
Supplementary information

Environmental signal in the evolutionary diversification of bird skeletons

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Supplementary Information from

Environmental signal in the evolutionary diversification of bird skeletons

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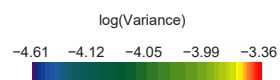
*Corresponding authors: gn315@cam.ac.uk, roger.benson@earth.ox.ac.uk.

Consisting of Figs. S1-S37. Presents extensive data on detailed patterns of skeletal evolution in birds per different regions and clades.

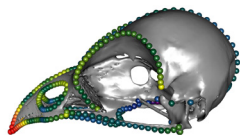
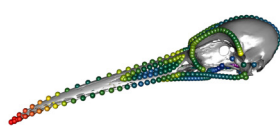
Also see Supplementary Materials (available online):

- **Table S1. List of specimens used in this study.**
- **Table S2. ANOVA tables used for proportions-normalising individual elements.**
- **Table S3. Pairs of landmarks used to calculate maximum distances in each of the spatial axes**
- **File S1. Bird_landmarks_Navalon_2022. Raw landmark coordinates for all specimens used in this study.**
- **File S2. Read_bird_landmarks_Navalon_2022. R code to read the raw landmarks coordinates in File S1.**
- **File S3. Bird_processed_landmarks_Navalon_2022. Allometry free and proportions free landmark coordinates for all specimens used in this study.**
- **File S4. Read_bird_processed_landmarks_Navalon_2022. R code to read the raw landmarks coordinates in File S3.**
- **File S5. Combined phylogeny used in this study.tre**
- **File S6. Custom R functions used in this study.**
- **File S7. Custom R code used in this study**

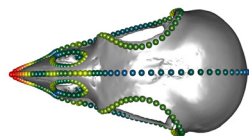
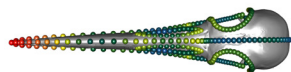
Allometry-free shape



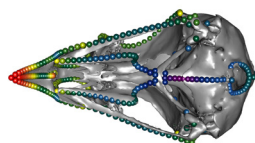
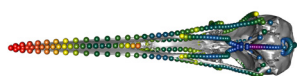
PC1



Lateral view

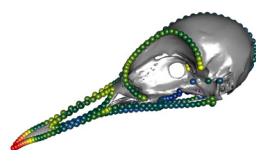
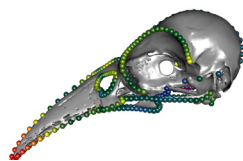


Dorsal view

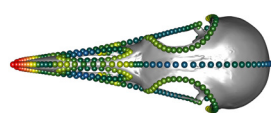
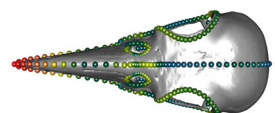


Palatal view

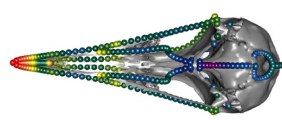
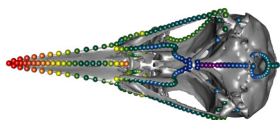
PC2



Lateral view



Dorsal view

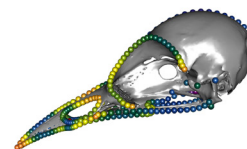
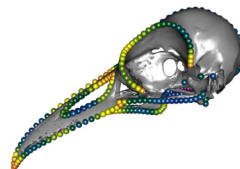


Palatal view

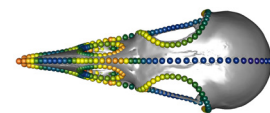
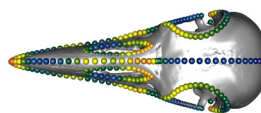
Proportions-normalised shape



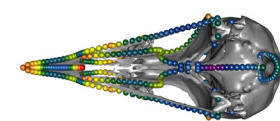
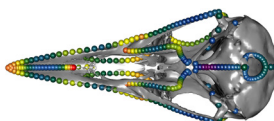
PC1



Lateral view

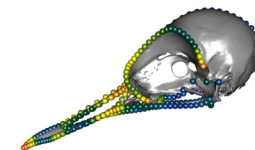
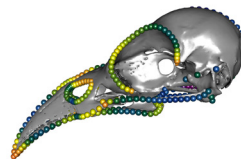


Dorsal view

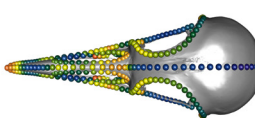
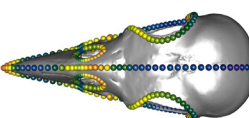


Palatal view

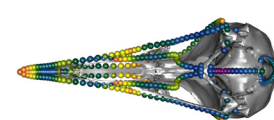
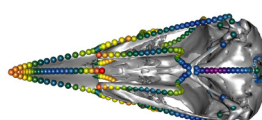
PC2



Lateral view



Dorsal view



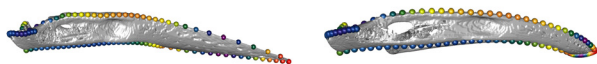
Palatal view

Figure S1. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the skull. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

Allometry-free shape



PC1



Lateral view



Dorsal view



Palatal view

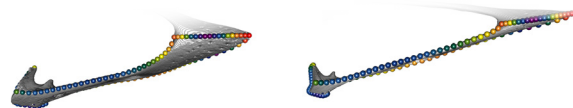
PC2



Lateral view

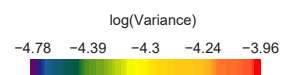


Dorsal view

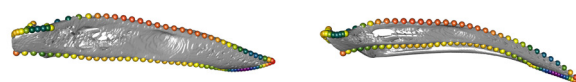


Palatal view

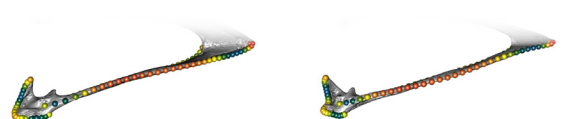
Proportions-normalised shape



PC1



Lateral view



Dorsal view



Palatal view

PC2



Lateral view



Dorsal view



Palatal view

Figure S2. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the mandible. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

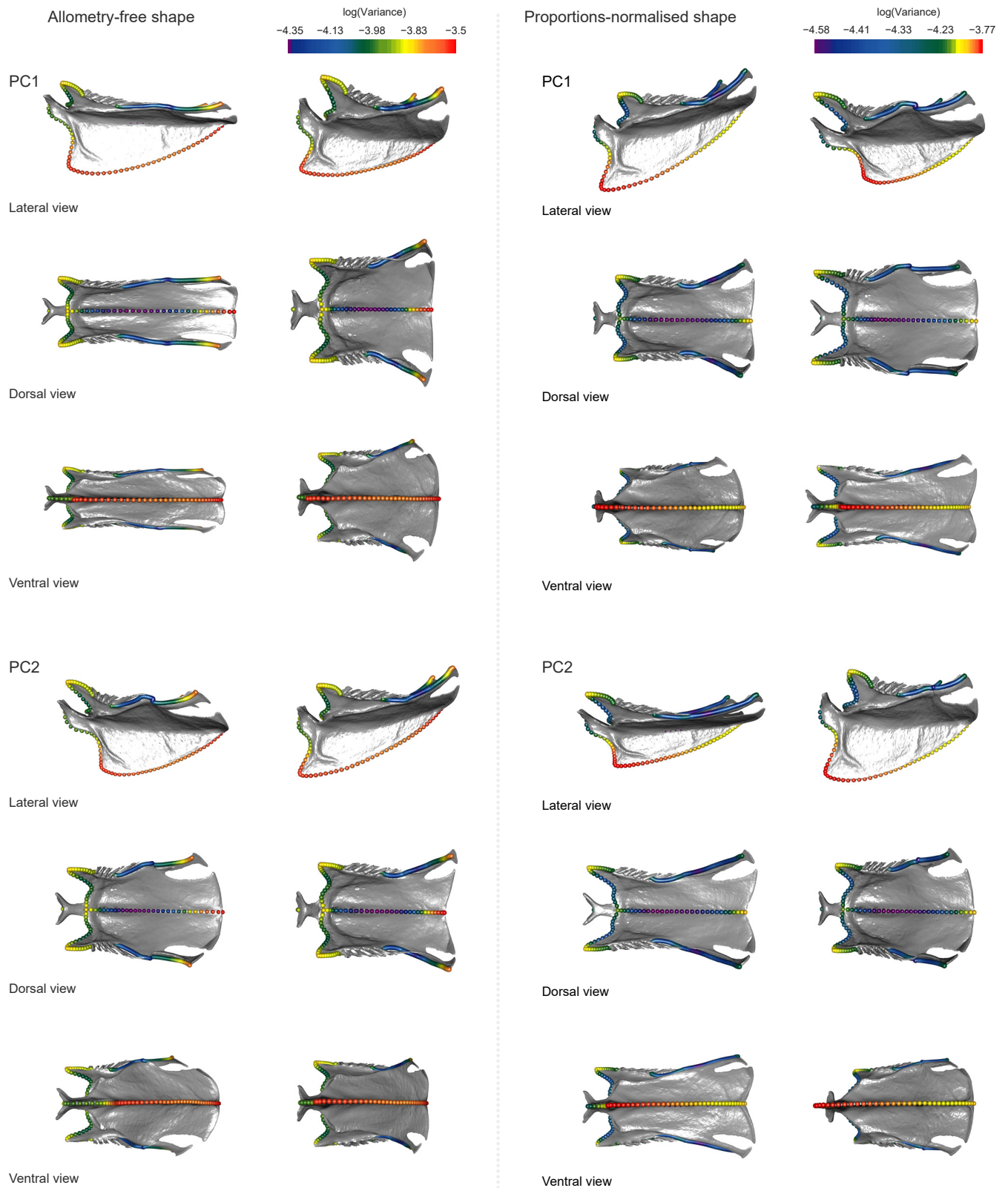


Figure S3. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the sternum. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

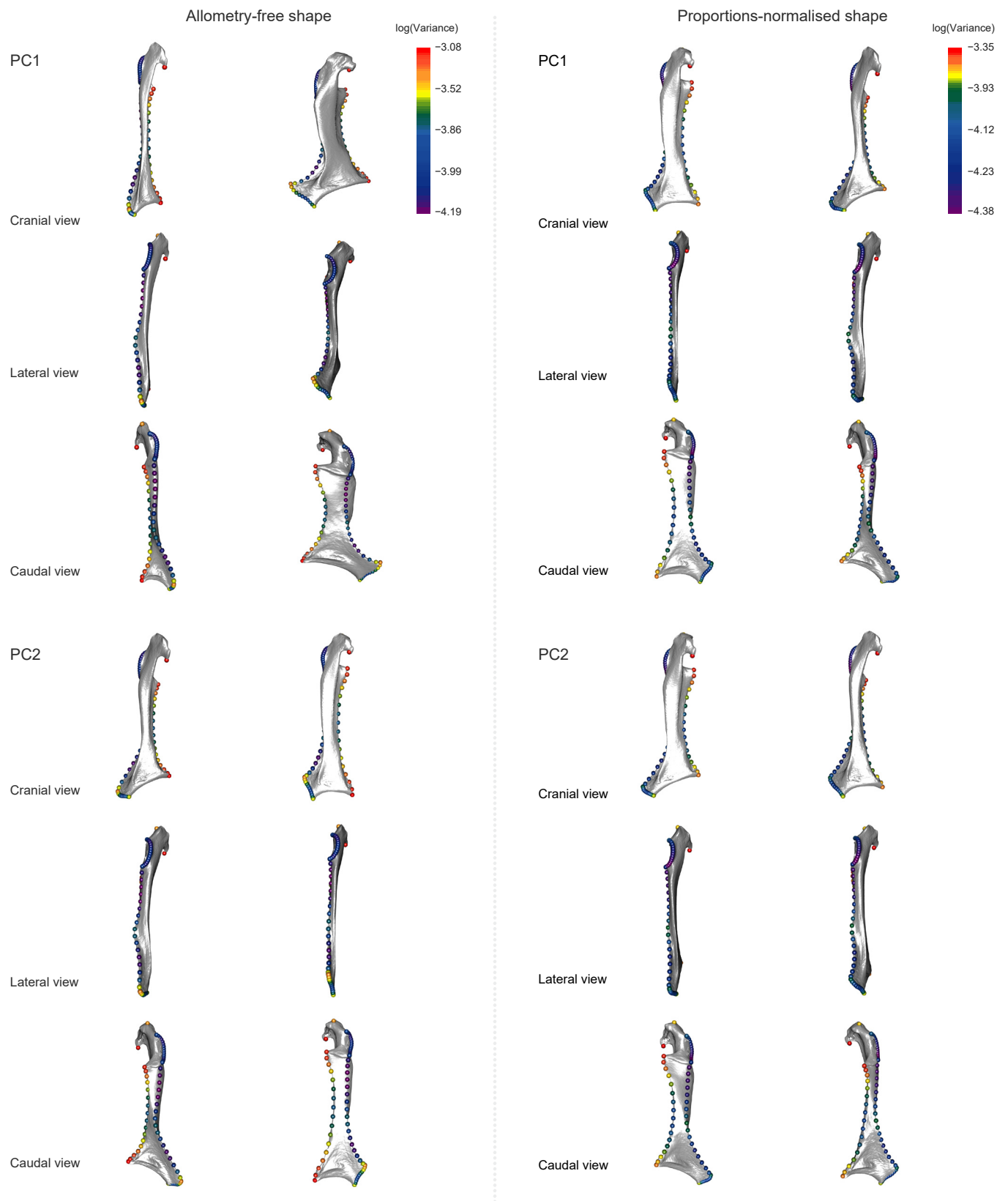


Figure S4. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the coracoid. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

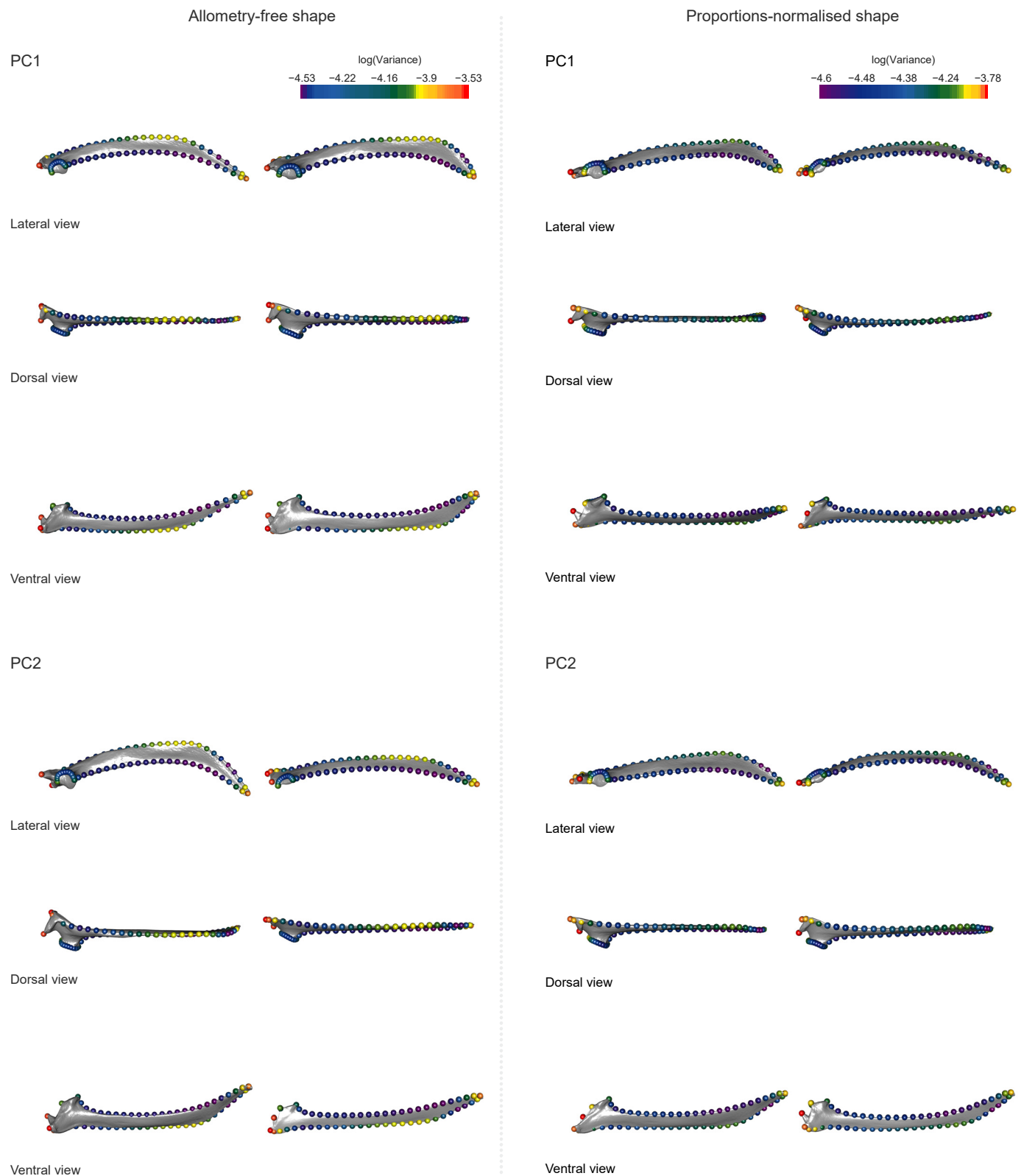


Figure S5. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the scapula. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

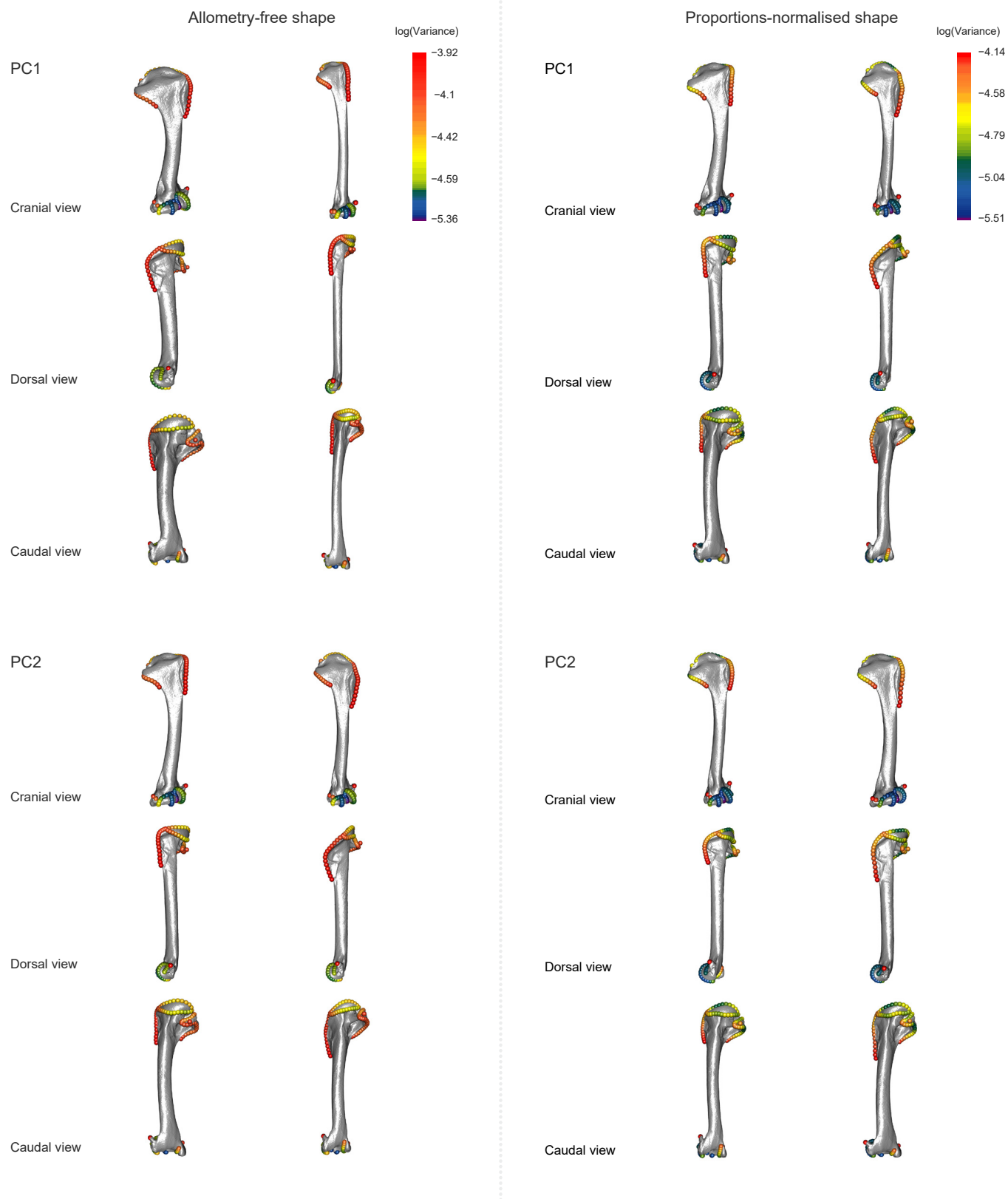


Figure S6. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the humerus. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

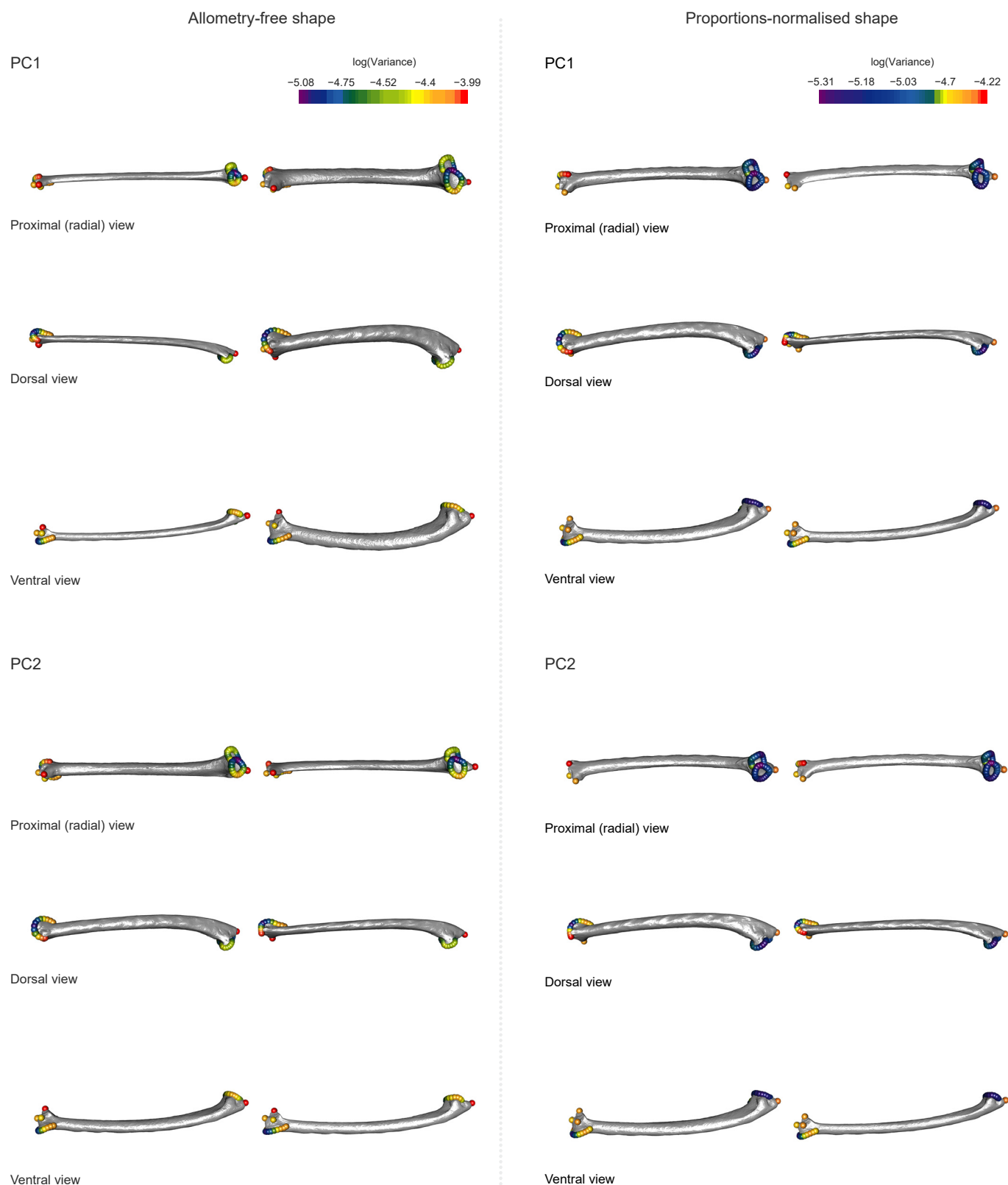


Figure S7. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the ulna. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

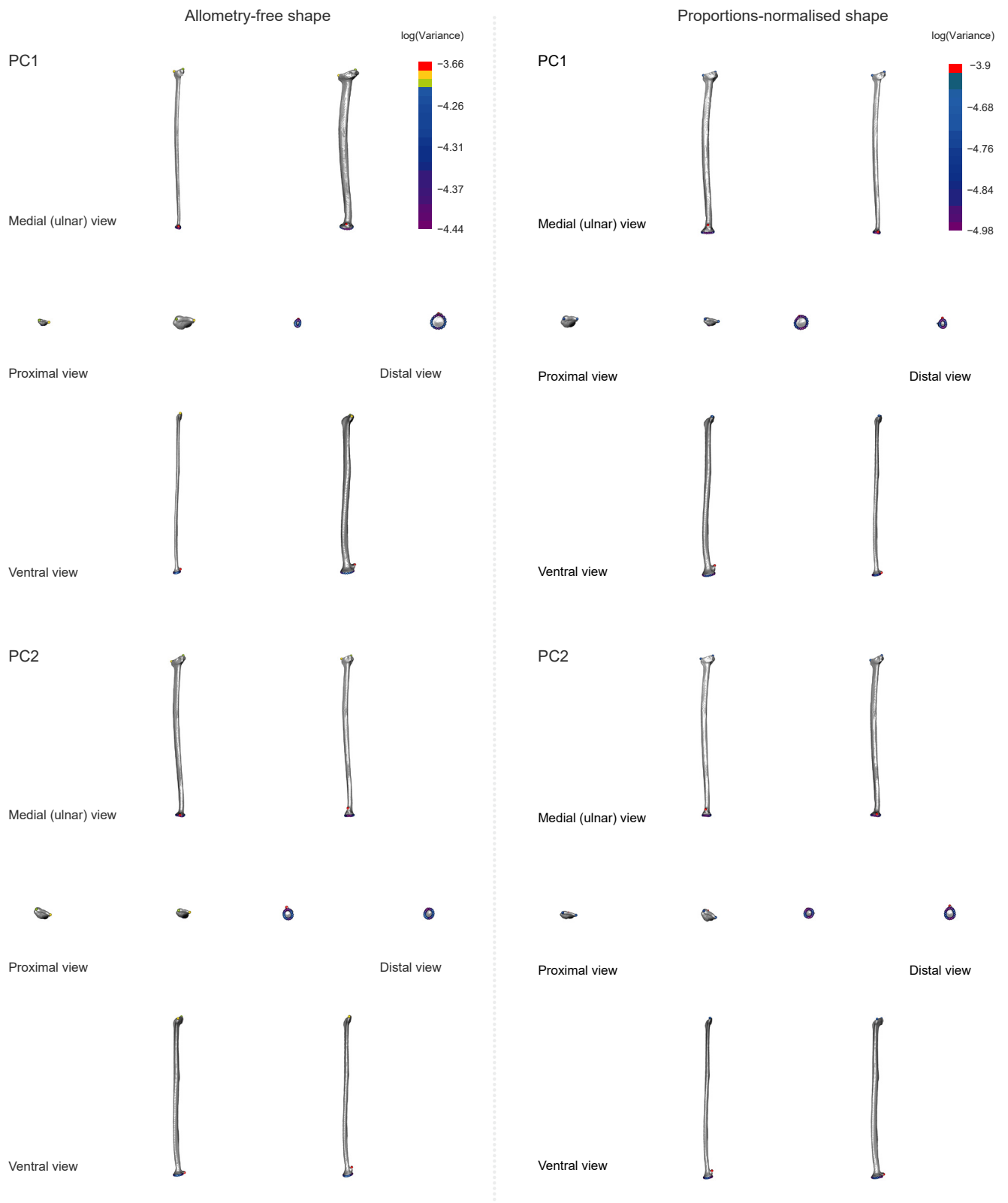
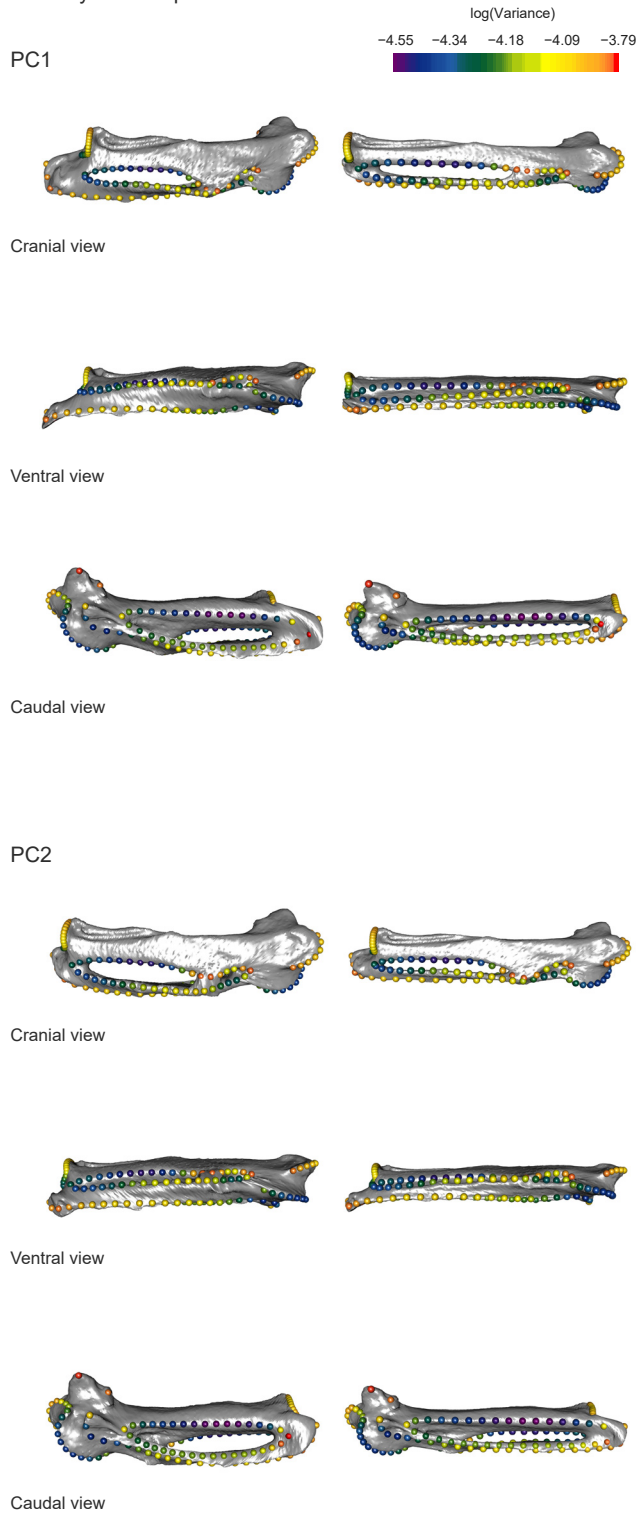


Figure S8. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the radius. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

Allometry-free shape



Proportions-normalised shape

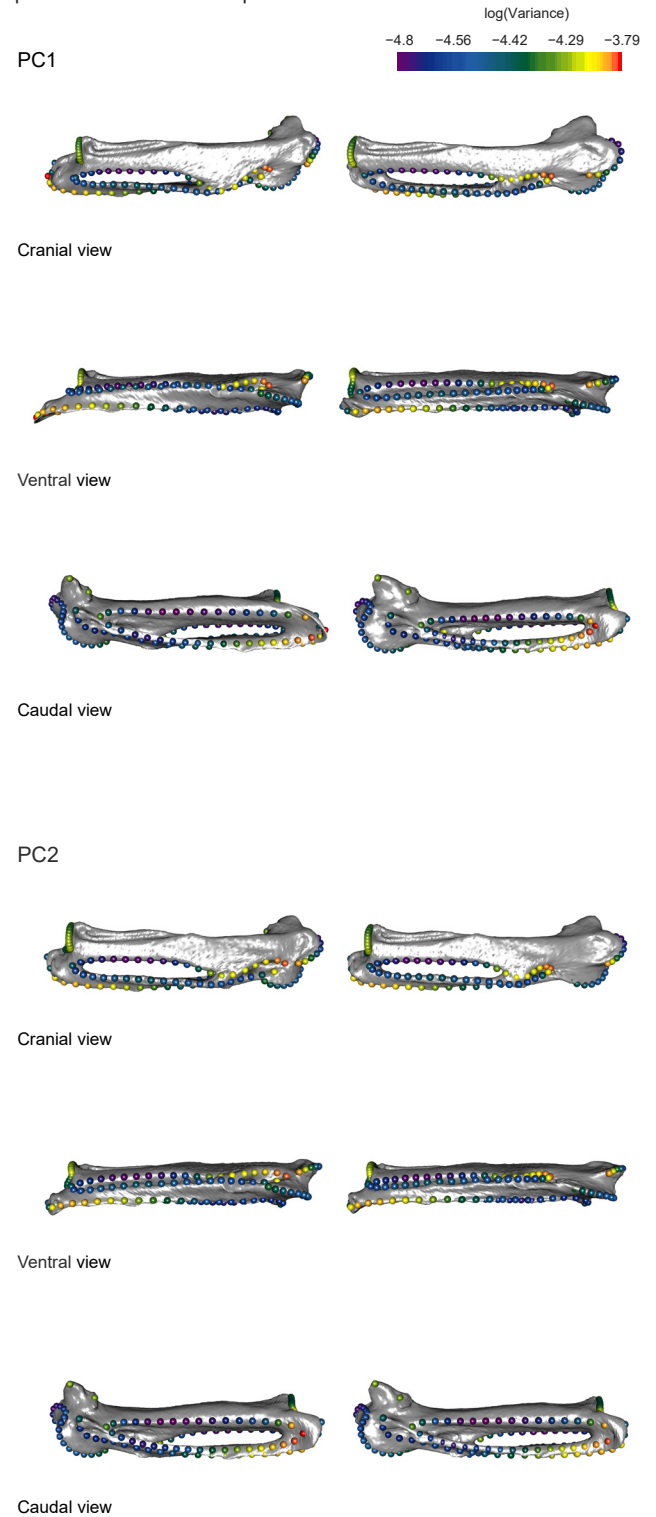
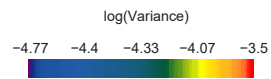
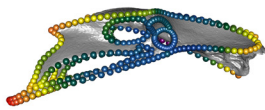


Figure S9. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the carpometacarpus. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

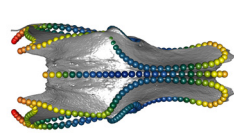
Allometry-free shape



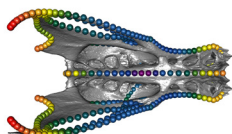
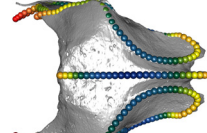
PC1



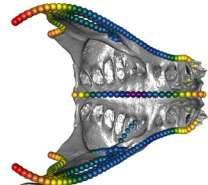
Lateral view



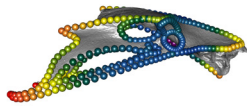
Dorsal view



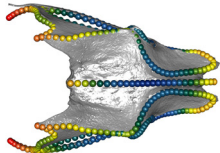
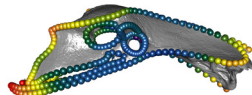
Palatal view



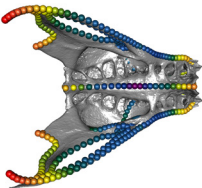
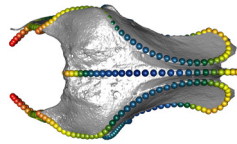
PC2



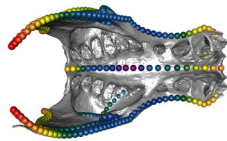
Lateral view



Dorsal view



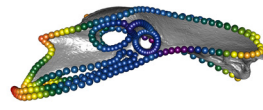
Palatal view



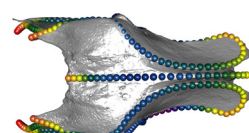
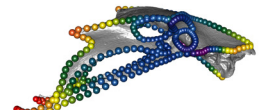
Proportions-normalised shape



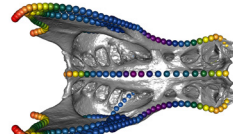
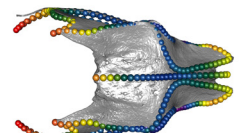
PC1



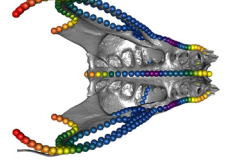
Lateral view



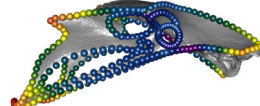
Dorsal view



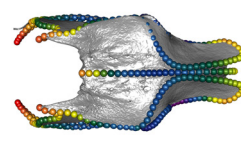
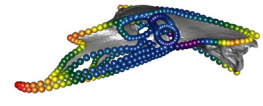
Palatal view



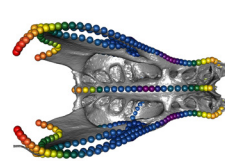
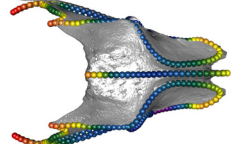
PC2



Lateral view



Dorsal view



Palatal view

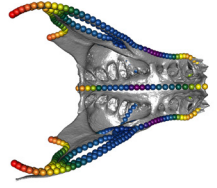


Figure S10. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the synsacrum. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

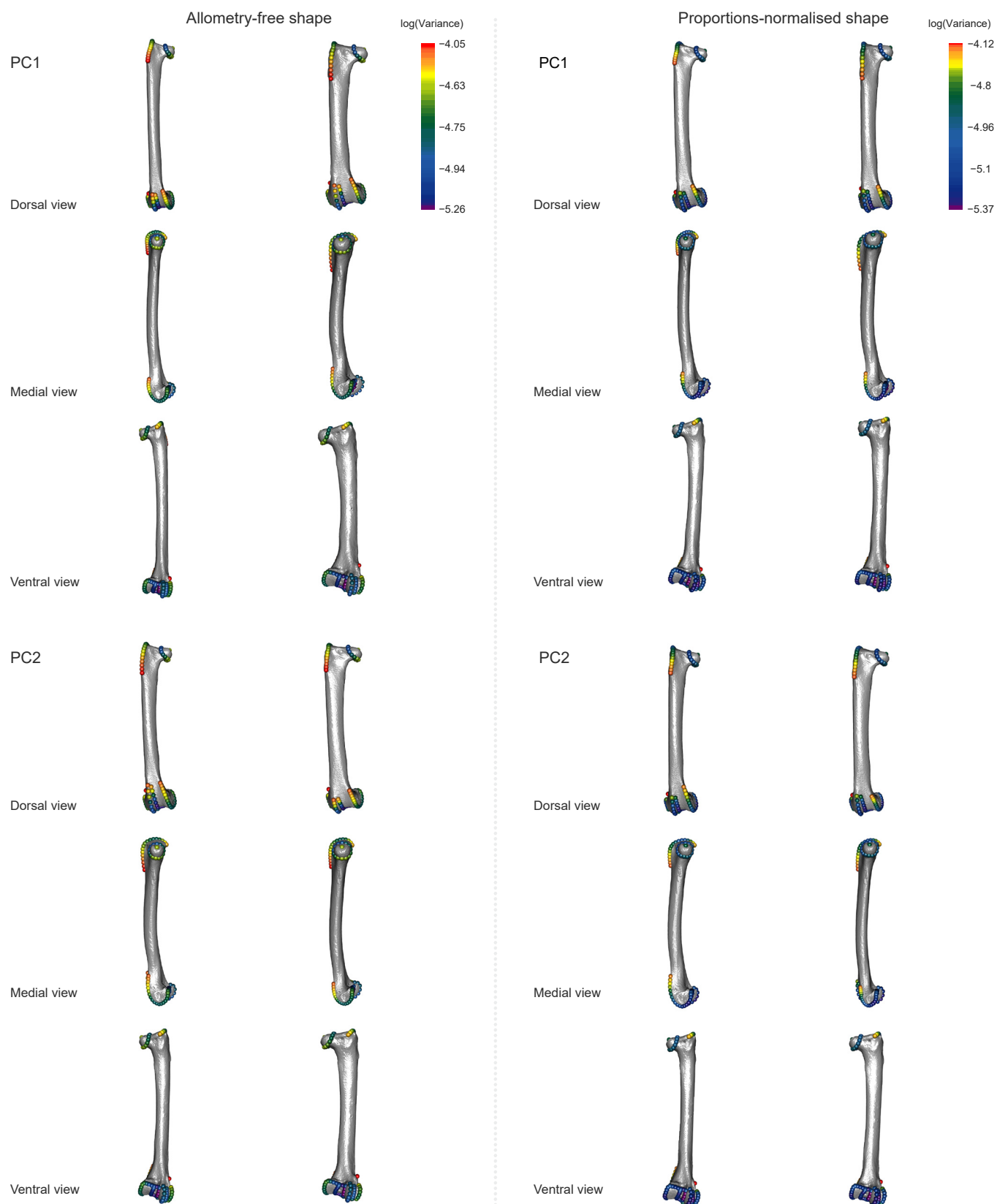


Figure S11. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the femur. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.



Figure S12. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the tibiotarsus. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

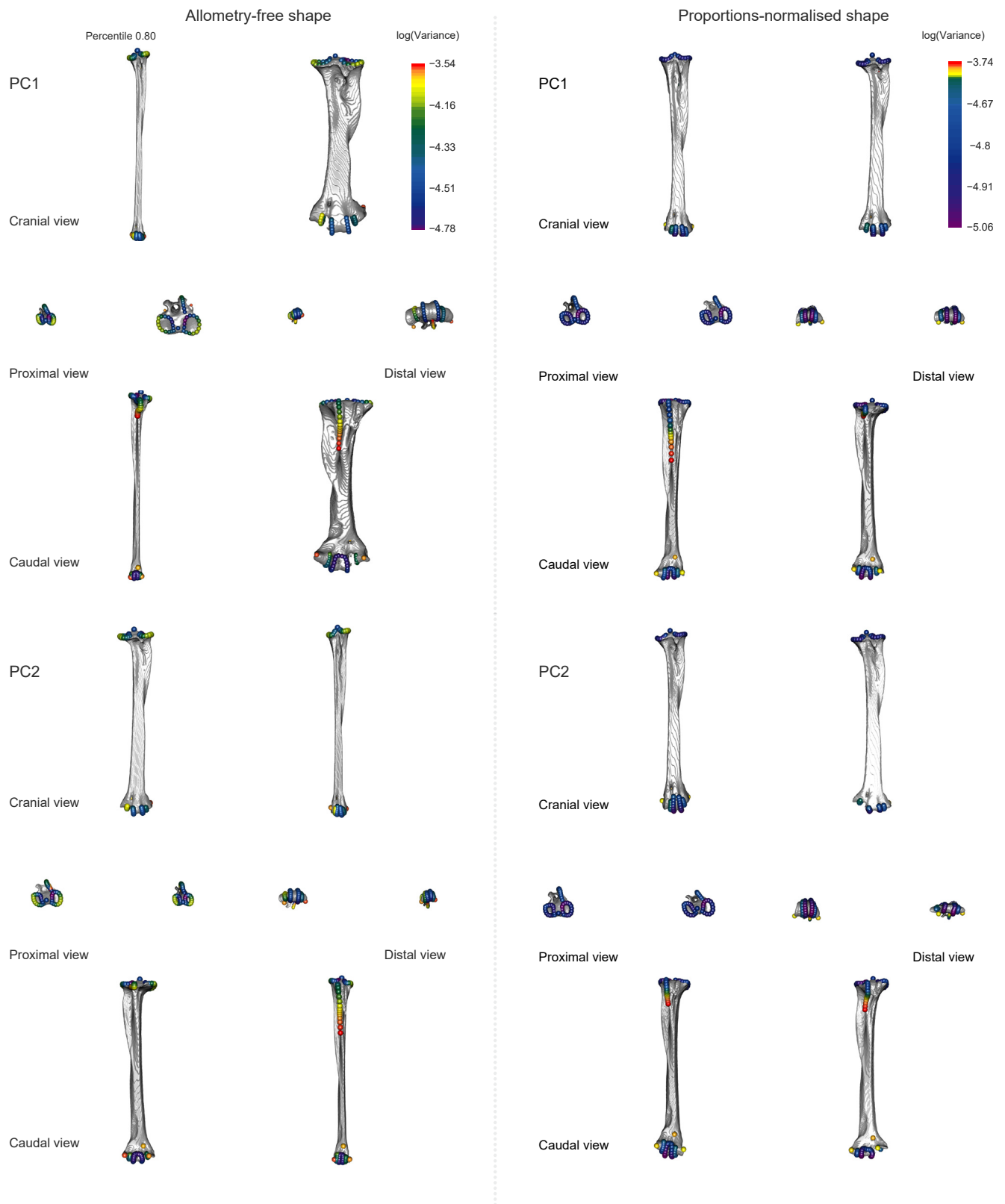
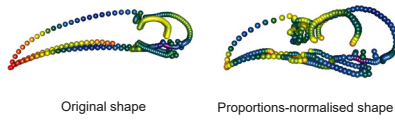
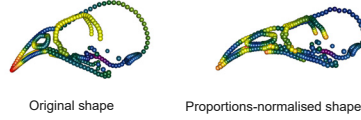


Figure S13. Main shape (size normalized shape; left panel) and local shape variation (proportions normalized shape; right panel) for the tarsometatarsus. Per landmark variances are color coded and placed on top of warped meshes for extreme shapes in each major axis of shape variation. Warped original mesh after the individual closer to mean shape.

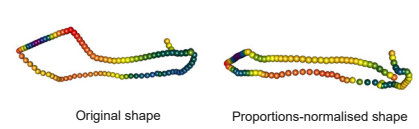
a. *Ramphastos ambiguus* (skull, lateral)



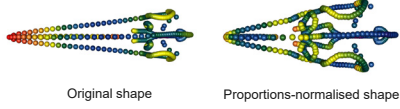
c. *Geospiza fuliginosa* (skull, lateral)



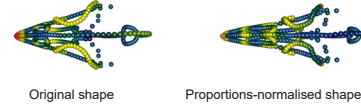
e. *Probosciger aterrimus* (mandible, lateral)



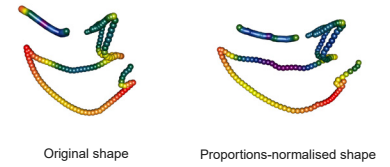
b. *Ramphastos ambiguus* (skull, dorsal)



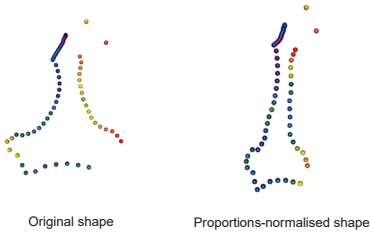
d. *Geospiza fuliginosa* (skull, dorsal)



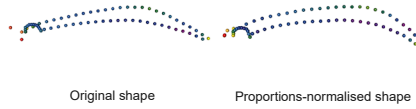
h. *Fregata aquila* (sternum, lateral)



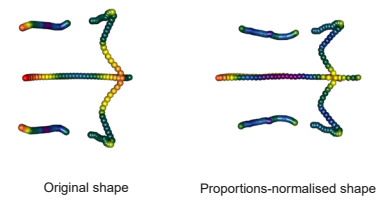
f. *Diomedea irrorata* (right coracoid, cranial)



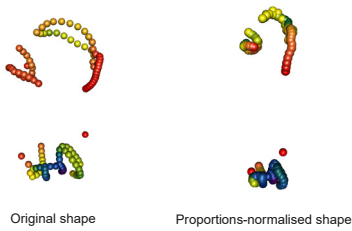
g. *Eremophila alpestris* (left scapula, lateral)



i. *Fregata aquila* (sternum, dorsal)



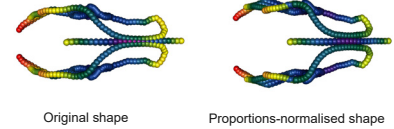
j. *Topaza pyra* (left humerus, cranial)



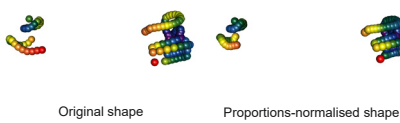
k. *Psaltriparus minimus* (left carpometacarpus, caudal)



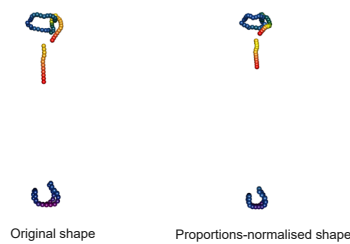
l. *Vultur gryphus* (synsacrum, dorsal)



m. *Phoenicopterus roseus*
(right femur, cranial)



n. *Leipoa ocellata* (right tibiotarsus, lateral)



o. *Spheniscus humboldti*
(tarsometatarsus, cranial)

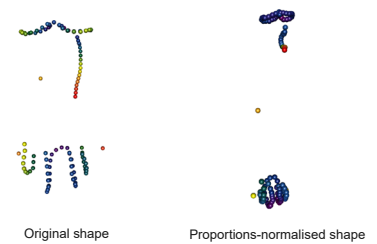


Figure S14. Effects of normalisation for proportions in selected taxa for all 13 skeletal elements.



Neornithes (Regions)

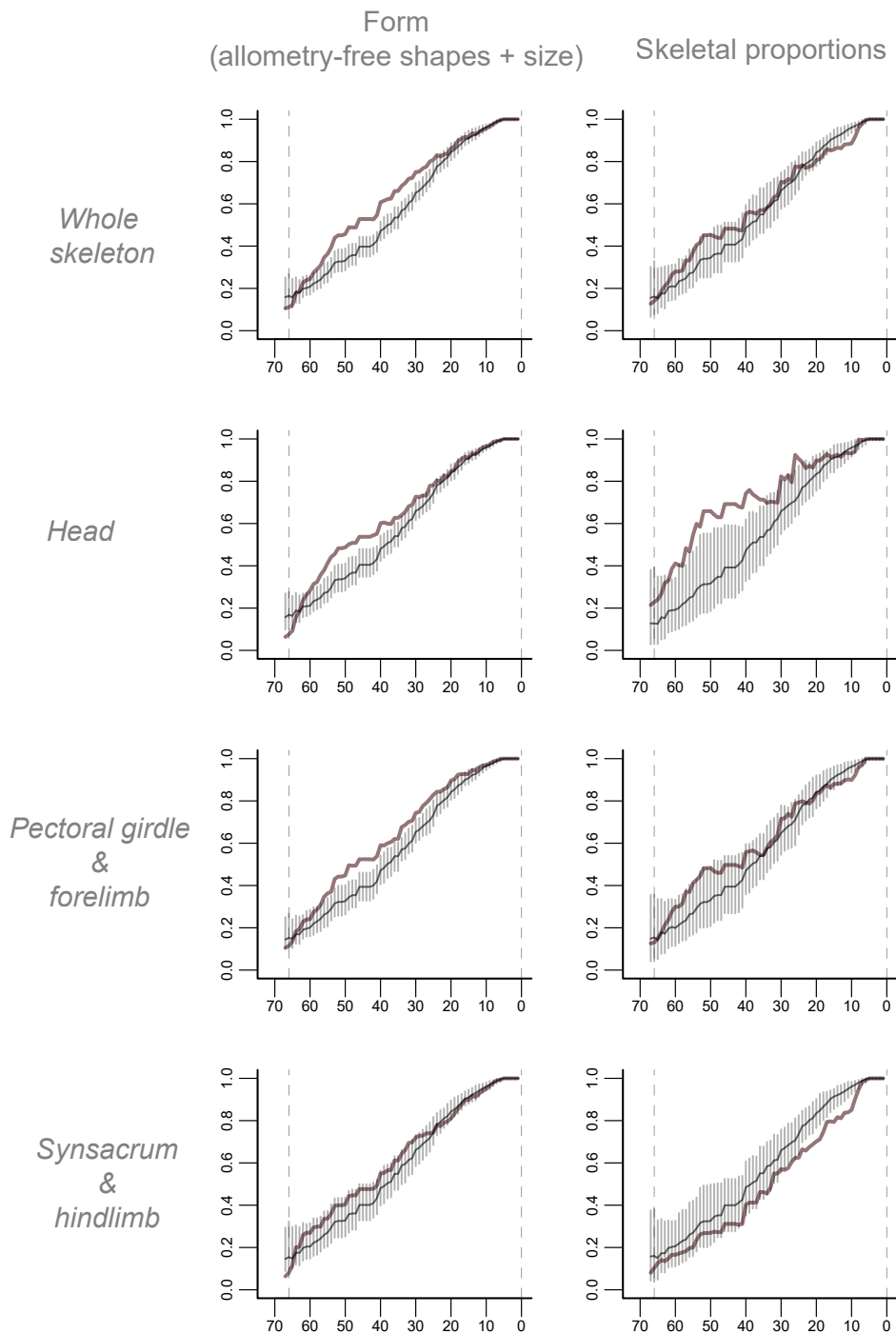


Figure S15. Whole clade disparity-time plots (patterns of morphospace establishment) for the three studied aspects of morphological variation for the whole skeleton and body regions for Neornithes. Empirical 1-million-year time bin disparity values for Neornithes indicated by the brown continuous line. Confidence intervals (grey vertical lines) and mean values (dark grey continuous line) for the 1-million-year time binned disparities for multivariate simulations under a Brownian Motion model of evolution. X axes represent disparity (mean pairwise distance) and Y axes represent time in million years before the present.



Neornithes (Individual bones)

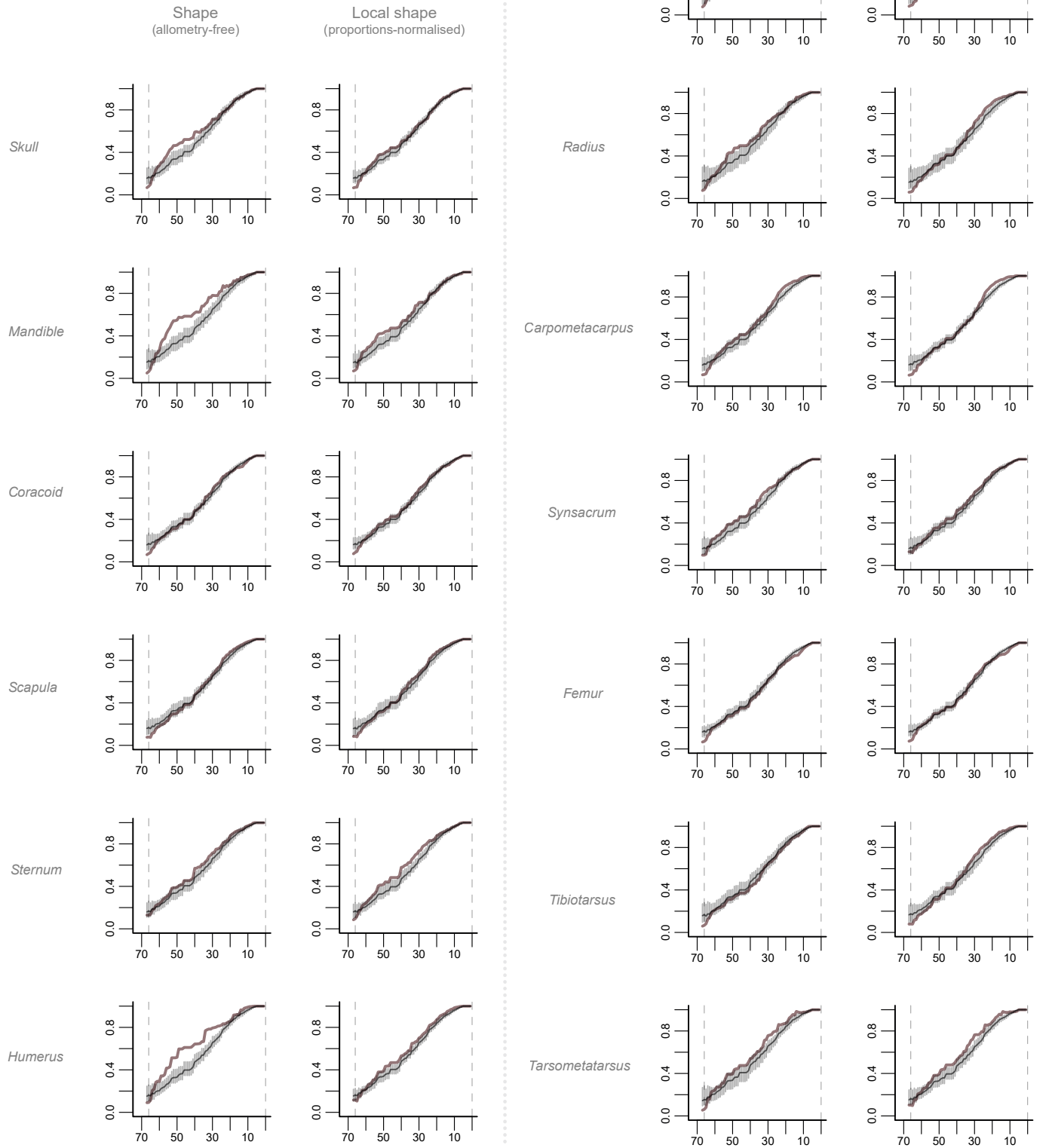


Figure S16. Whole clade disparity-time plots (patterns of morphospace establishment) for the two studied aspects of morphological variation for the individual elements for Neornithes. Legend as in Figure S15.

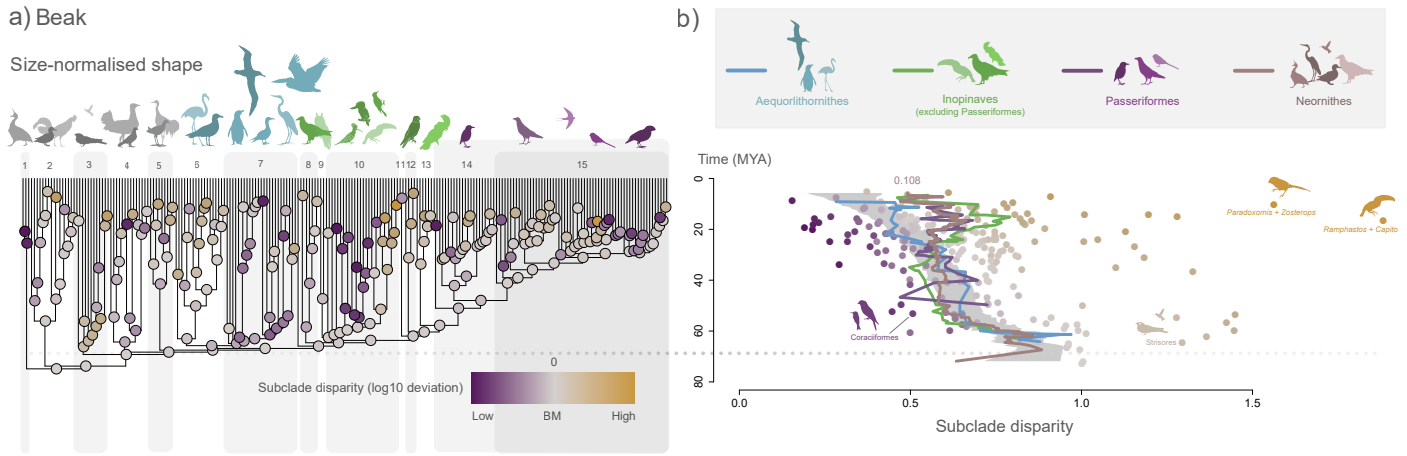


Figure S17. Subclade disparity–age plotted across avian phylogeny and through time for beak shape. a) Subclade disparity values colour-coded and plotted for each of the studied clades in their basal nodes. Subclade disparity values are log-10 transformed deviations of empirical values from means of 200 simulations of morphological evolution under a constant diffusive model of evolution (Brownian Motion, BM). Purples represent lower disparities than expected under BM, ochres represent higher disparities than expected under BM. b) Patterns of mean binned values of disparity through time for all birds (Neornithes) and three target lineages. Grey envelope represents the maximum and minimum values for each bin of the 200 simulations of morphological evolution under BM. Individual colour coded lineage values are plotted and some extreme values are labelled. Time scale in million years apply for both parts of the figure and the dotted horizontal line at 67 MYA indicates the timing of K-Pg extinction. Clades in a) indicated as numbers: 1. Palaeognathae, 2. Galloanserae, 3. Strisores, 4. Columbaves, 5. Gruiformes, 6. Mirandornithes + Charadriiformes, 7. Ardeae, 8. Accipitriformes, 9. Strigiformes, 10. Eucavitaves, 11. Cariamiformes, 12. Falconiformes, 13. Psittaciformes, 14. Suboscines (Passeriformes), 15. Oscines (Passeriformes).

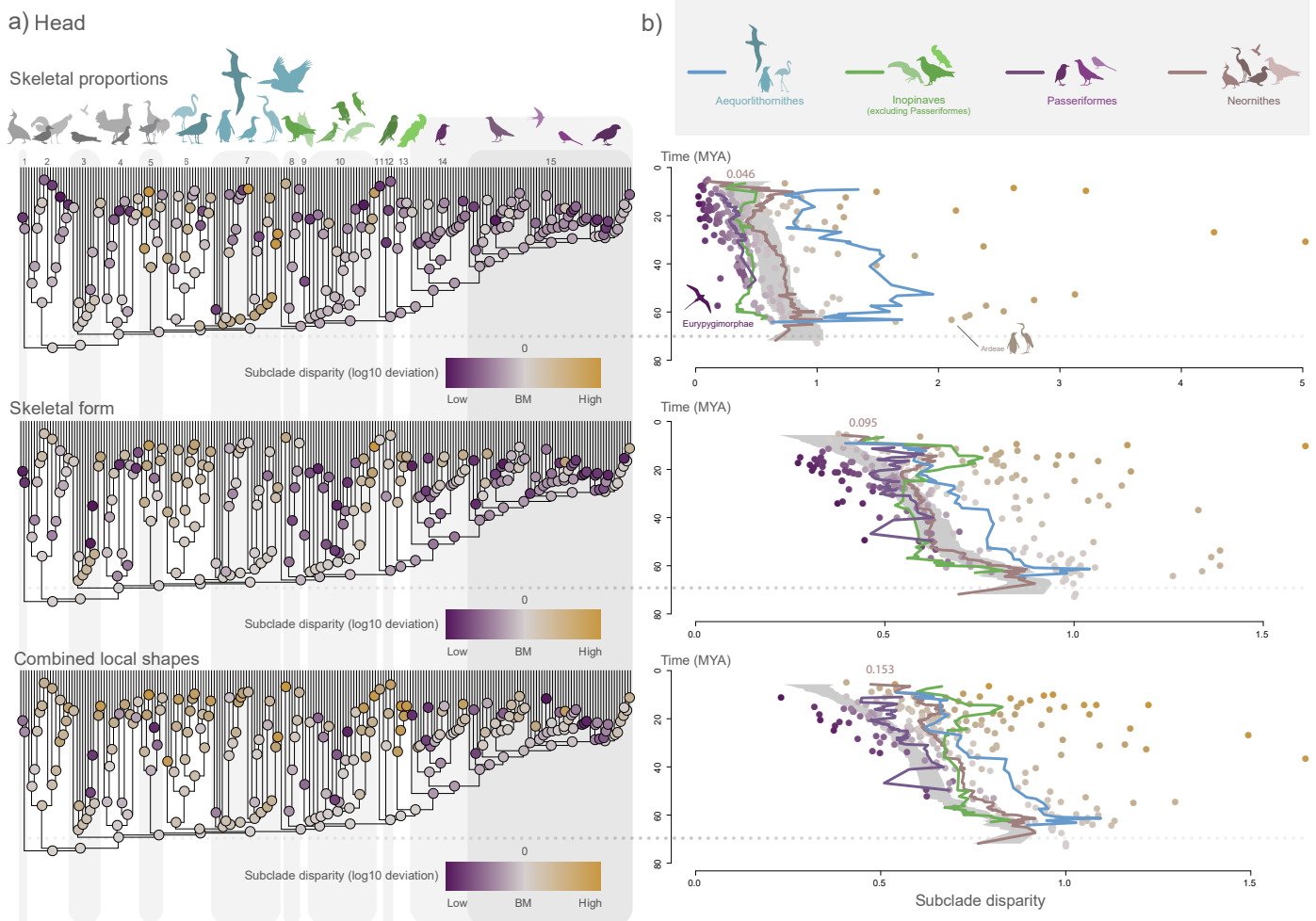


Figure S18. Subclade disparity–age plotted across avian phylogeny and through time for head skeletal proportions, form and combined local shape. Legend as in Figure S15 and Figure 1 in the main text.

a) Pectoral girdle and forelimb

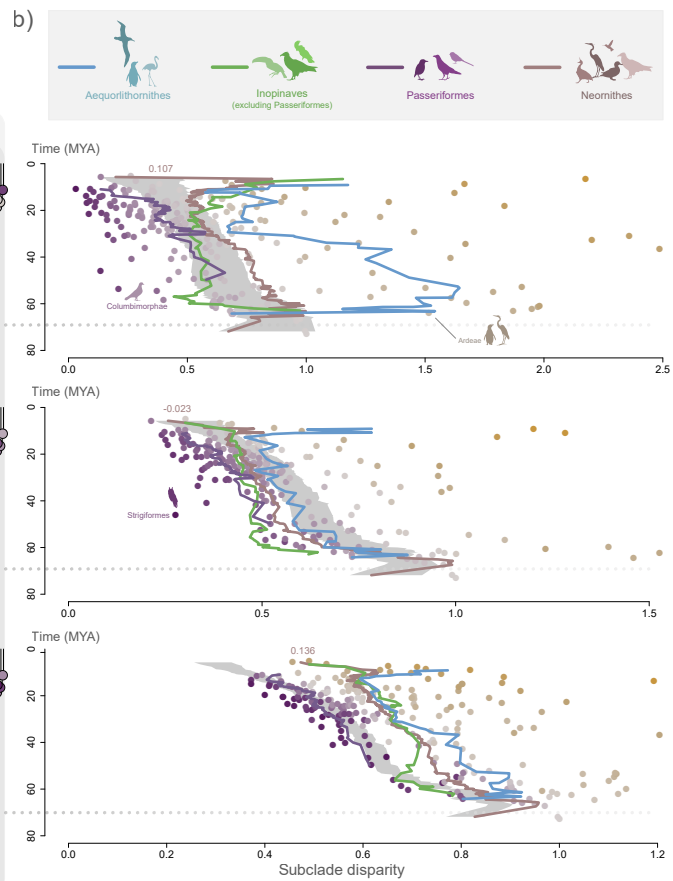
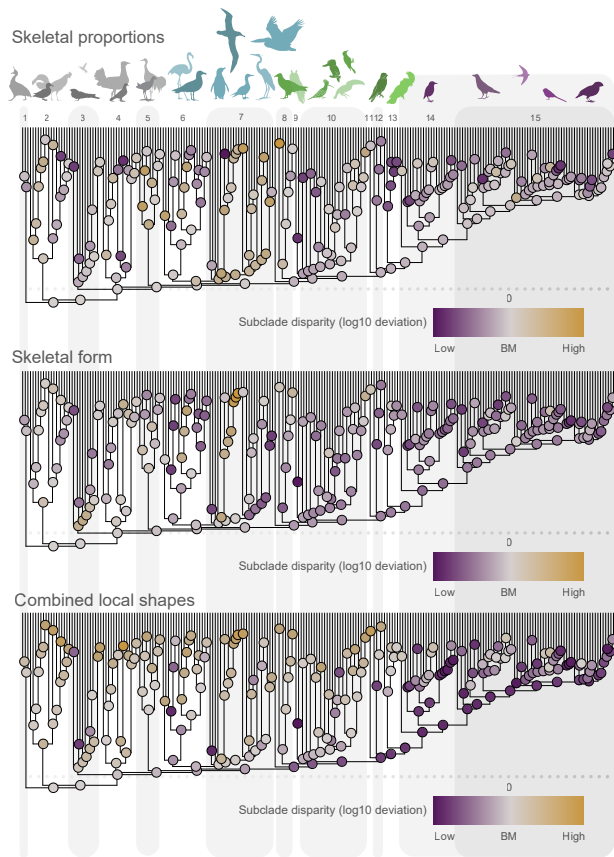


Figure S19. Subclade disparity–age plotted across avian phylogeny and through time for pectoral girdle and forelimb’s skeletal proportions, form and combined local shape. Legend as in Figure S15 and Figure 1 in the main text.

a) Synsacrum and hindlimb

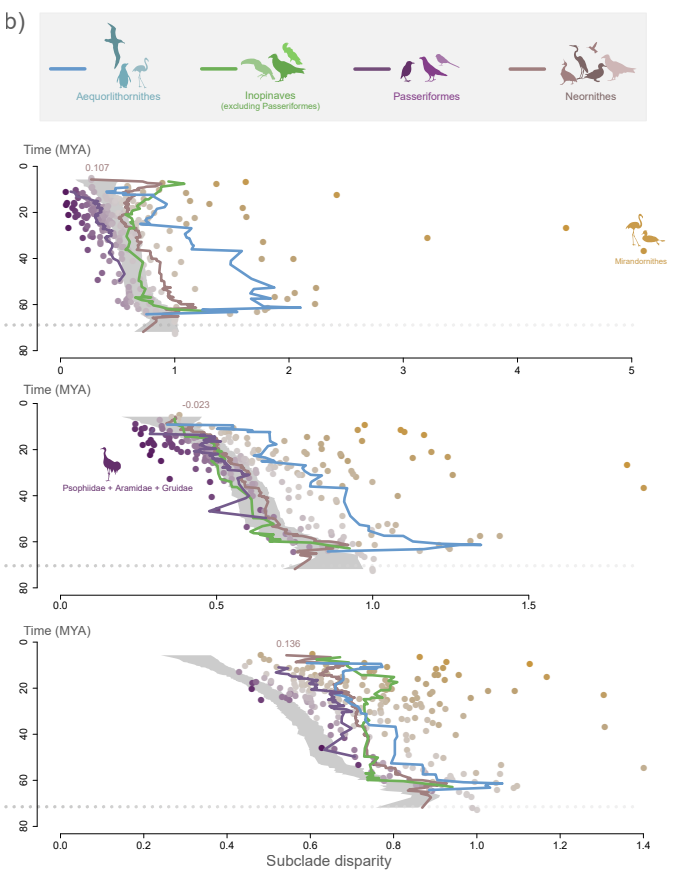
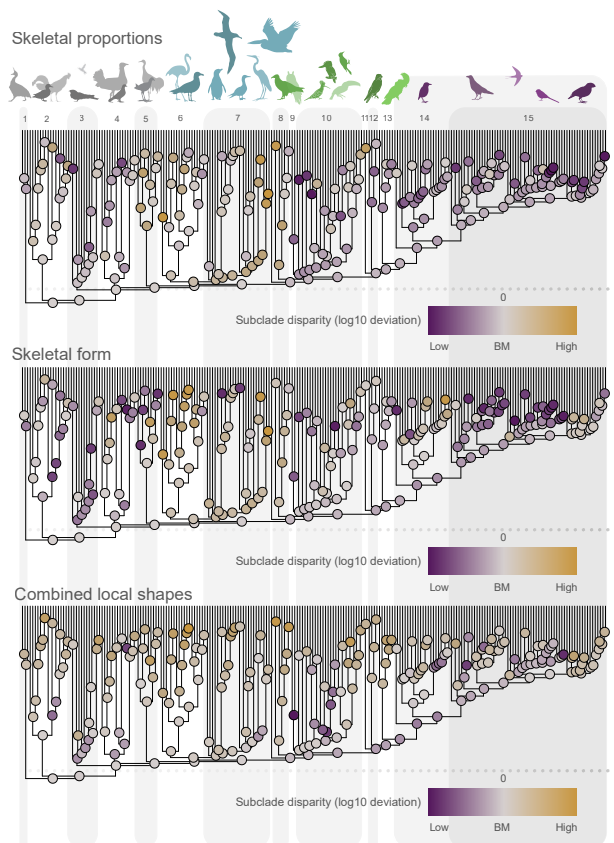
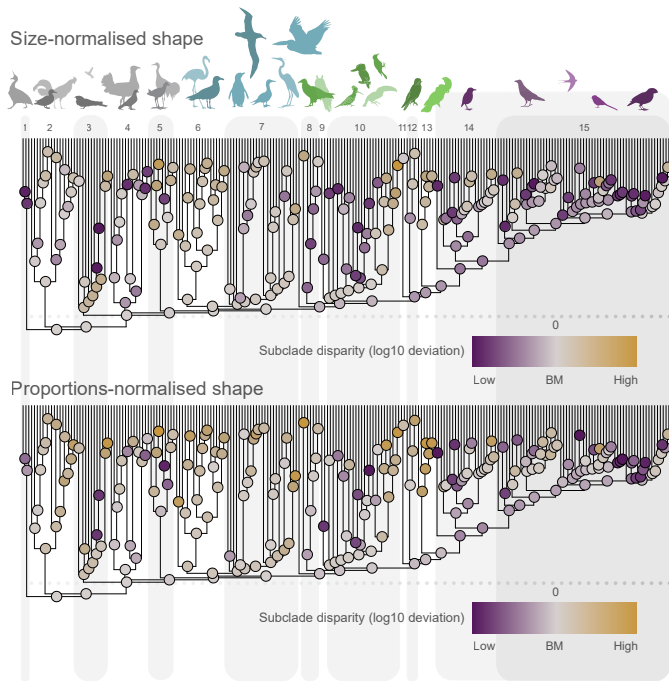


Figure S20. Subclade disparity–age plotted across avian phylogeny and through time for synsacrum and hindlimb’s skeletal proportions, form and combined local shape. Legend as in Figure S15 and Figure 1 in the main text.

a) Skull



b)

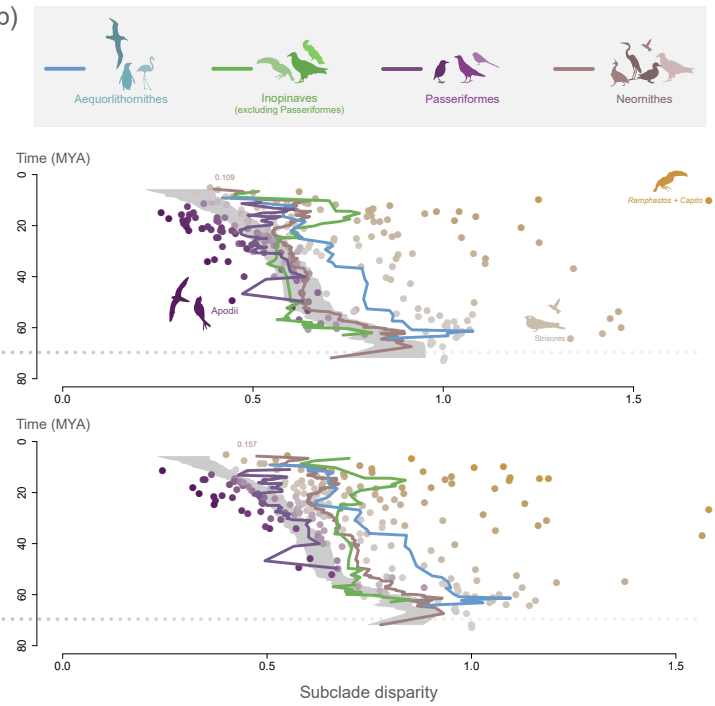
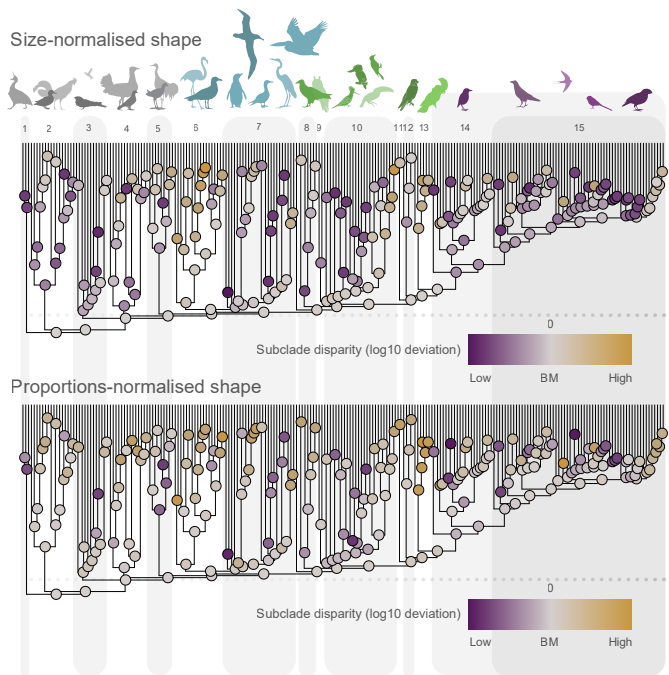


Figure S21. Subclade disparity–age plotted across avian phylogeny and through time for skull shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Mandible



b)

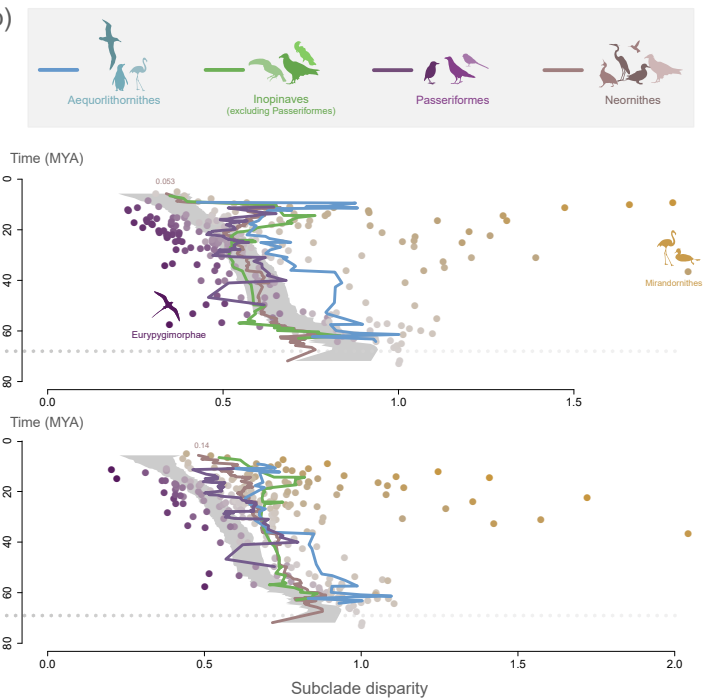
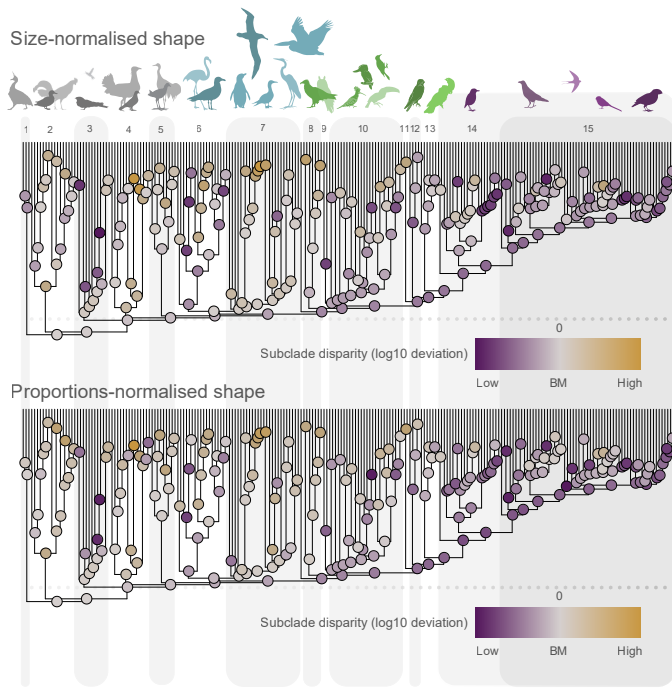


Figure S22. Subclade disparity–age plotted across avian phylogeny and through time for mandible shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Sternum



b)

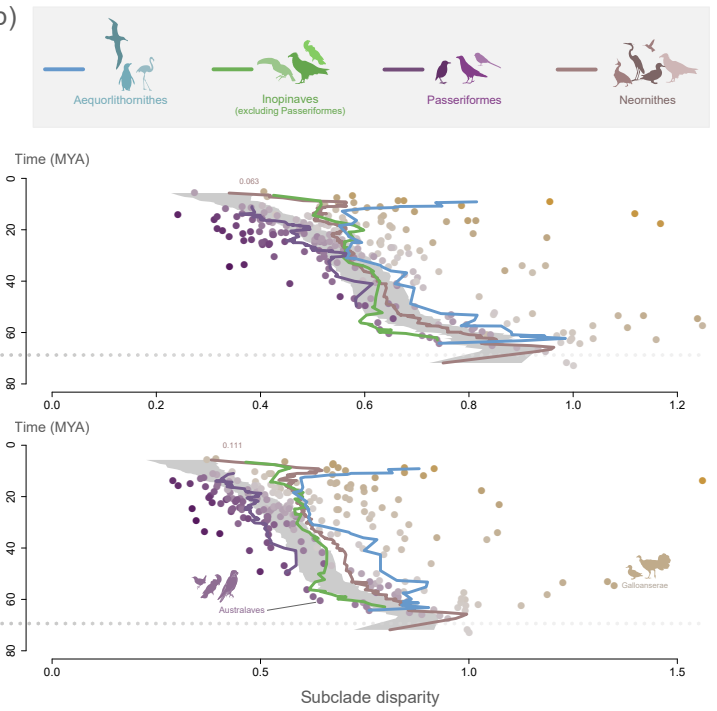
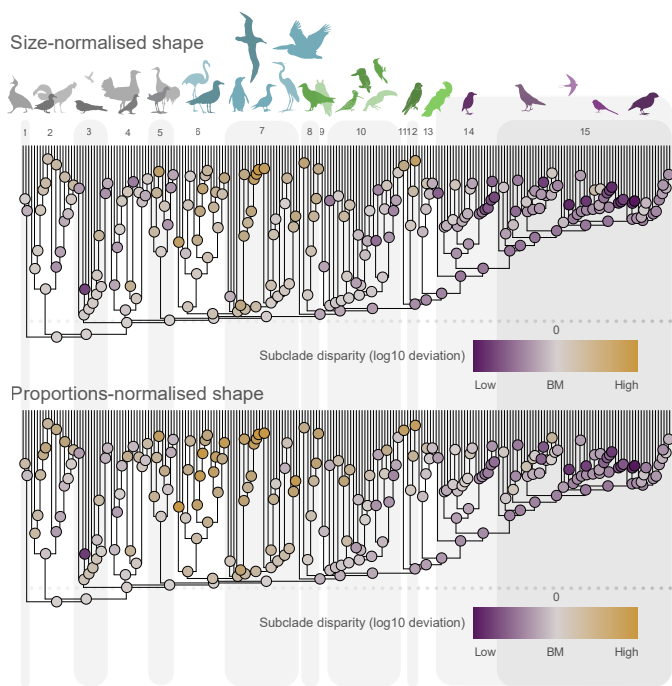


Figure S23. Subclade disparity–age plotted across avian phylogeny and through time for sternum shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Coracoid



b)

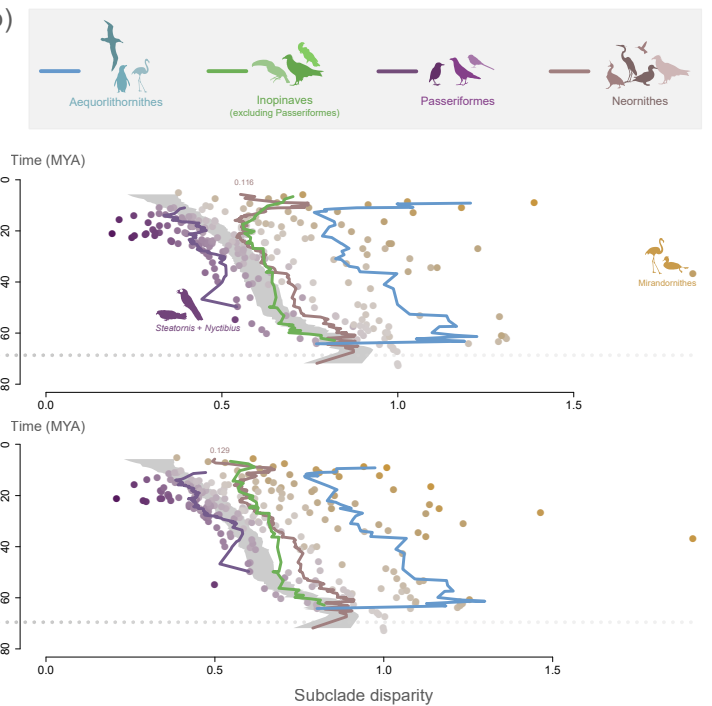
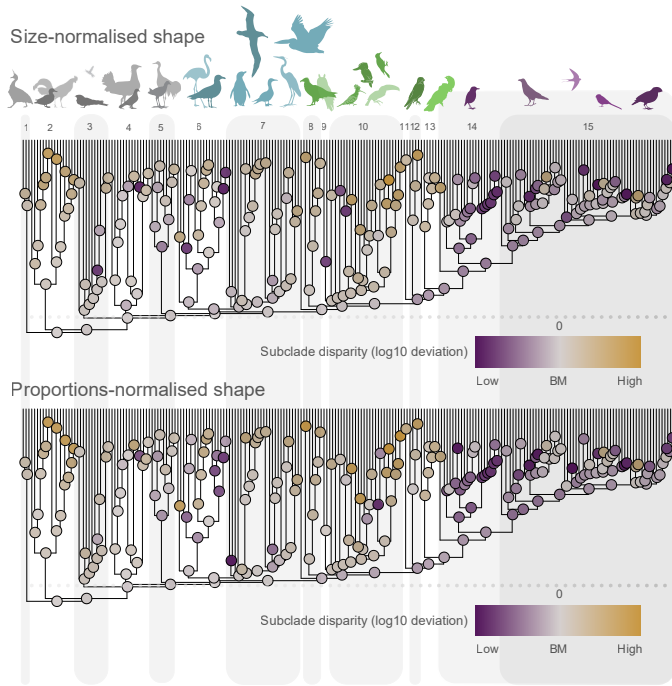


Figure S24. Subclade disparity–age plotted across avian phylogeny and through time for coracoid shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Scapula



b)

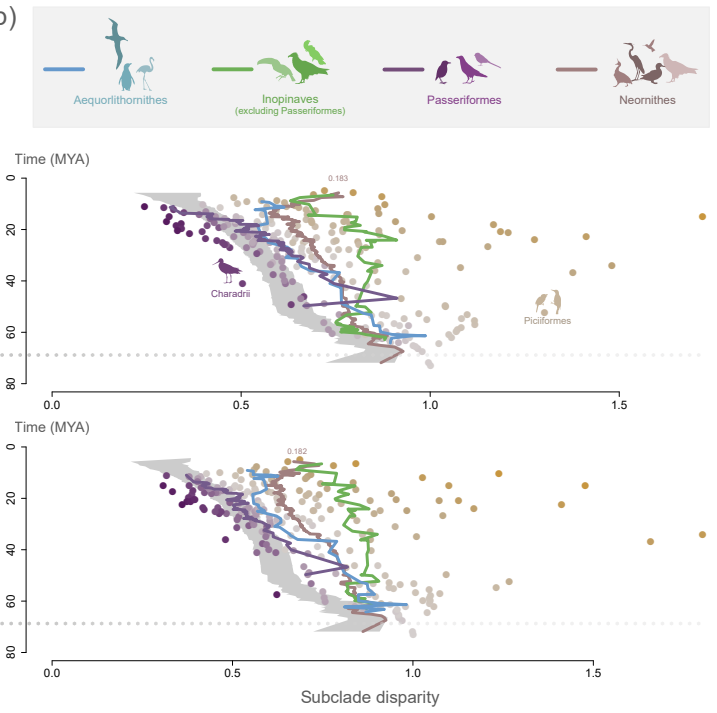
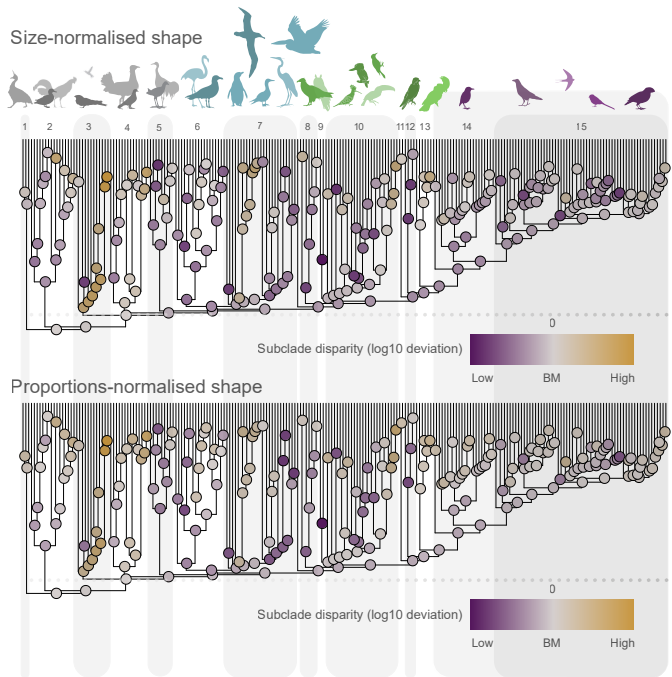


Figure S25. Subclade disparity–age plotted across avian phylogeny and through time for scapula shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Humerus



b)

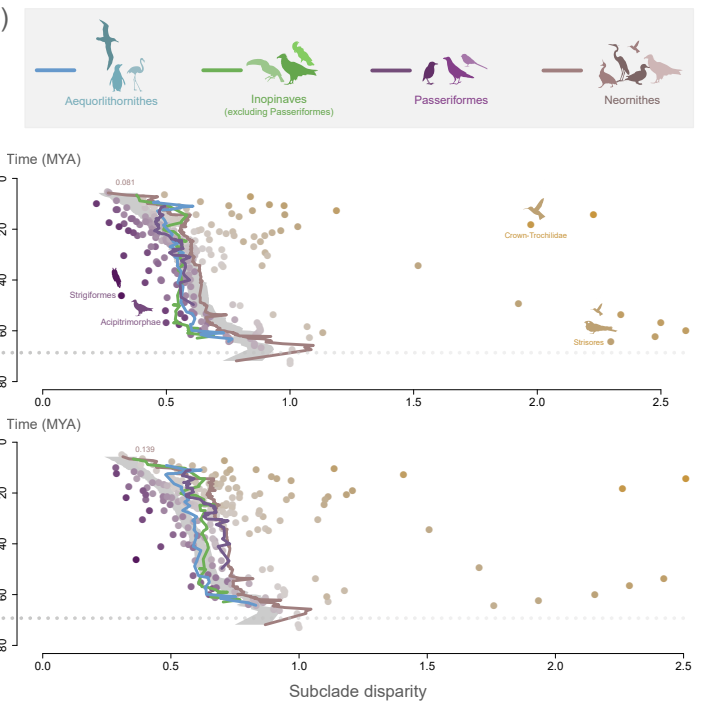
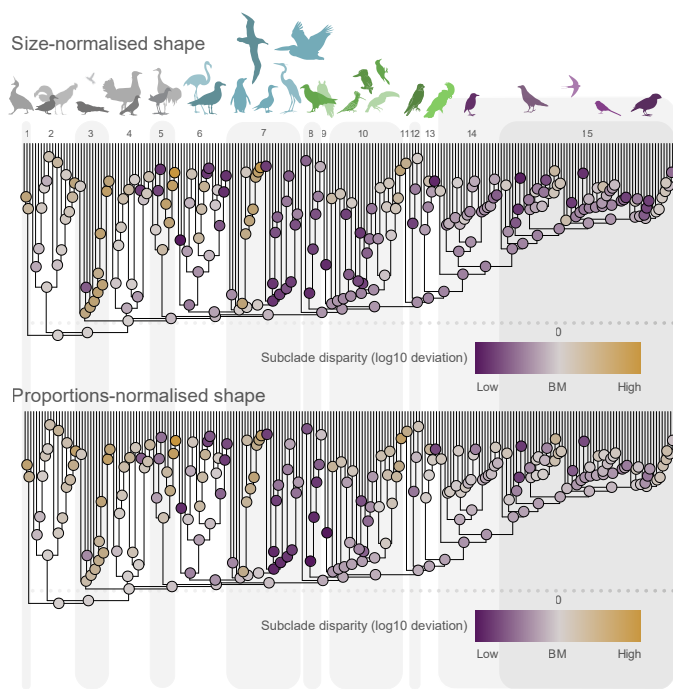


Figure S26. Subclade disparity–age plotted across avian phylogeny and through time for humerus shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Ulna



b)

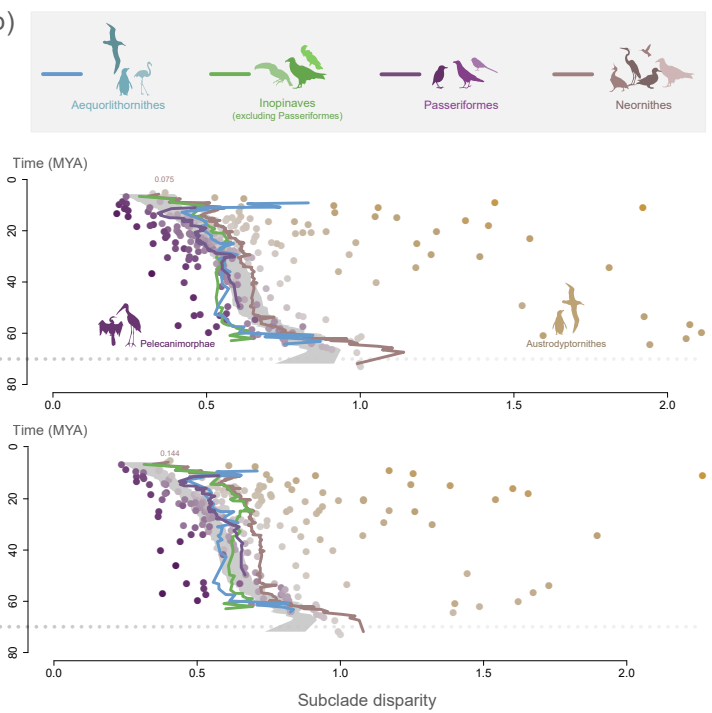
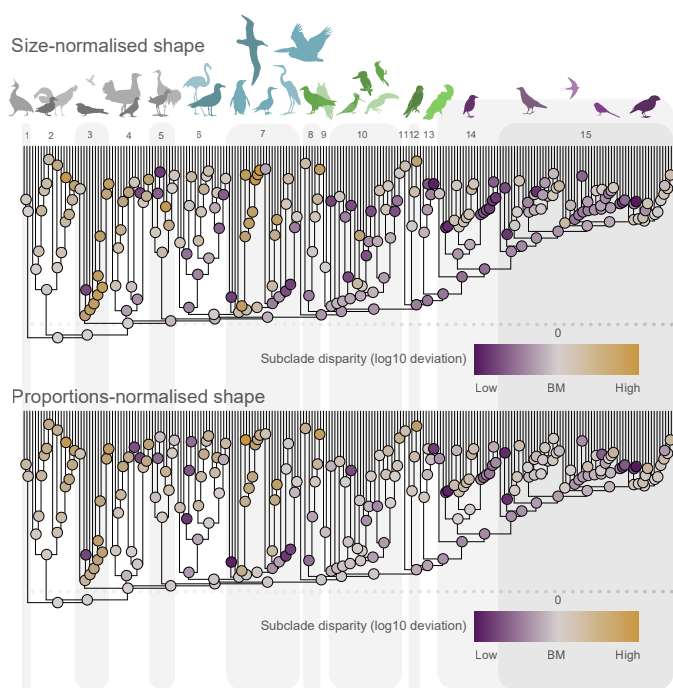


Figure S27. Subclade disparity–age plotted across avian phylogeny and through time for ulna shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Radius



b)

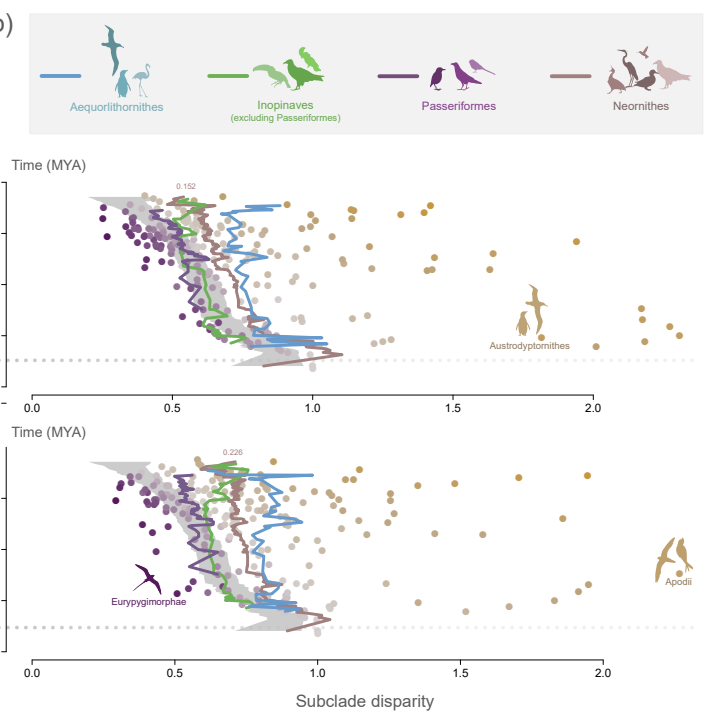


Figure S28. Subclade disparity–age plotted across avian phylogeny and through time for radius shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Carpometacarpus

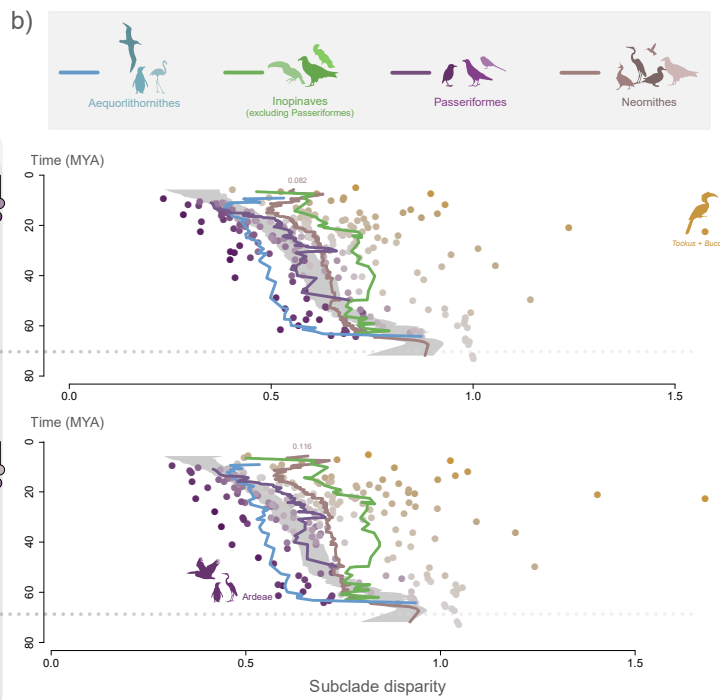
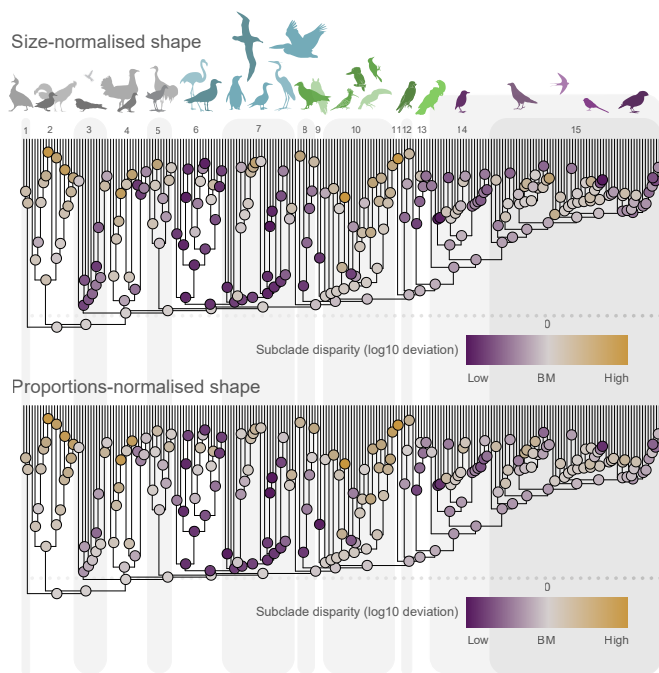


Figure S29. Subclade disparity–age plotted across avian phylogeny and through time for carpometacarpus shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Symsacrum

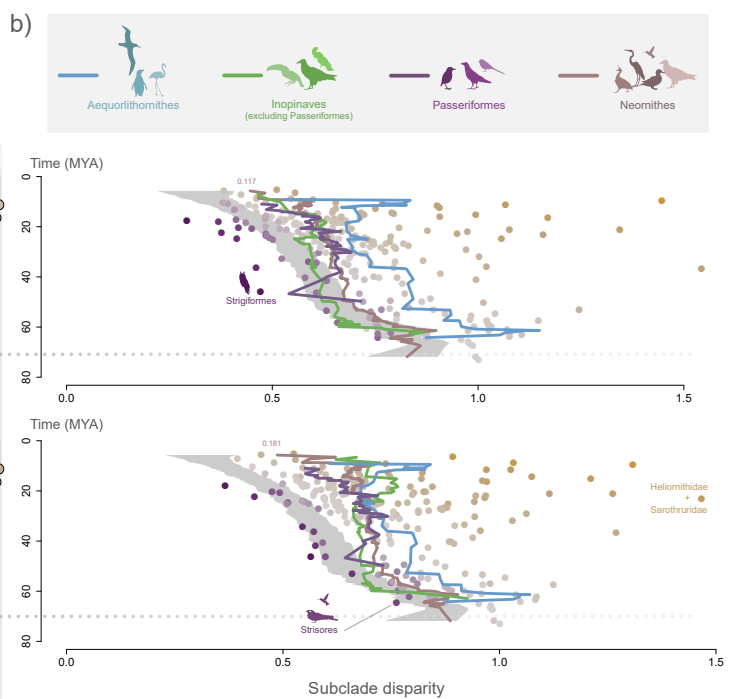
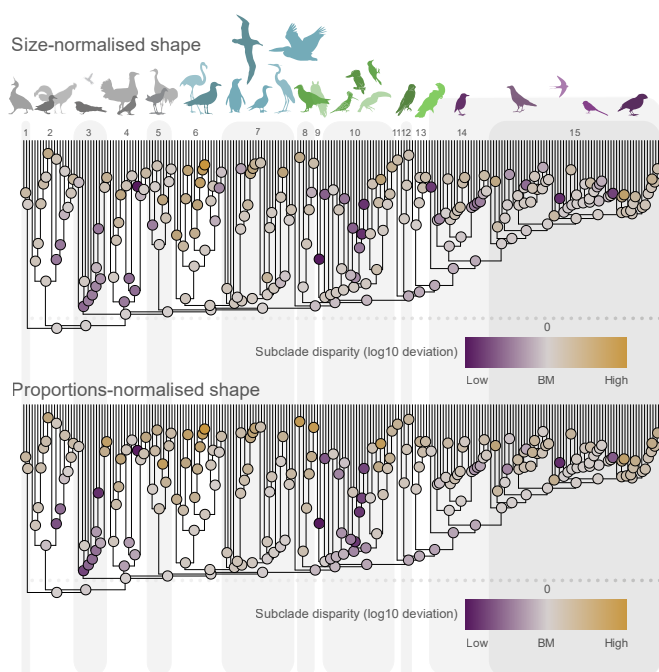


Figure S30. Subclade disparity–age plotted across avian phylogeny and through time for symsacrum shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Femur

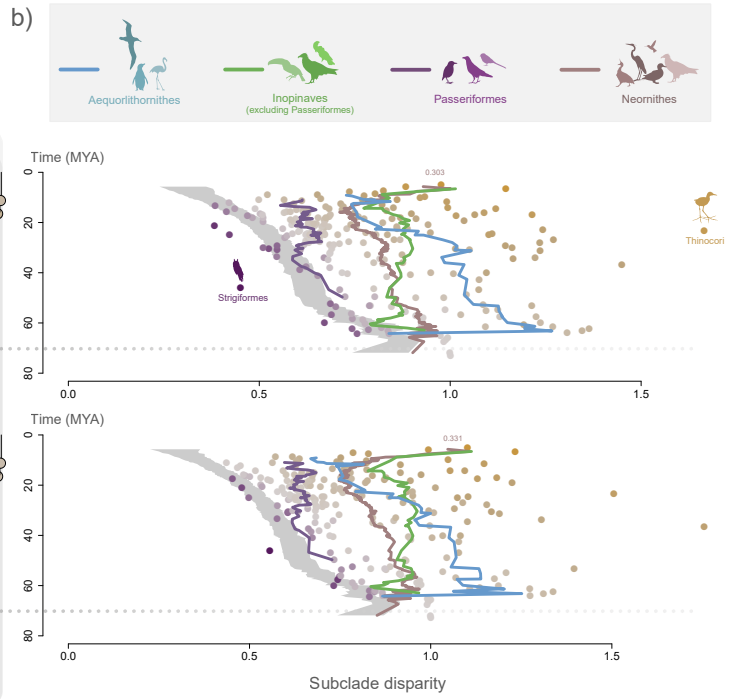
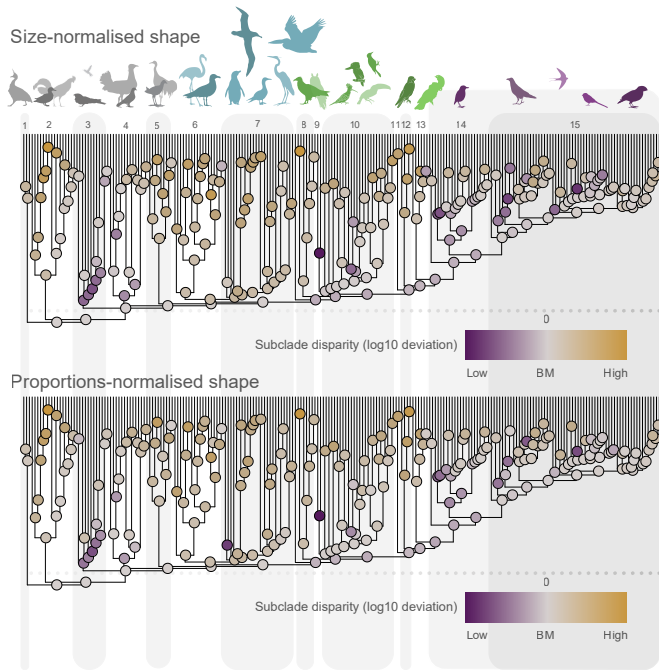


Figure S31. Subclade disparity–age plotted across avian phylogeny and through time for femur shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Tibiotarsus

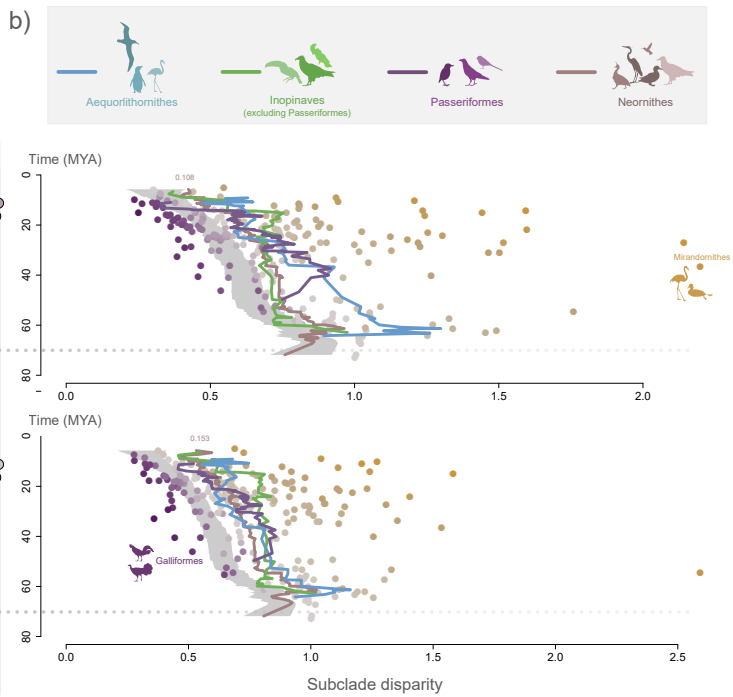
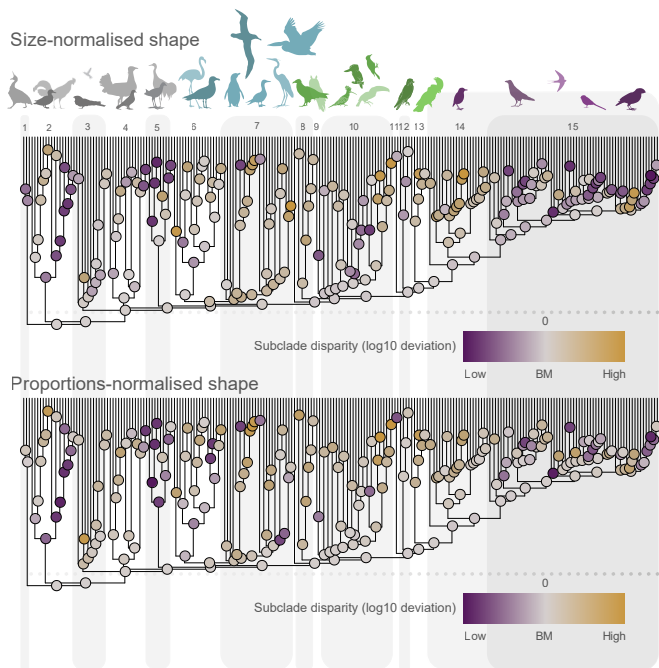


Figure S32. Subclade disparity–age plotted across avian phylogeny and through time for tibiotarsus shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Tarsometatarsus

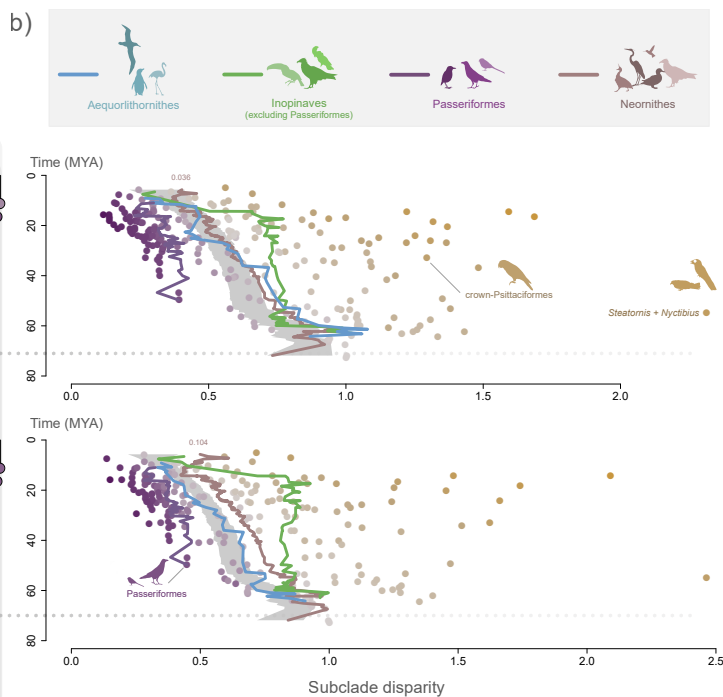
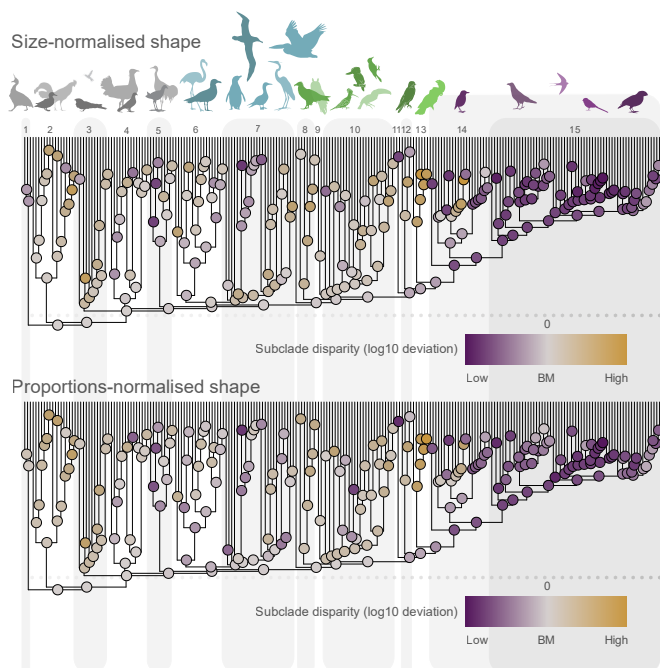


Figure S33. Subclade disparity–age plotted across avian phylogeny and through time for tarsometatarsus shape (size-normalised shape) and local shape (proportions-normalised shape). Legend as in Figure S15 and Figure 1 in the main text.

a) Whole skeleton

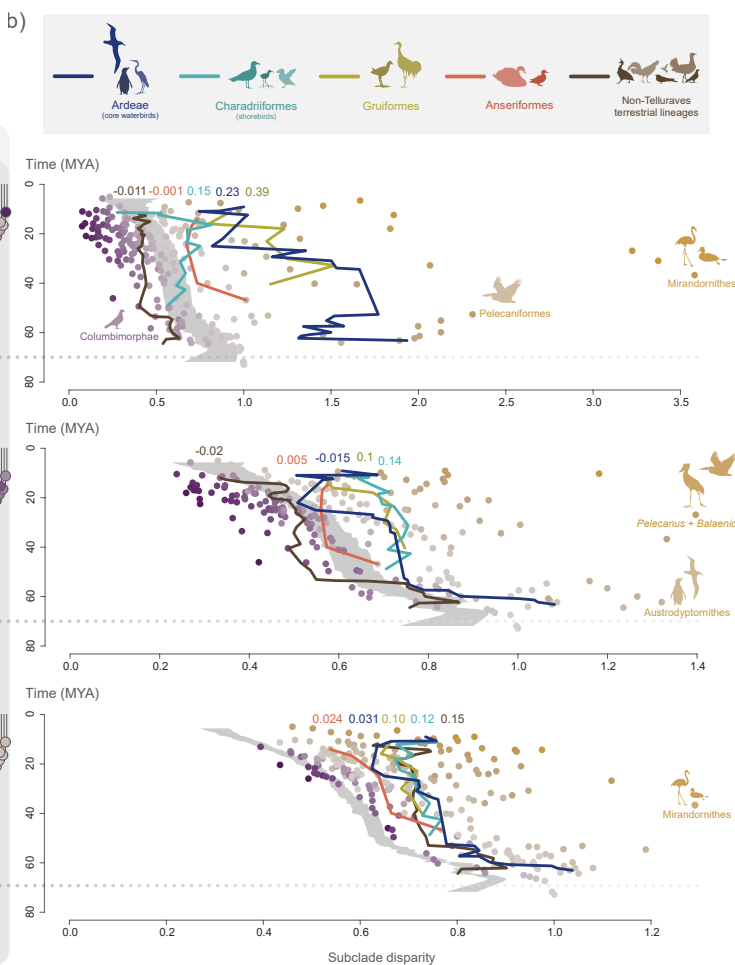
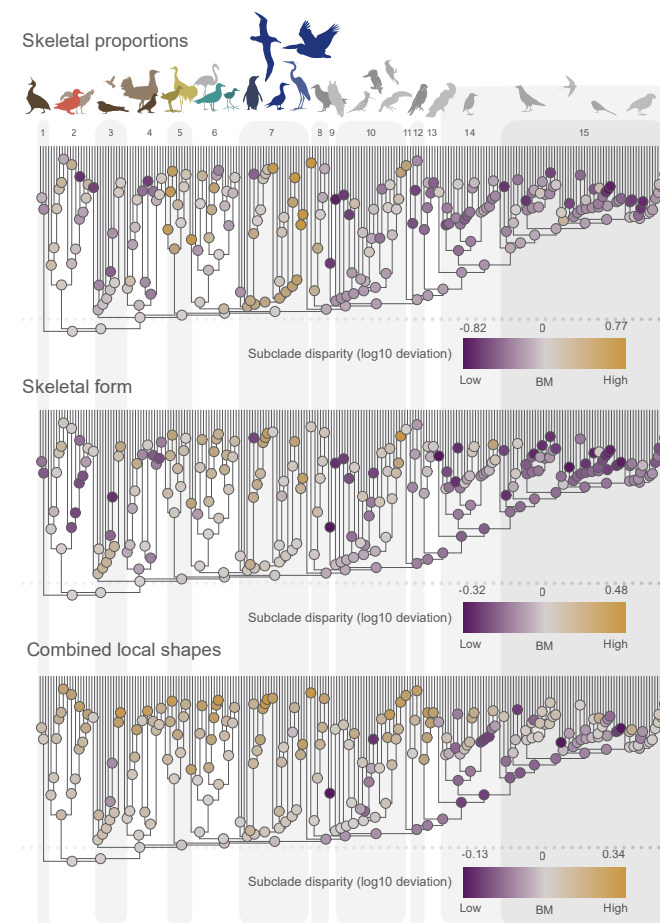


Figure S34. Whole skeletal subclade disparity–age plotted across avian phylogeny and through time (additional water-linked and terrestrial groups).

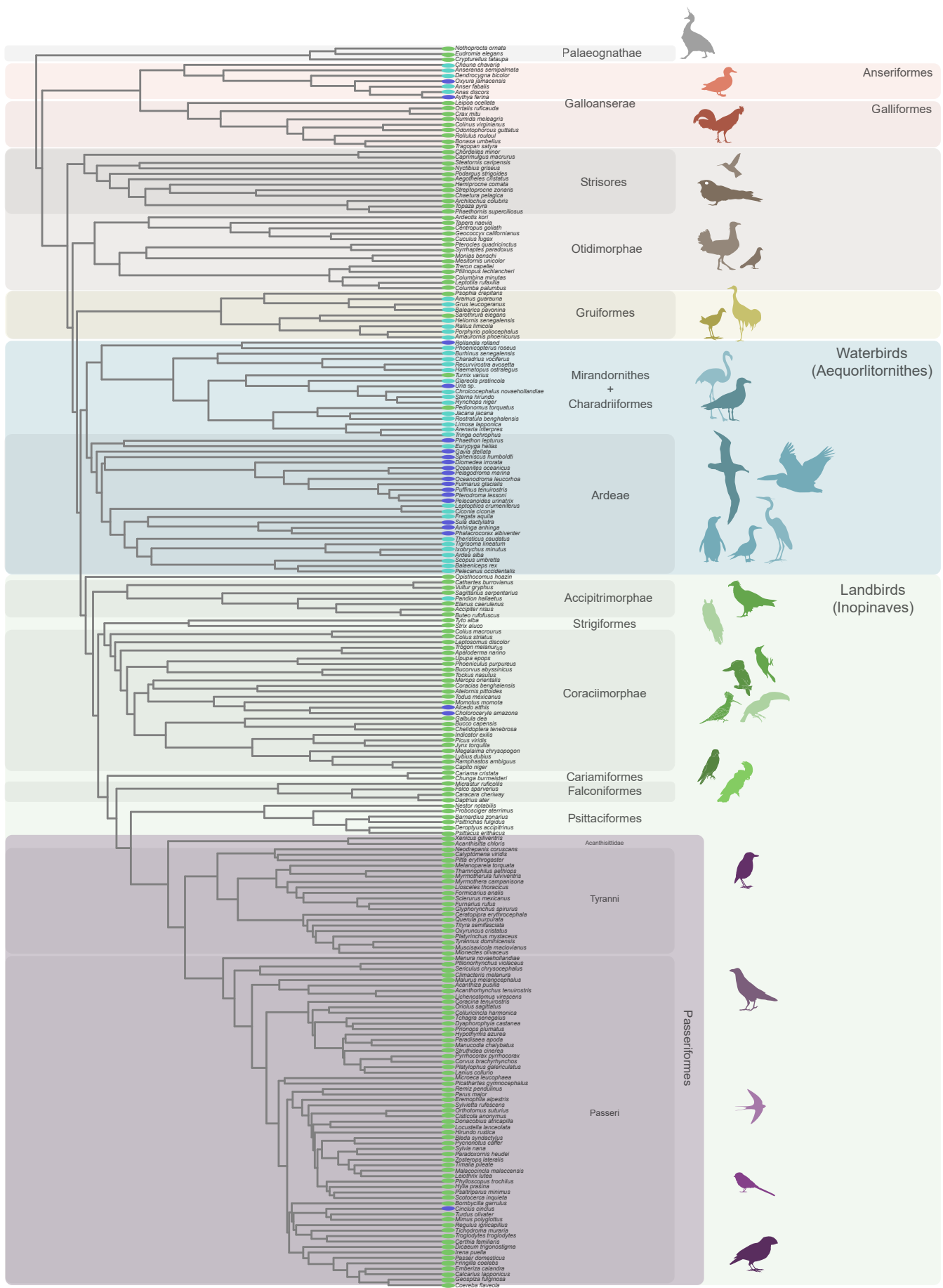


Figure S36. Phylogeny of Neornithes and phylogenetic distribution of water versus non-water linked autecologies in neornithines (finer partitioning of water-linked ecologies). Composite phylogenetic framework combining recent phylogenetic hypotheses for non-passerines¹ and passerines². Subdivision among water-linked ecologies follows³.

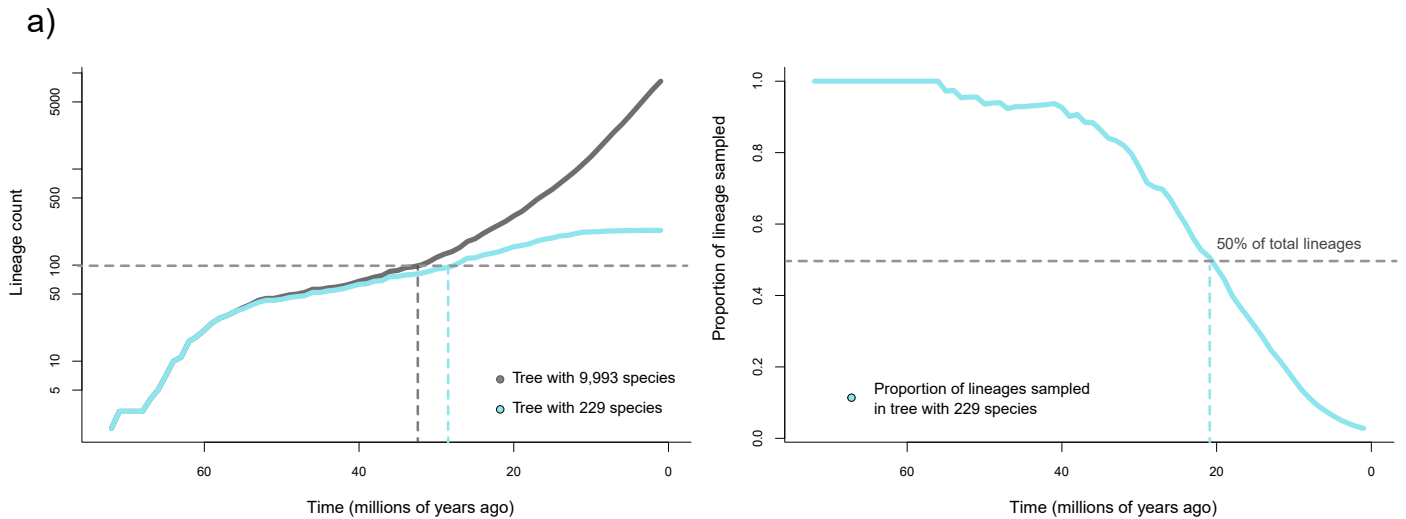


Figure S37. Proportional sampling of lineages of the tree used in this study compared with the total living bird diversity across time. Count of lineages through time for the total supertree from⁴ with backbone from¹ (black line) as compared with the phylogenetic subset used in this study (blue line). Horizontal dashed line indicates 100 lineages, achieved at slightly different times for both subsets (vertical dashed lines). Proportion of total lineages sampled in the subset tree used in this study. The proportion drops below 50% only at around 20 million years while before 40 million years the proportion is higher than 80%. This indicates our phylogenetic subsample effectively captures most deep divergences in avian diversity.

References

- 1 Prum, R. O. *et al.* A comprehensive phylogeny of birds (Aves) using targeted next-generation DNA sequencing. *Nature* (2015).
- 2 Oliveros, C. H. *et al.* Earth history and the passerine superradiation. *Proceedings of the National Academy of Sciences* **116**, 7916-7925 (2019).
- 3 Fabbri, M. *et al.* Subaqueous foraging among carnivorous dinosaurs. *Nature* **603**, 852-857 (2022).
- 4 Jetz, W., Thomas, G., Joy, J., Hartmann, K. & Mooers, A. The global diversity of birds in space and time. *Nature* **491**, 444-448 (2012).