

Jurassic fossil juvenile reveals protracted life history in early mammals

Supplementary

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Institutional abbreviations:

OUMNH, Oxford University Museum of Natural History, Oxford, UK; NHMUK, Natural History Museum, London UK; NMS, National Museums Scotland, Edinburgh, UK.

S1. Body Mass Estimation

Various scaling relationships have been used to estimate body mass in Mesozoic mammals. These include relationships based on molar length and area, and lengths of the dentary, skull, and long bones (Gingerich et al. 1982; Anyonge 1993; Luo et al. 2001; Hopkins 2008; Foster 2009). Some of the most widely used equations for estimating body mass in limbed vertebrates come from Campione and Evans (2012), based on the sum of the minimum shaft circumferences of the humerus and femur. Campione and Evans (2012) used a dataset of extant species (primarily mammals) to show that femoral and humeral shaft circumferences of terrestrial quadrupeds have a relatively strong and predictive relationship with individual body mass, providing substantially more accurate estimates of body mass than either skull length, humeral or femoral length measurements. Furthermore, evidence so far suggests that the relationship between body mass and femoral/humeral shaft circumferences is relatively invariant with respect to variation in limb orientations and body proportions among extant tetrapods (Campione and Evans 2012). We therefore use femoral and humeral shaft minimum circumferences as our primary method of body mass estimation for extinct species on the mammalian stem lineage. We also used dentary length to estimate body mass. However, proportional differences in skull (and dentary) length and limb lengths (and orientations) have the potential for systematic estimation errors when used to estimate docodontan body masses. In particular, docodontans have proportionally long skulls (and dentaries) and short limb bones compared to extant mammals of similar body mass (Meng et al. 2015).

The method of inferring body mass from limb bone shaft circumferences, and the dataset on which it was originally based (Campione & Evans 2014), presents some limitations for estimating the body masses of Mesozoic mammals: 1) most mammals in the Mesozoic are <100g in body mass. However, because of the difficulties obtaining physical measurements from small specimens, this size class is not well

represented in the dataset of Campione and Evans (2012; only 19 species out of N = 189 mammal species in their dataset have body masses <100g); 2) Campione and Evans (2012) proposed that the relationship of body mass with humeral measurements may be different for mammals smaller than 20 kg than it is for larger mammals.

Supplementary Table 3. Results from pGLS regressions of body mass on the sum of the minimum shaft circumferences of the femur and humerus ($\log_{10}[\text{body mass}] \sim \log_{10}[\text{FC} + \text{HC}]$) using variants of the dataset of Campione & Evans (2012). Results are summarised as the upper 95%, median, and lower 5% quantiles of coefficients estimated over 35 different phylogenetic topologies from Upham et al. (2019). N = 171 is the number of species from Campione & Evans (2012) for which we could obtain species-specific body masses from the literature. These results show that using species adult body masses from the literature increases scatter in the relationship, but does not significantly change its coefficients.

	N	lambda	R ²	Variable	Estimate	Std. Error	t value	Pr(> t)
<u>Campione & Evans (2012) data, log₁₀ individual specimen body masses</u>								
Upper quantile (95%) results	171	0.382	0.955	Intercept	-1.154	0.115	-10.160	<0.0001
				log ₁₀ (HC+FC)	2.734	0.047	59.973	<0.0001
Median results	171	0.349	0.953	Intercept	-1.163	0.111	-10.487	<0.0001
				log ₁₀ (HC+FC)	2.729	0.047	58.615	<0.0001
Lower quantile (5%) results	171	0.315	0.951	Intercept	-1.1771	0.105	-11.011	<0.0001
				log ₁₀ (HC+FC)	2.726	0.046	57.533	<0.0001
<u>Campione & Evans (2012) data, log₁₀ adult body masses from Nowak, (1999); Smith et al. (2003); Ocampo et al. (2021)</u>								
Upper quantile (95%) results	171	0.704	0.977	Intercept	-1.149	0.105	-10.972	<0.0001
				log ₁₀ (HC+FC)	2.749	0.034	84.402	<0.0001
Median results	171	0.683	0.976	Intercept	-1.157	0.099	-11.642	<0.0001
				log ₁₀ (HC+FC)	2.746	0.033	82.929	<0.0001
Lower quantile (5%) results	171	0.650	0.975	Intercept	-1.164	0.093	-12.395	<0.0001
				log ₁₀ (HC+FC)	2.743	0.033	80.967	<0.0001

To address these issues, we assembled a new dataset of high-precision skeletal measurements of small-bodied mammals obtained from our micro CT-scans (available at www.morphosource.org/projects/00000C428; and links to individual scan data and limb bone models are included in Supplementary Table 2). In total we added data for 158 species, spanning 4.0 g – 130 kg adult body mass, including 79 species weighing less than 1 kg. Unlike the dataset of Campione & Evans (2012), the specimens we measured did not have individual measured body masses, so our analyses use species body mass from the literature (Nowak, 1999; Smith et al. 2003; Ocampo et al. 2021). We show that this adds scatter to the relationship between body mass and skeletal measurements using the dataset of Campione & Evans (2012) (Supplementary Table 3; $R^2 = 0.976$ when using individual body masses and $R^2 = 0.953$ when using species body masses from the literature), but does not substantially alter its coefficients (Supplementary Table 3; coefficients are well within one standard error of each other). We therefore proceeded using species body

masses to infer the relationship between skeletal measurements and body mass for our extended dataset.

Circumferences of limb bones were taken at the narrowest point of the limb, as in the methodology of Campione and Evans (2012), as this reflects the minimum circumference for weight-bearing in the limb bone. Digital meshes (.ply) were generated from micro-CT scans of mammals. These .ply files were imported into Avizo Lite 9.7.0 (ref) and: 1) the length of the dentary, humerus and femur were each measured using the 3D measurement tool; then the humerus and femur were cross-sectioned using the clipping tool, a scale added using the 3D measurement tool, and a snapshot exported for measurements of humeral and femoral minimum shaft circumference using ImageJ/Fiji (Schindelin et al. 2012).

Dentary lengths were measured from the anteriormost point of the alveolar rim of i1, to the posteriormost point of the dentary condyle. This is following Foster (2009) and has the benefit of being more applicable to the fossil record because the incisors are not always preserved in Mesozoic mammals.

We analysed the relationships between body mass and skeletal measurements using phylogenetic generalised least squares regression (pGLS; Grafen 1989) in the R package caper 1.0.1 (Orme et al. 2018), co-estimating the phylogenetic signal parameter λ (Pagel 1999) alongside other regression parameters (the slope and y-intercept). We repeated our analyses across a distribution of 35 phylogenetic topologies from the VertLife project (<https://vertlife.org/data/mammals>) (Upham et al. 2019) to accommodate the impact of uncertainty about phylogenetic relationships among living mammal species. We summarised variation in results across this distribution as the medians and the lower and upper 5th percentiles. We evaluated the relationships between species body mass and the summed humeral and femoral minimum shaft circumferences (HC+FC) as well as dentary length (DL).

We compared results for the full dataset of 158 species to a subset of our data comprising 70 species with species body masses less than 1.0 kg. We used the sample of small-bodied mammals as the primary dataset to estimate docodontan body masses.

We report a highly similar relationship of body mass to the sum of the minimum shaft circumferences of the humerus and femur (HC + FC) (y-intercept = -1.065; slope = 2.674 for the full dataset of 158 species; y-intercept = -0.987; slope = 2.595 for the dataset of 70 small-bodied species; Supplementary Table 4) to those returned from dataset of the Campione & Evans (2012) dataset (y-intercept = -1.157; slope = 2.749; Supplementary Table 4). These values are within two standard errors of each other (Supplementary Table 3) suggesting that the scaling relationship for small-bodied mammals is similar to that for larger taxa. Nevertheless, we proceeded to use the relationship derived for small-bodied mammals (Supplementary Table 4) to estimate body sizes of NMS G.1992.47.122.1 and NMS G.2023.8.1 herein.

Supplementary Table 4. Results from pGLS regressions of body mass on the sum of the minimum shaft circumferences of the femur and humerus ($\log_{10}[\text{body mass}] \sim \log_{10}[\text{FC} + \text{HC}]$) and of body mass on dentary length ($\log_{10}[\text{body mass}] \sim \log_{10}[\text{dentary length}]$) using both the complete dataset of N = 158 extant mammals

species, plus the subset of N = 70 mammals species weighing less than 1 kg. Results are summarised as the upper 95%, median, and lower 5% quantiles of coefficients estimated over 35 different phylogenetic topologies from Upham et al. (2019).

	N	lambda	R2	Variable	Estimate	Std. Error	t value	Pr(> t)
<u>log₁₀(body mass) ~ log₁₀(HC+FC) using entire dataset</u>								
Upper quantile (95%) results	158	0.647	0.953	Intercept	-1.056	0.141	-7.579	<0.0001
				log ₁₀ (HC+FC)	2.681	0.048	56.448	<0.0001
Median results	158	0.612	0.952	Intercept	-1.065	0.131	-8.157	<0.0001
				log ₁₀ (HC+FC)	2.674	0.048	55.741	<0.0001
Lower quantile (5%) results	158	0.565	0.951	Intercept	-1.072	0.120	-8.864	<0.0001
				log ₁₀ (HC+FC)	2.670	0.048	55.193	<0.0001
<u>log₁₀(body mass) ~ log₁₀(HC+FC) using small-bodied mammals (adult body mass <1 kg)</u>								
Upper quantile (95%) results	70	0.005	0.922	Intercept	-0.987	0.102	-9.689	<0.0001
				log ₁₀ (HC+FC)	2.597	0.091	28.445	<0.0001
Median results	70	0.000	0.922	Intercept	-0.987	0.102	-9.692	<0.0001
				log ₁₀ (HC+FC)	2.595	0.091	28.429	<0.0001
Lower quantile (5%) results	70	0.000	0.922	Intercept	-0.990	0.102	-9.692	<0.0001
				log ₁₀ (HC+FC)	2.595	0.091	28.429	<0.0001
<u>log₁₀(body mass) ~ log₁₀(dentary length) using entire dataset</u>								
Upper quantile (95%) results	158	0.811	0.889	Intercept	-2.176	0.273	-8.027	<0.0001
				log ₁₀ (DL)	3.023	0.087	35.288	<0.0001
Median results	158	0.783	0.887	Intercept	-2.203	0.258	-8.557	<0.0001
				log ₁₀ (DL)	3.015	0.086	34.964	<0.0001
Lower quantile (5%) results	158	0.751	0.884	Intercept	-2.230	0.237	-9.305	<0.0001
				log ₁₀ (DL)	2.997	0.085	34.498	<0.0001
<u>log₁₀(body mass) ~ log₁₀(dentary length) using small-bodied mammals (adult body mass <1 kg)</u>								
Upper quantile (95%) results	70	1.000	0.856	Intercept	-2.181	0.348	-6.305	<0.0001
				log ₁₀ (DL)	2.997	0.155	20.107	<0.0001
Median results	70	0.771	0.848	Intercept	-2.208	0.279	-7.898	<0.0001
				log ₁₀ (DL)	2.979	0.153	19.484	<0.0001
Lower quantile (5%) results	70	0.708	0.844	Intercept	-2.231	0.265	-8.334	<0.0001
				log ₁₀ (DL)	2.959	0.148	19.186	<0.0001

The juvenile specimen (NMS G.2023.8.1) lacks a preserved femur, so we estimated its femoral minimum shaft circumference (FC) from its humeral minimum shaft circumference (HC), assuming that the juvenile (NMS G.2023.8.1) was proportionally identical to the adult (NMS G.1992.47.122.1). We also estimated the body mass of both individuals from dentary length (DL) to provide an alternative mass estimate independent of the limb skeleton, but we expect these values to be substantial overestimates of body mass for docodontans given that: (i) Skull length measurements show considerably greater scatter and so greater prediction error for

body mass among extant mammals (Supplementary Table 4), and (ii) Docodontans have proportionally long skulls (Meng et al. 2015).

The minimum humeral shaft circumference of the adult NMS.G.1992.47.122.1 is 5.755 mm and the minimum femoral shaft circumference is 5.429 mm, providing a mass estimate of 54.1 g (95% prediction interval: 23.1 g – 127 g) using coefficients in Supplementary Table 4. The minimum humeral shaft circumference of the juvenile NMS G.2023.8.1 is 4.721 mm, providing a mass estimate of 32.4 g (13.8 g – 76.0 g) when assuming an identical ratio of FC to HC as that of the adult specimen.

The dentary length in the adult NMS.G.1992.47.122.1 is 30 mm, providing a body mass estimate of 156 g (95% prediction interval: 40.5 g – 598 g) using coefficients in Supplementary Table 4. The dentary length in the juvenile NMS G.2023.8.1 is estimated at 24 mm, providing an estimate of 80.2 g (95% prediction interval: 22.3 g – 327 g).

Although these approaches provide different body mass estimates, they result in similar relative body mass differences between the adult and juvenile specimens (59.9% for HC+FC; 51.4% for dentary length), and these proportional differences are also similar to those that would be obtained from developmental mass extrapolation (Erickson & Tumanova 2000) based on the dentary lengths (51.2%) or humeral minimum shaft circumference (59.9%).

S2. Systematics and Anatomy of *Krusatodon kirtlingtonensis*

SYSTEMATIC PALAEONTOLOGY

DOCODONTA – Kretzoi, 1946

DOCODONTIDAE – Simpson, 1929

Krusatodon – Sigogneau-Russell, 2003

Type and only species: Krusatodon kirtlingtonensis Sigogneau-Russell, 2003

Etymology: genus name *Krusatodon* honours Dr George Krusat, who worked on docodontans, and species name *kirtlingtonensis* refers to the locality in which this taxon was first found, Kirtlington Quarry in Oxfordshire.

Holotype: NHMUK M.46526 (formerly BMNH J. 526), right lower molar, from the Forest Marble Formation of Kirtlington, Oxfordshire (Extended Data Fig. 1).

Referred specimens: From the Kilmaluag Formation, Isle of Skye: NMS G.1992.47.122.1, near complete skeleton of fully grown adult; NMS G.1992.47.124, the anterior tip of the left dentary (part of NMS G.1992.47.122.1) and NMS G.2023.8.1, partial skeleton of juvenile. From the Forest Marble Formation of Kirtlington, Oxfordshire: NHMUK M.46784, left lower molar; NHMUK M.46222, left upper molar; NHMUK M.46437, left upper molar; NHMUK M.46667, left upper; molar; NHMUK M.46872, right upper molar; NHMUK M.46442, lingual half of left

upper molar; NHMUK M.46872, right upper molar; OUMNH J.79446, left lower molar in fragment of dentary; NHMUK M.46838.

Possible referred specimens: From the Forest Marble Formation of Kirtlington, Oxfordshire: NHMUK M.46456, left lower molar; NHMUK M.46531, upper molar; NHMUK M.46803, labial portion of right upper molar; NHMUK PV M.46445, upper molar fragment; OUMNH J.79514, lower right molar; OUMNH J.79450, lower left molar; NHMUK M.46804, right lower molar.

No longer referred to Krusatodon: From the Forest Marble Formation of Kirtlington, Oxfordshire: NHMUK M.46333 herein identified as *Wareolestes* molar; NHMUK M.46333, lower molar ?megazostrodonid; NHMUK M. 46778, left lower molar (was identified as *Cyrtlatherium* [Freeman 1979], then *Krusatodon* [Sigogneau-Russel 2003]) herein identified as *Boreolestes* sp.; NHMUK PV M46693 left lower molar holotype of *Periaocynodon major*, was identified as juvenile *Krusatodon kirtlingtonensis* by Averianov (2004), herein confirmed not to belong to *Krusatodon*; OUMNH J.49447, upper right molar herein identified as *Boreolestes cuillinensis*.

Revised differential diagnosis: (see Extended Data Fig. 1) Adult dental formula: 4.1.4.4 / 4.1.4.4 (5 premolars in juveniles). There is a postdentary trough as in other early mammaliaforms, but *Krusatodon* possesses a posteriorly facing ectotympanic notch in the angular region of the dentary, an autapomorphy of Docodonta. *Lower molars:* resemble most docodontans in having a larger cusp A positioned labially, with smaller cusps c and g lingually, longer anteroposteriorly than transversely, and with a 'pseudotalonid' formed by the a, b and g cusps. *Krusatodon* has a strong crest on the posterior of the molar, as in *Agilodocodon*, *Dobunnodon*, and to a lesser extent, *Boreolestes* and *Tegotherium*, but unlike *Simpsonodon*, *Itatodon* or *Dsungarodon* in which this crest is reduced. In *Krusatodon* this posterior crest bears two to three cusps, d, df, and a 3rd cuspule that is variable in presence and size. Cusp g well developed as in *Simpsonodon* and *Khorotherium*, more so than in *Boreolestes*, *Dobunnodon*, *Haldanodon* and *Docodon*. Cusp c larger than cusp g, unlike in *Simpsonodon*. Cusp a relatively dorsoventrally higher and narrower than *Simpsonodon*, similar to *Tegotherium*, but not as tall and pointed as *Agilodocodon*. Cusp c positioned anterolingual to main cusp a, as in most docodontans, but unlike more anteroposteriorly adjacent position in *Tegotherium*, *Sibirotherium*, *Docodon* and *Agilodocodon*. Lack of a lingual or labial cingulum, unlike *Tegotherium*, *Itatodon* and *Dsungarodon*. Cusp e moderately sized, similar to *Boreolestes*, larger than in *Simpsonodon* and *Agilodocodon*, but smaller than *Dobunnodon* or *Tegotherium*. Strong a-b, a-c, and a-g crests, similar to *Dobunnodon*, *Simpsonodon* and *Agilodocodon*, and to a lesser extent *Tegotherium*. Deep vertical furrow created between the a-c and a-d crests similar to *Dobunnodon*, but lacking the more extensive developed furrows seen in *Docodon*, and *Simpsonodon*.

Upper molars: The upper molars resemble most docodontans except *Simpsonodon* in shape, with the labial half of the molar anteroposteriorly longer than the lingual half, and a constricted 'waist' delineating the labial and lingual halves of the molar. The lingual half of the molar is extended transversely and forms a deeply concave occlusal basin resembling most docodontan upper molars in appearance, but unlike in *Docofossor* or *Simpsonodon*. Inside this lingual basin, two faint crests emanate

from cusp Y labially and anteriolabially; and two faint crests emanate from cusp Z labially and distolabially, but these can be lost with wear. The cusps are lower (dorsoventrally shorter) than *Agilodocodon*, but more so than *Simpsonodon*, similar to *Borealestes*. There is no A-X crest (anterolabial) on cusp A, as in *Borealestes serendipitus*, *Khorotherium* and *Microdocodon*, but unlike most docodontans including *B. cuillinensis*, *Haldanodon* and *Docodon*. Cusp B is larger than *Borealestes*, more like *Simpsonodon*, *Tegotherium*, *Khorotherium* and *Agilodocodon*. There is a cusp Z, as in *Borealestes serendipitus*, *Hutegotherium* and *Agilodocodon*, but not *B. cuillinensis* and most other docodontans. Lingual cusp X is linked by crests to the distal cusp Y as in most docodontans, and mesial cusp Z. There is no anterior fovea, like most docodontans except *Borealestes* and *Docodon*. There is a distinct cingulum on the anterior, posterior, and labial side of the labial portion of the tooth, as in *Docodon*, *Hutegotherium* and *Khorotherium*. The labial cingulum culminates anteriorly in two small cusps, cusp B and E, which bear a crest that joins anteriorly with cusp A as in *Khorotherium* and *Microdocodon*. Cusp B is well developed, but less so than in *Hutegotherium*.

Notes: There is a relatively large diastema between canine and p1 in dentary in the adult and juvenile (Extended Data Fig.3f and 4d and f). The ultimate premolar in juvenile very molariform, and juvenile tends to show more pointed cusps than the permanent teeth of the adult. The early erupting molar(s) tend to show greater degree of wear, which is common pattern of tooth wear through ontogeny. The deep vertical furrow created between the a-c and a-d crests is similar to *Dobunnodon*, but lacks the extensive “complicated pattern of furrows and ridges” (Simpson 1929: 91) in the posterior part of the lower molar, as seen in *Docodon*, and *Simpsonodon*, and to some extent also in *Agilodocodon* (Meng et al. 2015).

In the original description of *Krusatodon*, similarities were noted with *Tegotherium*, including the ‘ribs and deep furrows anteriorly, lingually and posteriorly’ on cusp a (Sigogneau-Russell 2003: p361). These were considered to be better developed than in other taxa (Sigogneau-Russell 2003), but more recent studies show these features are present in *Dobunnodon*, *Simpsonodon* and *Agilodocodon*. The resemblance of *Krusatodon* to *Tegotherium* is therefore less pronounced than previously observed. The original description also described three cusps on the posterior rim of the tooth, two of these are d and df. The distinctiveness of the third cusps appears variable in *Krusatodon*, varying between individuals and along the tooth row, possibly also related to age and tooth wear. However, the posterior rim of the tooth as a whole is always distinct. In the juvenile NMS G.2023.8.1 there is also an additional cusps on the anterior of the molar in m2 and m3, which may correspond to the proposed ‘cusp bb’ (e.g. Averianov et al 2018), but this accessory cusps also appears to be variable and is not present in all specimens of *Krusatodon*, or in all teeth in the same tooth row.

Sigogneau-Russell (2003) also noted that the pseudotalonid was wider and deeper than *Simpsonodon*, and differed from *Borealestes* and *Docodon*, but the depth of this feature is variable depending on wear. In the original description there were no diagnostic characters for upper molars, but in the description she noted variability in the ‘individualisation’ of cusp Z, and of the crests that emanate labially from cusps Y and Z (Sigogneau-Russell 2003:p367). We concur with this observation, and further note that the distolabial crest on cusp Y is not always present and appears to be

worn in some specimens (e.g. NHMUK M46872). Where Sigogneau-Russell stated that the cusp Y ('distal lingual cusp') is always dominant, we find cusp Y often larger, but not always. Cusp A has a straight to slightly concave posterior face, but this is not always clear depending on wear, or on the resolution of the CT data. Posteriorly the labial cingulum on the upper molar sometimes bears small cuspsules posterior to the cusp C, but this also appears variable.

Averianov (2004) suggested that *Peraiocynodon major* (Sigogneau-Russell 2003) is a junior subjective synonym of *Krusatodon kirtlingtonensis*, but we find no support for this. Concurring with Sigogneau-Russell (2003), we interpret that *P. major* is sufficiently different from *K. kirtlingtonensis*.

Description

All elements of specimen NMS.G.1992.47.122.1 and NMS G.2023.8.1 are available to download from morphosource: www.morphosource.org/projects/00000C428

Crania

The adult skull of NMS.G.1992.47.122.1 and the juvenile skull of NMS G.2023.8.1 are both crushed, but the skull elements remain close to their original positions, making identification and reconstruction of most elements of the skull possible (Main Figure 1, 2 and 3a-d, Extended Data Fig. 2). In NMS.G.1992.47.122.1 the skull lies ventral side 'upwards', relative to the exposed surface of the specimen slab, with the anterior of the dentaries' visible on the prepared surface of the specimen, beneath scattered ribs and other postcrania (Main Figure 1a-c). The skull is dorsoventrally crushed, and the dentaries' - particularly the coronoid processes - have been pushed into the crania. As a result, the pterygoid region is not well preserved. The parietal region has been pushed against the basisphenoid and petrosals, creating a concavity, but the majority of the bones of this region are present, if somewhat broken.

In the juvenile *Krusatodon* specimen, NMS G.2023.8.1, the skull is less well preserved than the adult, possibly due to the under development of ossification and suturing. As in the adult, the dentaries have been pushed upwards into the skull, but there is also displacement of the left and right sides of the skull relative to one another, both anteroposteriorly and mediolaterally (left and right sides often sit underneath one another) (Main Figure 3b and d). Parts of the postcrania, including multiple vertebra, have been pushed into the skull, displacing elements such as the left petrosal, which is located away from the rest of the skull.

Dentaries and Postdentary Bones

The dentary in the adult NMS.G.1992.47.122.1 is fully preserved from the tip of the symphysis to the dentary condyle. The total length 30 mm, providing a body mass estimate of 152 g (95% prediction interval: 39.9 g – 580 g) using coefficients in Supplementary Table 4. The dentary in the juvenile NMS G.2023.8.1 shows a relatively intact symphyseal region, but the dentary penduncle and condyle are not preserved. However, because the squamosal glenoid is fully preserved in this juvenile as in adult docodontans, we infer the dentary condyle was developed but not preserved in the crushed fossil. The juvenile dentary is estimated at 24 mm, providing an estimate of 84 g (95% prediction interval: 22 g – 321 g).

The adult dentaries of *Krusatodon* are proportionally long and slender, similar to *Borealestes* (Panciroli et al., 2019, 2021) and *Agilodocodon* (Meng et al. 2015) (Extended Data Fig. 3). The mandibular symphysis is relatively short and distinct, running anteroposteriorly from the anterior tip of the jaw to a point ventral to the canine, a pattern seen in both the adult and juvenile specimen (Extended Data Fig. 3a and 4b and e). In *Borealestes* it remains distinct until ventral to the anteriormost premolars. The c-p1 diastema is large and present in both adult and juvenile, although appears to be more prominent relative to the shorter jaw of the juvenile (Extended Data Fig. 3d and f, and 4). There is a large lingual foramen on the dentary located ventral to the mandibular symphysis, ventral to i3 (Extended Data Fig. 3a). This foramen is known in other Mesozoic mammals (Luo and Martin 2023). There are three labial mandibular foramina ventral to i3, i4, c, and the c-p1 diastema, and these are present in both the adult and juvenile, although the anteriormost three foramina are positioned slightly further anteriorly in the juvenile. The incisors are single-rooted, and the canine, premolars and molars are double-rooted.

The efflected angular process is similar to other docodontans, and protrudes more strongly posteroventrally than in *Borealestes* or *Agilodocodon*, similar to *Docodon* except that it is more pointed in shape when viewed laterally in *Krusatodon*, whereas *Docodon* has a rounded angular process (Schultz et al. 2019). The Meckel's cartilage is an ossified rod (preserved in NMS G.1992.47.122.1), sitting inside the Meckel's sulcus and terminating ventral to the penultimate molar (m3) (Extended Data Fig. 3a). The mandibular canal opening, which was the passage of the inferior alveolar nerve, sits dorsal to the Meckel's sulcus, as seen in other docodontans, and in the adult *Krusatodon* sits posterior to the ultimate molar, ventral to the V3 notch, whereas in the juvenile the opening is next to the emerging m3 (Extended Data Fig. 4b and e). This difference is caused by the lengthening of the dentary through ontogeny (see below). A fragment of the right ectotympanic and malleus are preserved in the juvenile *Krusatodon* (Extended Data Fig. 4e and h), and resemble those known in *Agilodocodon* (Meng et al 2015: fig 2).

In the adult, the Meckel's sulcus is open until approximately ventral to the m2/m3, after which it forms a faint indent visible until ventral to the ultimate premolar. In the adult it does not reach the ventral edge of the dentary, similar to *Docodon*, but unlike in *Borealestes*. However, in the juvenile *Krusatodon*, although the Meckel's element and its corresponding sulcus also terminates below m2, it reaches the ventral border of the dentary. This suggests that the relative position of the Meckel's sulcus shift as the dentary grows, resulting in changes in the location of the sulcus termination (and point where the canal would start) position through ontogeny. A similar observation was also made for *Docodon* (Schultz et al. 2019). Schultz et al. (2019) suggested that in all docodontans the Meckel's sulcus extends to the mandibular symphyseal region in juveniles and retreats posteriorly through ontogeny, based on observations of juvenile *Docodon*, as well as *Haldanodon* (Krusat 1980). This also appears to be the case for the earlier mammaliaform *Morganucodon* (Kermack et al 1973). However, there is no sign of the Meckel's sulcus near the symphyseal region in *Krusatodon*, suggesting it retreated earlier in ontogeny. We interpret that this developmental pattern is variable among docodontans.

In *Docodon* the coronoid process is also shown to shift posteriorly relative to the ultimate molar through ontogeny, and in mature individuals shifts to be in line with the tooth row - earlier in ontogeny the coronoid process is offset laterally as the ultimate molars continue to erupt medial to the coronoid process. This change through growth has also been observed in the dentaries of *Borealestes* (Pancioli et al. 2020, 2021), and is seen in these specimens of *Krusatodon*. Similar ontogenetic changes also occur in *Morganucodon watsoni* (Parrington 1971) and in *Hadrocodium* (Luo et al. 2022: fig11), and are also known from some crown mammal clades of Mesozoic mammals such as dryolestids including *Henkelotherium*, [Luo and Martin 2023]. Based on this character of the coronoid, and the fact the last upper molar (M4) is fully erupted (see below), we assert that the adult NMS.G.1992.47.122.1 is a mature individual, and the juvenile is from a very early ontogenetic stage (see below for further discussion and evidence for this).

Supplementary Table 5: Ontogenetic changes in *Krusatodon*.

Change through ontogeny	Juvenile	Adult
Meckel's Sulcus-Canal: Termination of open Meckel's sulcus at enclosure of canal shifts posteriorly through ontogeny.	Meckel's sulcus open medially along length of dentary to where it meets the ventral margin of the dentary below m2.	Meckel's sulcus is enclosed into canal below premolar and anterior molar(s); the sulcus remains open to a point ventral to m3, does not meet the ventral margin of the dentary.
Coronoid margin: Anterior margin of the coronoid process shifts posteriorly relative to the ultimate molar, resulting in a gap in older individuals.	Molars erupt medial to coronoid process; anterior part of the coronoid process is lateral to m2, and the emerging m3 and m4 alveolus are positioned medially to it.	Anterior margin of the coronoid process in alignment with the tooth row; the ultimate molars are positioned in front of coronoid process.
Premolars: Loss of deciduous premolar 2 with no replacement, resulting in diastema between the adult premolar 2 and premolar 4.	Deciduous premolar 2 present and no diastema between the premolar 2 and premolar 3.	Diastema between the adult premolar 2 and premolar 4, and lower premolar count.
Tooth Function Loci: Functional loci of canine and molars shifts as teeth are replaced and dentary lengthens: canine function shifts from dP1/dp1 to C/c, molar function shifts from dP4/dp5+molars to only molars.	Small deciduous canines; large deciduous dP1/dp1 with replacement adult premolar 1 in alveolus; molariform lower and upper dP5/dp5, both with their respective replacement teeth appearing in alveolus; upper and lower molars 1-2 emergent, upper and lower molar 3 emerging but still in alveolus.	Large upper and lower canine; P5/p5 not molariform; upper and lower molars 1-4 fully erupted.
Humerus: the humeral condyles become more pronounced through ontogeny, and distal humerus widens.	Radial and ulnar condyles small and not pronounced, entepicondyle and ectepicondyles small and not well developed.	Radial condyle very pronounced, larger than the ulnar condyle, which is also pronounced. Flared ectepi- and entepicondyles.
Ulna: the olecranon process of the ulna becomes larger through ontogeny; the semi-lunar notch deepens.	Olecranon process present, but small; semi-lunar notch shallow.	Olecranon large with a medial flange; the semi-lunar notch is deeper.

In the juvenile the lower i2 and i4 appear to be the permanent incisors (= 'second generation'), based on their relatively larger size compared the deciduous incisors remaining in the other incisor alveoli. The deciduous canine in the juvenile is more procumbent than the adult canine, a difference observed between the deciduous and adult generations at this locus (Martin 1997; Luo et al. 2004; Luo and Martin 2023). The deciduous canine is also extremely small compared to the i4 or p1, and smaller than the permanent canine cusp that is forming beneath it in the same tooth position (Extended Data Fig. 4a and f). In the adult specimen, the canine is much larger than the i4 or p1, indicating that the deciduous canine is replaced by a much larger successor canine. The di4 is also slightly caniniform (especially compared to the permanent i4) in NMS G.2023.8.1.

There are five premolars in the juvenile, and four in the adult (see main paper for more on this). In the juvenile the permanent i1, i3, c, p4 and p5 are developed within their alveoli but have not erupted above alveolar line in the dentaries (Extended Data Fig. 4a and f), and the permanent teeth in these positions are co-existing with their

respective deciduous precursors, which remain in place. The dp2 does not have a replacement, and we suggest that this tooth is lost soon after this point in ontogeny, based on the presence of an emerging p4 within the left dentary (Extended Data Fig. 2h, and 4a and f), and newly forming caps for p3 and p4 in the right dentary. The loss of dp2 without replacement likely contributes to the opening up of the p3-p4 diastema in the adult (Extended Data Fig. 3a-f). The ultimate deciduous premolar, dp5, is very molariform in the juvenile NMS G.2023.8.1, unlike the p5 in the adult, which is similar to the rest of the premolars in having three cusps arranged in an anteroposterior row, with the middle being the largest.

Molars m1 and m2 (permanent generation) have fully erupted in the juvenile, although M2 roots are still open at the apices (Extended Data Fig. 4a and f). The lower m3 has a fully formed crown but the roots are yet to be developed and the crown is erupting through the alveolar level in this individual. The m4 is not present, but there is a distinct concavity posterior to the m3, which is clearly a dental crypt for the m4 (Extended Data Fig. 4b, e and g). The lower m4 would form later in development as the dentary body elongated to accommodate its position, and anterior margin of the coronoid processes shifted posteriorly with the lengthening of the dentary. In summary, the replacement of diphyodont teeth in the ante-molar positions and the eruption sequence of the molars suggest that the juvenile is still undergoing the development process.

In the adult individual of *Krusatodon*, there is a medial ridge above the postdentary trough on the medial surface of the posterior part of the dentary, with a protruberance at its posterior termination, just ventral to the back of the coronoid process (Extended Data Fig. 3a and f). In the juvenile of *Krusatodon*, the medial ridge above the postdentary trough is already developed (Extended Data Fig. 4e and g), although its posterior extent is not clear because the dentary peduncle and condyle are lost. Overall the medial ridge is slightly deeper dorsoventrally than in *Borealestes* or *Microdocodon*, more similar to *Docodon*. There is a small masseteric foramen positioned ventrally in the masseteric fossa on the labial side of the dentary (Extended Data Fig. 3c and d, and 4d), as in *Borealestes*, and this foramen is proportionally much larger in the juvenile specimen. This feature occurs, convergently, in some zatherians of the Mesozoic (Davis 2012), phylogenetically distant from the stem mammaliaforms.

Premaxillae, Maxillae and Upper Teeth

The premaxillae and maxillae are preserved in both the adult and juvenile *Krusatodon*, with the premaxillae better preserved in the juvenile, and maxillae better preserved in the adult specimen (Extended Data Fig. 3 and 5). The junction between the premaxilla and maxilla is only preserved in the left side of the juvenile (Extended Data Fig. 5b), this area being damaged in the right side in this specimen, and in both sides of the adult specimen. The maxilla projects anteriorly to dorsal to the I3/I4, and the premaxilla continues behind this projection (Extended Data Fig. 2g). The posterior termination of the premaxilla underneath the maxilla is unclear due to damage in this region on the left side of the juvenile. However, the I4 is anchored in the maxilla in the adult in the left maxilla (Extended Data Fig. 3g and j), and no suture is present in the undamaged area immediately anterior or posterior to the canine in the adult in the left maxilla. The canine is usually anchored by the maxilla

in mammaliaforms (Kermack et al. 1981; Lillegraven and Krusat 1991; Crompton and Luo 1993), and this is the case in *B. cuillinensis* (Panciroli et al. 2021).

In the juvenile *Krusatodon*, the left premaxilla is very well preserved, it indicates that the lateral surfaces of the premaxillae are dorsoventrally straight, and when seen laterally are dorsoventrally shallowest dorsal to I1/I2, before gently sloping to their dorsoventrally deepest above the I4. Anteriorly, both the left and the right premaxillae have a dorsally pointed internarial process preserved, bearing an anterior premaxillary foramen (Extended Data Fig. 5b and e). This is the same as in *Borealestes* (Panciroli et al. 2021) and overall, the proportion of the premaxilla, and its relationship to the maxilla are essentially the same as in *Haldanodon* (Lillegraven and Krusat 1991) and other mammaliaforms such as *Morganucodon* and *Sinoconodon* (Kermack et al. 1981; Crompton and Luo 1993), suggesting that the internarial process likely extended dorsally to connect with the nasals in *Krusatodon*.

There is a large foramen on the anterior surface of the premaxilla, the anterior premaxillary foramen, which is located at the base of the internarial process (or the median process of the premaxillary bone), dorsal to I1. This anterior premaxillary foramen is connected to the premaxillary canal, as observed in *Borealestes* (Panciroli et al. 2021). There is also a foramen on the medial surface of the internarial processes, where the left and right premaxillae contact one another.

The anterior premaxillary foramen on the palatal process of the premaxilla in *Krusatodon* is medial to I2 (Extended Data Fig. 5d and g), as in *Borealestes*. These vascular channels are probably for the terminal endings of the smaller nerves derived originally from the greater palatine nerve, and their companion small vessels (Benoit et al. 2016). On the ventral (palatal) plate of the premaxilla, the incisive foramen is positioned medial to I2/I3, and as in *Borealestes*, a small posterior projection of the premaxillary palatal plate creates a heart-shaped anterior margin on the foramen (Extended Data Fig. 5g). There is another small foramen medial to I4.

The maxillae of *Krusatodon* are similar to those seen in other docodontans and other early mammaliaforms. There are small foramina on the palatal process of the maxilla medial to the canine, P4, and between the alveoli of M2 and M3 (Extended Data Fig. 3j). On the lateral surface of the maxilla a small foramen is present dorsal to the canine, and larger infraorbital foramina lie dorsal to P4 and M1 (Extended Data Fig. 3g-h). There is no lateral bulge in the maxilla for the canine, which is small with two roots.

In *Krusatodon* the P4 comprises a large main cusp and posterior smaller cusp, arranged anteroposteriorly, with a third smaller cusp medial to these, as seen in the upper premolars of *Borealestes* (Panciroli et al. 2021: fig 6), but unlike *Agilodocodon*, in which the third medial cusp is much reduced (Meng et al. 2015: fig 2). The dP5 in NMS G.2023.8.1 is molariform (Extended Data Fig. 5), but the emerging P4 is clearly premolar in shape, with three cusps in a straight line, characteristic of the permanent premolar in the adult. This molariform posteriormost upper deciduous premolar mirrors that seen in the lower deciduous premolar, dp5, which is also being replaced with a non-molariform permanent premolar in close association with dp5 (Extended Data Fig. 5a and f). In the lower dentition the dp2 is not replaced (see above), which explains the why the juvenile possesses five premolars whereas the adult has four.

The same pattern must occur in the upper premolars, but it is not clear which tooth is lost without replacement. The dP2 in the right maxilla has a replacement, so it is must be either the dP3 or dP4 that is not replaced. It is not clearly visible in NMS G.2023.8.1 due to damage in dorsal part of the maxillae in this region.

The palatal process of the maxilla can be seen extending to at least medial to the dP5/P5 in the juvenile *Krusatodon* (Extended Data Fig. 5g). There is a deep pit in between lingual cusps of adjacent upper molars, in both the juvenile and the adult. These are pits for accommodating the tallest lower molar cusp, common in Mesozoic mammaliaforms (Kermack et al. 1981; Schultz et al. 2019) and also seen in *Borealestes* (Pancioli et al. 2021). The preserved palatal process is fractured and incomplete posteriorly in the adult and juvenile specimens, therefore the morphology of the palatal process and its connection to the palatine and pterygoids posterior to it is not known in *Krusatodon*.

Septomaxillae, Nasals and Reconstruction of External Nares

Both septomaxillae are preserved in the juvenile *Krusatodon*, NMS G.2023.8.1 (Extended Data Fig. 2e), but the left septomaxilla is better preserved than the right. Pieces of the septomaxilla and the premaxilla are mingled and more difficult to separate in the adult specimen NMS G.1992.47.122.1. The position of the septomaxilla can now be reconstructed in *Krusatodon* on the basis of the juvenile skull (Extended Data Fig. 2f-g). Overall, the septomaxilla is U-shaped in lateral (external) view, rotated to its side. The septomaxilla consists of a smaller lateral plate on the (external) aspect of rostrum, and a ventral shelf that is longer and overlaps on top of the palatal process of the premaxilla. Both the septomaxillary ventral shelf and the palatal process of the premaxilla contribute to form the floor of the nasal passage. The lateral (external) plate of the septomaxilla overlaps dorsomedially with the lateral edge of the nasal. The posterior and ventral edges of the lateral plate of the septomaxilla contact the facial part of the premaxilla. The septomaxillary canal and its related foramen are not present in the septomaxilla itself, although the latter foramen could be located at the junction of the septomaxilla, the premaxilla and the maxilla (as well documented in *Sinoconodon*). In this feature the *Krusatodon* juvenile specimen differs from cynodonts in which the septomaxilla has a septomaxillary canal tunneling through the ventral shelf of the bone and the posterior opening of septomaxillary canal is connected to the septomaxillary foramen at the lateral surface of rostrum, as seen in *Thrinaxodon* (Wible et al. 1990). In other early mammaliaforms such as *Sinoconodon* and *Morganucodon* (Wible et al. 1990; Crompton and Luo 1993), the septomaxillary foramen is present on the lateral surface of rostrum and at the juncture of the septomaxilla, the premaxilla and the maxilla, although these intact fossils do not show a septomaxillary canal tunneling through the ventral shelf. The septomaxillary foramen in *Krusatodon*, if present, would be located at the junction of the septomaxilla, premaxilla, and maxilla, presumably like in *Sinoconodon* (Wible et al. 1990; Crompton and Luo 1993).

For comparison to other docodontans, a septomaxilla was inferred to be present in *Haldanodon* (Lillegrave and Krusat 1991: figs 3 - 5), but the junction of the septomaxilla and premaxilla of the rostrum corresponding to the septomaxillary foramen is not very well preserved in *Haldanodon*. The septomaxilla was also reported in the docodontan *Docofossor* (Luo et al 2015: fig 1). Luo et al. (2015: fig. 1)

further interpreted a septomaxillary foramen through its lateral plate. But this putative foramen interpreted for *Docofossor* could be from a displaced bone piece that would correspond to the well-preserved in the base of the internarial process where the premaxillary foramen is located in *Krusatodon*. To resolve the character variation of the septomaxillary foramen among docodontans would require a full re-segmentation of *Docofossor*'s compressed cranium, which is beyond the scope of this work on *Krusatodon*.

The nasals are preserved in both the adult and juvenile specimen (Extended Data Fig. 2a and e), and are mediolaterally narrowest anteriorly, widening posteriorly to form a large portion of the dorsal part of the rostrum, dorsal to the molars and lacrimals, as in *Haldanodon* (Lillegraven and Krusat 1991). On the endocranial surface of the anterior half of the nasals there are anterioposterior ridges – also observed in the nasals of *Borealestes* (Pancioli et al. 2021), and identified as the base of the nasoturbinate. Anteriorly, the rim of the nasal notch is well preserved in the juvenile *Krusatodon* NMS G.2023.8.1. In *Haldanodon* the midline suture of the nasals suture is described as having many interdigitating laminae (Lillegraven and Krusat 1991: p66). This is not the case along most of the midline internasal suture in *Krusatodon*, or *Borealestes* (Pancioli et al. 2021), but may be true for the posteriormost portion of the suture in the adult *Krusatodon*, although damage in this area makes this interpretation uncertain. No interdigitation is present in this region in the juvenile.

Along the lateral edge of the nasal is a ridge indicating the suture ventrolaterally with the septomaxilla, premaxilla, and maxilla, all of which it underlies (Extended Data Fig. 2g). Pancioli et al. (2021:fig 12B) identified this suture in *Borealestes* nasal fragment NMS G.1992.47.121.4 as being the suture with the maxilla, but based on *Krusatodon*, we suggest in NMS G.1992.47.121.4 it is more likely to be the suture with the septomaxilla, assuming these taxa had a similar skull arrangement.

There are foramina on the dorsal surface of the nasal, approximately in line with the position of I3, the canine, and P3. Posteriorly, the nasal thickens at the temporal ridge of the nasal, and is highly vascularised within the bone, as seen in *Haldanodon* (Lillegraven and Krusat 1991). There does not appear to be a temporal ridge of the nasal in the juvenile, suggesting this may develop later in ontogeny. An alternative hypothesis is that the ridge we identify in the adult NMS G1992.47.122.1, is actually the ridge on the orbital edge of the frontal, as identified in the juvenile NMS G.2023.8.1 (see below). However, we discount this possibility because there is a large foramen in the lateral part of the frontal, clearly visible in the juvenile NMS G.2023.8.1 (Extended Data Fig. 2e), which is not present in the same position lateral to the ridge in the skull of the adult. They therefore do not represent the same part of the skull. The suture with the frontals is not interdigitated as in *Haldanodon*, but appears to be straight in *Krusatodon*, and slants slightly dorsoposteriorly.

Lacrimals and Frontals

The lacrimals are not well preserved in NMS G1992.47.122.1, and are identified mainly through their position relative to other parts of the skull, and features of their internal surface, which resemble the well-preserved lacrimals in *Borealestes* (Pancioli et al., 2021). The right lacrimal is well preserved in the juvenile *Krusatodon*

NMS G.2023.8.1. There are two lacrimal foramina, both of them large and oriented posteriorly (Extended Data Fig. 2a-f). The ventrolateral part of the lacrimal process contributes to the anterior base of zygoma, and it has a deep groove along its lateral margin where it received the anterior part of the jugal. This groove extends to a line level with the lacrimal foramina, indicating a long extension of the jugal wedged between the lacrimal and the zygomatic process of the maxilla. Anterior to this, a ridge continues anteriorly along the ventral lateral edge of the lacrimal, indicating the suture with the maxilla. A ridge on the anterior lateral surface of the lacrimal marks the suture with the overlying nasal, which clearly extends quite far laterally to meet the dorsal edge of the maxilla.

Exactly how the lacrimal contacts the frontals and orbitosphenoid is not clear from these specimens. However, the frontal orbital ridge clearly aligns with the orbital ridge of the lacrimal, the latter extends to the lacrimal foramen, then curves posteriorly to connect with the dorsal portion of the zygomatic arch. This is most clearly seen in the right frontal in NMS G.2023.8.1. The frontal forms the dorsal portion of the orbit, and possesses a large supraorbital foramen on the ventral lateral portion of the frontal, posterior to the contact with the lacrimal, as seen clearly in the left frontal in NMS G.2023.8.1 and in the left frontal in NMS G1992.47.122.1. A suture line on the posterior part of the left frontal in NMS G1992.47.122.1 indicates that the orbitosphenoid and/or epipterygoid overlies the frontal in the middle part of the lateral cranium.

Parietals and Lateral Braincase

The lateral part of the braincase is not well known in early mammaliaforms, as this region is rarely preserved in the fossil record. Although these bones are present in these two specimens of *Krusatodon*, they are broken and so their exact relationship is difficult to decipher. Along its margins, the orbitosphenoid appears to underlie the lacrimal anteriorly, the epipterygoid posteriorly, and the frontal dorsally. This relationship is best preserved in the right hand side of NMS G.2023.8.1. The epipterygoid forms a large portion of the lateral braincase, as evidenced by the suture present on the ventral margin of the frontal and parietal which overlies. It is preserved on the left side of the skull of in NMS G1992.47.122.1, pressed against the endocranial surface of the left petrosal. The suture of the orbitosphenoid and epipterygoid with the pterygoid region is not preserved.

The parietals are large and have a deep midline suture as in *Borealestes* (Pancioli et al 2021), which is straight and not interdigitated. They are raised slightly at the midline and form a very small sagittal and nuchal crest that is stronger than in *Borealestes* but not as prominent as in *Haldanodon* (Lillegraven and Krusat 1990), or *Morganucodon* (Kermack et al. 1981). The parietals contact the postparietal along the posterior edge of the skull, and extend to form a large part of the posterior lateral braincase, except where they underlie the dorsal flange of the squamosals posteroventrally, and the anterior lamina of the petrosal ventrally, similar to *Morganucodon* (Kermack et al. 1981) and *Haldanodon* (Lillegraven and Krusat 1991).

Jugal and Squamosal

The jugal and squamosal of *Krusatodon* are both 'strap like' (as in *Morganucodon*, Kermack et al [1981: p49]), being even more dorsoventrally deep, and mediolaterally compressed (Extended Data Fig. 2a-f). There is a long contact between the anterior extension of the jugal and the lacrimal, extending to a point close to the lacrimal foramen on the lateral part of the lacrimal. This is further anteriorly than suggested for *Morganucodon* (Kermack et al 1981). Posteriorly the jugal widens dorsoventrally and there is a groove where the anterior part of the squamosal sits, and this groove indicates that the zygomatic process of the squamosal almost reaches the jugal's contact with the maxilla, as interpreted for *Haldanodon* (Lillegraven and Krusat 1991).

The squamosal in *Krusatodon* is dorsoventrally deeper than in *Borealestes* (Panciroli et al 2021: figs 19 and 21) or *Haldanodon* (Lillegraven and Krusat 1991), and narrower when viewed dorsally. The glenoid fossa, which articulates with the dentary condyle, is teardrop shaped, shallow and concave as in *Borealestes*, and as in other docodontans there is a mediolateral narrowing of the squamosal just posteromedial to the glenoid facet, which is the constriction between the cranial moiety of the squamosal and the glenoid part of the squamosal (Luo 1994; Ruf et al. 2013). A very shallow entoglenoid recess is visible just posterior to the glenoid facet, and posterior to that a shallow facet indicates where the squamosal contacts the petrosal (see below).

Postparietal, Occipital Region and Basicranium

The postparietal is preserved in both specimens of *Krusatodon*, and appears similar to that seen in *Borealestes*, with both taxa lacking the interparietal described in *Haldanodon* (Panciroli et al 2021; Lillegraven and Krusat 1991). All three docodontan taxa share the vascularisation of the postparietal, which is thickened with foramina on its surface and a bulge down the midline. In *Borealestes* there was no supraoccipital preserved, but in the adult *Krusatodon* NMS G1992.47.122.1, the crushed remnant of a supraoccipital remains in position between the postparietal and the foramen magnum, forming the dorsal rim of the foramen. Damage to this bone makes it unclear if the supraoccipital extended laterally to contact with the parietal, or if only the postparietal and lateral part of the exoccipital extended to the parietal.

The foramen magnum is wide, formed dorsally by the supraoccipital and ventrally and laterally by the exoccipital and occipital condyles (Extended Data Fig. 2d). In *Haldanodon* there are no clear sutures between the basioccipital, exoccipital, and supraoccipital bones (Ruf et al. 2013: p386). In *Krusatodon* it is not clear if the cracks observed in this region are natural sutures, or simply breakage due to compaction. However, there does appear to be a suture between the supraoccipital and exoccipital along the dorsal edge of the occipital condyles. Ventrally, there are two possible suture lines identifiable between the exoccipital and basioccipital, then the basioccipital and basisphenoid. The suture between the exoccipital and basioccipital runs medially along the ventral rim of the occipital condyles and then moves anteriorly at the level of the odontoid notch, creating a 'w-shape' across the basicranium. The basioccipital is anteroposteriorly at its largest between the occipital condyles and the suture with the petrosal. A narrow band connects the left and right

portions of the basioccipital, sandwiched between the exoccipital posteriorly and the basisphenoid anteriorly.

The basisphenoid possesses a keel, which runs anteroposteriorly along the ventral midline of the skull. It is not interrupted into an anterior and posterior keel, as in *Haldanodon* (Lillegraven and Krusat 1991; Ruf et al. 2013). Some nutritive foramina are preserved in the basisphenoid, but throughout the basicranium in NMS G1992.47.122.1 breakage along the edge of the sutures has destroyed major foramina such as the perilymphatic, hypoglossal, and carotid, hindering interpretation.

The petrosals are relatively well preserved, and unlike in *Borealestes*, also preserve the lateral canals and more of the lateral and posterior portions of the petrosals. A full description will be published in a subsequent paper.

Postcrania

Vertebral Column

The vertebrae of *Krusatodon* appear similar to those of *Borealestes* (Pancioli et al. 2022: figs 7-8) and *Microdocodon* (Zhou et al. 2019; supplementary), but with some wider lateral flaring in the caudal vertebrae, similar but not as pronounced as *Castorocauda*. There are at least 35 vertebrae preserved in the adult specimen NMS G1992.47.122.1, and 12-18 preserved in the juvenile NMS G.2023.8.1 (Main Figure 1e-f) – this estimate has been made based on the number of centra, and dorsal portions of vertebrae, that can be confidently identified. Although each region of the vertebral column (cervical, thoracic, lumbar, sacral and caudal) is incomplete, we can identify and assign many vertebrae to each of these regions based on their diagnostic features.

Atlas and Axis

The atlas arches (parts of Cervical 1) and axis (Cervical 2) are present in both specimens, but are best preserved in NMS G1992.47.122.1. The neural arch is preserved in two separate elements in docodontans, as in most early mammaliaforms, a plesiomorphic condition retained from earlier cynodonts and therapsids (Jenkins 1969; Jenkins and Parrington 1976; Pancioli et al. 2021). In *Krusatodon* the atlas arches are not co-ossified with the ventral lamina or with each other, as seen the ring-like structure of atlas in crown mammals. *Krusatodon* is identical to *Borealestes* (Pancioli et al. 2022) in these two preserved parts, except for the larger and wider ventrolateral projection in *Krusatodon*, forming a flange projecting ~8 mm laterally (compared to ~2 mm in *Borealestes*). This projection is the base for contact of the dorsal head of the two-headed cervical rib (transverse process of the atlas). By this pattern of preservation, we infer that the transverse process (atlas cervical rib) was not fused to the neural arch in *Krusatodon*, a plesiomorphic pattern of mammaliaforms, also known from some nonmammaliaform cynodonts (Sues and Jenkins 2006). The arch elements are convex laterally and bear the anterior facing articular area for the occipital condyle and the posterior-facing facet for articulating with the axis body. Both of these facets are slightly concave and oval in shape. The articular area for the occipital is larger and projects strongly anterodorsally.

The axis (C2) is large. Its centrum is dorsoventrally compressed, and the peg-like dens is solidly fused to the centrum. The centrum is missing its posterior end, and the neural arch with its zygopophyses is missing. Also the transverse process (axis cervical rib) is missing, and inferred here to be un-fused to the axis body. The preserved parts of the atlas and axis are similar to those described for *Kayentatherium* (Sues and Jenkins 2006), *Morganucodon* (Jenkins and Parrington 1976) and for *Borealestes* (Pancirolì et al. 2022: fig7).

Postaxial Vertebrae and Hemal Arches

Five vertebrae can be assigned to the cervical series in NMS G1992.47.122.1. They are identified based on size, and the two processes respectively from the neural lamina and from the centrum, for articulation of the two-headed cervical rib. The ribs themselves for the identified cervicals are missing, presumably because the ribs had not been fused to the main body of the vertebra to encircle the transverse foramina, as typical in adults of extant mammals. These cervicals show also thin neural arch with horizontally oriented zygapophyses and without the dorsal neural spine, as in many small extant mammals. Their vertebral centra are oval-shape dorsoventrally lower than wide. The total number of identified cervical is seven (atlas, axis and five postaxial cervicles), as typical for extant mammals and other well preserved docodontans (e.g., *Agilodocodon* and *Microdocodon*).

There are approximately nine vertebrae that can be unambiguously assigned to the thoracic series in NMS G1992.47.122.1. They indicate that *Krusatodon* possessed long dorsal spines with length twice that of the centrum, similar to *Borealestes* (Pancirolì et al. 2022:figs 7-8). Three of these vertebrae are most probably from the anterior thoracic region where vertebral column is curved (slightly concave dorsally) through the cervico-thoracic transition. The thoracics in this section commonly have longer dorsal spines than succeeding thoracics. Two thoracics with shorter spinal processes are likely from the middle part of the thoracic region. Two partly articulated vertebrae are from the thoraco-lumbar transition, the zygapophyseal facets are partly vertical in these, which can be either a diaphragmic vertebra (one of the last thoracics), or a lumbar. One thoracic is represented by the centrum with stumps of incomplete neural lamina, but it is separated from broken neural arch by a short distance. This is tentatively identified as a thoracic. The total number of preserved thoracics is 10 or 11.

Two vertebrae can be identified, unambiguously, to the lumbar series of NMS G1992.47.122.1, with an additional one vertebral centrum also likely lumbar by its cylindrical shape. The two well preserved lumbar have intact pre- and post-zygapophyses with vertically oriented articular facets, which are the diagnostic features of lumbar series. These two lumbar also show a low neural spine on a median ridge, as seen in better preserved vertebral series of *Microdocodon* (Zhou et al. 2019:fig s11). Only one is well preserved, and the neural spine is a low ridge as in *Microdocodon*. One lumbar vertebra identified here for *Krusatodon* also shows the deep notch below the postzygapophysis similar to the fossa for vertebral foramen in *Microdocodon* (Zhou et al. 2019: figure s11).

There are 17 caudal vertebrae preserved in NMS G1992.47.122.1. There are 21 caudals in the well preserved caudal series of *Microdocodon* (Zhou et al. 2019) and 25 caudals preserved in *Castorocauda* (Ji et al. 2006), so we interpret that a large portion of the caudal series are preserved in the adult of *Krusatodon*. These include two from an anterior position – likely between ca1-ca6 based on the expanded transverse process of both sides of the centrum, and a half vertebra with a rectangular process, which are similar to the most proximal caudals of *Castorocauda*. The caudal vertebrae have strong transverse processes, as present in the caudal vertebrae nearest the pelvis in all mammals including *Castorocauda*. The next set of four caudal vertebrae are oblong and dorsoventrally compressed, which are comparable in shape to the other anterior caudals (Ca5 through Ca9), as seen in *Microdocodon*. The rest of caudal vertebrae are from approximately ca10 posteriorly. Three or four of the distal caudals are rod-like and elongate, similar to the pattern in the caudal vertebrae of more derived cladotherian *Henkelotherium* (Krebs 1991; Jäger et al. 2019). The morphology of these vertebrae indicates that the tail of *Krusatodon* was long and tapering, wider proximal to the body, similar to the known caudal vertebral column morphology of *Microdocodon*. The individual caudal vertebrae are also similar to the best preserved caudals currently known from *Borealestes* (Pancioli et al. 2021:fig 7Q).

There are 9 hemal arches preserved in NMS G1992.47.122.1: two larger proximal/anterior arches, four from a more distal position in the tail, and the three very small arches from a more distal position than the rest. We interpret that these larger and longer hemal arches were likely to be associated with the anterior (post-pelvic) caudals with oblong outlines. The size of the proximal hemal arches supports the interpretation that *Krusatodon* had a thick tail base nearest to the body.

The vertebrae of the juvenile *Krusatodon*, NMS G.2023.8.1, are less well preserved than in the adult specimen, but include one of the sacral vertebrae (see below and Pelvic Girdle), not present in NMS G1992.47.122.1. Based on the size and shape of the preserved centra and comparison with the adult specimen, most of the vertebrae in NMS G.2023.8.1 are from the lumbar and thoracic regions of the spine. The dorsal portions of the vertebrae are separated from the centra and broken into fragments, but three preserve a partial thoracic spine.

The juvenile *Krusatodon* has preserved two sacrals that are fused together (Extended Data Fig. 6c-d). This offers important information on the sacrals that missing from the adult specimen. The fused transverse processes of the sacrals form a continuous surface for the iliosacral contact. Overall, the configuration of the sacrals in *Krusatodon* are similar to the sacral vertebrae described for *Morganucodon* (Jenkins and Parrington, 1976). The left transverse process of an anterior caudal is preserved in NMS G.2023.8.1, similar to that seen in the adult specimen. There is only one, very large caudal vertebra preserved, and based on comparison with the adult *Krusatodon*, *Castorocauda* and *Microdocodon* this is likely from position ca8-ca13 – posterior to this the caudal vertebrae are much less laterally flared in the adult. Its size suggests that *Krusatodon* juveniles also had a very large tail proximally.

Ribs

At least 32 ribs are preserved in NMS G1992.47.122.1, based on the number of rib heads present, and most are preserved in a cluster around the skull (Main Figure 1). A few are relatively complete, but most are broken into smaller sections. They include smaller, possibly cervical ribs, to larger thoracic ribs with larger tubercles and distinct capitulae.

The number of ribs in NMS G.2023.8.1 is hard to estimate, because all are fragmentary and few are in any discernible alignment to suggest they belong together. We tentatively suggest portions of at least 10 ribs are present, based on the size and relative proportions of the fragments. The longest fragment preserved is 0.39 mm in length.

Appendicular Skeleton

Pectoral Girdle

The scapulacoracoid is present in the adult, and the ventral portion of it in the juvenile specimen. The procoracoid is intact with the scapula in both juvenile and adult of *Krusatodon*. With the interclavicle and scapulacoracoid known from *Microdocodon*, and the multiple scapulas of *Haldanodon*, this new finding of *Krusatodon* can provide a comprehensive understanding of the shoulder girdle of docodontans (see S5. Loss of Procoracoid for discussion and Extended Data Fig. 8).

In the adult, NMS G1992.47.122.1, the coraco-glenoid are well preserved, and the acromion is intact in the left scapulacoracoid, and in the right it is detached but present. Both scapulacoracoids include the lower half of the scapular blade, but only the left preserves the dorsal portion of the blade, which, although crushed, is comparatively intact in its position pressed against the cranium. In the juvenile specimen, NMS G.2023.8.1, only the lower part of the coraco-glenoid is preserved intact.

From these specimens it is clear that the procoracoid is present in *Krusatodon*, as in *Sinoconodon*, and *Morganucodon* (Jenkins and Parrington 1976; Meng et al. 2017). The procoracoid has a procoracoid foramen, well preserved in both the adult and the juvenile of *Krusatodon*. This bone is similar to those of *Sinoconodon*, *Morganucodon*, and the haramiyidan *Maiopatagium* (Meng et al. 2017: fig4 and video S1). The procoracoid foramen appears to be absent in *Haldanodon* and *Borealestes*. The procoracoid foramen is excluded from the glenoid facet in *Krusatodon*, and the glenoid facet is laterally facing as in all docodontans and early mammaliaforms. But in *Microdocodon* the region of the procoracoid is compressed onto the interclavicle-sternal apparatus; the preservation status of its procoracoid needs to be reassessed. The procoracoid foramen appears to be absent in *Haldanodon* and *Borealestes*. For more discussion on procoracoid and implications for this feature in the evolution of mammals, see 'Loss of the Procoracoid in Mammaliaforms'.

The glenoid facet is oval, elongate and saddle-shaped, formed from both the dorsal part of the coracoid and the ventral part of the scapula. The scapulo-coracoid suture lies just above the dorsoventral midpoint of the glenoid facet. The coracoid is approximately 69% of the length of the glenoid facet in *Krusatodon* (coracoid is approximately 3.2 mm, glenoid is 4.6 mm), which is quite different from *Haldanodon*

at 86% (coracoid 3.2 mm, glenoid 3.7 mm) and *Borealestes* 79% (coracoid 2.2 mm, glenoid 2.8 mm). It has been illustrated that the coracoid part of the glenoid facet is longer than the scapular part of the glenoid in the stem mammaliaforms *Morganucodon* and *Sinoconodon*, and in the cynodont *Kayentatherium* (Sues and Jenkins 2006) in contrast to other cynodonts (Fahn-Lai et al. 2018). The anterior “hook-like” process of the coracoid is shorter in the latter taxa than the length of the glenoid articulating facet in adult *Krusatodon*. The shorter proportion of the coracoid anterior process versus the glenoid facet is a derived pattern of all docodontans for which this part of the anatomy is preserved. and for haramiyidans (Meng et al. 2017; Zhou et al. 2019), compared to the condition of cynodont outgroups (Sues and Jenkins 2006; Fahn-Lai et al. 2018). Extant monotremes have a hypertrophied procoracoid that lacks the procoracoid foramen, and this bone is so large as to reach and overlap with the interclavicle. Monotremes are distinct from cynodonts and docodontans in these features, which are considered here to be an autapomorphic condition (Luo 2015; Meng et al. 2017; Regnault et al. 2020), distinct from fossil mammaliaforms.

The scapula has a trough-like infraspinous fossa, which appears to occupy the main part of the blade, as in *Sinoconodon*, *Morganucodon* and *Haldanodon* (Martin 2005; Luo 2015). This is identified in *Tachyglossus* as the insertion for the infraspinitus, permitting humeral external rotation (Gambaryan et al. 2015; Fahn-Lai et al. 2018; Regnault et al. 2020). The postscapular fossa of Martin (2005:fig 3) identified in *Haldanodon* is present and well-developed in *Krusatodon*. This is for the origination of the teres major muscle in *Tachyglossus* (Regnault et al. 2020), permitting humeral internal rotation and powerful flexion and retraction of the humerus to the scapula (Martin 2005). The scapula in *Krusatodon* (and *Haldanodon*) is proportionally narrower anteroposteriorly than in *Tachyglossus*, similar to the proportions of *Ornithorhynchus*. The acromion is longer than in *Borealestes*, with its tip extending ventrally almost to the level of half way along the glenoid facet, approximately to the level of the scapula-coracoid suture.

There is one clavicle (Extended Data Fig. 6a), and the paired manubria (Extended Data Fig. 6b), preserved in NMS G1992.47.122.1, but the interclavicle is not preserved. The clavicle is curved, and the proximal end is wide and flat for articulation with the interclavicle, more so than in *Sinoconodon*, in which it is more pointed (Luo 2015; Meng et al. 2017), or *Borealestes* (Panciroli et al. 2022). In *Microdocodon* the jagged medial end of the clavicle suggests that they are joined in a midline suture in that taxon (Zhou et al. 2012: Supplementary Online Materials: p34). However, it is not clear whether the rough medial end of the clavicle in *Borealestes* is evidence of a jagged midline suture in that taxon, or a post-mortem breakage. In monotremes the clavicles meet midline (Cave 1970; Bendel et al. 2022) and are sutured to the interclavicle. In Mesozoic theriimorphs including eutriconodonts and multituberculates, the clavicles do not meet in the midline, as exemplified in *Repenomamus* and *Yanoconodon* (Chen et al. 2017: fig 7). The medial ends of clavicle have separate and have a mobile articulation to the interclavicle. The interclavicle lost in adult crown therians (Klima 1973), although the anlagen of interclavicular identity are incorporated into the fused manubria (Brent et al. 2023). The clavicles of extant therians directly articulate with the fused manubrium.

The claviculo-acromion contact on the clavicle is concave, similar to *Borealestes* (Panciroli et al 2022), but unlike the more rounded end in *Agilodocodon* and *Microdocodon*, or the pointed lateral end of the clavicle in monotremes. The paired manubria with a median suture-line in *Krusatodon* are similar to *Microdocodon*, with a distinct anterolateral facet for contact with thoracic rib 1, and a posterolateral facet for contact with rib 2 (Zhou et al. 2012: Supplementary Online Materials: p34). As in *Microdocodon* and other docodontans for which these elements are known, the clavicle, interclavicle and manubria are not fused.

Humerus

There are two well preserved humeri in NMS G.1992.47.122.1, and a single left humerus in the juvenile NMS G.2023.8.1 (Extended Data Fig. 6g-h). The latter is well preserved distal to the estimated position of the teres tuberosity, but the proximal portion of the humerus is crushed, and the humeral head detached (Extended Data Fig. 6h). The length of the adult humeri is approximately 16.5 mm, and the length of the juvenile NMS G.2023.8.1 is estimated at 11 mm.

The proximal and distal ends of the humerus are strongly rotated relative to one another (approximately 90 degrees), known as humeral torsion, as in many mammaliaforms, monotremes and some crown therians. The humeral head is subspherical, and the lesser tubercle is wider than the greater tubercle, all as in other docodontans (except *Microdocodon*, in which the lesser tubercle is narrower, Zhou et al. 2019). The deltopectoral crest extends just over one third of the length of the humeral shaft (Extended Data Fig. 6g), and the teres tuberosity is more developed than in *Agilodocodon*, but much less developed than in *Borealestes* or *Haldanodon*.

The ulnar condyle and the radial condyle are positioned close to one another. The ulnar condyle projects further distally than the radial condyle, unlike in other docodontans. The radial condyle is spherical and large. The entepicondyle and ectepicondyle both flare strongly, as in many other docodontans except *Microdocodon* and *Agilodocodon*; the width compared to humeral length (approximately 47%) is wider than in *Microdocodon* (approximately 39%), but less than in *Haldanodon* (61%) or *Borealestes* (57%) (Martin 2005; Zhou et al. 2019; Panciroli et al 2022).

The most obvious differences between the humeri of the juvenile and adult *Krusatodon* is in the fuller development of the radial and ulnar condyles and much greater width of the distal portion of the humerus in the adult. The condyles are slightly larger and more bulbous and the distal humerus proportionally wider in the adult. This likely reflects the fuller development of ossification of the long bones in a more mature individual. Similar differences between limb bones from different ontogenetic stages has been observed in the femur of *Haldanodon*, in which the trochanters are more developed in ontogenetically older individuals (Martin 2005: p231). The strengthening and continual use of muscles that attach to the entepicondyle and ectepicondyle of the humerus likely leads to remodelling and enlargement of these areas. We infer that the enlarged entepicondyle correspond to stronger flexors of the forearm and the wrist, and for stronger insertion of the latissimus dorsi, as seen in *Tachyglossus* for example (Gambaryan et al. 2015;

Regnault et al. 2020). The enlarged ectepicondyle suggest strong muscle action for outward rotation of the forearm and extension of the elbow and wrist.

We can estimate the growth range from one year to late maturity (~6 years) for *Krusatodon kirtlingtonensis* using the length of the humeri and age estimates provided by cementum (see S6. Cementum Data). The age of six years in the adult *Krusatodon* is likely to represent the upper limit of longevity for this taxon, as supported by other studies of cementum data for docodontans (Newham et al. 2020). The juvenile *Krusatodon* humerus is 67% the length of the adult, so we can infer that the humerus reaches 67% of the adult length when juvenile is between 1/6th to 1/3rd of the adult lifespan.

In the marsupial *Didelphis virginiana*, the length of humerus is ~70 mm in fully grown adults, and full growth is reached at around 340 days (Maunz and German 1997), which is approximately 14% of their average 6.6 year maximum life span. The humerus in *Didelphis* reaches 67% of adult humerus length (46 mm) at around 150 days, or 6% of the maximum adult lifespan. This suggests that growth is significantly slower in *Krusatodon* than in extant mammals such as *Didelphis*, consistent with the pattern seen the tooth development, cementum layers, and body mass data for *Krusatodon kirtlingtonensis*.

Radius and Ulna

The radii and ulnae are preserved in NMS G.1992.47.122.1, all four bones are fractured post-mortem but their morphology is otherwise well-preserved (Extended Data Fig. 6i-j). The proximal left ulna is present in NMS G.2023.8.1 (Extended Data Fig. 6k). Overall the radius and ulna are less robust than in docodontans inferred to be capable diggers and swimmers, such as *Haldanodon* or *Docofossor*. The radius is approximately 81% the length of the ulna, proportionally longer than in *Haldanodon* (70%, Martin 2005: p228) – or *Tachyglossus*, at 72%. The radius/humerus length ratio is 106% for *Krusatodon*, which is similar to that seen in the small gracile docodontan *Microdocodon* (112%).

The radii are slightly wider at the distal end than the proximal, and the proximal end has a cup-shaped and projecting articular fovea that slopes medially (Extended Data Fig. 6i), as in *Borealestes*. The radius of *Krusatodon* is slightly more slender than in *Borealestes* or *Haldanodon*, and there is a blunt styloid process on the medial side of the distal end.

There is little difference between the adult and juvenile ulnae, although the semi-lunar notch is slightly deeper and better defined in the adult, and the olecranon process more distinct. The proximal part of the ulna, including olecranon and articulation facets, comprises much less than half of the ulnar length in *Krusatodon* (36%), unlike in *Haldanodon* at 48% (Martin 2005: p228), but more similar to *Borealestes* at 30% (Panciroli et al 2022: p24). The olecranon process is curved medially – a feature of all docodontans – and in the well-preserved right ulna of NMS G.1992.47.122.1 there is a clear projection on the medioventral edge, as seen in *Borealestes* (Panciroli et al 2022: fig 12).

Pelvic Girdle

In NMS G.1992.47.122.1 both ilia are preserved, the right virtually intact and the left with a crushed iliac blade detached from the acetabular portion bearing the iliac acetabular facet (Extended Data Fig. 6l). The right ischium and pubis are both preserved relatively intact, with some crushing to the ischial plate (Extended Data Fig. 6l). In the juvenile NMS G.2023.8.1, only the posterior part of the left ilium is preserved – the medial side is crushed and pushed laterally, but the lateral surface is intact (Extended Data Fig. 6m). The iliac blade is not preserved in NMS G.2023.8.1. The acetabulum comprises approximately equal contributions from the ilium, ischium and pubis, as is other fossil mammaliaforms.

The ilium is similar to other docodontans in shape, being more paddle shaped rather than the pointed spear-like shape of the iliac blade in tritylodontids and morganucodontids. The medial surface of the ilium has a distinct sacroiliac contact area, delineated by a ridge posteriorly that extends to the posterior ilium process (sacral tuber). The posterior ilium process is less pronounced than in *Haldanodon*, and the anterior process (coxal tuber) is prominent. The sacroiliac contact area is convex medially, and the blade-like iliac blade is slightly concave laterally. The gluteal line, a prominence along the length of the ilium found in mammals that extends from the rim of the acetabulum toward the iliac blade, is present in *Krusatodon* on the posterior part of the ilium, but only weakly on the iliac blade.

The ischium of *Krusatodon* is similar to that of other docodontans, and morganucodontids. The dorsal and posterior margins of the obturator foramen are formed from the evenly rounded ventral surface of the ischium, as seen in *Microdocodon* (Zhou et al 2019) and *Morganucodon* (Jenkins and Parrington 1976). Although the ischiopubic symphysis is damaged, it is clear that the anterior and dorsal margins of the obturator foramen is formed by the pubis. The anterior rim of the obturator foramen is formed predominantly from the pubic neck and acetabular parts of the pubis, and is nearly straight and slopes posterodorsally. Overall this gives the obturator foramen a teardrop shape.

There is a deep acetabular notch in the pubis, located ventral to the ischiopubic suture. The ischial plate is relatively thin and large, flaring strongly from the ischial neck, and the ventral half curves medially to meet the symphyseal contact with the pubis, and the contact with the opposite ischium.

The pubis contributes a wide shallow acetabular surface, with a strong ridge along the anterior rim of the acetabulum. There is a constriction to form a pubic neck, and a distinct pubic tubercle emerges ventrolateral to the neck. Anterior to the tubercle lies the contact surface for the epipubic bone in *Krusatodon*, located on the ventrolateral surface of the pubis. The epipubic bone itself cannot be identified from among the bones present in NMS G.1992.47.122.1 or NMS G.2023.8.1. There is no evidence yet for the epipubic bone in Morganucodontans (Jenkins and Parrington, 1976), however a probable epipubis was identified in *Castorocauda* (Ji et al. 2006), and a similar contact area for the epipubic bone is evident in the pubis of *Microdocodon* (Zhou et al 2019: sp35), so it can be inferred for docodontans as a whole. They are also present in the close outgroup of mammaliaforms, tritylodontids. This supports the assertion that the presence of an epipubic bone is plesiomorphic for mammaliaforms.

Femur

A single left femur is preserved in the adult, NMS G.1992.47.122.1, which includes the shaft of the femur and a relatively intact distal end (Extended Data Fig. 6e-f). The femur is approximately 19 mm in length. The proximal part of the femur is damaged, but the femoral head and greater trochanter are present, although both are situated a short distance from the broken proximal end of the femoral shaft. The lesser trochanter is not preserved, and the third trochanter is absent on the shaft of diaphysis.

The expanded distal end of the femur is certainly wider and more robust than *Morganucodon*, *Microdocodon* or *Borealestes* (Jenkins and Parrington 1976; Zhou et al. 2019: s10; Panciroli et al, 2022). It is similar to the femur of *Haldanodon* (Martin 2005). The lateral condyle in *Krusatodon* is much larger than the medial condyle – more so than in *Krusatodon* – it is bulbous on the articular surface, and forms a shelf where it meets the distal end of the femoral shaft. There is a deep intercondylar fossa, and a patellar groove on the dorsal surface of the distal femur.

Tibia

Two tibiae are preserved in NMS G.1992.47.122.1, the left tibia is intact (Extended Data Fig. 6n and p), and the right is complete but broken twice, just below the proximal end, and halfway down the tibial shaft. There is no fibula present in either specimen of *Krusatodon*. The proximal part of the tibia is laterally flared and forms a strong proximo-lateral tuberosity, similar in overall appearance to the proximal tibia of *Morganucodon* (Jenkins and Parrington 1976: fig 15), and *Microdocodon* (Zhou et al. 2019: fig S10G). In *Haldanodon* the tibia is stouter, approximately the same length as the humerus – whereas the tibia is longer than the humerus in *Krusatodon* and the entire proximal half of the bone being proportionally wider (Martin 2005: fig 13).

There is a well-developed, peg-like distal tibial malleolus (Extended Data Fig. 6p), a feature shared with *Agilodocodon*, *Microdocodon* (Zhou et al 2019: figs s10G, s11B and s12), and *Docofossor* (Luo et al 2015: figS1), but not detected in *Haldanodon*, although this area was partially obscured in the specimen described by Martin (2005: p231). The medial tibial condyle and lateral tibial condyle, as exemplified by multituberculates (Yuan et al 2013:fig S5), are not well differentiated in other docodontans or other non-mammalian mammaliaforms. However, the medial and lateral tibial condyles are better differentiated in *Krusatodon*, and the medial tibial malleolus is well-developed (strongly projecting distally).

In docodontans the distal tibial malleolus articulates with the astragalar medial concavity. In multituberculate mammals *Rugosodon* and *Eucosmodon*, the medial and lateral tibial condyle articulate with the medial astragalotibial facet and lateral astragalotibial facet (respectively) of the astragalus (Yuan et al. 2013: fig 3B and E) previously characterised by Jenkins and Krause (1983). Zhou et al. (2019) noted that when the peg-like distal tibial malleolus of *Microdocodon* was in articulation, it would 'guide the other part of distal tibia to glide in the dorsal trochlea of the astragalus' (Supplementary p37). This is somewhat similar to the tibio-astragular configuration

described in *Rugosodon* and *Eucosmodon* (Extended Data Fig. 6o). In all three taxa it is linked to increased mobility in the ankle joint, supporting arboreal capabilities. However the tibia/femur ratio in *Krusatodon* is approximately 91%, much less than in arboreal docodontans *Agilodocodon* and *Microdocodon* (116%, Zhou et al. 2019). The shape of the astragalus (see below) suggests that the mobility may be related to foot posture.

A faint epiphysial line is present on the distal tibia, demarcating the distal articulation from the shaft of the tibia (Extended Data Fig. 6n). This is also present in tibia and fibula of *Microdocodon*, but is absent from the other long bones of this taxon (Zhou et al. 2019: SP35-36). This also appears to be the case in *Krusatodon*; although the distal ulnae are damaged, the distal radii do not appear to have an epiphysial line.

Manus and Pes

There are a single left calcaneus (Extended Data Fig. 7b-f) and astragalus (Extended Data Fig. 7k-m), 14 carpal/tarsal elements, at least 29 metatarsals/metacarpals and 4 terminal phalanges preserved in NMS.G.1992.47.122.1, none of them in articulation – a speculative reconstruction of the right manus and pes has been attempted (Extended Data Fig. 7a-b), to demonstrate what the manus and pes may have looked like. There are one carpal/tarsal, five metatarsals/metacarpals, and three terminal phalanges in NMS G.2023.8.1. The placement of the unidentified elements in the reconstructions of the right manus and pes is speculative.

Overall, the calcaneus is morphologically similar to those of *Morganucodon* and eutriconodontans (Jenkins and Parrington 1976; Szalay 1994; Chen et al. 2017). The calcaneus of *Krusatodon* resembles other docodontans, and is superficially similar to that of *Borealestes* (Panciroli et al. 2022:fig 16), but slightly more elongate, as in *Agilodocodon*. In *Borealestes* the astragalar facet and the calcaneofibular facet are more rounded and project further, whereas in *Krusatodon* the calcaneofibular facet is flattened and the astragalar facet comprises a small rounded protrusion anteriorly before sweeping back towards the calcaneal sulcus. The calcaneal tuber is ventrally oriented and ends in a slight swelling, as in *Agilodocodon* and other Chinese docodontan species to date. The gently concave cuboid facet is strongly ventrally oriented with a distinct ventral rim. There is some damage to this rim, but it appears that it rims laterally to join the projection ventrolateral to the sustentacular facet and calcaneal sulcus.

The astragalus is very similar to *Docofossor* (Luo et al 2015:fig 3) in that the tibial malleolus provides a 'pivot in the medial concavity of the astragalus' (p762). This is similar to the morphology seen in the astragalus of monotremes, in which the distal tibial facet glides over the medial trochlear crest of the astragalus, enabling habitual abduction of the foot relative to the limb. *Krusatodon* has a longer astragalar neck than other docodontans except *Docofossor*, with a slightly constricted neck narrower than the head, unlike *Docofossor*.

There is an os calcaris with an ossified cornu calcaris preserved in NMS.G.1992.47.122.1 (Extended Data Fig. 7h-i). Such venomous spurs are present in living monotremes, and fossil mammals including the eutriconodontan *Gobiconodon* (Jenkins and Schaff, 1988) (Extended Data Fig. 7j), the spalacotheroid

Zhangotherium (Hu et al., 1997), and a number of multituberculates (Hurum et al. 2006). It has been suggested that this feature is plesiomorphic for mammals (Hurum et al. 2006), and the presence of this structure in *Krusatodon* suggests they may be plesiomorphic for Mammaliaformes. The remaining elements of the wrist and ankle are difficult to identify with certainty, but may include a cuboid, navicular, hamate and trapezium. The only wrist/ankle element preserved in NMS G.2023.8.1 is also present in NMS.G.1992.47.122.1.

The phalanges of *Krusatodon* (Extended Data Fig. 7a) are more elongate and slender than those of *Haldanodon* (Martin 2005:figs 14-15) or *Borealestes* (Pancioli et al. 2022:figs 14-15). The terminal phalanges of *Krusatodon* (Extended Data Fig. 7a-b and g) resemble those of other docodontans, being long and dorsoventrally curved, slightly narrow mediolaterally, and possessing a lateral groove on either side for attachment of the claw sheath in the living mammals. The terminal ungual shows a large proximal flexor process and proximal overhanging process.

S3. Phylogenetic Analysis

The new cranial and postcranial material for *Krusatodon* NMS. G.1992.47.122.1 and juvenile NMS G.2023.8.1 were scored to assess the phylogenetic placement of *Krusatodon* within Docodonta. For this we employed the matrix of Analysis 4 in Pancioli et al. (2022), and we amended characters 19, 20, 43, 55, 82, 90, 132, 177, 206, 207, 233, 268, 335, 505, 519, 525, where our interpretations differed from previous authors (for details see Supplementary Table 6). This matrix includes 129 taxa scored for 556 characters: 40 mandibular; 187 dental; 145 postcranial; 176 cranial characters and 8 soft-tissue characters. In total we scored 352 characters (63%) for *Krusatodon*.

Supplementary Table 6: Characters in phylogenetic analysis updated from matrix of Pancioli et al. (2022).

Character	Taxon/Taxa Changed	Reason for change
#19. Pterygoid muscle fossa on the medial side of the ramus of the mandible: (0) Absent; (1) Present.	Change this from 1 to 0 in <i>Borealestes</i> and <i>Haldanodon</i>	This is marked as present in <i>Haldanodon</i> in the analysis in Zhou et al. (2019), presumably due to the recent interpretation of the muscles of the posterior portion of the dentary in Schultz et al. (2019:fig 6). Pancioli et al (2022) therefore also included it for <i>Borealestes</i> . But this 'fossa' is here interpreted as being too indistinct in <i>Borealestes</i> and <i>Haldanodon</i> to be scored as 1.
#20 Medial pterygoid ridge (shelf) along the ventral border of the body of the mandible: (0) Absent; (1) Present; (2) Pterygoid shelf present and reaching the dentary condyle via a low crest.	Changed <i>Borealestes</i> back to 0.	Like for #19, it's not entirely clear what to score for this. If we're talking about the large area for the insertion of the pterygoid on the medial part of the dentary below the postdentary trough, then it should be scored (1) for <i>Borealestes</i> , <i>Haldanodon</i> , <i>Docodon</i> , and possibly <i>Microdocodon</i> (based on the figures in Zhou et al. 2019). But is that really the same structure as this is referring to? See Schultz et al. (2019) for some discussion of this muscle, which is not shown to be as extensive in other early mammaliaforms, and might be linked to tooth complexity and function in Docodonta.
#55 Ultimate lower premolar—symmetry of the main (middle) cusp a (= protoconid): (0) Asymmetrical (anterior edge of cusp a is more convex in outline than the posterior edge); (1) Symmetrical (anterior and posterior cutting edges are equal or subequal in length; neither	Changed <i>Haldanodon</i> from (1) to (0)	Based on our observation and interpretation.

edge is more convex or concave than the other in lateral profile).		
#82 Relationships between the cusps of the opposing upper and lower molars: (0) Absent; (1) Present, lower primary cusp a occludes in the groove between upper cusps A, B; (2) Present, lower main cusp a occludes in front of the upper cusp B and into the embrasure between the opposite upper tooth and the preceding upper tooth; (3) Present, parts of the talonid occluding with the lingual face (or any part) of the upper molar; (4) Lower multicuspsate rows alternately occluding between the upper multicuspsate rows; (5) Columnar tooth without cusps and with beveled wear across the entire crown contact surface.	Changed docodontans to (2)	It is (2) for Docodon, according to the Schultz et al (2019) paper, and this is applicable to all docodontans.
#90 Protoconid (cusp a) and metaconid (cusp c) height ratio (on the lower second molar): (0) Protoconid distinctively higher; (1) Protoconid and metaconid nearly equal in height.	Changed from (?) to (0) in <i>Haldanodon</i> .	Based on our observation and interpretation.
#132 Height and size of upper molar cusp B and cusp C (metacone) of triconodont-type molariform (based on the upper second molar if available): (0) Paracone noticeably higher and larger at the base than metacone; (1) Paracone and metacone of equal size or paracone, or sub-equal.	Changed docodontan scores to (?)	N/a to docodontans because they don't have triconodont dentition.
#177 Number of upper incisors: (0) Five; (1) Four; (2) Three; (3) Two; (4) One; (5) No incisors.	Changed <i>Haldanodon</i> from (1) to (0).	There are 5-6 in <i>Haldanodon</i> , so changed from (1) to (0).
#206 Enlarged diastema in the lower incisor-canine region (better developed in older individuals): (0) Absent; (1) Present and behind the canine; (2) Present and behind the posterior incisor.	Changed from (?) to (0) in <i>Borealestes</i> .	Based on our observation and interpretation.
#207 U-shaped transverse ridge in the lower multi-rowed molars: (0) Absent; (1) Present, at second anterior cusp; (2) Present, at the anterior rim.	Changed from (0) to (?) in docodontans	There are no multirowed molars in docodontans, so following other scoring above, this is not applicable.
#233 Anticlinal vertebra: (0) Absent; (1) Present.	Changed from (0) to (1) in <i>Castorocauda</i>	Scored as present in the following character #234
#268 Teres tuberosity on medial side of humerus. (0) Absent; (1) Present; (2) Hypertrophied.	Changed from (2) to (1) in <i>Borealestes</i>	Panciroli et al (2022) scored <i>Borealestes</i> (2), but amended here to (1) based on our observation and interpretation.
#335 Anterior ventral (plantar) tubercle of the calcaneus: (0) Absent; (1) Present, at the anterior edge (just lateral to the cuboid facet); (2) Present, set back from the anterior edge.	Changed the scores that were (3) to (2)	Some taxa in matrix are scored (3) for this, even though there is no state (3).
#505 External bulging of the braincase in the parietal region: (0) Absent; (1) Expanded (the parietal part of the cranial vault is wider than the frontal part, but the expansion does not extend to the lambdoidal region); (2) Greatly expanded (expansion of the cranial vault extends to the lambdoidal region).	Changed <i>Borealestes serendipitus</i> from (?) to (0)	Based on our observation and interpretation.
#519 Contact between nasals and parietals: (0) Absent; (1) Present.	Changed <i>Borealestes</i> species from (?) to (0)	Based on our observation and interpretation.
#525 Lambdoidal (nuchal) crest orientation in lateral view: (0) Vertical orientation; (1) Forms a posterior flare and overhang on lateral portion of lambdoidal crest; (2) Forms a posterior flare and overhang on median portion of lambdoidal crest (e.g., therians and stem-therians).	Changed <i>Borealestes serendipitus</i> from (?) to (0)	Based on our observation and interpretation.

As for Panciroli et al. (2022), we carried out parsimony analysis using PAUP v.4 (Swofford 2003). A heuristic search was carried out with equally weighted characters, unordered, using the tree bisection reconnection (TBR) branch swapping algorithm, with a reconnection limit of 8 and steepest descent option in effect. We

used stepwise addition with one tree held at each step, random addition sequence, 5000 replicates, and MulTrees was turned on.

Our analysis returned a tree of 2862 steps, and the scores for this tree can be found in Supplementary Table 7 (full tree in Supplementary Files). The topology of Docodonta is similar to Panciroli et al. (2022), placing *Krusatodon* in a clade with *Borealestes* (Extended Data Fig. 1q). Additionally, our analysis found *Castorocauda* and *Docofossor* to be sister taxa, recovering *Haldanodon* on its own as the sister taxon to all other docodontan taxa in this analysis. This also supports the findings in Panciroli et al. (2019, 2021) that the previously proposed clades within Docodonta, Docodontidae and Tegotheriidae, are paraphyletic.

Supplementary Table 7: Scores for the tree in our analysis. CI, consistency index; HI, homoplasy index; RI, retention index; RC, rescaled consistency index.

Length	2862
CI	0.314
HI	0.686
RI	0.801
RC	0.251

S4. Loss of the Procoracoid in Mammaliaformes and Mammalia

The shoulder girdle connects the forelimb to the axial skeleton, and has undergone many changes in the transition from pre-mammalian cynodonts to mammals. The presence of the procoracoid is a plesiomorphic character in cynodonts, being present in *Oligokyphus* (Kühne 1956), *Sinoconodon*, and *Morganucodon* (Luo 2015; Meng et al. 2017). It is also present in the eleutherodont haramiyidan *Maiopatagium* (Meng et al. 2017). It was proposed to have been lost in the common ancestor of docodontans + the rest of Mammaliaformes, and present in the branch that includes monotremes as an example of homoplasy (Luo 2015). This interpretation was based on the scapulacoracoid in a number of Late Jurassic docodontans *Haldanodon*, *Agilodocodon*, and *Docofossor*, in which the procoracoid is not present. In *Microdocodon* (Zhou et al. 2019), the entire scapula-coracoid complex is preserved in impression, and it is not feasible to determine if the procoracoid is absent, or if this region is simply not preserved. The only other docodontan taxa for which the scapulacoracoid was previously known is the Middle Jurassic taxon *Borealestes*, found in the same locality as *Krusatodon* in Scotland (Waldman and Savage 1972; Panciroli et al. 2019, 2021). However, the only scapulacoracoid known from *Borealestes* currently is damaged in the region where a procoracoid would be expected, hindering interpretation.

In *Krusatodon*, the presence of a procoracoid (Extended Data Fig. 8c-d) indicates that loss of this structure occurred along the docodontan branch, not in their common ancestor with the rest of Mammaliaformes. Two scenarios are possible: 1) the procoracoid was lost twice in the evolution of mammals, once in docodontans, and later in the common ancestor of theriimorphs (Extended Data Fig. 8a); 2) the procoracoid was lost once in the common ancestor of docodontans + the rest of Mammaliaformes and re-emerged as a homoplasy in *Krusatodon*, monotremes, and *Maiopatagium* (Extended Data Fig. 8b).

Scenario 2 requires three homoplasies in three separate orders (Docodonta, Australosphenida and Haramiyida) - although if *Maiopatagium* is placed stemward of docodontans as in Meng et al. (2017), only two homoplasies are required. Scenario 1 is more probable, requiring only two losses and no homoplasies. This would mean that the procoracoid was retained in *Krusatodon* and in monotremes from the plesiomorphic condition.

S5. Cementum Data

Propagation phase-contrast synchrotron X-ray radiation computed tomography (PP-SRCT) datasets used to obtain cementochronology data are available to download here: www.morphosource.org/projects/00000C428. These include all scans listed in Supplementary Table 8.

Each synchrotron slice data stack of processed .tiffs was uploaded to VGStudioMax (Volume Graphics) v3.1, and the slices re-oriented along the tooth long-axis. The area just below the alveolar margin on each tooth root was visually inspected. And where potential evidence of cementum was identified, an image was captured (at right angles to the long axis of the tooth root), along with an embedded image of the location of the slice (full data available: www.morphosource.org/projects/00000C428).

The images captured in VGStudioMax were uploaded to ImageJ, where the area with potential cementum increments was processed by carrying out the following steps:

- 1) The segmented line tool was used to capture a section containing potential cementum increments (the line was widened to include the area of interest). A .tiff image was captured of this selected area using Plugins>Utilities>Capture Image.
- 2) The selected area was straightened using Edit>Selection>Straighten. This straightened image was then adjusted using Ctrl+Shift+C, and converted to 8-bit, before being saved as a .tiff (Plugins>Utilities>Capture Image).
- 3) A histogram of the selected area from step 1 was then plotted using Ctr+K. The data was saved using Data>Save Data, and an image of the histogram saved as a .tiff using Plugins>Utilities>Capture Image.

This process was repeated on all of the successful synchrotron scan data. Additional histological data were gathered for samples of *Procavia* and *Macroscelides* of known age. The *Procavia* samples were: NMS Z.2009.105.1, a female animal aged 10 months; *Procavia* NMS GH101.10, a male animal aged 1 year 5 months. Cementum increments were not visible in either sample. The *Macroscelides* samples the same used in Asher & Olbricht (2009) and obtained via the University of Cambridge: W11, ages 3 months; W30 aged 5 months and W12 aged ~14 months. No cementum increments were visible in W11 or W30, but there was a tentative possible increment in the i1 of W12, suggesting that the first increment may have begun to form around this time.

Supplementary Table 8: Counts of cementum increments from synchrotron tomographic data, ordered by tooth locus. Abbreviations: L = left, R = right, d = deciduous, I/i = upper/lower incisor, C/c = upper/lower canine, P/p = upper/lower premolar, M/m = upper/lower molar.

Scan name	Side	Tooth locus	Increment count
JUVENILE <i>Krusatodon</i>			
NMS G.2023.8.1			
Scan Number			
16_Elgol2+B2:F31017_002			
bb_babyK_teeth1	left	m2	1
19_Elgol2017_002_bb_babyK_teeth4	left	m1	2
20_Elgol2017_002_bb_babyK_teeth5	left	dp5	1
22_Elgol2017_002_bb_babyK_teeth7	left	p3	1
24_Elgol2017_002_bb_babyK_teeth9	right	M1	1 or 2
25_Elgol2017_002_bb_babyK_teeth10	right	dP5	?
26_Elgol2017_002_bb_babyK_teeth11	right	dP4	2
27_Elgol2017_002_bb_babyK_teeth12	right	dp4	1 or 2
28_Elgol2017_002_bb_babyK_teeth13	left	dP1	1
30_Elgol2017_002_bb_babyK_teeth15	left	dP2	2
33_Elgol2017_002_bb_babyK_teeth18	left	dP4	2
34_Elgol2017_002_bb_babyK_teeth19	left	M1	2
35_Elgol2017_002_bb_babyK_teeth20	left	M2	1 or 2
36_Elgol2017_002_bb_babyK_teeth21	right	p3	1
37_Elgol2017_002_bb_babyK_teeth22	right	dp5	1
40_Elgol2017_002_bb_babyK_teeth25	right	m1	2
41_Elgol2017_002_bb_babyK_teeth26	right	m2	1
47_Elgol2017_002_bb_babyK_teeth3	left	di3	2
48_Elgol2017_002_bb_babyK_teeth4	left	i4	1
51_Elgol2017_002_bb_babyK_teeth7	left	dp2	2
52_Elgol2017_002_bb_babyK_teeth8a	left	di2	2
56_Elgol2017_002_bb_babyK_teeth12	right	di2	2
57_Elgol2017_002_bb_babyK_teeth13	right	di3	?
58_Elgol2017_002_bb_babyK_teeth14	right	c	?
59_Elgol2017_002_bb_babyK_teeth15	right	p1	?
60_Elgol2017_002_bb_babyK_teeth16	right	dp2	?
61_Elgol2017_002_bb_babyK_teeth17	right	di2	2
62_Elgol2017_002_bb_babyK_teeth18	right	dC	1
63_Elgol2017_002_bb_babyK_teeth19	right	dP1	2
64_Elgol2017_002_bb_babyK_teeth20	right	dP2	2
ADULT <i>Krusatodon</i>			
NMS G.1992.47.122.1			
75_KrusatodonBlockBSnout_teeth1	left anterior root	canine	3
75_KrusatodonBlockBSnout_teeth1	left posterior root	canine	6
76_KrusatodonBlockBSnout_teeth2	left i3	i3	4

S6. R Code

Body size against postcanine dentition, as in Asher and Lehman (2008)

#Enter the file path of the working directory

```
setwd( "...")
```

```
install.packages("ggplot2")
```

```
install.packages("hrbrthemes")
```

```
install.packages("tidyverse")
```

```
library(ggplot2)
```

```
library(hrbrthemes)
```

```
library(tidyverse)
```

```
#Read in Data
```

```
AsheLem2008<-read.csv("Asher_Lehman_2008_Data.csv", header=TRUE, row.names=1)
```

```

#subset the data
under39<-subset(AsheLem2008, erupted.10<=3.9)
intermediatestep<-subset(AsheLem2008, erupted.10>=4.0)
fortyto59<-subset(intermediatestep, erupted.10<=5.9)
over60<-subset(AsheLem2008, erupted.10>=6.0)
#Plot the data for 40-59%
ggplot(fortyto59, aes(x=taxon, y=prop_adultJaw, colour=genus, shape=genus))+
  geom_point(size=3)+
  labs(x="40-59% permanent cheek teeth", y="jaw length/median adult jaw length")+
  scale_y_continuous(expand=c(0,0), limits=c(0.20, 1.20)) +
  scale_shape_manual(values=c(17, 2, 11, 1, 4, 18, 0, 8, 9, 14, 2, 5, 7, 25, 10, 16, 3,
6, 15, 17, 18))+
  scale_color_manual(values=c('#CC3311','#CC3311','#997700', '#B8B8B8',
'#DDCC77', '#DDAA33', '#7572fc', '#FF2400', '#DDAA33', '#117733', '#88CCCE',
'#DDAA33', '#DDAA33', '#117733', '#EE99AA', '#B8B8B8', '#FFFF00', '#117733',
'#7572fc', '#117733', '#00008B') )+
  theme_ipsum(base_size = 12, axis_title_size = 12, axis_title_just = "cc")+
  theme(axis.text.x=element_blank(),panel.grid.major.x = element_blank(),
panel.grid.minor = element_blank(),
  panel.grid.major.y = element_line(colour = "grey"), axis.line =
element_line(colour = "black"))

```

Percentage of Postcanine Eruption at Weaning

```

#Enter the file path of the working directory
setwd( "...")
data <- read.csv( "Table S1_Main Dataset.csv" )
hist( data$Weaning.percent.eruption , breaks = 30 , direction =
"r" , xlab = "% eruption at weaning" , main = "" )
abline( v = 0.49 , lwd = 2 , col = "grey" , lty = 2 )

```

Body Mass Against Age, Plotting Birth, Weaning, Adult Masses

```

#Enter the file path of the working directory
setwd( "...")
install.packages("ggplot2")
install.packages("hrbrthemes")
install.packages("tidyverse")
library(ggplot2)
library(hrbrthemes)
library(tidyverse)
data<-read.csv("DATASET_ALL_revised.csv",header=T)

#extract needed columns. c means concatenate, concatenation is a way of
appending two or more strings into a single string
plot.data<-data[,c("Common.name", "Placental","Marsupial", "Monotreme",
"Krusatodon", "Female.maturity..days.", "Weaning..days.",
"Birth.weight..g.", "Weaning.weight..g.", "Adult.weight..g.",
"first.perm.tooth.erupt.days",
"last.perm.tooth.erupt.days")]

```



```

#create new columns. $ means list subset. / divides, and *100 multiplies by 100, to
get the percentage
##all 0 for birth day
birth.days<-rep(0,nrow(plot.data))
##percent mass at birth.
birth.perc<-(plot.data$Birth.weight..g./plot.data$Adult.weight..g.)*100
####percent mass at weaning
wean.perc<-(plot.data$Weaning.weight..g./plot.data$Adult.weight..g.)*100
####all 100s for adult
adult.perc<-rep(100,nrow(plot.data))

#####bind new rows to old
plot.data<-
cbind(plot.data,birth.days,birth.perc,wean.perc,adult.perc,"first.perm.tooth.erupt.days
",
      "last.perm.tooth.erupt.days")

#####remove rows with missing data. == means equal to
plot.data<-plot.data[which(is.na(plot.data$birth.perc)==F),]
plot.data<-plot.data[which(is.na(plot.data$wean.perc)==F),]
plot.data<-plot.data[which(is.na(plot.data$Female.maturity..days.)==F),]
plot.data<-plot.data[which(is.na(plot.data$Weaning..days.)==F),]
#plot.data = drop_na(plot.data, first.perm.tooth.erupt.days)

##subset the marsupials vs placentals vs monotremes vs fossils
placentals<-subset(plot.data, Placental=="1")
marsupials<-subset(plot.data, Marsupial=="1")
monotremes<-subset(plot.data, Monotreme=="1")
Krusatodon<-subset(plot.data, Krusatodon=="1")
#####empty plot
plot(-5,-5,xlim=c(1,max(plot.data$Female.maturity..days.,na.rm=T)),
     ylim=c(0,100),xlab="days after birth",ylab="% adult mass")

#####legend
legend("bottomright",legend=c("placentals","marsupials","monotremes",
"Krusatodon"),bty="n", pt.cex=c(1, 1, 1, 1), pch=c(17,15,19,8),
      col=c("#CC79A7","#0072B2","#009E73", "#D55E00"), cex=c(1,1,1,1))

#####lines
for(i in 1:nrow(placentals))
{
  lines(c(placentals$birth.days[i],placentals$Weaning..days.[i],
        placentals$Female.maturity..days.[i],
        c(placentals$birth.perc[i],placentals$wean.perc[i],placentals$adult.perc[i])
        ,col="mistyrose")
}
for(i in 1:nrow(marsupials))
{

```

```

lines(c(marsupials$birth.days[i],marsupials$Weaning..days.[i],
      marsupials$Female.maturity..days.[i]),
      c(marsupials$birth.perc[i],marsupials$wean.perc[i],marsupials$adult.perc[i])
      ,col="lightcyan")
}
for(i in 1:nrow(monotremes))
{
  lines(c(monotremes$birth.days[i],monotremes$Weaning..days.[i],
        monotremes$Female.maturity..days.[i]),

c(monotremes$birth.perc[i],monotremes$wean.perc[i],monotremes$adult.perc[i])
      ,col="009E73")
}

#####points for placentals
points(placentals$birth.days,placentals$birth.perc,pch=24,col="lightpink")
points(placentals$Weaning..days.,placentals$wean.perc,pch=17, col="#CC79A7")
points(placentals$Female.maturity..days.,placentals$adult.perc,
      pch=24,col="lightpink")

#####points for marsupials
points(marsupials$birth.days,marsupials$birth.perc,pch=22,col="lightskyblue")
points(marsupials$Weaning..days.,marsupials$wean.perc,pch=15, col="#0072B2")
points(marsupials$Female.maturity..days.,marsupials$adult.perc,
      pch=22,col="lightskyblue")

#####points for monotremes
points(monotremes$birth.days,monotremes$birth.perc,cex=1.75,pch=20,col="#009E
73")
points(monotremes$Weaning..days.,monotremes$wean.perc,cex=2,pch=19,col="#0
09E73")
points(monotremes$Female.maturity..days.,monotremes$adult.perc,
      cex=1.75,pch=20,col="#009E73")

#####points for Krusatodon
arrows(x0=210, y0=55, x1=730, y1=55, code=3, col="#D55E00", lwd=1, angle=90,
length=0.1)
arrows(x0=470, y0=51, x1=470, y1=59, code=3, col="#D55E00", lwd=1, angle=90,
length=0.1)
points(470,55,pch=8,col="#D55E00")

###Below and equal to 156g body mass#####

##subset the marsupials vs placentals vs monotremes vs fossils
placentalstiny<-subset(placentals, Adult.weight..g.<157)
marsupialstiny<-subset(marsupials, Adult.weight..g.<157)

plot(-5,-5,xlim=c(1,max(730,na.rm=T)),
      ylim=c(0,100),xlab="days after birth",ylab="% adult mass")

```

```

####legend
legend("bottomright",legend=c("placentals","marsupials","Krusatodon"),bty="n",
pt.cex=c(1, 1, 1), pch=c(17,15,8),
      col=c("#CC79A7","#0072B2","#D55E00"), cex=c(1,1,1))

#####lines
for(i in 1:nrow(placentalstiny))
{
  lines(c(placentalstiny$birth.days[i],placentalstiny$Weaning..days.[i],
          placentalstiny$Female.maturity..days.[i]),

c(placentalstiny$birth.perc[i],placentalstiny$wean.perc[i],placentalstiny$adult.perc[i])
      ,col="mistyrose")
}
for(i in 1:nrow(marsupialstiny))
{
  lines(c(marsupialstiny$birth.days[i],marsupialstiny$Weaning..days.[i],
          marsupialstiny$Female.maturity..days.[i]),

c(marsupialstiny$birth.perc[i],marsupialstiny$wean.perc[i],marsupialstiny$adult.perc[i]
])
      ,col="lightcyan")
}
for(i in 1:nrow(plot.data))

#####points for placentals
points(placentalstiny$birth.days,placentalstiny$birth.perc,pch=24,col="lightpink")
points(placentalstiny$Weaning..days.,placentalstiny$wean.perc,pch=17,col="#CC79
A7")
points(placentalstiny$Female.maturity..days.,placentalstiny$adult.perc,
      pch=24,col="lightpink")

#####points for marsupials
points(marsupialstiny$birth.days,marsupialstiny$birth.perc,pch=22,col="lightskyblue"
)
points(marsupialstiny$Weaning..days.,marsupialstiny$wean.perc,pch=15,
col="#0072B2")
points(marsupialstiny$Female.maturity..days.,marsupialstiny$adult.perc,
      pch=22,col="lightskyblue")

#####points for Krusatodon
arrows(x0=210, y0=55, x1=730, y1=55, code=3, col="#D55E00", lwd=1, angle=90,
length=0.1)
arrows(x0=470, y0=51, x1=470, y1=59, code=3, col="#D55E00", lwd=1, angle=90,
length=0.1)
points(470,55,pch=8,col="#D55E00")

####to add a line for the first and last known eruption in days
##values taken from the remaining dataset under 100g

```

```
abline(v=13, col="#F0E442")
abline(v=145, col="#F0E442")
```

Body Mass Scaling Relationships

##Written for R version 4.2.2 (<https://www.r-project.org/>) on Mac OS 13.0

```
require( ape ) #ape version 5.6-2 from cran binaries (https://cran.r-project.org/)
require( caper ) #caper version 1.0.1 from cran binaries (https://cran.r-project.org/)
require( abind ) #abind version 1.4-5 from cran binaries (https://cran.r-project.org/)
```

```
#Enter the file path of the working directory
setwd( "..." )
source( "pgls.table.caper.R" )
```

```
##Prepare data version for analysis
data <- read.csv( "Limb measurements Panciroli et al juvenile Krusatodon docodont
05July2023.csv" )
data <- data[ data$tree_names != "" , ]
data$Femur.Circumference <- as.numeric( data$Femur.Circumference )
data$Humerus.Circumference <- as.numeric( data$Humerus.Circumference )
data <- data[ complete.cases( data[ , c( "Femur.Circumference" ,
"Humerus.Circumference" ) ] ) , ] data <- data[ data$Bi_Quad == "Q" , ] #Remove
bipeds, following Campione & Evans (2012) data <- data[ data$Family != "Talpidae" ,
] #Remove talpids, following Campione & Evans (2012) data <- data[ order(
data$Dataset , decreasing = T ) , ] data$tree_names <- gsub( " " , "_" ,
data$tree_names )
```

```
##Read phylogenetic trees from Upham et al. 2019
trees <- read.nexus( "tree-pruner-601c5198-cae8-40a2-b838-
9182a8ef1af6/output.nex" )
data.temp <- data
data.temp[ , "FCHC" ] <- data.temp$Femur.Circumference +
data.temp$Humerus.Circumference
```

```
##Plots of scaling relationships
dev.new ( width = 9 , height = 8 ) close.screen ( all.screens = T ) split.screen( c(2,2))
screen( 1 ); par (mar = c(4,4,1,1))
plot( data.temp$FCHC , data.temp$Body_mass_literature..g. , log = "xy" , bty = "l" ,
xlab = "Femoral + humeral shaft circumference (mm)" , ylab = "Body mass (g), from
literature" , cex = 0 , cex.lab = 0.8 , cex.axis = 0.85 , ylim = range( c(
data.temp$Body_mass_literature..g. , data.temp$Body.Mass..g. ) , na.rm = T ) , yaxt
= "n" ) axis( 2 , cex.axis = 0.8 , at = c( 10,100,1000,10000,100000,5000000 ) , labels
= c( "10g","100g","1kg","10kg","100kg","5 tonnes" ) )
```

```
#text( data.temp$FCHC , data.temp$Body_mass_literature..g. , labels =
data.temp$tree_names , cex = 0.5 )points( data.temp$FCHC[ data.temp$Dataset ==
"Campione and Evans 2012" ] , data.temp$Body_mass_literature..g.[
```

```

data.temp$Dataset == "Campione and Evans 2012" ] , , pch = 21 , bg = "grey" , col =
"darkgrey" )
points( data.temp$FCHC[ data.temp$Dataset == "A. New data (Panciroli et al 2023)"
] , data.temp$Body_mass_literature..g.[ data.temp$Dataset == "A. New data
(Panciroli et al 2023)" ] , , pch = 21 , bg = "cadetblue1" ) Sys.sleep(3) legend( "topleft"
, legend = c( "New data" , "Campione & Evans (2012) lit. body masses" ) , bty = "n" ,
cex = 0.65 , pch = 21 , pt.bg = c( "cadetblue1" , "grey" ) , pt.cex = 1 ) screen( 2 ); par
(mar = c(4,4,1,1))

plot( data.temp$FCHC , data.temp$Body_mass_literature..g. , log = "xy" , bty = "l" ,
xlab = "Femoral + humeral shaft circumference (mm)" , ylab = "Body mass (g),
Campione & Evans sample" , cex = 0 , cex.lab = 0.8 , cex.axis = 0.85 , ylim = range(
c( data.temp$Body_mass_literature..g. , data.temp$Body.Mass..g. ) , na.rm = T ) ,
yaxt = "n" )
axis( 2 , cex.axis = 0.8 , at = c( 10,100,1000,10000,100000,5000000 ) , labels = c(
"10g","100g","1kg","10kg","100kg","5 tonnes" ) )
#text( data.temp$FCHC , data.temp$Body.Mass..g. , labels = data.temp$tree_names
, cex = 0.5 )
points( data.temp$FCHC[ data.temp$Dataset == "Campione and Evans 2012" ] ,
data.temp$Body_mass_literature..g.[ data.temp$Dataset == "Campione and Evans
2012" ] , , pch = 21 , bg = "grey" , col = "darkgrey" )
points( data.temp$FCHC[ data.temp$Dataset == "Campione and Evans 2012" ] ,
data.temp$Body.Mass..g. [ data.temp$Dataset == "Campione and Evans 2012" ] , ,
pch = 21 , bg = "gold2" )
Sys.sleep(3)
legend( "topleft" , legend = c( "Campione & Evans (2012) ind. body masses" ,
"Campione & Evans (2012) lit. body masses" ) , bty = "n" , cex = 0.65 , pch = 21 ,
pt.bg = c( "gold2" , "grey" ) , pt.cex = 1 )
screen( 3 ); par (mar = c(4,4,1,1))
plot( data.temp$Humerus.Length , data.temp$Body_mass_literature..g. , log = "xy" ,
bty = "l" , xlab = "Humerus length (mm)" , ylab = "Body mass (g), from literature" ,
cex = 0 , cex.lab = 0.8 , cex.axis = 0.85 , ylim = range( c(
data.temp$Body_mass_literature..g. , data.temp$Body.Mass..g. ) , na.rm = T ) , yaxt
= "n" ) axis( 2 , cex.axis = 0.8 , at = c( 10,100,1000,10000,100000,5000000 ) , labels
= c( "10g","100g","1kg","10kg","100kg","5 tonnes" ) )
#text( data.temp$Humerus.Length , data.temp$Body_mass_literature , labels =
data.temp$tree_names , cex = 0.5 )
points( data.temp$Humerus.Length[ data.temp$Dataset == "Campione and Evans
2012" ] , data.temp$Body_mass_literature..g.[ data.temp$Dataset == "Campione
and Evans 2012" ] , pch = 21 , bg = "gold2" )
points( data.temp$Humerus.Length[ data.temp$Dataset == "A. New data (Panciroli
et al 2023)" ] , data.temp$Body_mass_literature..g.[ data.temp$Dataset == "A. New
data (Panciroli et al 2023)" ] , pch = 21 , bg = "cadetblue1" )
legend( "topleft" , legend = c( "New data" , "Campione & Evans (2012)" ) , bty = "n" ,
cex = 0.65 , pch = 21 , pt.bg = c( "cadetblue1" , "gold2" ) , pt.cex = 1 )

screen( 4 ); par (mar = c(4,4,1,1))
plot( data.temp$Dentary.Length..mm. , data.temp$Body_mass_literature..g. , log =
"xy" , bty = "l" , xlab = "Dentary length (mm)" , ylab = "Body mass (g), from literature" ,
cex = 0 , cex.lab = 0.8 , cex.axis = 0.85 , ylim = range( c(

```



```

data.temp$Body_mass_literature..g. , data.temp$Body.Mass..g. ) , na.rm = T ) , yaxt
= "n" ) axis( 2 , cex.axis = 0.8 , at = c( 10,100,1000,10000,100000,5000000 ) , labels
= c( "10g","100g","1kg","10kg","100kg","5 tonnes" ) )
#text( data.temp$Dentary.Length..mm. , data.temp$Body_mass_literature..g. , labels
= data.temp$tree_names , cex = 0.5 )
points( data.temp$Dentary.Length..mm. , data.temp$Body_mass_literature..g. , pch
= 21 , bg = "cadetblue1" )

```

##Phylogenetic regressions using new data

```

pgls.results.list.new.data <- list()
for( i in 1:35 ) {
  pgls.results.list.new.data[[ i ]] <- list()
  data.temp <- data[ data$Dataset == "A. New data (Panciroli et al 2023)" , ]
  tree.temp <- drop.tip( trees[[i]] , trees[[i]]$tip.label[ is.na( match( trees[[i]]$tip.label ,
data.temp$tree_names ) ) ] )
  data.tree <- data.temp[ match( tree.temp$tip.label , data.temp$tree_names ) , ]
  rownames( data.tree ) <- data.tree$tree_names
  data.tree[ , "log_HC" ] <- log10( data.tree$Humerus.Circumference )
  data.tree[ , "log_FC" ] <- log10( data.tree$Femur.Circumference )
  data.tree[ , "log_HL" ] <- log10( data.tree$Humerus.Length )
  data.tree[ , "log_FL" ] <- log10( data.tree$Femur.Length )
  data.tree[ , "log_FCHC" ] <- log10( data.tree$Femur.Circumference +
data.tree$Humerus.Circumference )
  data.tree[ , "log_DenL" ] <- log10( data.tree$Dentary.Length..mm. )
  data.tree[ , "log_BM" ] <- log10( data.tree$Body_mass_literature..g. )

  use.cols <- c( "tree_names" , "Body_mass_literature..g." , "Humerus.Circumference"
, "Femur.Circumference" , "log_HC" , "log_FC" , "log_FCHC" , "log_BM" , "log_DenL"
, "log_HL" , "log_FL" )

  data.temp <- comparative.data( trees[[i]] , data.tree[,use.cols] , names.col =
"tree_names" )
  pgls.results.list.new.data[[ i ]][[1]] <- pgls( log_BM ~ log_HC , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.new.data[[ i ]][[2]] <- pgls( log_BM ~ log_FC , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.new.data[[ i ]][[3]] <- pgls( log_BM ~ log_FCHC , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.new.data[[ i ]][[4]] <- pgls( log_BM ~ log_DenL , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.new.data[[ i ]][[5]] <- pgls( log_BM ~ log_FL , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.new.data[[ i ]][[6]] <- pgls( log_BM ~ log_HL , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  names( pgls.results.list.new.data[[ i ]] ) <-
c("HC","FC","FCHC","DenL","FL","HL")
}

```

```

##Phylogenetic regressions using data from Campione & Evans (2012) based on
measured specimen body masses ('spec') and literature species body masses ('lit')
pgls.results.list.Campione_spec <- list()
pgls.results.list.Campione_lit <- list()
  for( i in 1:35 ) {
    pgls.results.list.Campione_spec[[ i ]] <- list()
    pgls.results.list.Campione_lit[[ i ]] <- list()

data.temp <- data[ data$Dataset == "Campione and Evans 2012" , ]
tree.temp <- drop.tip( trees[[i]] , trees[[i]]$tip.label[ is.na( match( trees[[i]]$tip.label ,
data.temp$tree_names ) ) ] )
data.tree <- data.temp[ match( tree.temp$tip.label , data.temp$tree_names ) , ]

rownames( data.tree ) <- data.tree$tree_names
  data.tree[ , "log_HC" ] <- log10( data.tree$Humerus.Circumference )
  data.tree[ , "log_FC" ] <- log10( data.tree$Femur.Circumference )
  data.tree[ , "log_FCHC" ] <- log10( data.tree$Femur.Circumference +
data.tree$Humerus.Circumference )
  data.tree[ , "log_BMlit" ] <- log10( data.tree$Body_mass_literature..g. )
  data.tree[ , "log_BMspe" ] <- log10( data.tree$Body.Mass..g. )
use.cols <- c( "tree_names" , "Body_mass_literature..g." , "Humerus.Circumference"
, "Femur.Circumference" , "log_HC" , "log_FC" , "log_FCHC" , "log_BMlit" ,
"log_BMspe" )
data.temp <- comparative.data( trees[[i]] , data.tree[,use.cols] , names.col =
"tree_names" )
  pgls.results.list.Campione_lit[[ i ]][[1]] <- pgls( log_BMlit ~ log_HC , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.Campione_lit[[ i ]][[2]] <- pgls( log_BMlit ~ log_FC , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.Campione_lit[[ i ]][[3]] <- pgls( log_BMlit ~ log_FCHC ,
data.temp , lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  names( pgls.results.list.Campione_lit[[ i ]] ) <-
c("log_HC","log_FC","log_FCHC")
  pgls.results.list.Campione_spec[[ i ]][[1]] <- pgls( log_BMspe ~ log_HC ,
data.temp , lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.Campione_spec[[ i ]][[2]] <- pgls( log_BMspe ~ log_FC ,
data.temp , lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  pgls.results.list.Campione_spec[[ i ]][[3]] <- pgls( log_BMspe ~ log_FCHC ,
data.temp , lambda = "ML" , bounds = list( lambda = c(0,1) ) )
  names( pgls.results.list.Campione_spec[[ i ]] ) <-
c("log_HC","log_FC","log_FCHC")
  }
pgls.results.list.Campione_lit <- pgls.results.list.Campione_lit [ unlist( lapply(
pgls.results.list.Campione_lit , length ) ) == 3 ]
pgls.results.list.Campione_spec <- pgls.results.list.Campione_spec [ unlist( lapply(
pgls.results.list.Campione_spec , length ) ) == 3 ]

##Phylogenetic regressions using small-bodied mammals only (< 1 kg)
pgls.results.list.small.taxa <- list()
  for( i in 1:35 ) {

```

```

pgls.results.list.small.taxa[[ i ]] <- list()
data.temp <- data[ data$Body_mass_literature..g. < 1000 , ]
tree.temp <- drop.tip( trees[[i]] , trees[[i]]$tip.label[ is.na( match(
trees[[i]]$tip.label , data.temp$tree_names ) ) ] )
data.tree <- data.temp[ match( tree.temp$tip.label , data.temp$tree_names ) ,
]

rownames( data.tree ) <- data.tree$tree_names
data.tree[ , "log_HC" ] <- log10( data.tree$Humerus.Circumference )
data.tree[ , "log_FC" ] <- log10( data.tree$Femur.Circumference )
data.tree[ , "log_HL" ] <- log10( data.tree$Humerus.Length )
data.tree[ , "log_FL" ] <- log10( data.tree$Femur.Length )
data.tree[ , "log_FCHC" ] <- log10( data.tree$Femur.Circumference +
data.tree$Humerus.Circumference )
data.tree[ , "log_DenL" ] <- log10( data.tree$Dentary.Length..mm. )
data.tree[ , "log_BM" ] <- log10( data.tree$Body_mass_literature..g. )
use.cols <- c( "tree_names" , "Body_mass_literature..g." ,
"Humerus.Circumference" , "Femur.Circumference" , "log_HC" , "log_FC" ,
"log_FCHC" , "log_BM" , "log_DenL" , "log_HL" , "log_FL" )

data.temp <- comparative.data( trees[[i]] , data.tree[,use.cols] , names.col =
"tree_names" )
pgls.results.list.small.taxa[[ i ]][[1]] <- pgls( log_BM ~ log_HC , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
pgls.results.list.small.taxa[[ i ]][[2]] <- pgls( log_BM ~ log_FC , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
pgls.results.list.small.taxa[[ i ]][[3]] <- pgls( log_BM ~ log_FCHC , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
pgls.results.list.small.taxa[[ i ]][[4]] <- pgls( log_BM ~ log_DenL , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
pgls.results.list.small.taxa[[ i ]][[5]] <- pgls( log_BM ~ log_FL , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
pgls.results.list.small.taxa[[ i ]][[6]] <- pgls( log_BM ~ log_HL , data.temp ,
lambda = "ML" , bounds = list( lambda = c(0,1) ) )
names( pgls.results.list.new.data[[ i ] ] ) <-
c("HC","FC","FCHC","DenL","FL","HL")
}

pgls.results.list.small.taxa <- pgls.results.list.small.taxa[ unlist( lapply(
pgls.results.list.small.taxa , length ) ) == 6 ]

write.csv(rbind(apply( compiled.pgls.array( pgls.results.list.Campione_lit ) , c(1,2) ,
quantile , probs = 0.95 , na.rm = T )[5:6,],
apply( compiled.pgls.array( pgls.results.list.Campione_lit ) , c(1,2) , quantile ,
probs = 0.50 , na.rm = T )[5:6,],
apply( compiled.pgls.array( pgls.results.list.Campione_lit ) , c(1,2) , quantile ,
probs = 0.05 , na.rm = T )[5:6,],
apply( compiled.pgls.array( pgls.results.list.Campione_spec ) , c(1,2) ,
quantile , probs = 0.95 , na.rm = T )[5:6,],

```

```

    apply( compiled.pgls.array( pgls.results.list.Campione_spec ), c(1,2) ,
    quantile , probs = 0.50 , na.rm = T )[5:6,],
    apply( compiled.pgls.array( pgls.results.list.Campione_spec ), c(1,2) ,
    quantile , probs = 0.05 , na.rm = T )[5:6,]), "ED Table 1.csv")
    nrow( pgls.results.list.Campione_lit[[1]][[1]]$x )

write.csv(rbind(apply( compiled.pgls.array( pgls.results.list.new.data ) , c(1,2) ,
quantile , probs = 0.95 , na.rm = T )[5:6,],
    apply( compiled.pgls.array( pgls.results.list.new.data ) , c(1,2) , quantile ,
probs = 0.50 , na.rm = T )[5:6,],
    apply( compiled.pgls.array( pgls.results.list.new.data ) , c(1,2) , quantile ,
probs = 0.05 , na.rm = T )[5:6,],
    apply( compiled.pgls.array( pgls.results.list.small.taxa ) , c(1,2) , quantile ,
probs = 0.95 , na.rm = T )[5:6,],
    apply( compiled.pgls.array( pgls.results.list.small.taxa ) , c(1,2) , quantile ,
probs = 0.50 , na.rm = T )[5:6,],
    apply( compiled.pgls.array( pgls.results.list.small.taxa ) , c(1,2) , quantile ,
probs = 0.05 , na.rm = T )[5:6,],
    apply( compiled.pgls.array( pgls.results.list.new.data ) , c(1,2) , quantile ,
probs = 0.95 , na.rm = T )[7:8,],
    apply( compiled.pgls.array( pgls.results.list.new.data ) , c(1,2) , quantile ,
probs = 0.50 , na.rm = T )[7:8,],
    apply( compiled.pgls.array( pgls.results.list.new.data ) , c(1,2) , quantile ,
probs = 0.05 , na.rm = T )[7:8,],
    apply( compiled.pgls.array( pgls.results.list.small.taxa ) , c(1,2) , quantile ,
probs = 0.95 , na.rm = T )[7:8,],
    apply( compiled.pgls.array( pgls.results.list.small.taxa ) , c(1,2) , quantile ,
probs = 0.50 , na.rm = T )[7:8,],
    apply( compiled.pgls.array( pgls.results.list.small.taxa ) , c(1,2) , quantile ,
probs = 0.05 , na.rm = T )[7:8,]), "ED Table 2.csv")

nrow( pgls.results.list.new.data[[1]][[1]]$x )
nrow( pgls.results.list.small.taxa[[1]][[1]]$x )

lm.CI <- function( X , formula , model , newdata ){ predict( lm( as.formula( formula ) ,
data = X[[ model ]] $ data $ data ) , newdata , interval = "prediction" ) }

#Mass estimates of adult Krusatodon body mass from HC+FC using training set of
small-bodied mammals
    quantile( 10 ^ unlist( lapply( pgls.results.list.small.taxa , function(X){ predict(
X[[3]] , data.frame( log_FCHC = log10(5.755+5.429) ) ) } ) ) , probs =
c(0.05,0.50,0.95))
    10^lm.CI( pgls.results.list.small.taxa[[ 1 ]] , formula = "log_BM ~ log_FCHC" ,
model = 3 , newdata = data.frame( log_FCHC = log10(5.755+5.429) ) )

#Mass estimates of juvenile Krusatodon body mass from HC+FC using training set
of small-bodied mammals
    quantile( 10 ^ unlist( lapply( pgls.results.list.small.taxa , function(X){ predict(
X[[3]] , data.frame( log_FCHC = log10(4.721+(4.721*(5.429/5.755))) ) ) } ) ) , probs =
c(0.05,0.50,0.95))

```

```
10^lm.CI( pgls.results.list.small.taxa[[ 1 ]], formula = "log_BM ~ log_FCHC" ,
model = 3 , newdata = data.frame( log_FCHC = log10(4.721+(4.721*(5.429/5.755)))
) )
```

#Mass estimates of adult *Krusatodon* body mass from dentary length using training set of small-bodied mammals

```
quantile( 10 ^ unlist( lapply( pgls.results.list.small.taxa , function(X){ predict(
X[[4]] , data.frame( log_DenL = log10(30) ) ) } ) ) , probs = c(0.05,0.50,0.95))
10^lm.CI( pgls.results.list.small.taxa[[ 1 ]], formula = "log_BM ~ log_DenL" ,
model = 4 , newdata = data.frame( log_DenL = log10(30) ) )
```

#Mass estimates of juvenile *Krusatodon* body mass from dentary length using training set of small-bodied mammals

```
quantile( 10 ^ unlist( lapply( pgls.results.list.small.taxa , function(X){ predict(
X[[4]] , data.frame( log_DenL = log10(24) ) ) } ) ) , probs = c(0.05,0.50,0.95))
10^lm.CI( pgls.results.list.small.taxa[[ 1 ]], formula = "log_BM ~ log_DenL" ,
model = 4 , newdata = data.frame( log_DenL = log10(24) ) )
(24^3)/(30^3)
(4.721^3)/(5.755^3)
```

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