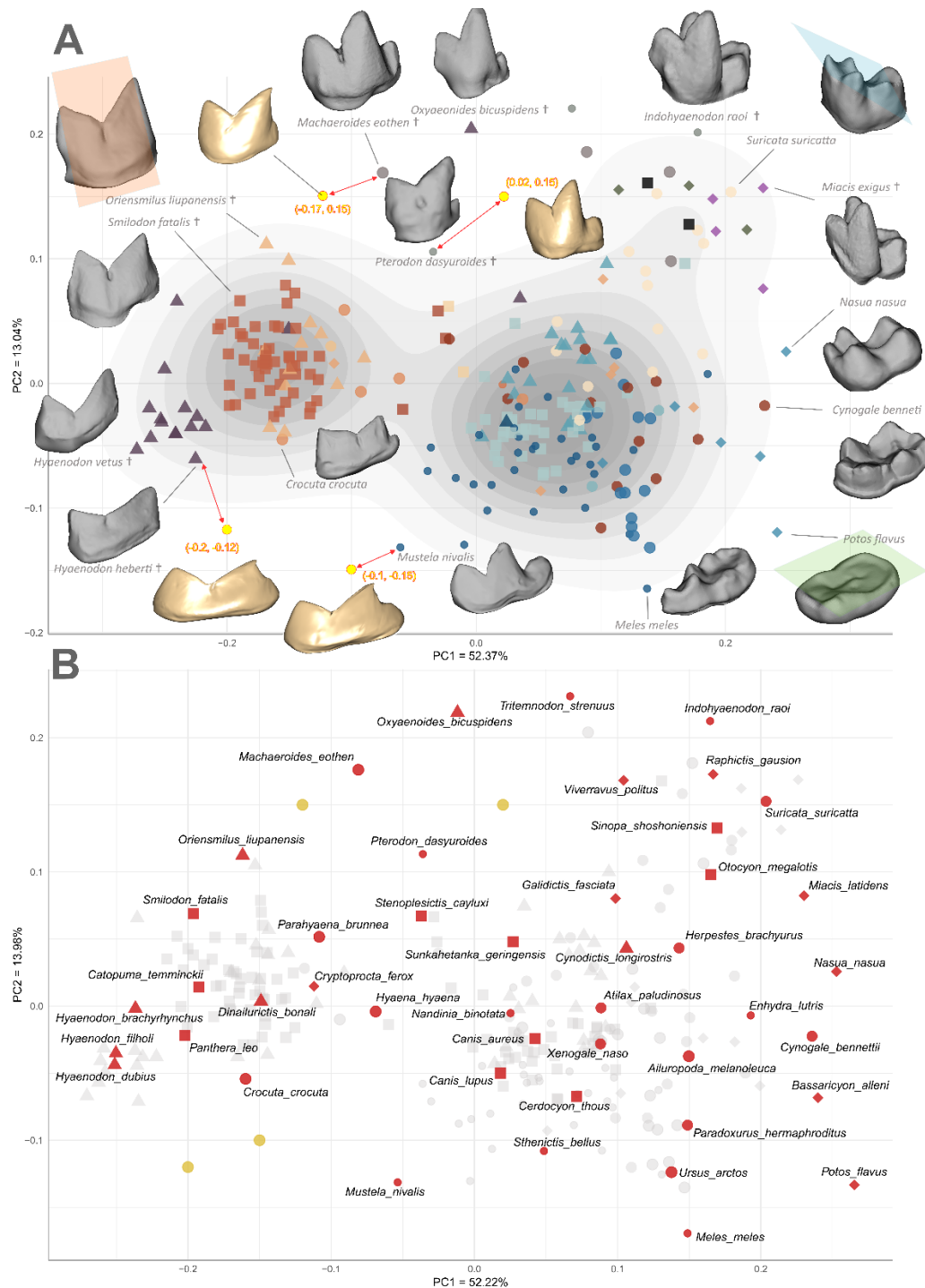


Fig. S2.

(A) Theoretical shape created for mechanical testing in addition to the 45 natural occurring shapes. Red arrows indicate the taxa used for the morphing. Coordinates in the morphospace used to estimate landmark coordinates are indicated next to each theoretical shape. Representative morphotypes are shown with schematic tangential occlusal planes: orange = vertical (constrained toward slicing), blue = oblique, green = near-horizontal. (B) Morphospace showing the 45 natural occurring shape (red) selected for physical testing.

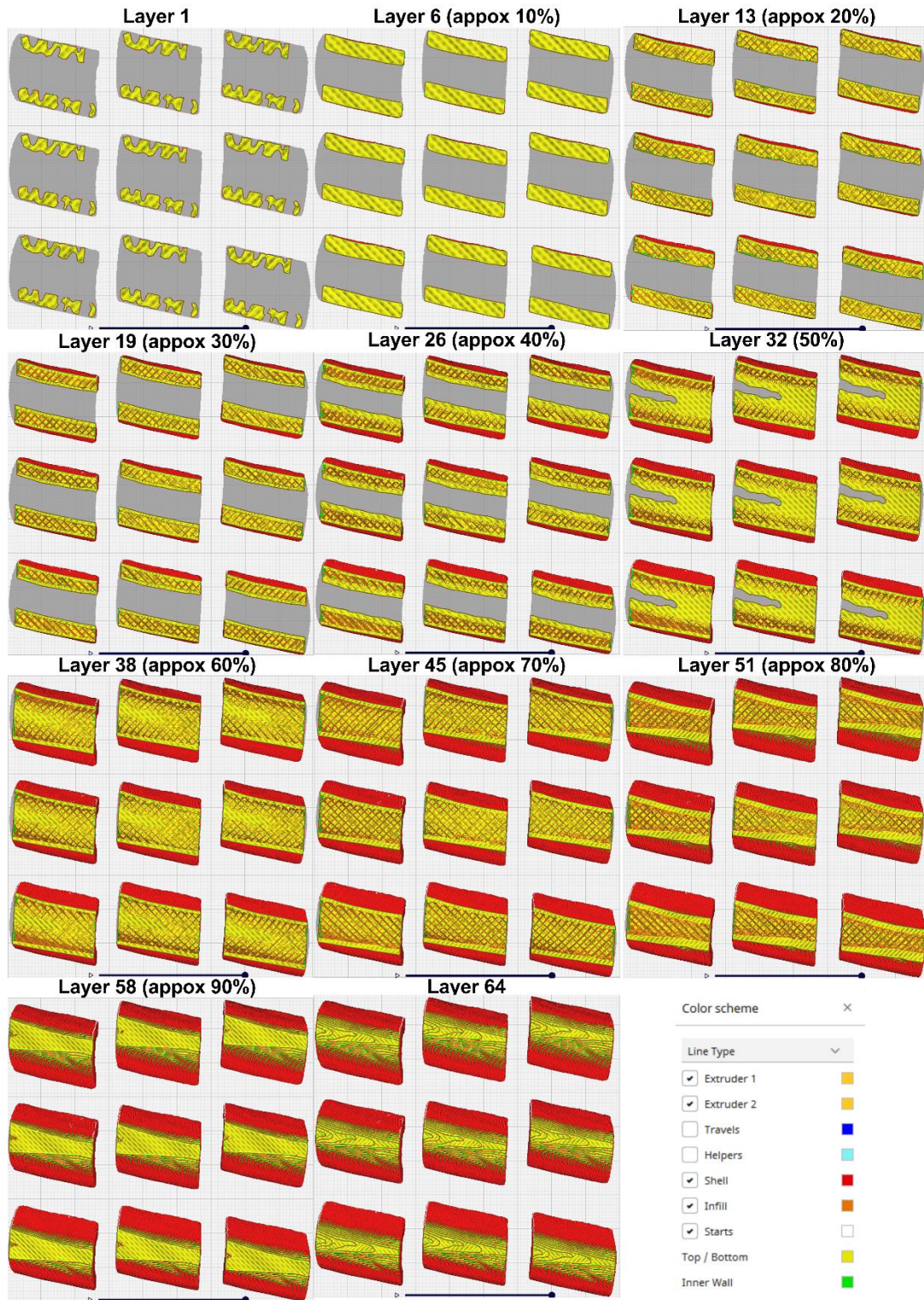


Fig. S3.

Graphical representation of infill pattern in the bone sections. Bone sections were printed in batch of 9 sections, the grid pattern was chosen for its symmetry, reducing the risk of infill variation between each section depending on their position on the printing plate.

Crushing variables

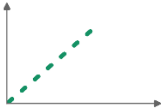
1. Peak Load (mean for the 3 runs)



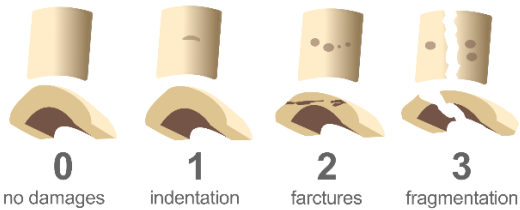
2. d Peak Load (mean for the 3 runs)



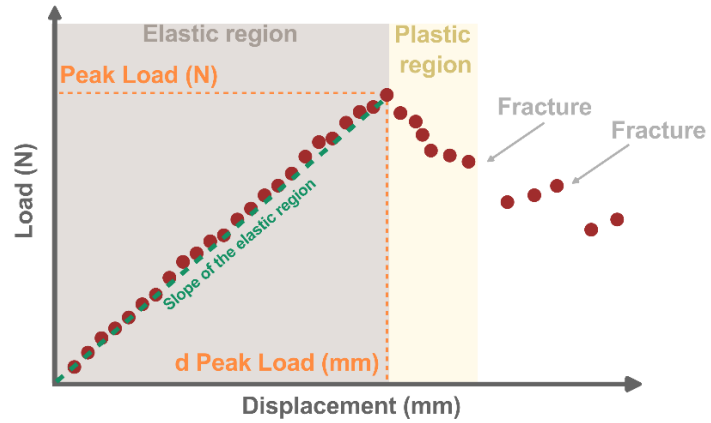
3. Slope (mean for the 3 runs)



4. Bone damage (sum of the 3 runs)



5. Tooth damage (sum of the 3 runs)



Slicing variables

1. Peak Load (mean for the 3 runs)



2. Maximum length (mean for the 3 runs)

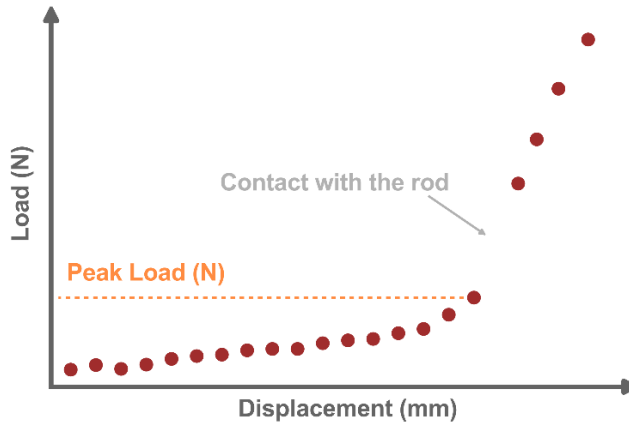
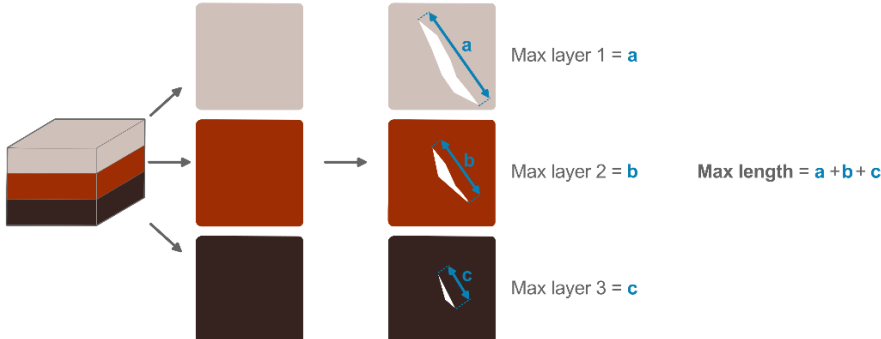


Fig. S4.

Graphical representation of the variable collected during the mechanical testing with the five crushing variables and three slicing variables.

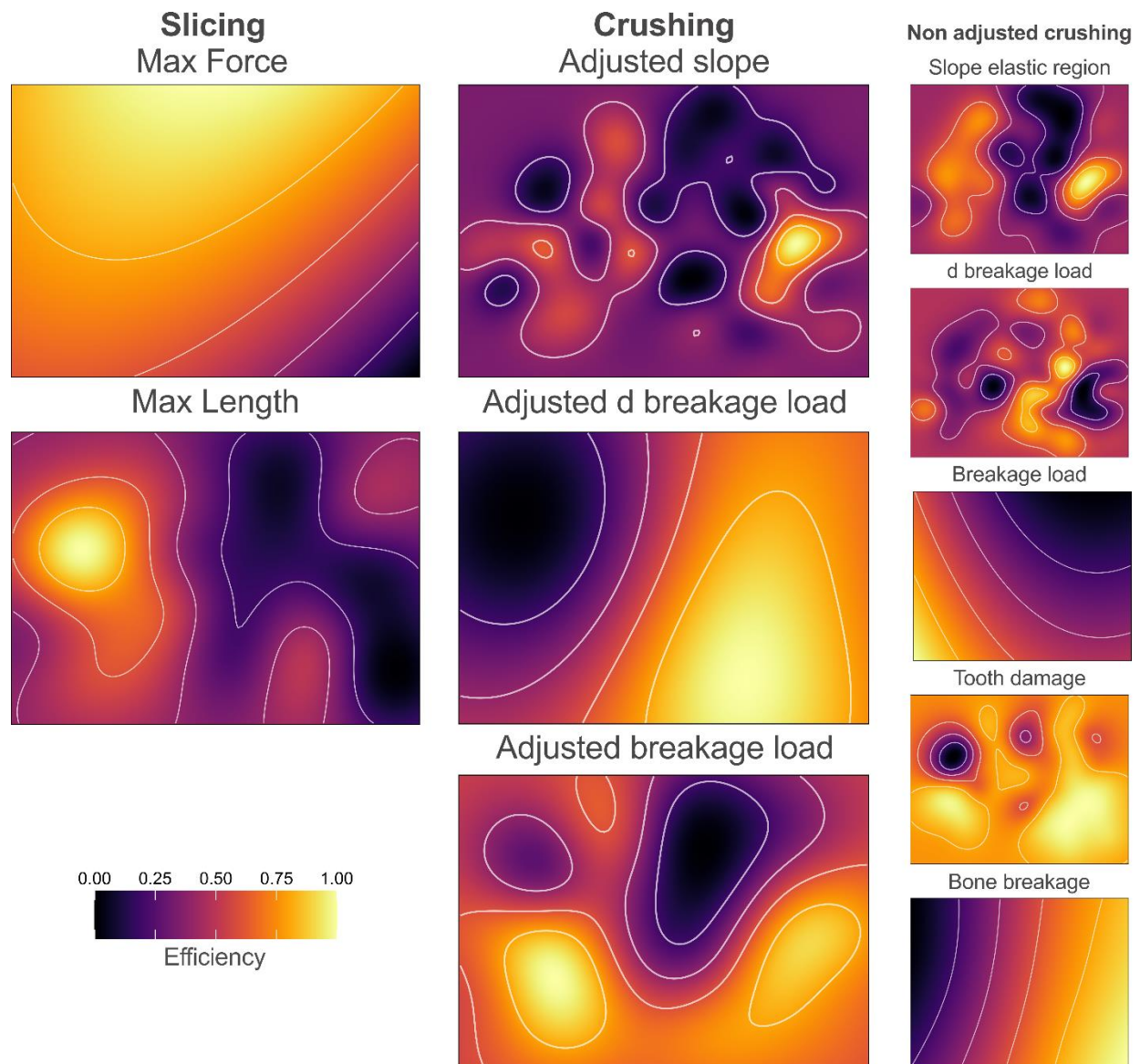


Fig. S5.

Performance surfaces for each of the slicing and crushing variables. Values were standardized between 0 and 1 for each trait, with 1 representing the most efficient value for a given trait.

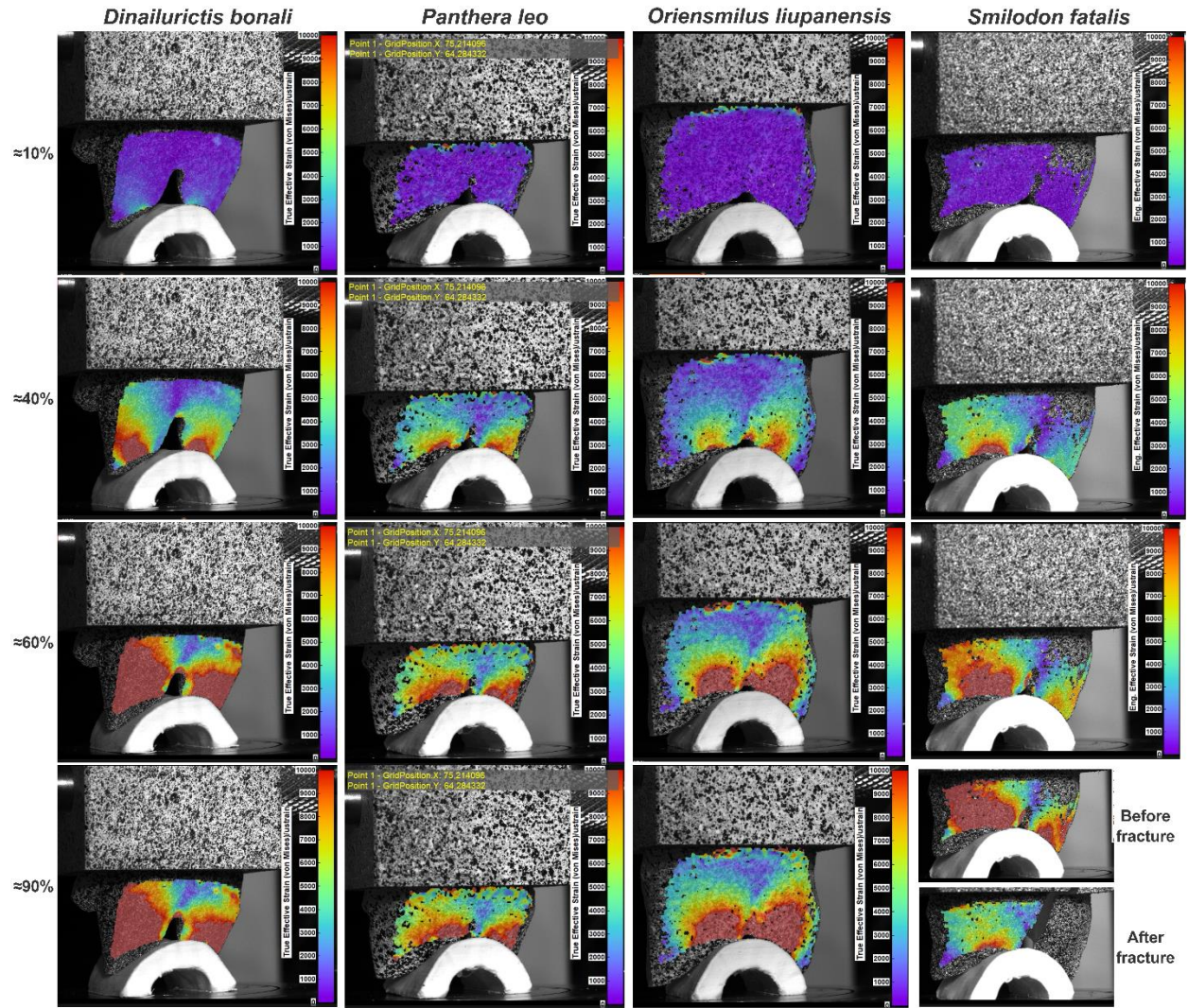


Fig. S6.

Screenshots showing surface plot of true effective strain on each tooth at different time obtained using a digital Image Correlation (DIC) system (Dantec, Inc.) employing two cameras (10 Hz; test speed 30 mm min^{-1}) to measure real-time surface strain and displacement during mechanical testing, after preconditioning by three slicing tests (max 500 N), a preload of 10N and a mechanical stop at 2000N to repeat actual testing conditions. Screenshots showing surface plot of true effective strain on each tooth at different time. Max = 10000.

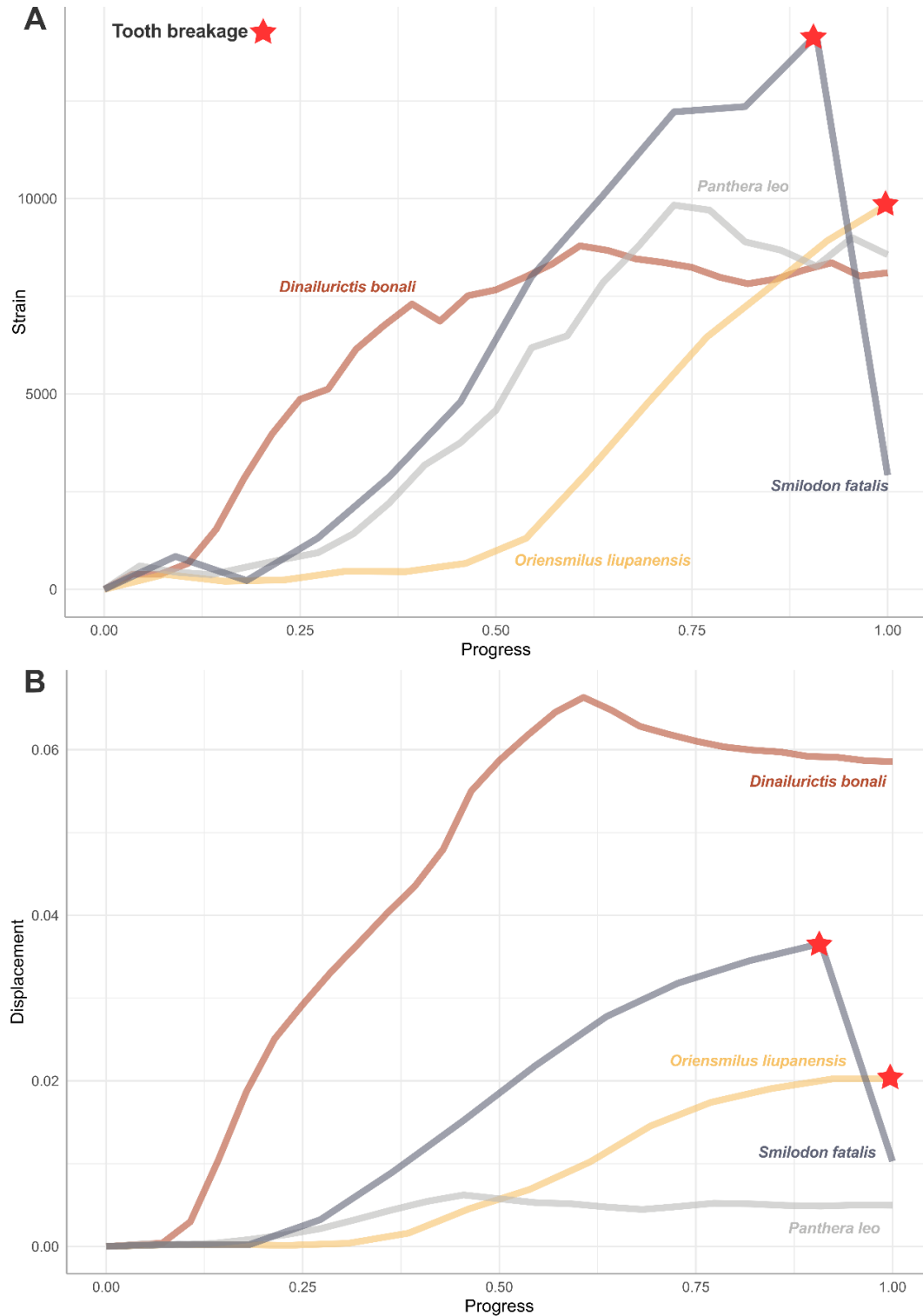


Fig. S7.

Evolution of (A) strain (True effective Strain, Von Mises) and (B) displacement (Total Displacement with Rigid Body Motion Removed) in the carnassial notch for the different taxa. Progress was obtained by standardizing experiment time (s) between 0 and 1 for each taxa.

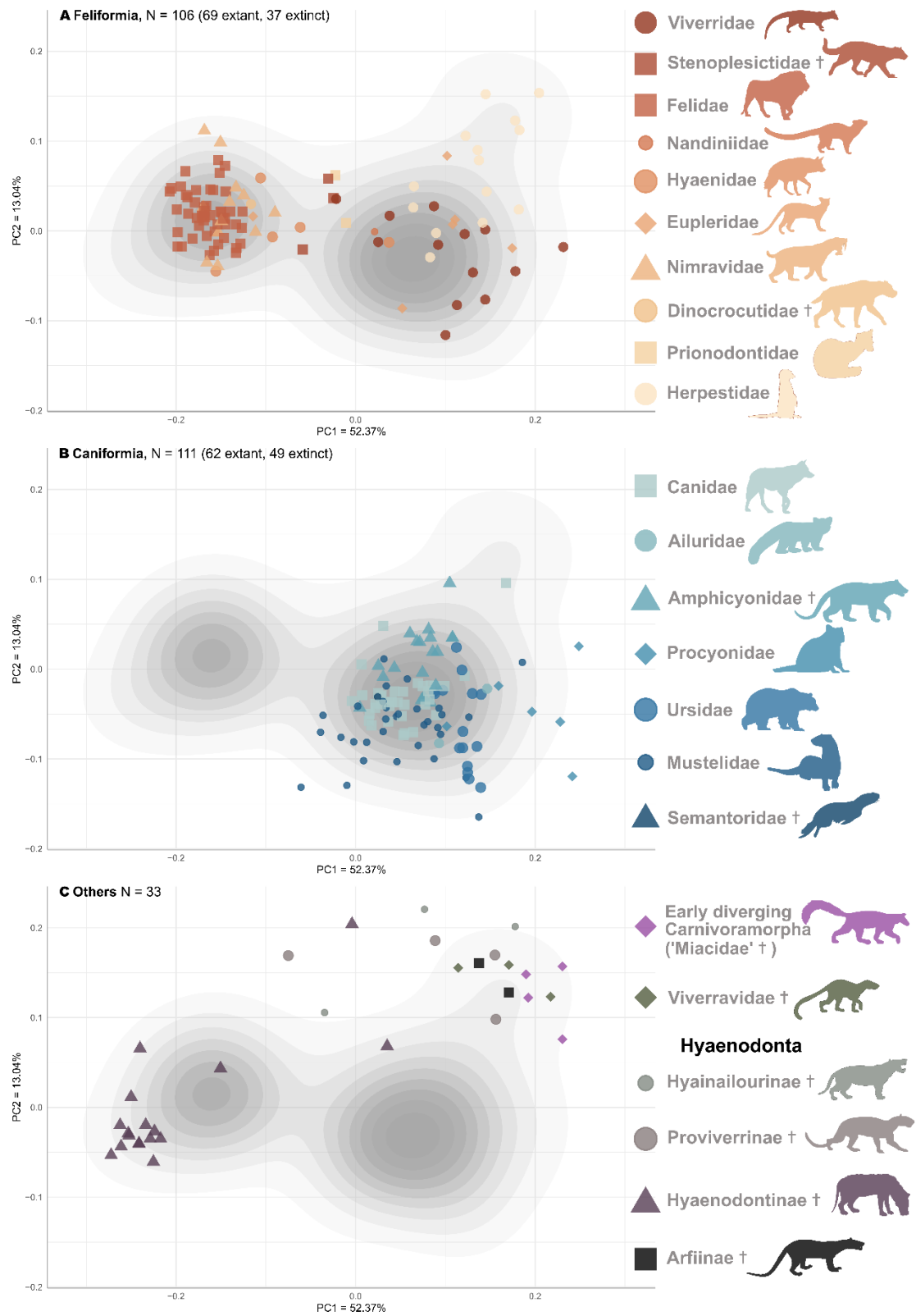


Fig. S8.

Morphospace occupation for different groups. (A) Feliformia & stem, (B) Caniformia, (C) others.

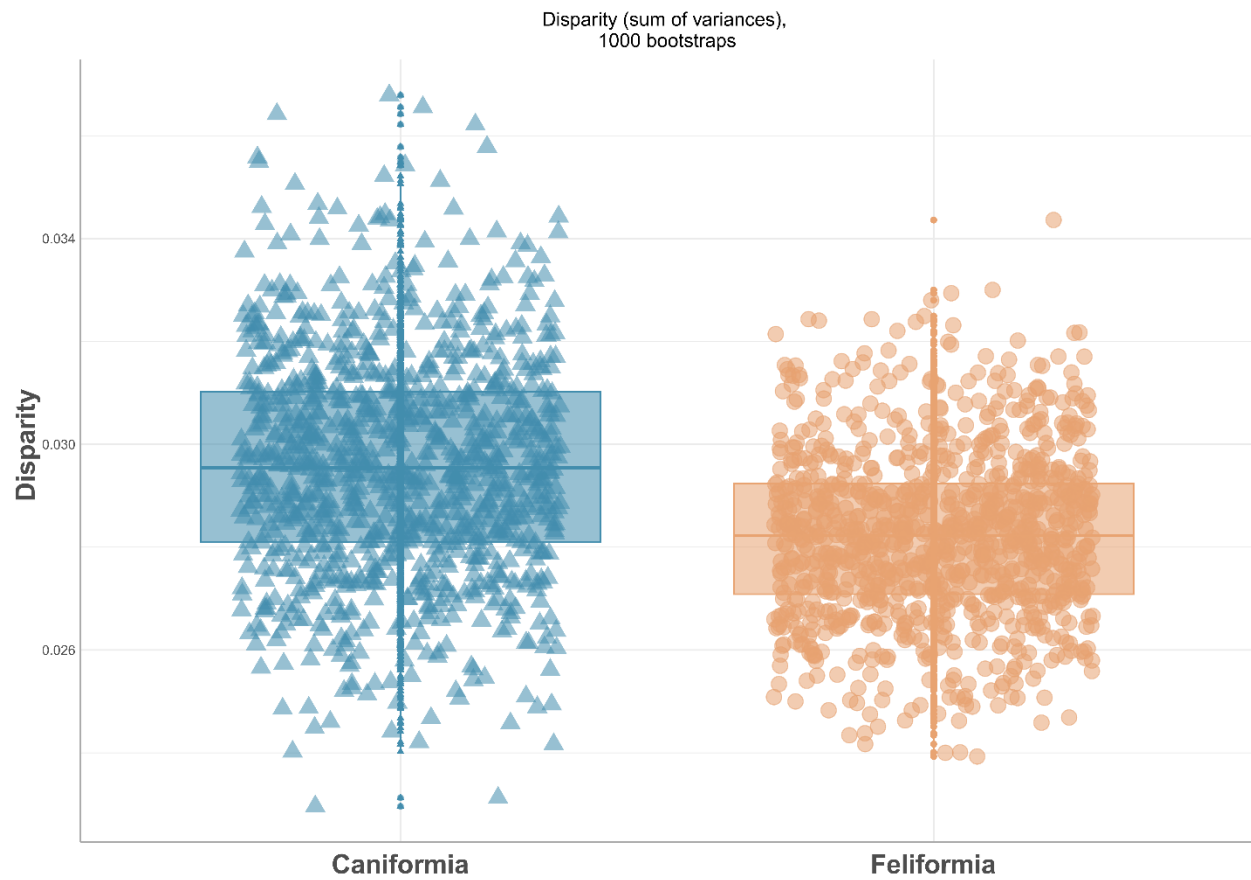


Fig. S9.
Disparity in tooth shape between the different suborders based on the whole set of landmark coordinates.

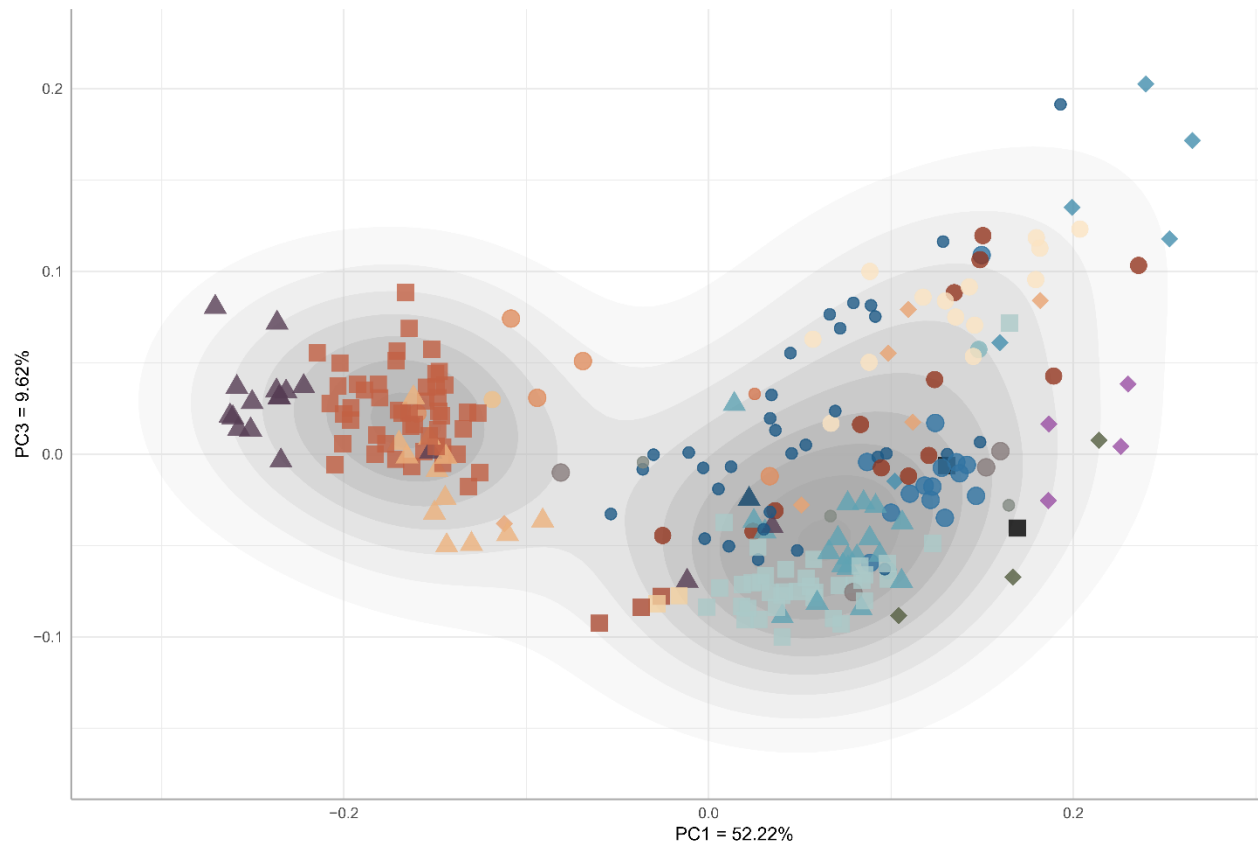


Fig. S10.

Morphospace resulting from the first and third axes of the principal component analysis. See Figure 2 in the manuscript for PC1 vs PC2 plot.

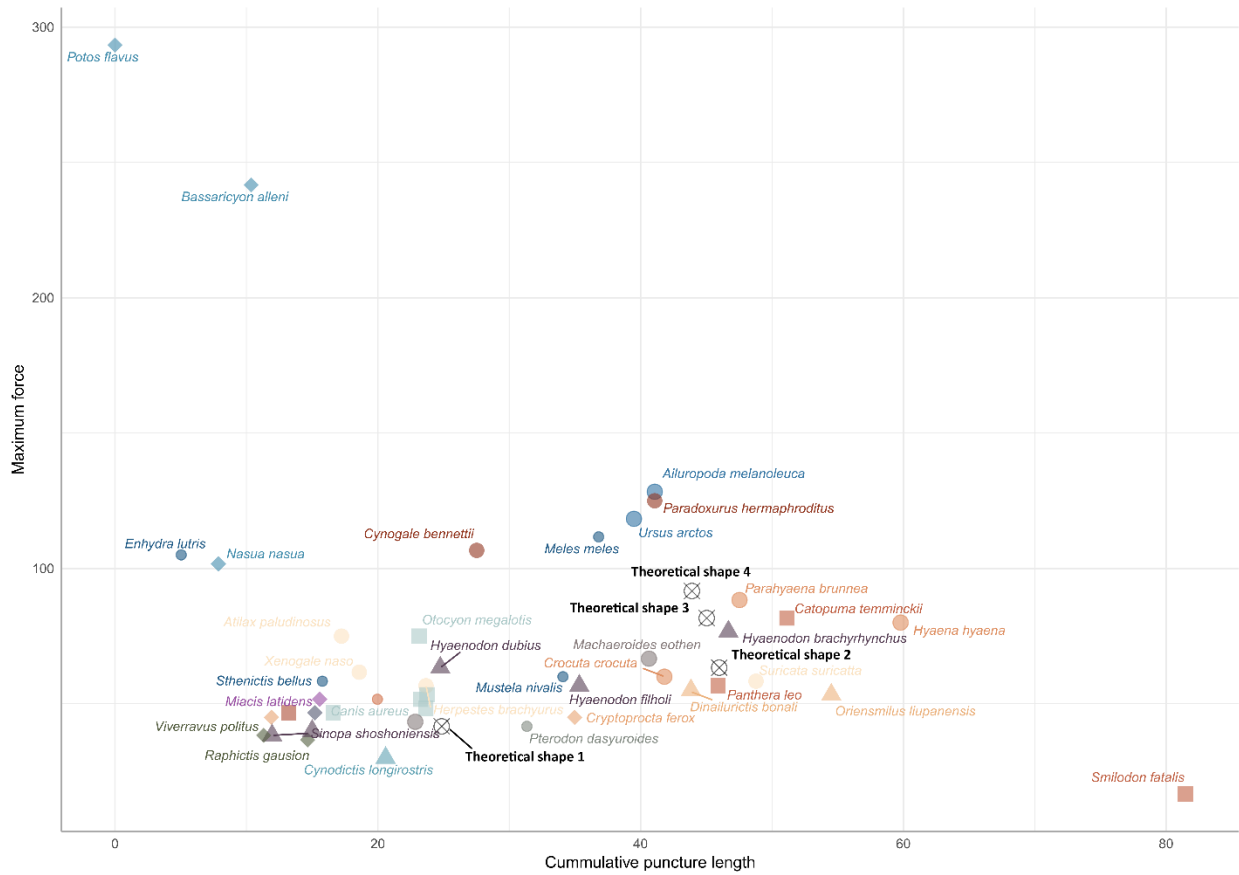


Fig. S11.

Results from the slicing simulations: maximum force (in N) vs cumulative puncture mark obtained by summing all the puncture marks in every gelatin layer.



Fig. S12. Results from the crushing simulations. (A) Slope vs Breakage Load (in N) and (B) Adjusted Slope vs Adjusted Breakage Load.

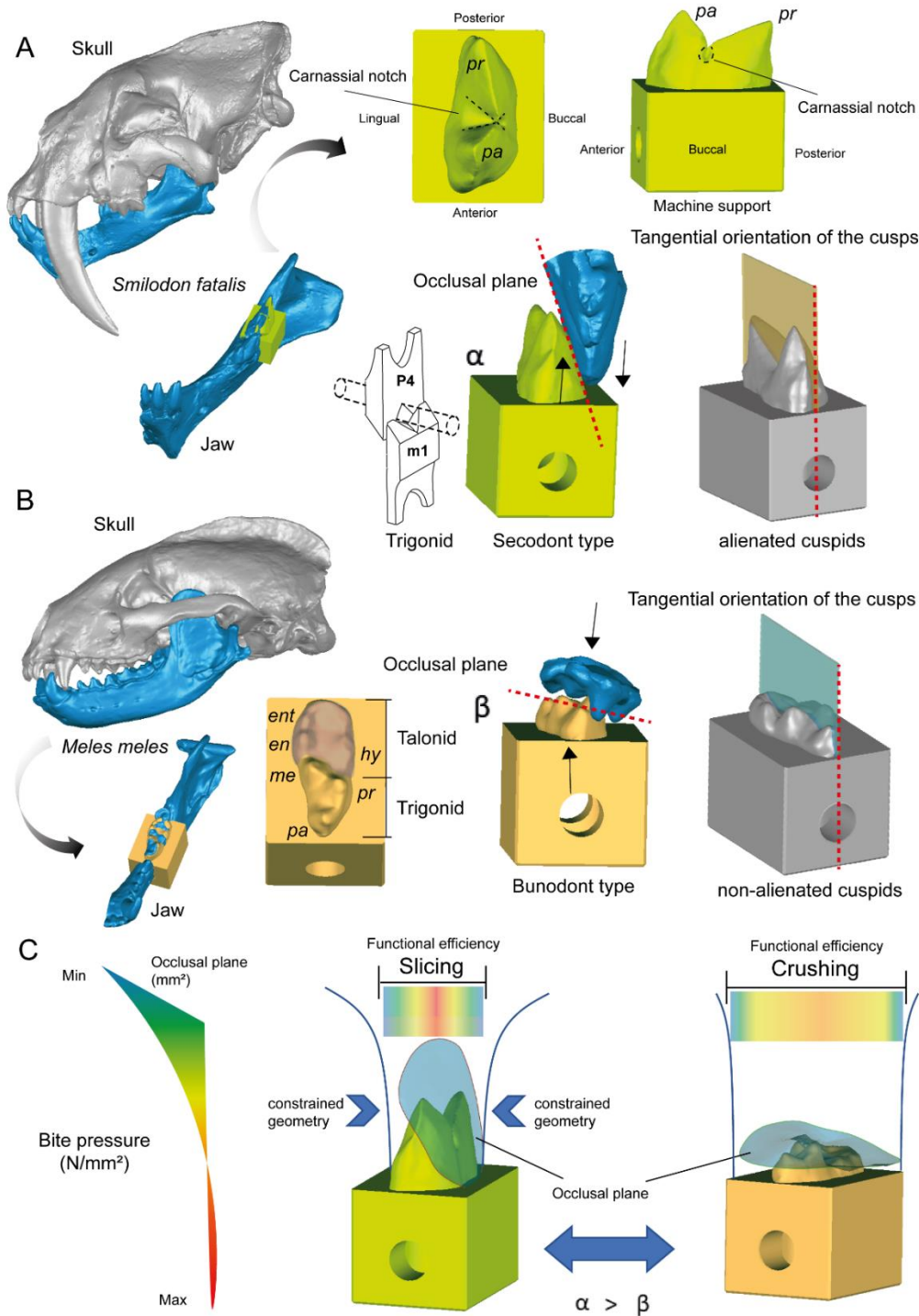
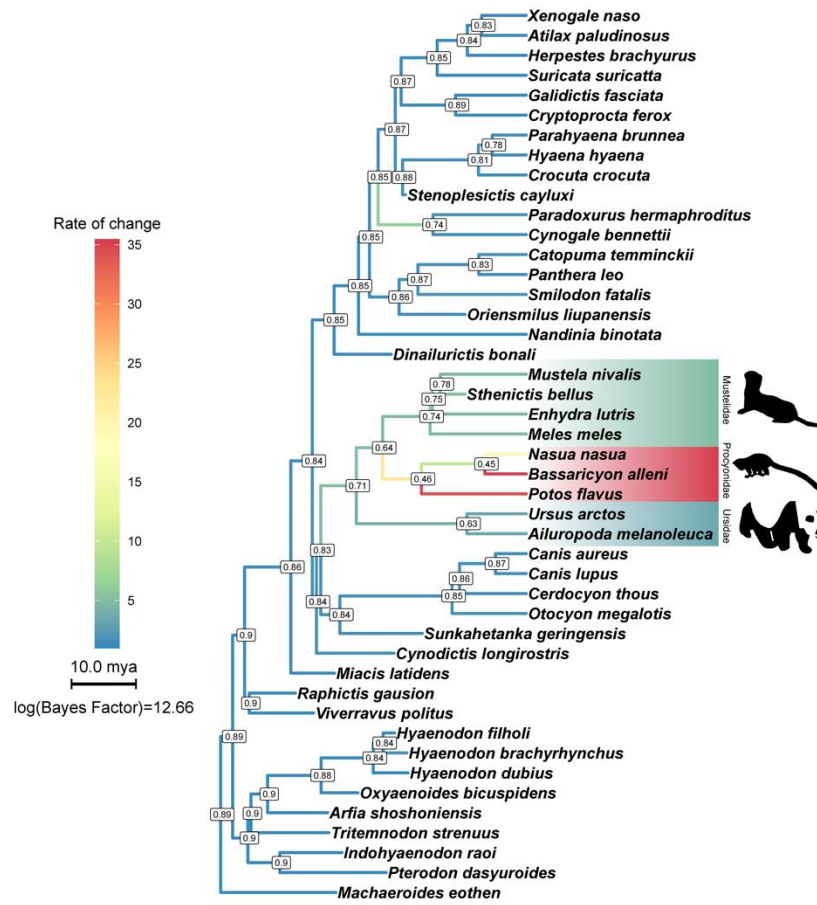


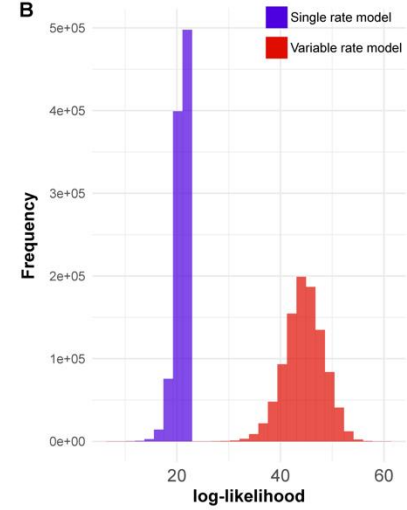
Fig. S13.

Example of two specimens with distinct adaptations to (A) Slicing (*Smilodon fatalis*) and (B) crushing (*Meles meles*) and (C) theoretical representation of the bite pressure produced by each morphotype. Abbreviations: Entoconid (en), Entoculid (ent), hypoconid (hy), metaconid (me), paraconid (pa), protoconid (pr). Note: α and β , angle between the occlusal plane and the tangential orientation of the main cusps. A steeper α enhances slicing efficiency (left), whereas a flatter β favors crushing efficiency (right); in our comparison $\alpha > \beta$.

A



B



C

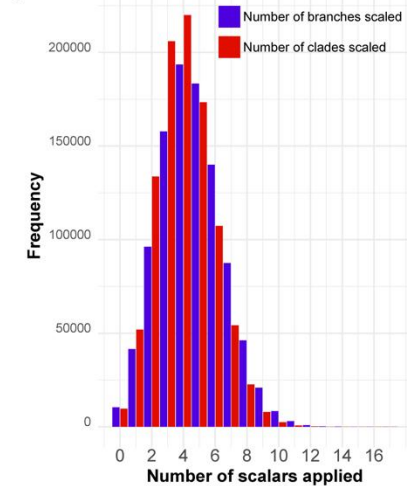


Fig. S14.

Mean inferred rate in the posterior distribution for the maximum force required to slice the three layers of gelatin. A) The phylogenetic tree with branch lengths colored according to the mean scalar applied to the branch and the estimated maximum force is labeled at each node. The support for the variable rates model over a single rate model is decisive (96). B) Posterior distribution of log-likelihoods for the fitted single rate model compared to the variable rates model. C) the posterior distribution for the number of branches or entire clades scaled.

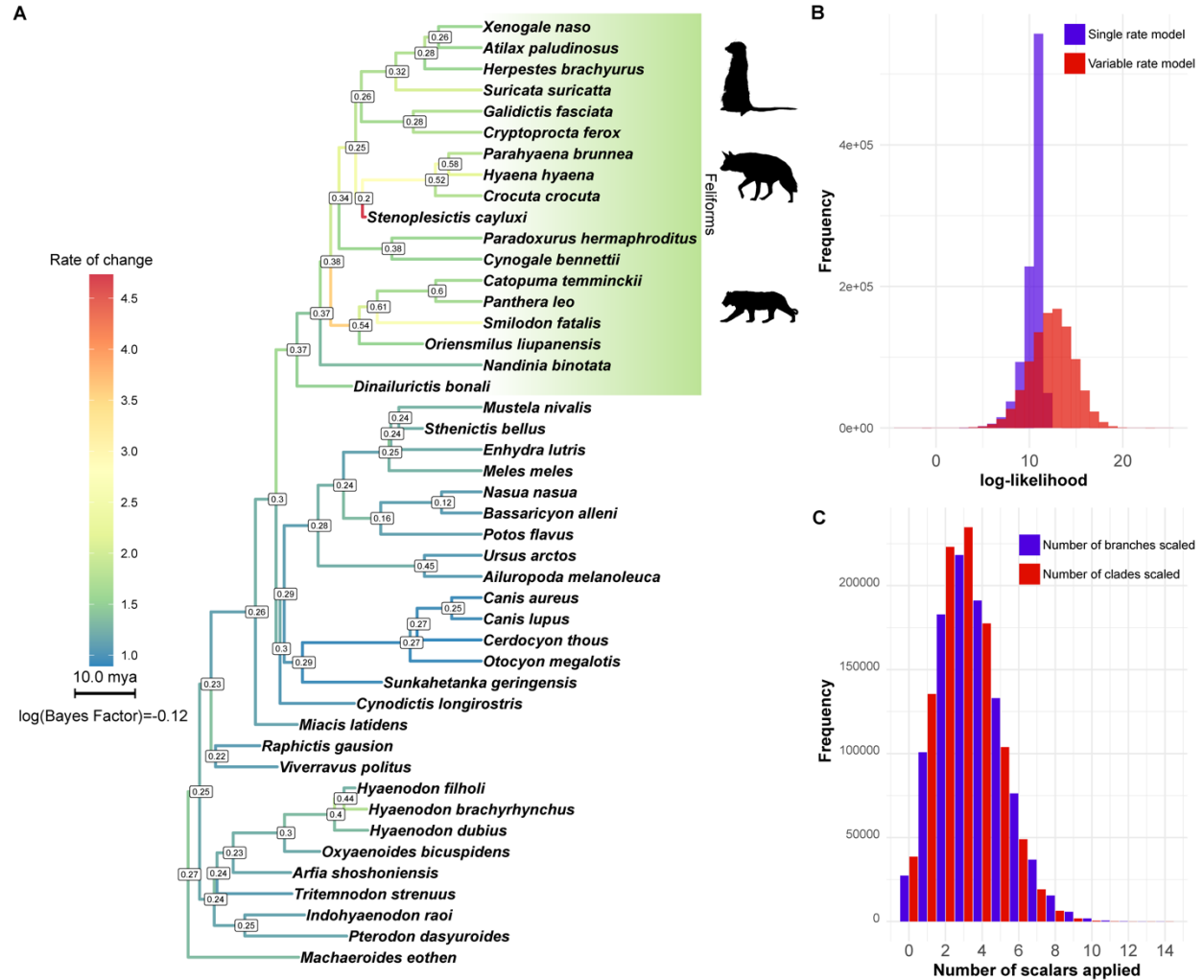


Fig. S15.

Mean inferred rate in the posterior distribution for the max length. A) The phylogenetic tree with branch lengths colored according to the mean scalar applied to the branch and the estimated maximum length is labeled at each node. The support for the variable rates model over a single rate model is inconclusive, but slightly in favor of the single rates model (96). B) Posterior distribution of log-likelihoods for the fitted single rate model compared to the variable rates model. C) the posterior distribution for the number of branches or entire clades scaled.

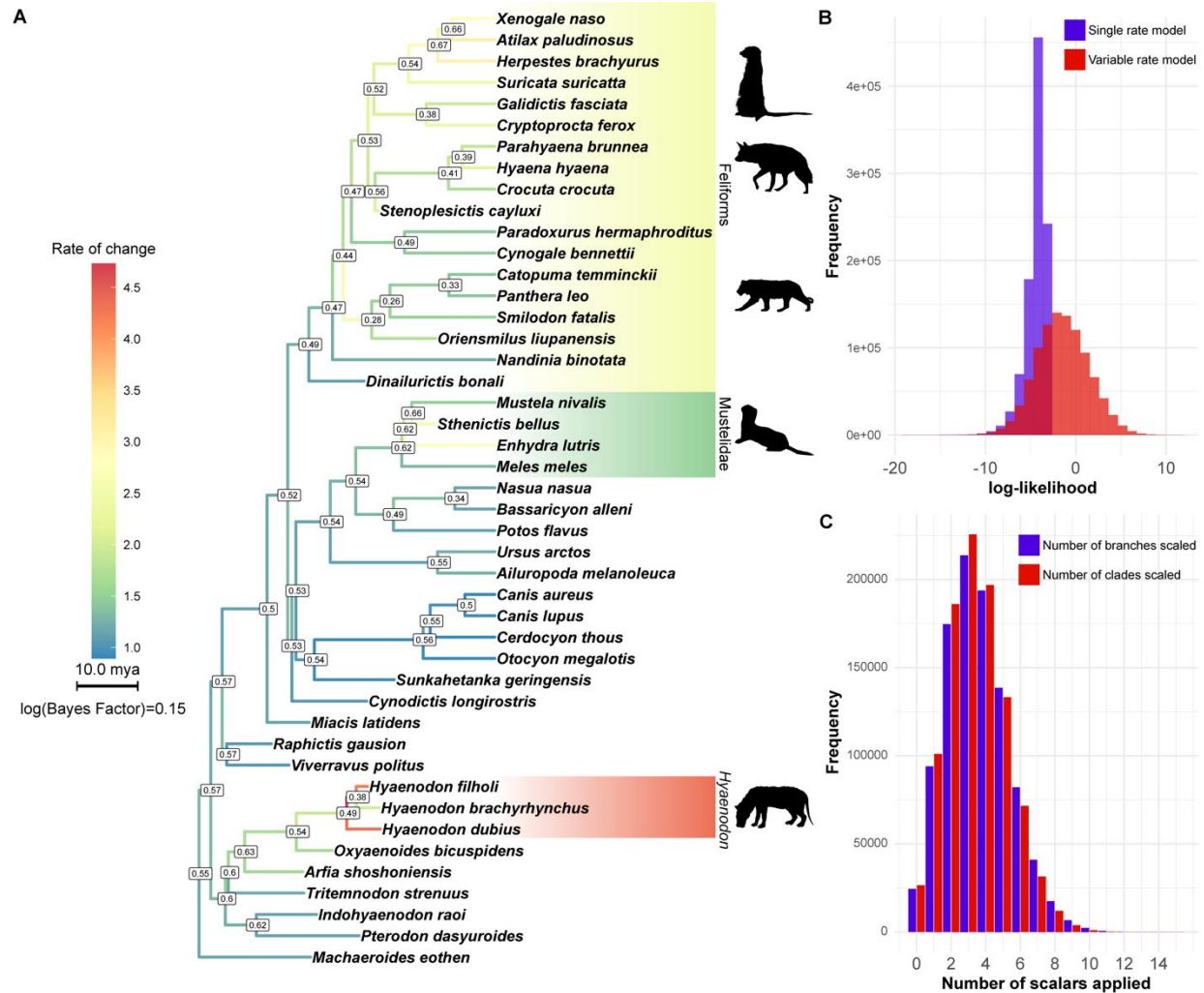


Fig. S16.

Mean inferred rate in the posterior distribution for the adjusted breakage load. A) The phylogenetic tree with branch lengths colored according to the mean scalar applied to the branch and the estimated adjusted breakage load is labeled at each node. The support for the variable rates model over a single rate model is inconclusive, but slightly in favor of the variable rates model (96). B) Posterior distribution of log-likelihoods for the fitted single rate model compared to the variable rates model. C) the posterior distribution for the number of branches or entire clades scaled.

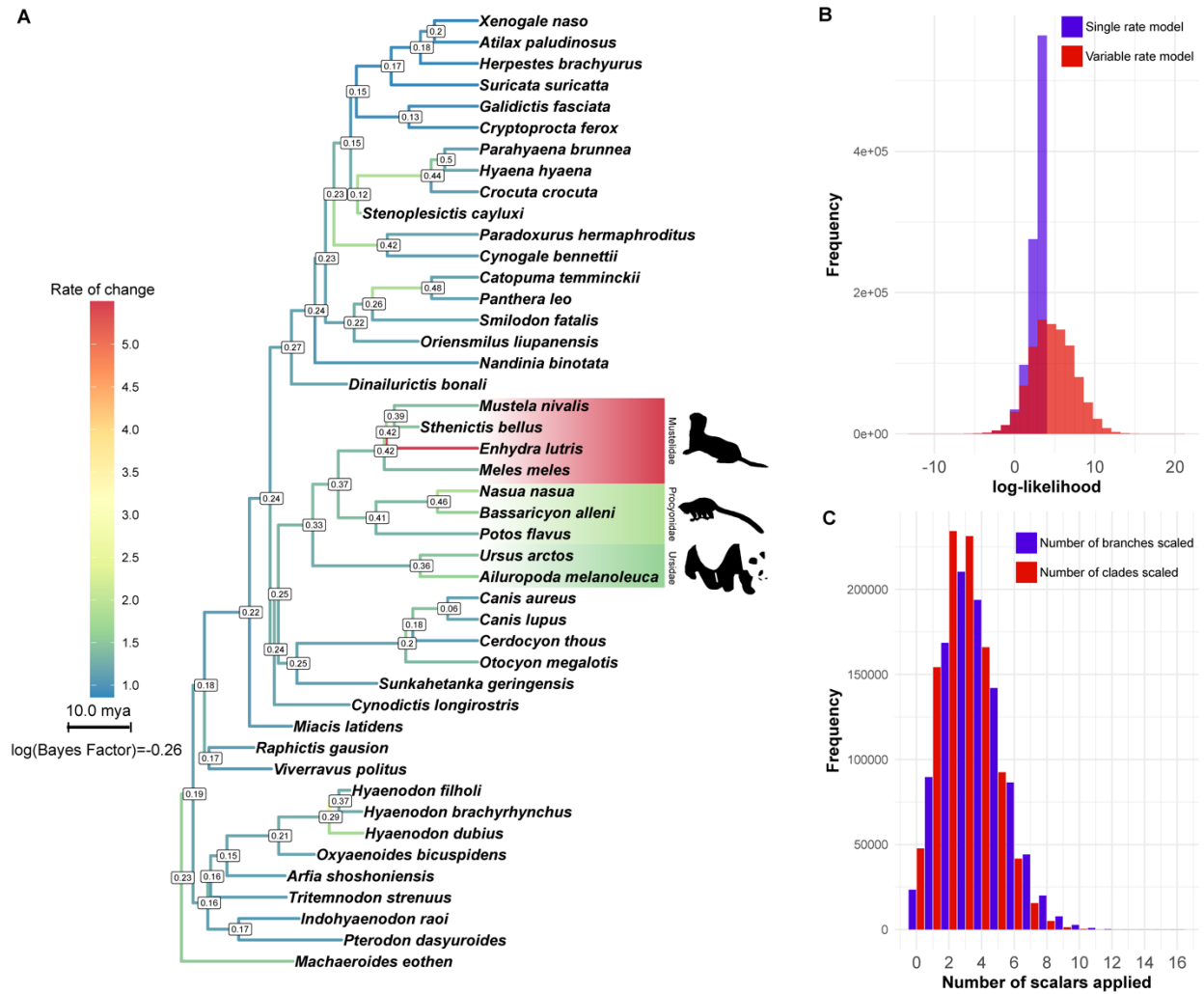


Fig. S17.

Mean inferred rate in the posterior distribution for the adjusted slope. A) The phylogenetic tree with branch lengths colored according to the mean scalar applied to the branch and the estimated adjusted slope is labeled at each node. The support for the variable rates model over a single rate model is inconclusive, but slightly in favor of the single rates model (96). B) Posterior distribution of log-likelihoods for the fitted single rate model compared to the variable rates model. C) the posterior distribution for the number of branches or entire clades scaled.

Table S1.

Properties of the ELEGOO Standard Photopolymer resin.

Wavelength	405 nm
Hardness	84
Viscosity	150-200 mPa.s
Liquid density	1.100 g/cm ³
Solid density	1.195 g/cm ³
Flexure strength	59-70 mPa
Extension strength	36-53 mPa

Table S2.

Printing properties for the bone sections. (Profile = normal – 0.15mm). Note that the two categories displayed here are the only ones differing from the basic ‘normal– 0.15mm’ settings.

QUALITY	
LAYER HEIGHT	0.15 mm
INITIAL LAYER HEIGHT	0.15 mm
LINE WIDTH	0.15 mm
WIDTH LINE WIDTH	0.15 mm
OUTER WALL LINE WIDTH	0.15 mm
INNER WALL(S) LINE WIDTH	0.15 mm
TOP/BOTTOM LINE WIDTH	0.15 mm
INFILL LINE WIDTH	0.15 mm
SKIRT/BRIM LINE WIDTH	0.15 mm
INITIAL LAYER LINE WIDTH	0.15 mm
BUILD PLATE ADHESION	
BUILD PLATE ADHESION TYPE	Brim
SKIRT/BRIM MINIMUM LENGTH	150.0 mm
BRIM WIDTH	4 mm
BRIM LINE COUNT	27

Table S3.

Properties of the gelatin used in the simulations.

	DENSITY (KG/M ³)	YOUNG'S MODULUS (MPA)	SPEED OF SOUND (M/S)	TISSUES
GELATIN #0	945.284	0.57	1449.30	Muscle, variety of organs
GELATIN #1	935.026	0.37	1465.20	Neck muscles, healthy skin
GELATIN #2	967.463	0.26	1457.42	Fattier tissues

Table S4.

Optimal weights obtained for each variable.

Slicing	
	Weight
MaxForce	0.7005
MaxLength	0.2995
Crushing	
Adjusted Breakage Load	0.4293
Adjusted dBreakage Load	0.4026
Adjusted Slope Elastic	0.1681
Combined	
MaxForce	0.2231
MaxLength	0.2058
Adjusted Breakage Load	0.1331
Adjusted d Breakage Load	0.2855
Adjusted Slope Elastic	0.1525

Movie S1. Dinailuricts_2000Nmax_simubone_compression1CORN1_Movie_001.avi

Video obtained from the digital correlation tests on *Dinailurictis bonali* showing true effective strain (Von Mises) through time.

Movie S2. Oriensmilus_2000Nmax_simubone_compression1CORN1_Movie_001.avi

Video obtained from the digital correlation tests on *Oriensmilus liupanensis* showing true effective strain (Von Mises) through time.

Movie S3. Panthera_leo_2000Nmax_simubone_compression1CORN1_Movie_001.avi

Video obtained from the digital correlation tests on *Panthera leo* showing true effective strain (Von Mises) through time.

Movie S4. Smilodon_1_2000Nmax_simubone_compression1CORN1_Movie_001.avi

Video obtained from the digital correlation tests on *Smilodon fatalis* showing true effective strain (Von Mises) through time.

Movie S5. Dinailurictis_1_2000Nmax_simubone_compression_video_Movie_001.avi

Video obtained from the digital correlation tests on *Dinailurictis bonali*.

Movie S6. Oriensmilus_1_2000Nmax_simubone_compression_video1_Movie_001.avi

Video obtained from the digital correlation tests on *Oriensmilus liupanensis*.

Movie S7. Panthera_leo_2_2000Nmax_simubone_compression_video1_Movie_001.avi

Video obtained from the digital correlation tests on *Panthera leo*.

Movie S8. Smilodon_1_2000Nmax_simubone_compression1_Movie_001.avi

Video obtained from the digital correlation tests on *Smilodon fatalis*.

Data S1. (Dataset_June2024.xlsx)

Detailed list of specimens used for the study.

Data S2. (Carnassial_mechanical_data.xlsx)

Raw results of the experimental testing.

Data S3. (Chatar&al_Carnassial_project.R)

R script.

Data S4. (DIC Data.zip)

Zip Containing all the ASCII files obtained from the DIC tests.

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