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Reporting Summary

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Statistical parameters

When statistical analyses are reported, confirm that the following items are present in the relevant location (e.g. figure legend, table legend, main text, or Methods section).

n/a	Confirmed
☐	☒ The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒ An indication of whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐ The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐ A description of all covariates tested
☒	☐ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒ A full description of the statistics including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐ For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐ Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated
☒	☐ Clearly defined error bars *State explicitly what error bars represent (e.g. SD, SE, CI)*

Our web collection on statistics for biologists may be useful.

Software and code

Policy information about availability of computer code

Data collection	LM: Lumenera Infinity Analyze, version 6.4.1 software (for imaging) FEG-SEM: Zeiss SmartSEM v05.04.05.00 and (EDX) Aztec version 3.3, Oxford Instrument Nanotechnology Tools Limited TEM: TEM Centre for JEM1400 Plus software (for imaging) ToF-SIMS: SurfaceLab, version 6.7 (IONTOF GmbH, Münster, Germany) Py-GC/MS: Varian MS Workstation, version 6.8 (Varian Inc., Palo Alto, USA) IHC: image data collected using the Axiovision software package (version 4.7.0.0) IR microspectroscopy: Bruker OPUS 7.5 (Bruker, Ettlingen, Germany), Agilent Resolutions Pro 5.3.0.1694 (Agilent Technologies Inc.) NanoSIMS: NS50L version 4.4 on Windows 7 64 bit platform
Data analysis	FEG-SEM/EDX: Aztec version 3.3, Oxford Instrument Nanotechnology Tools Limited ToF-SIMS: SurfaceLab, version 6.7 (IONTOF GmbH, Münster, Germany) Py-GC/MS: Varian MS Data Review, version 6.8 (Varian Inc., Palo Alto, USA) NanoSIMS: ImageJ software, using the OpenMIMS plugin (for image processing) IR microspectroscopy: Bruker OPUS 7.5 (Bruker, Ettlingen, Germany), Agilent Resolutions Pro 5.3.0.1694 (Agilent Technologies Inc.) SRXTM: Voxler 2 and 3 SRS-XRF: MicroAnalysis Toolkit (www.sams-xrays.com/smak)

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers upon request. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

The specimen of this study (MH 432) is accessioned in the collections at Urweltmuseum Hauff, Holzmaden, Germany. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Field-specific reporting

Please select the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences

For a reference copy of the document with all sections, see nature.com/authors/policies/ReportingSummary-flat.pdf

Life sciences

Study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	We provide an ultrastructural and biochemical investigation of a single fossil specimen: MH 432 (Stenopterygius).
Data exclusions	No data were excluded from the analyses.
Replication	As described in our 'Methods' section (notably in the new 'Statistics and reproducibility' paragraph) and 'Supplementary Information', almost all of our experiments (including LM, FEG-SEM, EDX, TEM, IHC, SRXTM, IR microspectroscopy, NanoSIMS, ToF-SIMS, Py-GC/MS, AHPO, and AAA) were replicated (often multiple times) with similar results. Those experiments that were not repeated include SRS-XRF and UV imaging of MH 432, the artificial maturation of the extant Phocoena integument, and TEM of bacteria.
Randomization	Not relevant to this study. We have a limited number of unique samples (from a single specimen) and corresponding control experiments.
Blinding	Not relevant to this study. We have a limited number of unique samples (from a single specimen) and corresponding control experiments.

Materials & experimental systems

Policy information about availability of materials

n/a	Involved in the study
☒	☐ Unique materials
☐	☒ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Research animals
☒	☐ Human research participants

Antibodies

Antibodies used	G-30 anti-alpha keratin, courtesy of R. Sawyer; anti-bovine elastin, courtesy of R. Mecham; anti-alligator HB, Biosynthesis BSYN6941; anti-ostrich HB, GenScript 70594-1; anti-beta-keratin, Biosynthesis BSYN6734; anti-alligator collagen, Biosynthesis BSYN6959; anti-tropomyosin, Abcam ab11190; anti-chicken actin, Capralogics Inc. P00851; anti-chicken collagen, USBiological C7510-13B; anti-peptidoglycan monoclonal, ABD Serotec 7263-1006; 18 nm Colloidal Gold AffiniPure Donkey Anti-Goat IgG, Jackson Immuno Research Inc. Cat.# 705-215-147; Biotinylated Goat Anti-Rabbit IgG, Vector BA-1000; Biotinylated Rabbit Anti-Sheep IgG, Vector BA-6000; Biotinylated Goat Anti-Mouse IgG, Vector BA-9200
Validation	G-30 anti-alpha-keratin—polyclonal, ag=chicken alpha-keratin, host: goat. Alibardi, L. & DeNardo, D. F. Ultrastructural and immunocytochemical features of the epidermis of the lizard Heloderma suspectum indicate richness in lipids and lack of a specialized shedding complex, Acta Zool. 94, 35–43 (2013). anti-bovine elastin—polyclonal, ag=bovine elastin, host: rabbit. Cleland, T. P. et al. Mass spectrometry and antibody-based characterization of blood vessels from Brachylophosaurus canadensis. J. Prot. Res. 14, 5252–5262 (2015). Schweitzer, M. H.,

Moyer, A. E. & Zheng, W. Testing the hypothesis of biofilm as a source for soft tissue and cell-like structures preserved in dinosaur bone. PLoS ONE 11, e0150238 (2016).

anti-alligator HB—polyclonal, ag=alligator hemoglobin, host: rabbit. Lindgren, J. et al. Biochemistry and adaptive colouration of an exceptionally preserved juvenile fossil sea turtle. Sci. Rep. 7, 13324 (2017).

anti-ostrich HB—polyclonal, ag=ostrich hemoglobin, host: rabbit. Schweitzer, M. H., Moyer, A. E. & Zheng, W. Testing the hypothesis of biofilm as a source for soft tissue and cell-like structures preserved in dinosaur bone. PLoS ONE 11, e0150238 (2016). Lindgren, J. et al. Biochemistry and adaptive colouration of an exceptionally preserved juvenile fossil sea turtle. Sci. Rep. 7, 13324 (2017).

anti-beta-keratin—polyclonal, ag=white chicken feathers, host: rabbit. Moyer, A.E., Zheng, W. & Schweitzer, M. H. Keratin durability has implications for the fossil record: results from a 10 year feather degradation experiment. PLoS ONE 11, e0157699 (2016). Moyer, A. E., Zheng, W. & Schweitzer, M. H. Microscopic and immunohistochemical analyses of the claw of the nesting dinosaur, Citipati osmolskae. Proc. R. Soc. B 283, 20161997 (2016). Pan, Y. H. et al. Molecular evidence of keratin and melanosomes in feathers of the early cretaceous bird Eoconfuciusornis. Proc. Natl. Acad. Sci. 113, E7900-E7907 (2016). Lindgren, J. et al. Biochemistry and adaptive colouration of an exceptionally preserved juvenile fossil sea turtle. Sci. Rep. 7, 13324 (2017).

anti-alligator collagen—polyclonal, ag=alligator skin collagen, host: rabbit. Moyer, A. E., Zheng, W. & Schweitzer, M. H. Microscopic and immunohistochemical analyses of the claw of the nesting dinosaur, Citipati osmolskae. Proc. R. Soc. B 283, 20161997 (2016).

anti-tropomyosin—ab11190: chicken tropomyosin polyclonal, host: rabbit; WB (1:100), ICC/IF (1:40). Goins, L. M. & Mullins, R. D. A novel tropomyosin isoform functions at the mitotic spindle and Golgi in Drosophila. Mol. Biol. Cell 26, 2491–2504 (2015). Cleland, T. P. et al. Mass spectrometry and antibody-based characterization of blood vessels from Brachylophosaurus canadensis. J. Prot. Res. 14, 5252–5262 (2015). Lindgren, J. et al. Biochemistry and adaptive colouration of an exceptionally preserved juvenile fossil sea turtle. Sci. Rep. 7, 13324 (2017).

anti-chicken actin—P00851: chicken actin polyclonal, host: rabbit; ammonium sulfate fractionation; WB (1:500); IHC (1:100); Pacheco, T. R., Moita, L. F., Gomes, A. Q., Hacohen, N. & Carmo-Fonseca, M. RNA interference knockdown of hU2AF35 impairs cell cycle progression and modulates alternative splicing of Cdc25 transcripts. Mol. Biol. Cell 17, 4187-4199 (2006). Yuan, D., Liu, L. & Gu, D. Transcriptional regulation of livin by beta-catenin/TCF signaling in human lung cancer cell lines. Mol. Cell Biochem. 306, 171-178 (2007). Cleland, T. P. et al. Mass spectrometry and antibody-based characterization of blood vessels from Brachylophosaurus canadensis. J. Prot. Res. 14, 5252–5262 (2015). Schweitzer, M. H., Moyer, A. E. & Zheng, W. Testing the hypothesis of biofilm as a source for soft tissue and cell-like structures preserved in dinosaur bone. PLoS ONE 11, e0150238 (2016).

anti-chicken collagen—polyclonal, chicken collagen type I, host: rabbit, E, IF (1:80), IHC(1:1000), RIA. Schweitzer, M. H. et al. Biomolecular characterization and protein sequences of the campanian hadrosaur B. canadensis. Science 324, 626-631 (2009). Moyer, A. E., Zheng, W. & Schweitzer, M. H. Microscopic and immunohistochemical analyses of the claw of the nesting dinosaur, Citipati osmolskae. Proc. R. Soc. B 283, 20161997 (2016).

anti-peptidoglycan—monoclonal, ag=Streptococcus mutans BHT, host: mouse. Robertson, J. et al. Intestinal APCs of the endogenous nanomineral pathway fail to express PD-L1 in Crohn's disease. Sci. Rep. 6, 26747 (2016). Miklossy, J. Bacterial amyloid and DNA are important constituents of senile plaques: further evidence of the spirochetal and biofilm nature of senile plaques. J. Alzheimers Dis. 53, 1459-1473 (2016). Schweitzer, M. H., Moyer, A. E. & Zheng, W. Testing the hypothesis of biofilm as a source for soft tissue and cell-like structures preserved in dinosaur bone. PLoS ONE 11, e0150238 (2016). Lindgren, J. et al. Biochemistry and adaptive colouration of an exceptionally preserved juvenile fossil sea turtle. Sci. Rep. 7, 13324 (2017).

18 nm colloidal gold affinipure donkey anti-goat IgG—polyclonal, ag=goat IgG(H+L), host: donkey, working dilution: 1:10. Ferrero, S. et al. Proliferation and morphogenesis of the ER driven by the membrane domain of 3-hydroxy-3-methylglutaryl coenzyme A reductase in plant cells. Plant Phys. 168, 899-914 (2015).

biotinylated goat anti-rabbit IgG—polyclonal, ag=rabbit IgG(H+L), host: goat, working dilution: 1:500. Cleland, T. P. et al. Mass spectrometry and antibody-based characterization of blood vessels from Brachylophosaurus canadensis. J. Prot. Res. 14, 5252–5262 (2015). Schweitzer, M. H., Moyer, A. E. & Zheng, W. Testing the hypothesis of biofilm as a source for soft tissue and cell-like structures preserved in dinosaur bone. PLoS ONE 11, e0150238 (2016). Lindgren, J. et al. Biochemistry and adaptive colouration of an exceptionally preserved juvenile fossil sea turtle. Sci. Rep. 7, 13324 (2017). Lui, S., Torontali, Z., Tadjalli, A. & Peever, J. Brainstem nuclei associated with mediating apnea-induced respiratory motor plasticity. Sci. Rep. 8, 12709 (2018).

biotinylated rabbit anti-sheep IgG—polyclonal, ag=sheep IgG(H+L), host: rabbit, working diluttion 1:500. Douvaras, P. et al. Abnormal corneal epithelial maintenance in mice heterozygous for the micropinna microphthalmia mutation Mp. Exp. Eye Res. 149, 26-39 (2016).

biotinylated goat anti-mouse IgG—polyclonal, ag=mouse IgG(H+L), host: goat. Schweitzer, M. H., Moyer, A. E. & Zheng, W. Testing the hypothesis of biofilm as a source for soft tissue and cell-like structures preserved in dinosaur bone. PLoS ONE 11, e0150238 (2016). Lindgren, J. et al. Biochemistry and adaptive colouration of an exceptionally preserved juvenile fossil sea turtle. Sci. Rep. 7, 13324 (2017). Lui, S., Torontali, Z., Tadjalli, A. & Peever, J. Brainstem nuclei associated with mediating apnea-induced respiratory motor plasticity. Sci. Rep. 8, 12709 (2018).

Method-specific reporting

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ Magnetic resonance imaging