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Supplementary Materials for

A Triassic plesiosaurian skeleton and bone histology inform on evolution of a unique body plan

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The PDF file includes:

- table S6. Local bone apposition rate to the end of the first year and relative body size at the end of the first year in selected sauropterygians.
- table S7. Comparison of local bone apposition rates in the femur of selected amniotes compared to local bone apposition rates in the humeri and femora of plesiosaurians.
- Legend for data file S1
- References (*63*–*75*)

Other Supplementary Material for this manuscript includes the following:
(available at advances.sciencemag.org/cgi/content/full/3/12/e1701144/DC1)

- data file S1 (.txt format). Character matrix in NEXUS format for phylogenetic analysis described in Materials and Methods.

Supplementary Anatomical Descriptions

Skull Anatomy. The skull is not fully preserved, but the occiput and the entire lower jaw are present (fig. S1A). The lower jaw rami are partially broken and disarticulated, but the total length of the right lower jaw can be reliably reconstructed as 215 mm. The mandibular symphysis is laterally expanded in ventral view (fig. S1A) and forms a distinctive ventral ridge. There is no participation of the splenial in the mandibular symphysis. The angular is short and extends less than half of the mandibular length. Although it is uncertain whether the surangular foramen is visible in lateral view, it is clear that the articular lacks a deep anteroposteriorly oriented notch posterior to the glenoid. Furthermore, the dorsoventral orientation of the long axis of the retroarticular process is subhorizontal, and the mediolateral orientation of the long axis is inflected slightly posteromedially (fig. S1A). There are five isolated teeth preserved in the matrix near the jaws, and these show the typical enamel ridges (fig. S1B and C) of plesiosaurians (*10*, *11*).

Postcranial Axial Skeleton. Because of the damage to the cervical vertebral column caused by quarrying, the number of cervical vertebrae is difficult to determine. The anteriormost 15 cervicals are preserved in perfect articulation on the matrix, including the atlas-axis complex. The 16th cervical (fig. S2C to E) was separated from the preceding ones during preparation and was completely free from the matrix. Based on the length of the gap between the posteriormost preserved cervical and the anteriormost trunk vertebra and on the length increase between these two vertebrae, we estimate that no more than 22 cervical vertebrae are missing. Although the gap could have been increased or decreased by disarticulation, we do not believe this to be the case because of the generally high degree of articulation of the axial skeleton, and in particular the anterior cervicals. The length of cervical centrum number 15 is 21 mm. Cervical vertebral anatomy is illustrated in Fig. 2A and C and fig. S2). The anterior cervical centra are distinctly shorter than tall (Fig. 2C), and their mediolateral width is subequal to height or less. The intervertebral articular surfaces are nearly flat, and there is no semi-oval "lip" (*11*) extending ventrally from the anterior articular surface. The space between adjacent articulated centra is only 2 mm wide, suggesting thin intervertebral cartilage (Fig. 2C). A longitudinal ridge is absent from the lateral surface of the centra. In lateral view, the more anterior preserved cervicals have neural spines that are inflected somewhat anterodorsally, whereas the more posterior cervical spines are curved posterodorsally. The anterior cervical neural spines are taller than their anteroposterior length. The width of the cervical zygapophyses is narrower than that of the centrum. Furthermore, the rib facets of the anterior to middle cervical vertebrae are co-joined. The prezygapophyses face dorsomedially and are planar. The medial contact between the left and right prezygapophyses is absent, and the distance between the left and right zygapophyses is subequal to the width of the neural canal. In ventral view, the cervical centra show paired lateral ridges on the ventral surface. The shape of the neurocentral suture in the anterior to middle cervical vertebrae is very distinctive: this suture is not only V-shaped as in some other early plesiosaurians (*11*), but the apex of the "V" nearly extends to the ventral margin of the centrum and the sides of the "V" are ventrally concave. The remarkable shape of the neurocentral suture in the anterior to middle cervical vertebrae is autapomorphic for *Rhaeticosaurus*. Other early plesiosaurians with a V-shaped neurocentral sutures have straight sides of the "V", whereas non-plesiosaurian sauropterygians, including basal pistosaurs (*51–53*) and *Bobosaurus* (*12*, *57*), have horizontal neurocentral sutures. The V-shaped neurocentral sutures of *Rhaeticosaurus* (Fig. 2C) and several other basal plesiosaurians (*11*) would have tightly integrated centrum and spine, even in growing animals. By increasing sutural surface area and complexity, the risk of sutural dislocation by forces generated during locomotion and feeding was reduced.

There are 21 trunk vertebrae preserved, all of which have the transverse process formed by the neural arch, indicating that they are dorsal vertebrae. Trunk vertebral anatomy is illustrated in Figs 2A and C and fig. S3). Presumably, there was a low number of transitional, so-called pectoral vertebrae, but these were lost before discovery. The length of the first dorsal centrum is 25 mm. The trunk is short compared to the limbs, the ratio of glenoid-acetabular distance to propodial length being 2.6 (see also the *Morphometric Analysis*). The height of the dorsal neural spines is low, less than the height of the centrum, and the transverse process is low on the neural arch, adjacent to the neural canal. The orientation of the transverse processes in the middle dorsal region is approximately horizontal. Neural spine morphology is constant throughout the dorsal series. The neural spines are laterally flattened and have unfinished tips, a sign of immaturity. A strong anteroposterior constriction at the base of the dorsal neural spines is absent, and in lateral view, all spines are anteroposteriorly symmetrical. The mid-posterior dorsal neural spines are not expanded transversely, but are narrow relative to their anteroposterior width. The orientation of the posteriormost dorsal neural spines is dorsal and not anterodorsally inclined, with the posterior dorsal rib facets having a prominent transverse process located entirely on the neural arch. The dorsal vertebrae are tightly integrated and, together with the wide rib cage and robust ribs, suggest an inflexible trunk. The gastralia are well developed and densely spaced in *Rhaeticosaurus* (fig. S3A and D) suggesting the presence of a well developed gastral basket. The gastralia of *Augustasaurus* (*52*) and *Bobosaurus* (*57*) appear thinner and less prominent, although this could be the result of disarticulation in the case of *Bobosaurus*. Immaturity of the holotype skeleton is also suggested by the unfused neurocentral sutures in the posterior dorsal and caudal column (fig. S3 and S4).

Four sacral vertebrae (fig. S4B and C) are present with the sacral ribs. The sacral ribs are cylindrical and have slightly expanded distal ends. The neural spines of the sacral and anterior caudal vertebrae also have distinctly unfinished neural spines. The length of the preserved dorsal region is about 553 mm, and that of the sacral region is 96 mm (cumulative length of the sacral centra), giving a total of 649 mm for the trunk region. The trunk must have been slightly longer because of the missing pectoral vertebrae.

In the caudal vertebral column (fig. S4), 25 vertebrae are preserved in articulation, and a few more probably were lost to disarticulation, leading to an estimate of <33 caudal vertebrae based on preserved vertebral proportions. However, no disarticulated caudals are preserved with the skeleton. The first caudal centrum is 21 mm long, with this dimension gradually decreasing to 10 mm in the last articulated caudal, the 25th. This relatively rapid decrease in size also makes it unlikely that the tail had the high vertebral count seen in non-plesiosaurian [e.g., about 70 caudals in *Yunguisaurus* (*58*), and at least 38 caudals in *Bobosaurus* (*57*)]. In addition, the caudals become relatively longer posteriorly in these taxa (*57*, *58*), unlike in *Rhaeticosaurus*. All caudal vertebral centra are at least twice as wide as long (fig. S4), with the proportions remaining constant. This gives the caudal centra a disk-shaped appearance, compared to *Bobosaurus* and all more basal eosauropterygians that have caudals that are longer than wide. Both the low number of caudals and the shortening of the individual caudals indicate an evolutionary shortening of the tail which is typical for plesiosaurians. The estimated length of the tail, based on a maximum reconstructed count of 33 caudals, is 577 mm, which is shorter than the trunk region. The rib facets of the proximal middle caudal vertebrae are located rather dorsally and almost connect with the base of the neural arch. The outline of the middle caudal centra is suboval in anterior view. The chevron facets of the middle and distal caudal vertebrae are in a low position and flush with the level of the ventral surface of the centrum. There are well developed gastralia (fig. S3D), forming a gastral basket, but the number of elements per segment cannot be reliably determined.

Girdle skeleton. The pectoral girdle is too damaged and poorly preserved to reveal important characters, but the left coracoid and scapula can be discerned, enclosing a pectoral fenestra between them. The pelvic girdle is well preserved. Both ilia are present, as are the left pubis and ischium which are exposed in dorsal view. The dorsoventral length of the well-preserved right ilium is 95 mm. The shaft of the ilium appears straight in lateral view, and the pelvic articular end is equally expanded anteriorly and posteriorly. In addition, the rotation of the dorsal blade relative to the long axis of the pelvic articular end is approximately 45 degrees. The iliac blade is expanded subequally in anterior and posterior direction, and the expanded portion occupies the dorsal half of the ilium. The anteroposterior width of the dorsal blade is expanded over the width of the shaft. There is no tubercle around the mid-length of the posterior surface of the ilium, and the broad fossa on the medial surface of the dorsal blade is absent as well. The mediolateral width of the well-preserved left pubis is 112 mm, and that of the left ischium is 97 mm. The anterolateral cornu of the pubis is absent, and the ratio of the anteroposterior length to the mediolateral width of the pubis is 1.02. The pubis and ischium are similar in shape to those of other basal plesiosaurians and offer no distinctive features. Ischium length to the width ratio is between 1.0 and 1.3.

Limb Skeleton. In the limbs, the left humerus and femur, the left radius, the left tibia and fibula, a single rounded carpal, three rounded tarsals and some metapodials and phalanges are preserved. The distal half of the dorsal and ventral surfaces of the propodials is flat with robust pre- and postaxial margins. Both propodials have a straight shaft and only slightly expanded distal ends. The length of the humerus is 183 mm, although this value may have been increased slightly by microfaulting. In addition, microfaulting gave the humerus an unnatural S shape, but its true shape can be discerned upon close inspection of the specimen. We thus conclude that in dorsal or ventral view, the preaxial margin of the distal humerus is straight. There is a sharp longitudinal ridge on the anterior surface of the shaft. The shape of the distal end of the humerus is uniformly convex, and the inclination of the proximal end appears straight in dorsal view. The radius is 48 mm long and thus much shorter than the humerus, reaching only 26% of the length of the latter. Among the taxa in the morphometric analysis, only *Rhomaleosaurus thorntoni* has a relatively shorter radius (table S4). The radius shows a concave preaxial margin with a prominent anterior flange extending from the anteroproximal surface. There is a posterodistal facet for the intermedium. Furthermore, the length to maximum width ratio of the radius is 1.21.

Like the humerus, the femur has a straight shaft, and both bones are very similar in shape, unlike in *Yunguisaurus* (*58*). Femur length (185 mm, also slightly increased by microfaulting) is about the same as humerus length, as in some other early plesiosaurians (table S4). In *Yunguisaurus*, the femur is clearly shorter than the humerus, achieving only 85% the length of the humerus. In *Pistosaurus*, the femur seems to be of the same length as the humerus, which is incompletely preserved in the only known partial skeleton (*50*). The humerus/femur ratio is unknown in *Bobosaurus*, although the authors suggest that the femur and hindlimb were shorter than the forelimb (*12*, *57*). However, the ratio of humerus to tibia length is 1.34 in *Bobosaurus*, the lowest in the data set (table S3), strongly suggesting that *Bobosaurus* lacked the short zeugopodials of plesiosaurians. This inference is also supported by the slender tibia of *Bobosaurus* (*12*, *57*). The straight shaft of the humerus and femur of *Rhaeticosaurus* is important because it is not seen in non-plesiosaurian pistosauroids such as *Bobosaurus* (*12*, *57*) and pistosaurs (*51*, *52*). The distal end of the femur is somewhat flattened and expanded, although these features may have been exaggerated somewhat by microfaulting.

The tibia is similarly short compared to the femur (23%) as the radius is compared to the humerus. Since both zeugopodials are preserved in the hindlimb, it can be seen that there is an epipodial foramen between the tibia and the fibula. The length of the tibia is 43 mm. The length to maximum width ratio of the tibia is lower than 1.0, the bone being somewhat wider (46 mm) than long. The fibula is 49 mm long. It has a concave preaxial side but lacks the dorsoventrally convex posterior margin of other basal plesiosaurians (*12*, *57*). In fact, the postaxial margin of the fibula is concave in dorsoventral view as well, resulting in the bone having a shaft, but this may be preservational. There are three rounded tarsals, suggesting that there was much cartilage between the tarsals as in many Early Jurassic plesiosaurians (*12*, *57*). Because of disarticulation and loss of elements from the distal limbs, we cannot be sure that *Rhaeticosaurus* had the same number of carpals and tarsals as later plesiosaurians. However, the preserved metapodials and phalanges are long and slender, being around two to three times as long proximodistally as broad anteroposteriorly, as in later plesiosaurians. Even if the carpus and tarsus were incompletely ossified, the proportions of the entire limb, particularly with respect to the zeugopodials, are consistent with a hydrofoil function of the limbs, as in later plesiosaurians.

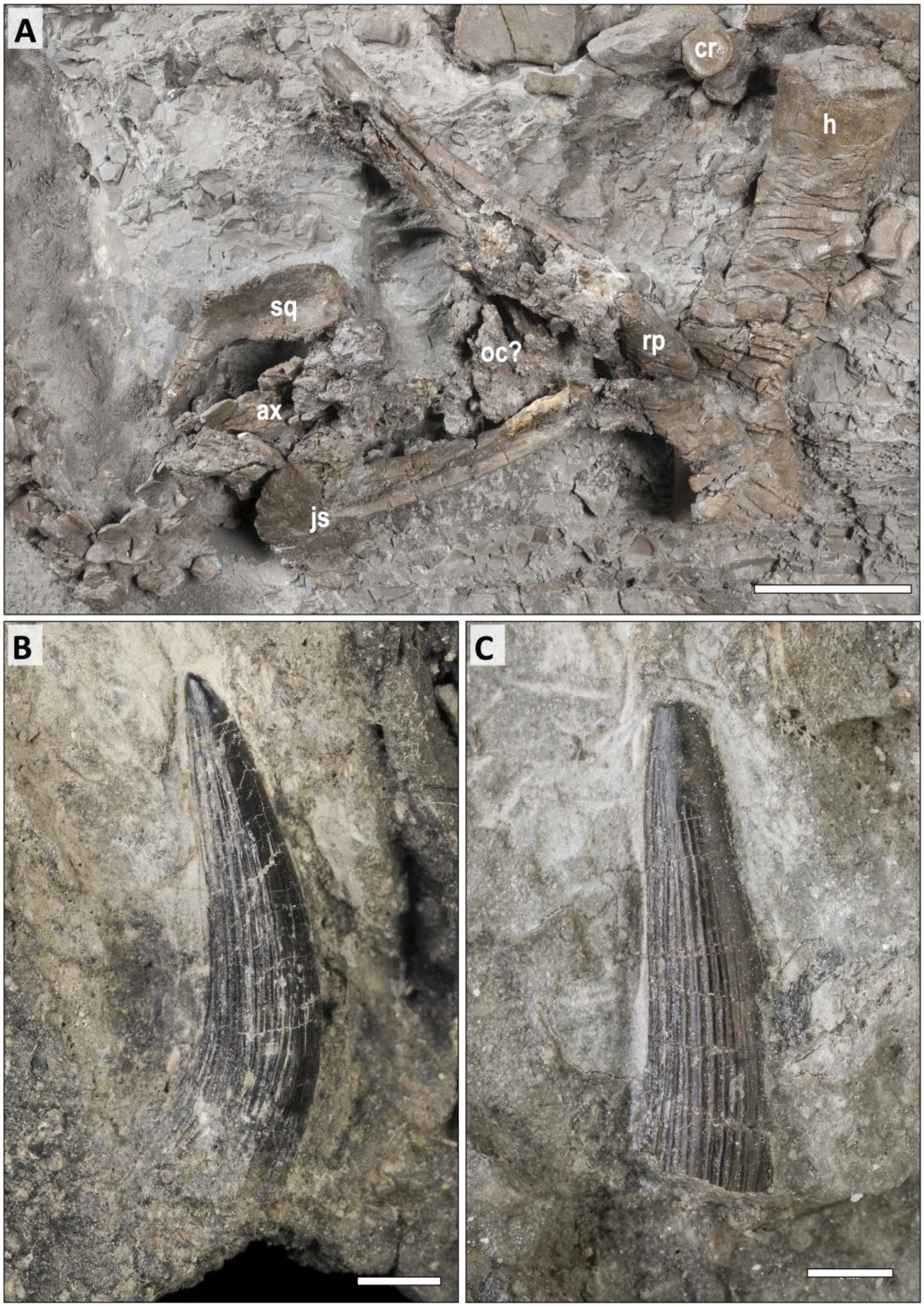

fig. S1. The holotype of *Rhaeticosaurus mertensi* gen. et sp. nov. (**A**) Skull, anterior cervical vertebrae and left humerus. Both lower jaws are seen in ventral view and articulate in the symphysis. The posterior part of the left lower jaw is broken off and rotated away. (**B**, **C**) Two isolated teeth associated with the lower jaws. Note the sharp longitudinal enamel ridges on the surface of the teeth. ax, atlas-axis complex; cr, carpal bone; h, humerus; js, jaw symphysis; oc?, probable occipital region; rp, retroarticular process of left lower jaw in ventral view; sq, squamosal. Scale bars, 5 cm (A), 3 mm (B), 2 mm (C).

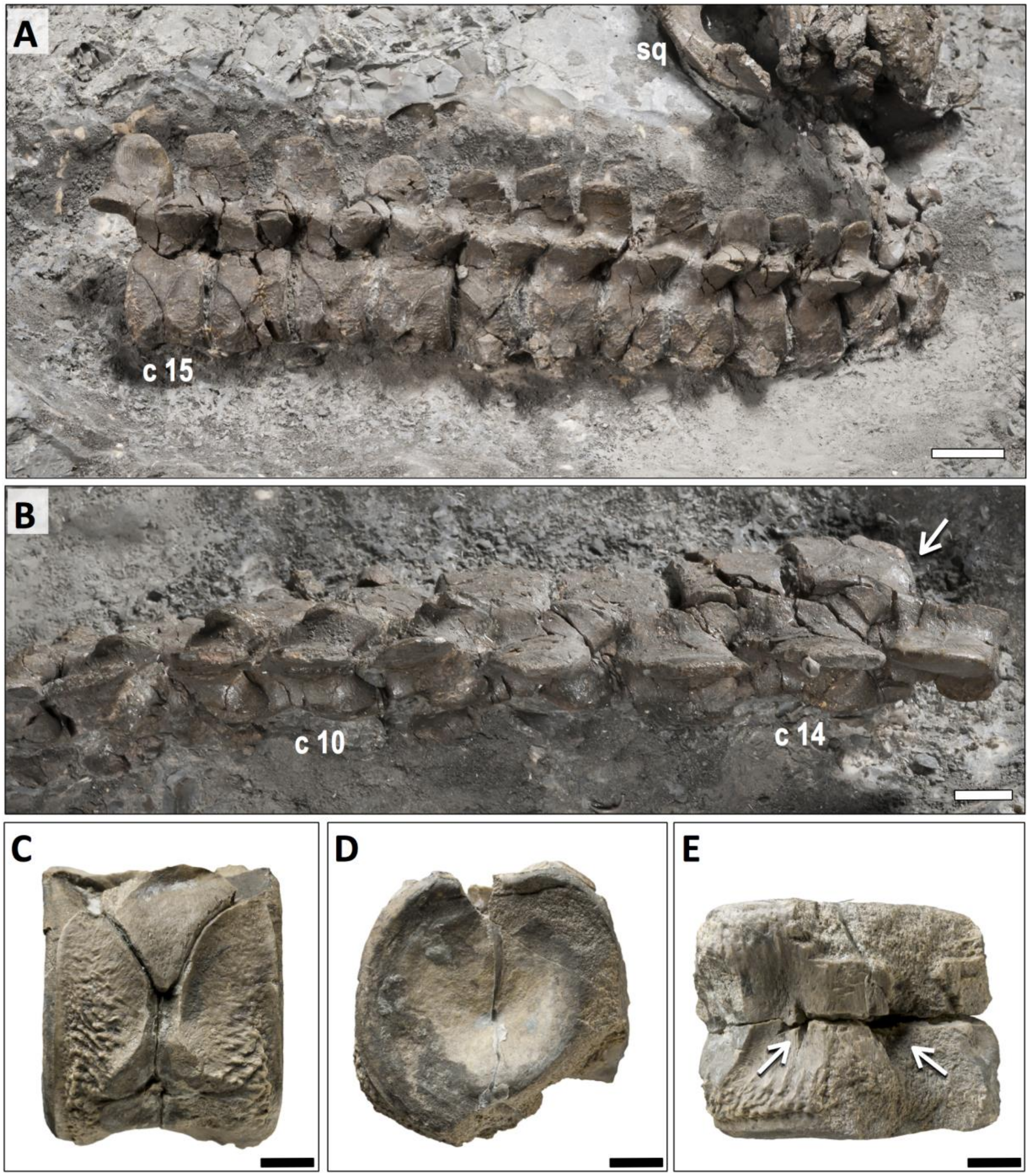

fig. S2. The holotype of *Rhaeticosaurus mertensi* gen. et sp. nov., anterior cervical vertebral column. (**A**) Anterior cervical vertebrae in lateral view and posterior skull region. (**B**) Anterior cervical vertebrae in dorsal view. Note that the width of the cervical zygapophyses (arrow) is narrower than that of the centrum. (**C**) The isolated 16th cervical vertebral centrum in left lateral view. Note the ventrally concave V-shaped neurocentral suture and the co-joined rib facets.(**D**) The same in anterior view, note the flat articular surface with the concave center. (**E**) The same in ventral view. Although the ventral surface is partially damaged, the ventrolateral ridges, the ventral keel, and the deeply sunken large subcentral foramina (arrow) are visible. c 10, cervical vertebra 10; c 14, cervical vertebra 14; c 15, cervical vertebra 15; sq, squamosal. Scale bars, 2 cm (A), 1 cm (B), 5 mm (C-E).

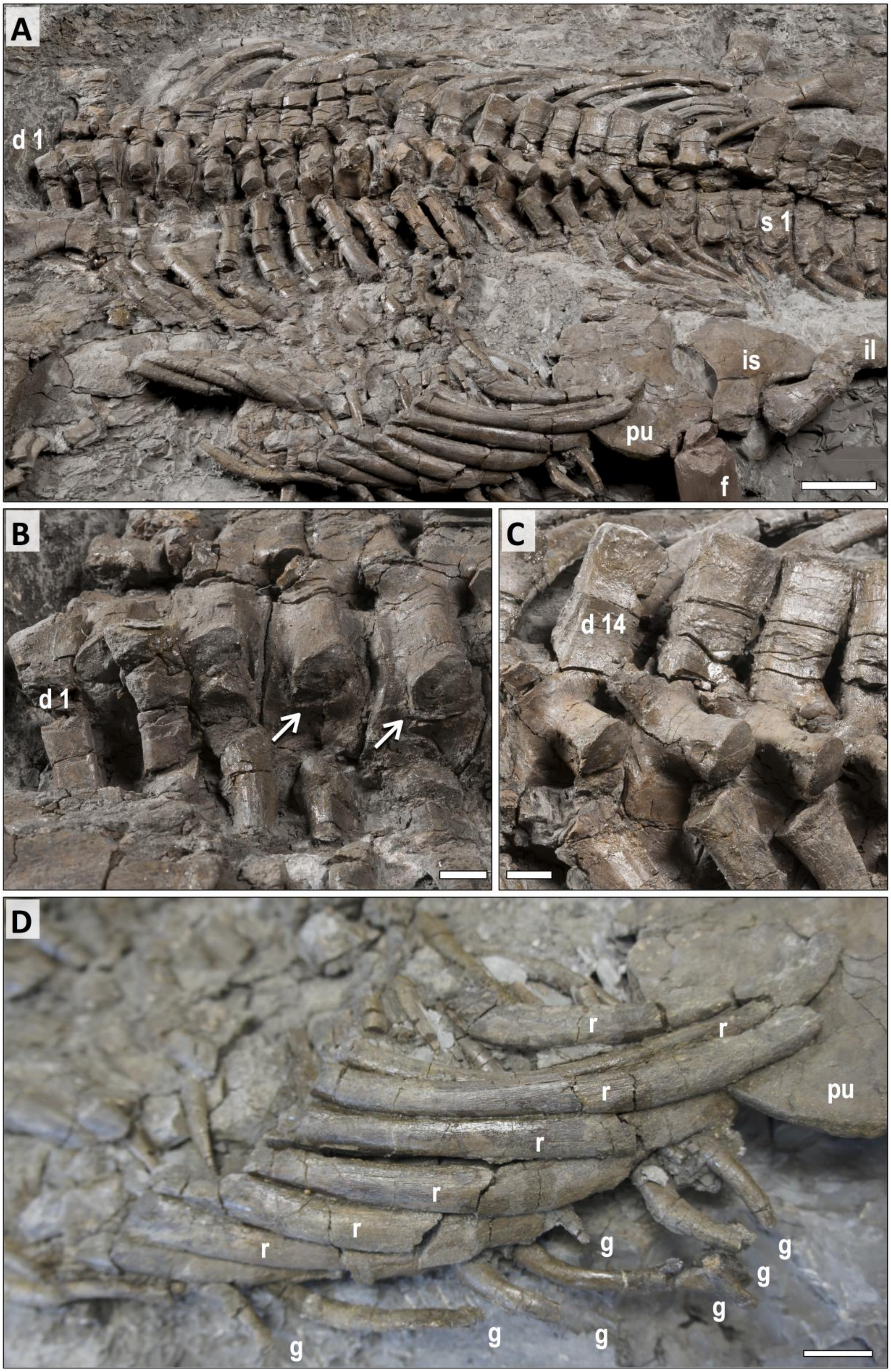
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fig. S3. The holotype of *Rhaeticosaurus mertensi* gen. et sp. nov. (**A**) Overview of trunk region, anterior is to the left. Note the tightly integrated vertebral column and the wide rib cage. (**B**) Dorsal vertebrae 1 to 5. Note the short transverse processes and the neurocentral suture ventral to these (arrows). (**C**) Middle dorsal vertebrae, the 14th to the 17th. Note the well developed transverse processes. (**D**) Distal portion of left trunk ribs and gastralia that underlie these. d 1, dorsal vertebra 1; d 14, dorsal vertebra 14; f, femur; g, gastral element; il, ilium; is, ischium; pu, pubis; r, rib; s 1, sacral vertebra 1. Scale bars, 5 cm (A), 1 cm (B, C), 2 cm (D).

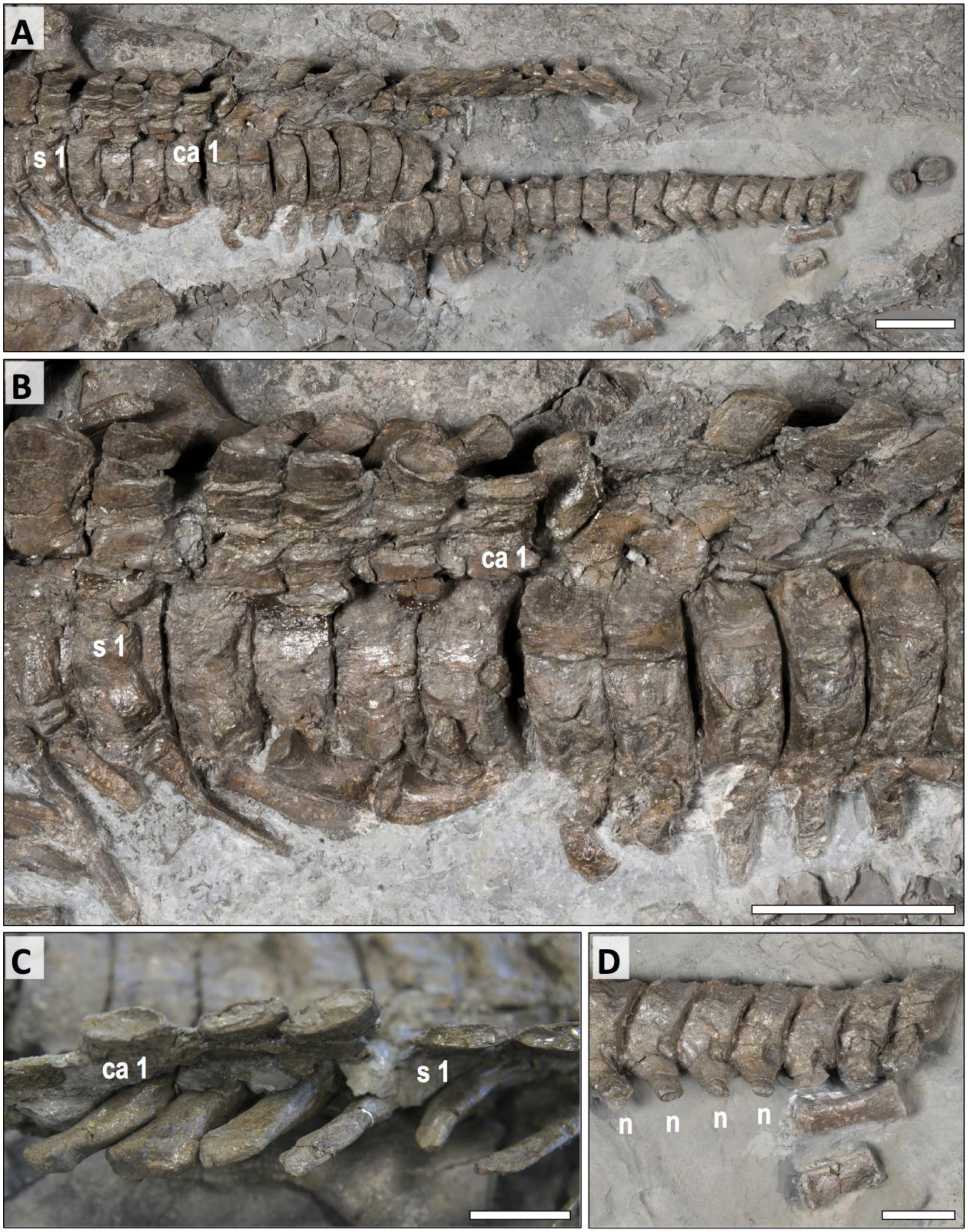

fig. S4. The holotype of *Rhaeticosaurus mertensi* gen. et sp. nov. (**A**) Overview of sacral and caudal vertebral column, anterior is to the left. Note two disarticulated posterior caudals and the isolated phalanges below the posterior tail. (**B**) Sacral and anteriormost caudal vertebral column, enlargement of (A). The first caudal neural arches have separate from the centra, exposing the floor of the neural canal. Note the disk-shaped caudal vertebrae. Note the unfinished ends of the sacral neural spines, suggesting a juvenile ontogenetic stage. (**C**) Sacral vertebrae in dorsal view, exposing the unfinished ends of the sacral neural spines. Anterior is to the right. (**D**) Articulated part of posterior caudal vertebral column. The vertebrae are exposed in right lateral view, with the neural spines pointing downwards. ca 1, caudal vertebra 1; n, neural arch; s 1, sacral vertebra 1. Scale bars, 5 cm (A, B), 2 cm (C, D)**.**

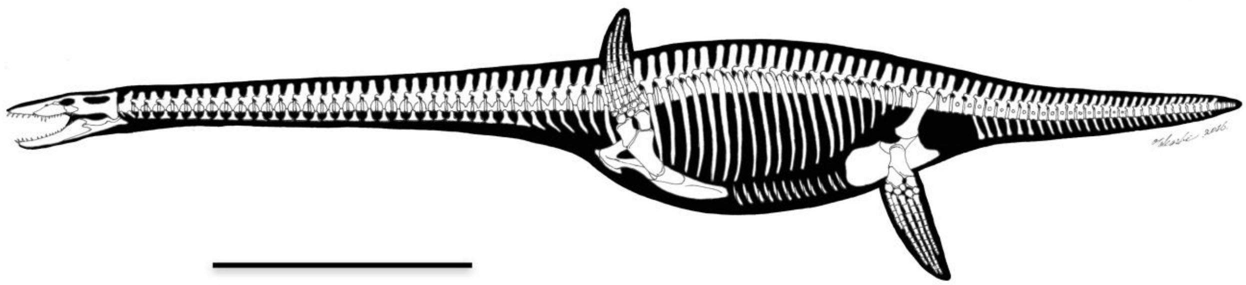

fig. S5. Reconstruction of the skeleton of *Rhaeticosaurus mertensi* gen. et sp. nov. based on the available measurements and proportions. The reconstruction visualizes locomotion by underwater flight with the forelimb at the beginning of the downstroke and the hindlimb at the beginning of the upstroke. Scale bar, 50 cm.

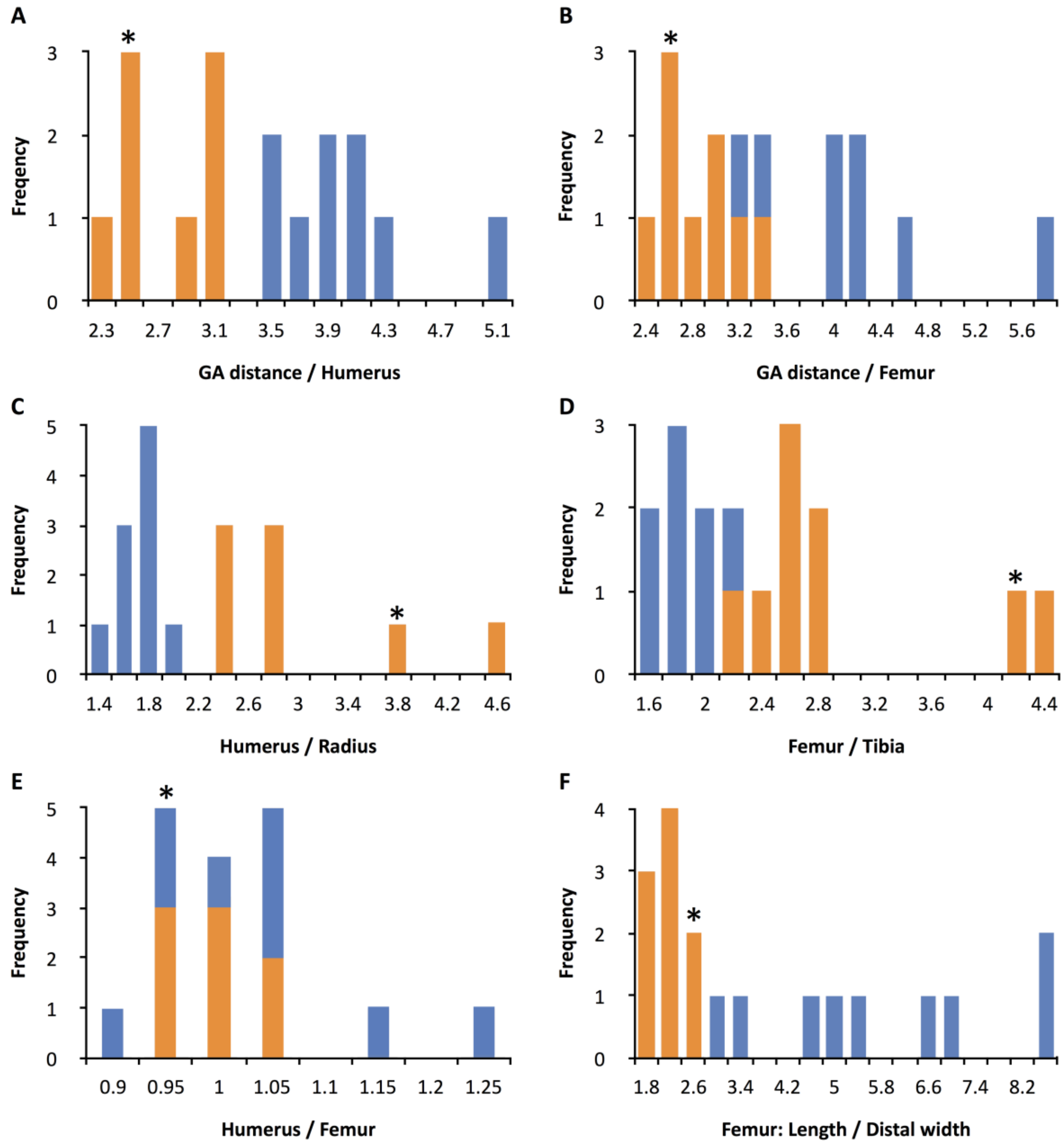

fig. S6. Selected skeletal proportions in Eosauropterygia. The histograms are based on the eight non-plesiosaurians and the eight plesiosaurians for which all variables in table S4 could be measured. Values on the x-axis are the lower value of the classes in the histogram. Orange: plesiosaurians; blue, non-plesiosaurians. Asterisks (*) indicate class of *Rhaeticosaurus mertensi* gen. et sp. nov. (**A**) Glenoid-acetabular distance/humerus ratio. Plesiosaurians do not overlap with non-plesiosaurians. Glenoid-acteabular distance is a proxy for trunk length. (**B**) Glenoid-acteabular distance/femur ratio. Plesiosaurians have a slight overlap with non-plesiosaurians. (**C**) Humerus/radius ratio. Plesiosaurians do not overlap with non-plesiosaurians. (**D**) Femur/tibia ratio. Plesiosaurians have a slight overlap with non-plesiosaurians. (**E**) Humerus/femur ratio. All plesiosaurians have humeri and femora of equal or subequal length whereas humerus/femur ratios vary more widely among non-plesiosaurians. (**F**) Femur length/distal width ratio. Plesiosaurians do not overlap with non-plesiosaurians. Note that *Rhaeticosaurus* ratios always plot with plesiosaurians. GA distance, glenoid-acteabular distance.

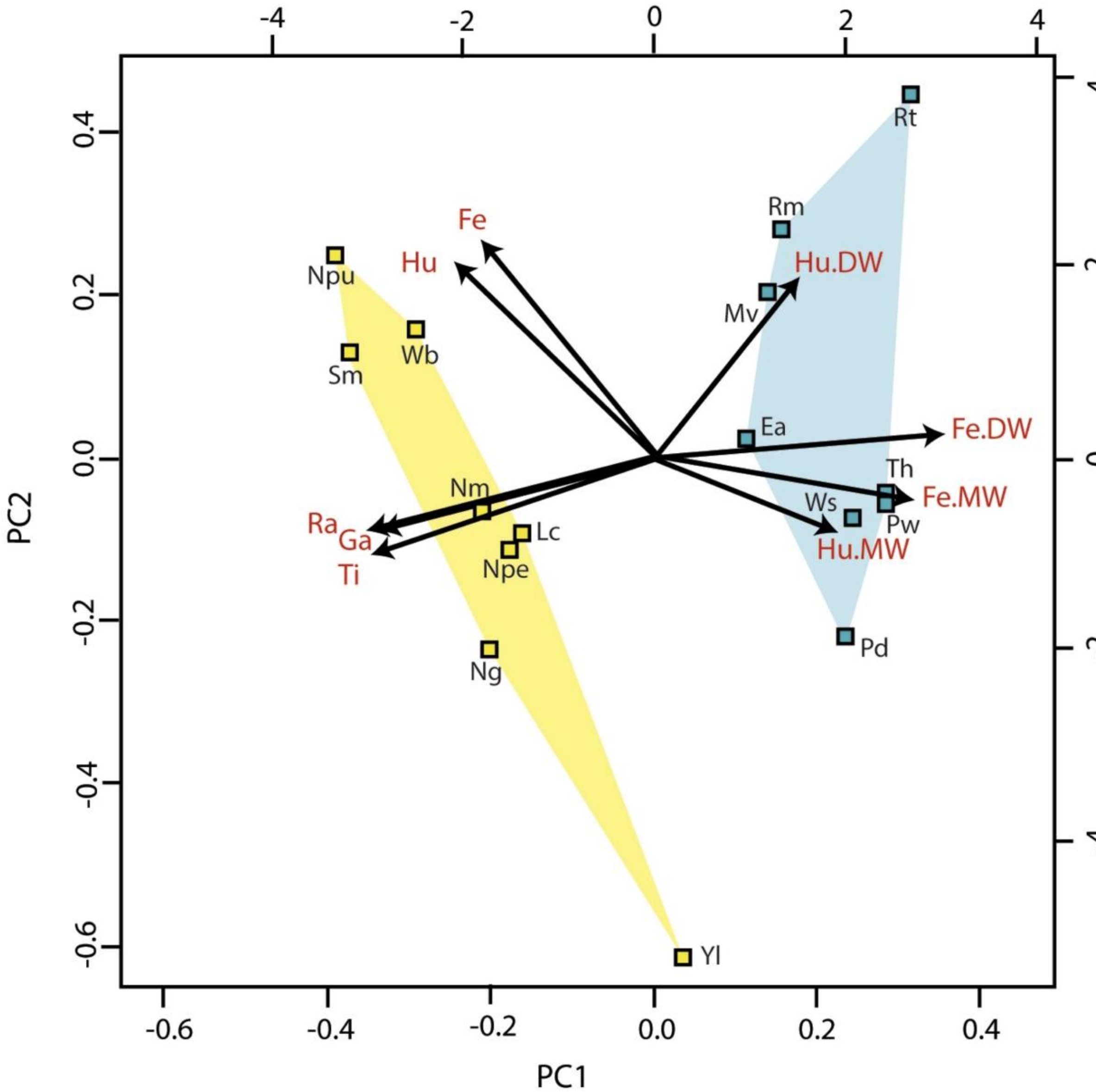

fig. S7. Principal component analysis of trunk and limb measurements in Eosauropterygia. The analysis is based on the eight non-plesiosaurians and the eight plesiosaurians for which all variables in table S4 could be measured. Graph showing the distribution of all taxa examined in the morphospace according to the PCA1 and PCA2 axes. Note the complete separation of plesiosaurians from non-plesiosaurians. Blue: plesiosaurians; Yellow: non-plesiosaurian taxa. Taxon abbreviations: Ep, *Eoplesiosaurus antiquior*; Lc, *Lariosaurus calcagnii*; Mv, *Meyerasaurus victor*; Npu, *Neusticosaurus pusillus*; Npe, *Neusticosaurus peyeri*; Ng, *Nothosaurus giganteus*; Nm, *Nothosaurus marchicus*; Pw, *Plesiopterys wildi*; Pd, *Plesiosaurus dolichodirus*; Rm, *Rhaeticosaurus mertensi* gen. et sp. nov.; Rt, *Rhomaleosaurus thorntoni*; Sm, *Serpianosaurus mirigiolensis*; Th, *Thalassiodracon hawkinsi*; Wb, *Wangosaurus brevirostris*; Ws, *Westphaliasaurus simonsensii*; Yl, *Yunguisaurus liae.* Variable abbreviations: Fe, femur length; Fe.DW, distal width of femur; Fe.MW, minimal shaft width of femur; Ga, glenoid-acetabular distance; Hu, humerus length; Hu.DW, distal width of humerus; Hu.MW, minimal shaft width of humerus; Ra, radius length; Ti, tibia length.

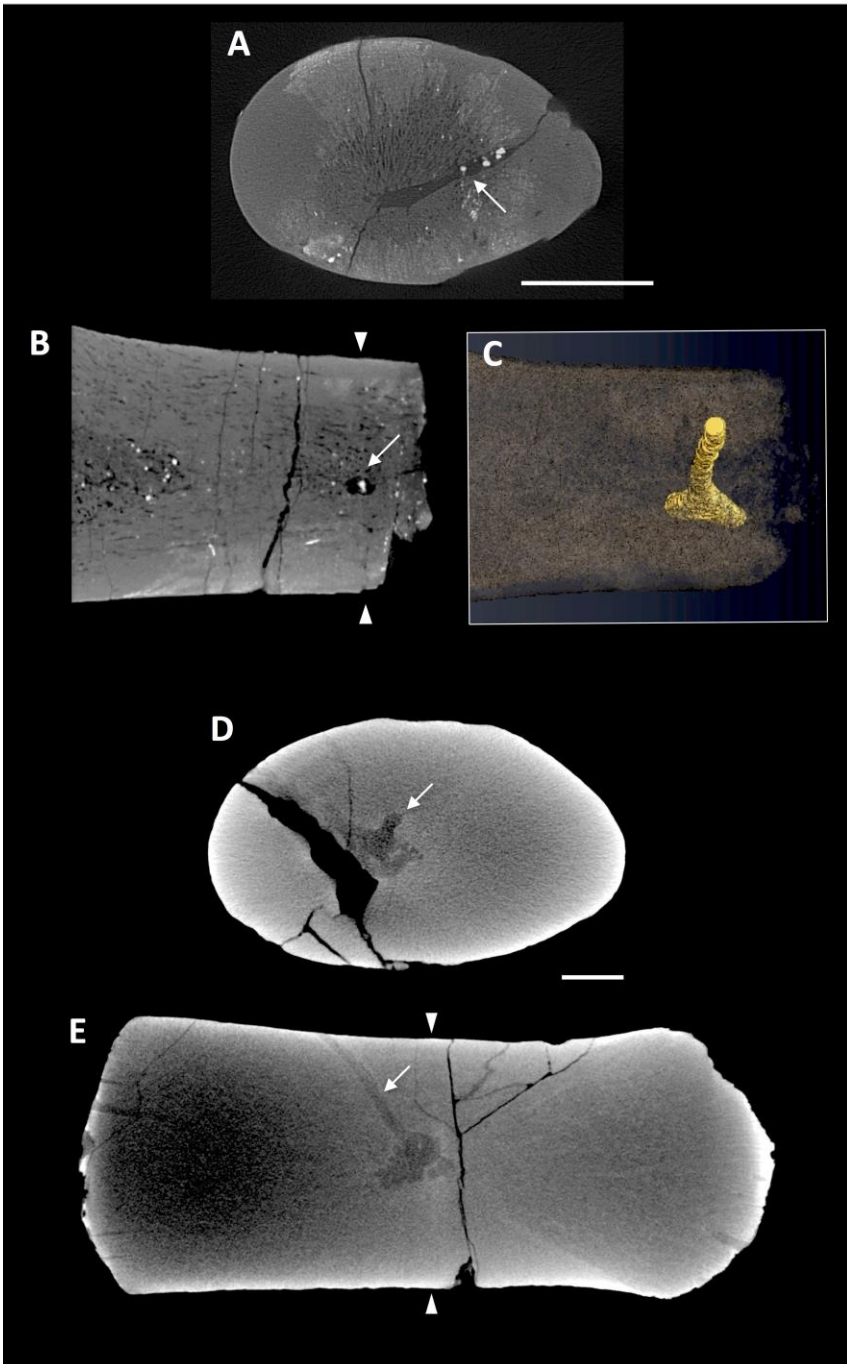

fig. S8. Examples of CT scans of plesiosaurian long bones used in locating the nutrient canal before sectioning. (**A**) Virtual midshaft cross section of the femur of the holotype of *Rhaeticosaurus mertensi* gen. et sp. nov. (**B**) Virtual longitudinal section of same, intersecting the nutrient canal. Proximal is to the left. (**C**) 3D reconstruction of nutrient canal (yellow). Note that the canal deviates only slightly towards proximal. (**D**) Virtual midshaft cross section of the humerus of the indeterminate juvenile elasmosaur OMNH MV 85. (**E**) Virtual longitudinal section of same in plane of nutrient canal. Proximal is to the left. Note that the canal deviates strongly towards proximal. Arrows point to nutrient canal. Arrow heads indicate planes of virtual midshaft sections. Scale bars, 10 mm.

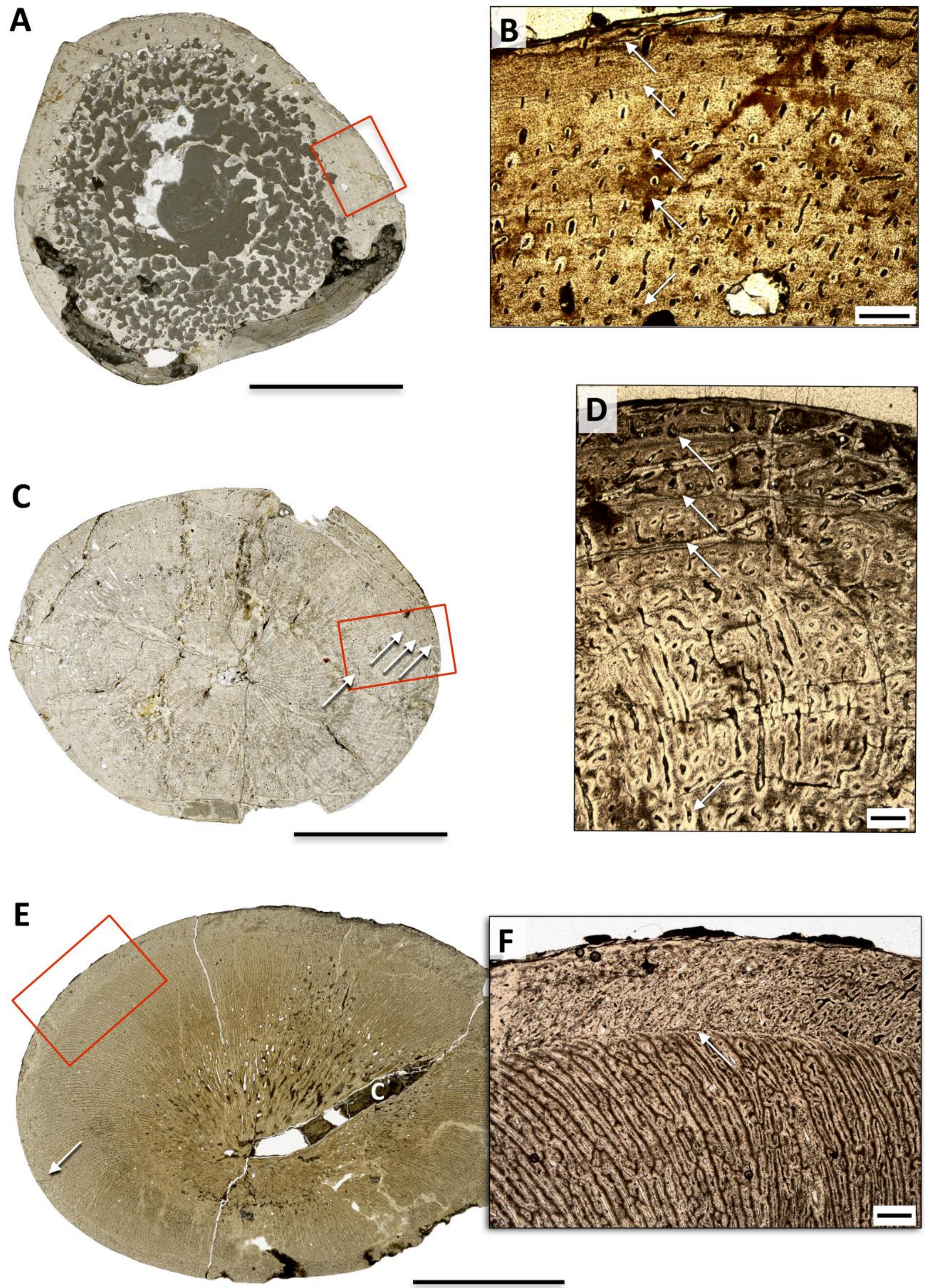
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fig. S9. Evolution of long bone histology in Triassic Eosauropterygia. (**A**) Midshaft cross section of the femur of *Nothosaurus mirabilis* STIPB R 49 in normal light. Box marks enlargement in (**B**). (B) Close-up of cortex. Note the low vascularity and well developed lines of arrested growth (arrows). (**C**) Midshaft cross section of the humerus of *Pistosaurus longaevus* SMNS 84825 in normal light. Box marks enlargement in (**D**). (D) Close-up of cortex. Note the radial vascularity in the inner cortex and well developed lines of arrested growth (arrows) in the outer cortex. (**E**) Midshaft cross section of the femur of the holotype of *Rhaeticosaurus mertensi* gen. et sp. nov. in normal light. Box marks enlargement in (**F**). (F) Close-up of outer part of first growth cycle and of second growth cycle. Note the abrupt directional change of the vascular canals at the cycle boundary. Arrows point to growth marks. c, nutrient canal. Scale bars, 10 mm (A, C, E) and 500 µm (B, D, F).

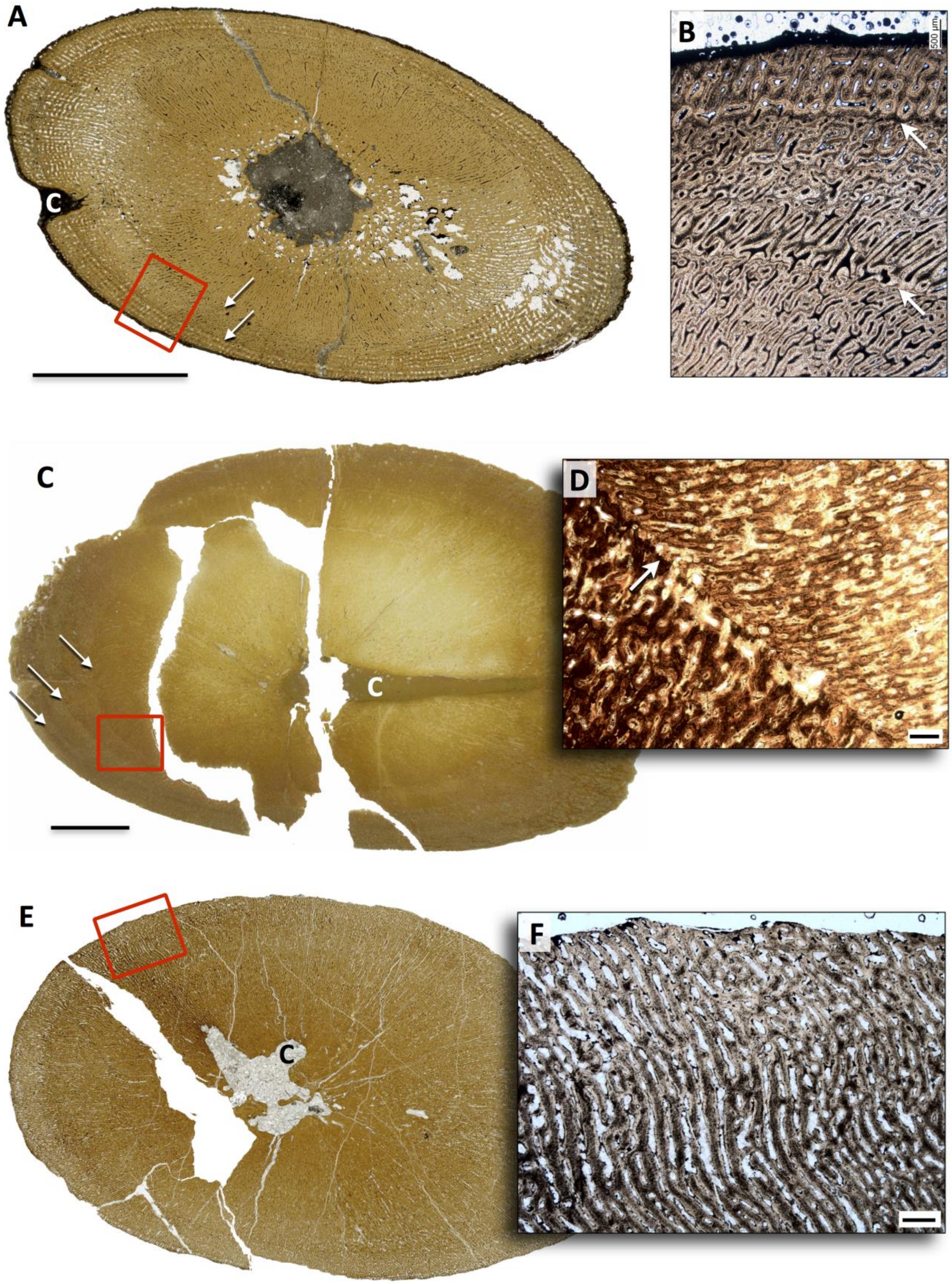

fig. S10. Long bone histology of Jurassic and Cretaceous plesiosaurians. (**A**) Midshaft cross section of the femur of *Plesiosaurus dolichodirus* STIPB R 89 in normal light. Note the small concavity on the left which marks the entrance of the nutrient canal. Box marks enlargement in (**B**). (B) Close-up of the second and third growth cycles. (**C**) Midshaft cross section of the femur of cryptoclidid plesiosaurian *Crytpoclidus eurymerus* STIPB R 324 in normal light. Note the large nutrient canal on the right. Box marks enlargement in (**D**). (D) Close-up of outer part of first and of second growth cycle, note the abrupt change in direction of the radial vascular canals. (**E**) Midshaft cross section of the humerus of the indeterminate juvenile elasmosaur OMNH MV 85 in normal light. Note the lack of growth marks. Box marks enlargement in (**F**). (F) Close-up of outer cortex. Note the high vascularity and the wavy course of the radial vascular canals. Arrows point to growth marks. c, nutrient canal. Scale bars, 10 mm (A, C, E) and 500 µm (B, D, F).

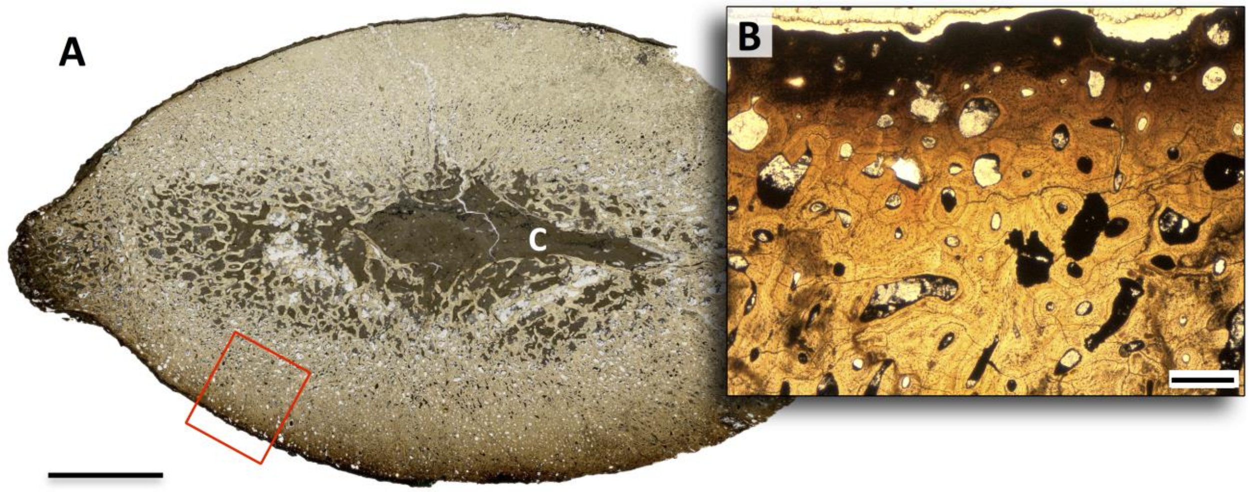

fig. S11. Long bone histology of a mature Middle Jurassic plesiosaurian. (**A**) Midshaft cross section of *Pliosaurus* sp. propodial SMNS 54025 in normal light. The entire cortex consists of dense Haversian tissue. Note the large nutrient canal on the right. Box marks enlargement in (**B**). (B) Close-up of outer cortex. Note the irregular arrangement of the secondary osteons and vascular canals. c, nutrient canal. Scale bars, 10 mm (A) and 500 μm (B).

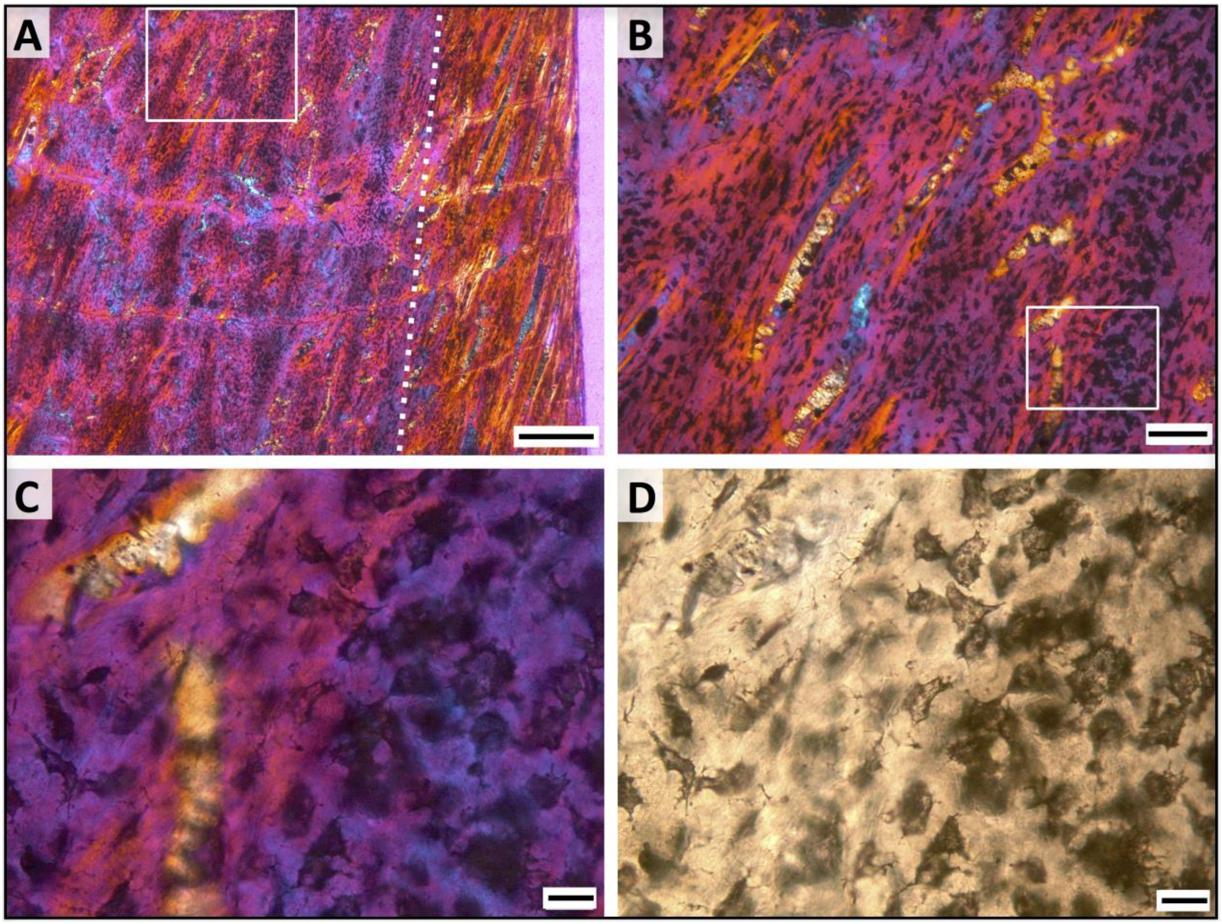

fig. S12. Long bone histology of the holotype of *Rhaeticosaurus mertensi* gen. et sp. nov. in longitudinal section. (**A**) Longitudinal section of the midshaft region of the femur in polarized light with lambda filter. Outer bone surface is to the left. The first growth mark is at the color change from magenta to orange (dotted line). Note the dominance of woven bone (magenta) with a few primary osteons (light blue) in the cortex to the left of the first growth mark. Box marks enlargement in (**B**). (B) Close-up of (A). Note the extreme density of plump, irregular osteocyte lacunae in the woven bone indicating dominance of static osteogenesis consistent with rapid tissue formation. Primary osteons are less distinct than in the cross section. Box marks enlargement in c. (**C**) Close-up of (B). (**D**) Same view as c but in normal light, again showing the plump and densely spaced osteocyte lacunae. Scale bars, 500 µm (A), 100 µm (B) and 20 µm (C and D).

table S1. Faunal list of bonebed above plesiosaurian discovery horizon. The material is accessioned to the collections of LWL-Museum für Naturkunde, Münster, Germany (*63*).

Taxon	Material	Clade	Frequency
Hybodus cloacinus	Teeth	Chondrichthyes	Very common
Lissodus minimus	Teeth	Chondrichthyes	Very common
Rhomphaiodon minor	Teeth	Chondrichthyes	Very common
Nemacanthus monilifer	Fin spines	Chondrichthyes	Very common
Hybodontiformes indet.	Fin spines	Chondrichthyes	Very common
Saurichthys sp.	Teeth	Actinopterygii	Common
Sargodon tomicus	Teeth	Actinopterygii	Common
Ceratodus latissimus	Teeth	Dipnoi	Moderately common
Temnospondyli indet.	Jaw fragments, limb bone	Temnospondyli	Rare
cf. *Shonisaurus*	Vertebrae	Ichthyosauria	Moderately common
Plesiosauria sp. A	Vertebrae	Plesiosauria	Moderately common
Plesiosauria sp. B	Vertebrae	Plesiosauria	Moderately common
Plesiosauria sp. C	Vertebrae	Plesiosauria	Moderately common
Pachystropheus rhaeticus	Vertebrae, limb bones	Choristodera/Thalattosauria	Very common
Lepagia gaumensis	Tooth	Cynodontia	Very rare

table S2. Unambiguous but not unique synapomorphies diagnosing *Rhaeticosuarus mertensi* gen. et sp. nov. in addition to the two autapomorphies. Numbers in parentheses indicate character number and state in the data matrix used in the phylogenetic analysis (Supporting Data). Character state descriptions are from ref. (*4*).

Mandible, retroarticular process, dorsoventral orientation of long axis: posteroventral or subhorizontal (122, 1).

Mandible, retroarticular process, mediolateral orientation of long axis: inflected slightly posteromedially (123, 1).

Splenial participation in mandibular symphysis: does not participate (125, 0).

Angular relative length and participation in mandibular symphysis: short, extends less than half mandibular length (126, 0).

Enamel ‘striations’ (grooves): present (136, 0).
Comment: This character description is poorly worded. The striations referred too are not grooves but thin and sharp ridges formed by the enamel.

Relative neck length: longer than (>1.2 times) trunk length (141, 2).

Cervical zygapophyses, combined width: distinctly narrower than the centrum (164, 2).

Caudal ribs facet location in proximal–middle caudal vertebrae: placed dorsally but neural arch does not form part of facet (188, 1/2).

Sharp longitudinal ridge on anterior margin of humerus: present (246, 1).

Width of epipodials of the hind limb: tibia larger (265, 0).

table S3. List of synapomorphies from phylogenetic analysis. The tree is the strict consensus tree of the phylogenetic analysis described in the "Methods" section and is based on the PAUP log file. This list of synapomorphies was used to diagnose Plesiosauria (node 60 to 59) and *Rhaeticosaurus mertensi* gen. et sp. nov. Abbreviations: H., *Hauffiosaurus*; M., *Microcleidus*; R., *Rhomaleosaurus*.

```
/------------------------------------------------------------------------ Neusticosaurus peyeri
|
+------------------------------------------------------------------------ Nothosaurus marchicus
|
|    /------------------------------------------------------------------- Yunguisaurus liae
62   |
|    +------------------------------------------------------------------- Pistosaurus longaevus
|    |
|    +------------------------------------------------------------------- Augustasaurus hagdorni
|    |
\---61    /-------------------------------------------------------------- Bobosaurus forojuliensis
     |    |
     |    |   /---------------------------------------------------------- Anningasaura lymense
     |    |   |
     |    |   |    /----------------------------------------------------- Macroplata tenuiceps
     |    |   |    |
     \---60   |    +----------------------------------------------------- Stratesaurus taylori
          |   |    |
          |   |    |                       /----------------------------- Avalonnectes arturi
          |   |    |                       |
          |   |    |                       |                       /----- Eurycleidus arcuatus
          \--59    +----------------------57    /-----------------51
              |    |                       |    |                  \----- Rhomaleosaurus megacephalus
              |    |                       |    |
              |    |                       \---56    /------------------- Archaeonectrus rostratus
              |    |                            |    |
              |    |                            |    |    /-------------- Meyerasaurus victor
              |    |                            \---55    |
              |    |                                 |    +-------------- Maresaurus coccai
              |    |                                 \---54
              \---58                                      |   /---------- Rhomaleosaurus thorntoni
                   |                                      |   |
                   |                                      \--53    /----- Rhomaleosaurus cramptoni
                   |                                          \---52
                   |                                               \----- Rhomaleosaurus zetlandicus
                   |
                   |                                      /-------------- Thalassiodracon hawkinsi
                   |                                      |
                   |                                      |        /----- Rhaeticosaurus mertensi
                   |    /--------------------------------39   /---36
                   |    |                                 |   |    \----- Peloneustes philarchus
                   |    |                                 |   |
                   |    |                                 \--38    /----- Hauffiosaurus longirostris
                   |    |                                     |    |
                   |    |                                     \---37----- Hauffiosaurus tomistomimus
                   \---50                                          |
                        |                                          \----- Hauffiosaurus zanoni
                        |
                        |    /------------------------------------------- Attenborosaurus conybeari
                        |    |
                        |    |    /-------------------------------------- Eoplesiosaurus antiquior
                        \---49    |
                             |    |   /---------------------------------- Plesiosaurus dolichodeirus
                             \---48   |
                                  |   |    /----------------------------- Eretmosaurus rugosus
                                  \--47    |
                                      |    |    /------------------------ Westphaliasaurus simonsensi
                                      \---46    |
                                           |    |                  /----- Plesiopterys wildi
                                           \---45    /------------43
                                                |    |             \----- Cryptoclidus eurymerus
                                                |    |
                                                \---44    /-------------- Seelyosaurus guilelmiimperatoris
                                                     |    |
                                                     \---42   /---------- Microcleidus tournemirensis
                                                          |   |
                                                          \--41    /----- Microcleidus brachypterygius
                                                              \---40
                                                                   \----- Microcleidus homalospondylus
```

Apomorphy lists:

Branch	Character	Steps	CI	Change
node_62 --> Neusticosaurus	2	1	0.143	1 ==> 0
	10	1	0.286	1 ==> 0
	40	1	0.500	1 ==> 0
	91	1	0.333	1 ==> 0
	111	1	0.333	1 ==> 0
	112	1	0.667	1 ==> 2
	116	1	0.500	1 ==> 0
	131	1	0.375	1 ==> 3
	133	1	0.250	1 ==> 0
	142	1	0.250	0 --> 1
	196	1	0.333	0 ==> 2
	242	1	0.429	1 ==> 2
	245	1	0.250	0 ==> 1
node_62 --> Nothosaurus	1	1	0.200	0 ==> 1
	7	1	0.286	1 ==> 2
	8	1	0.333	0 ==> 1
	9	1	0.500	0 ==> 1
	21	1	0.400	0 ==> 2
	25	1	0.500	0 --> 2
	26	1	1.000	0 ==> 1
	37	1	0.500	0 ==> 1
	41	1	1.000	0 --> 1
	55	1	1.000	0 ==> 1
	62	1	0.250	0 ==> 1
	73	1	0.250	0 --> 1
	78	1	0.333	0 ==> 1
	87	1	0.333	0 ==> 1
	109	1	0.286	0 ==> 1
	113	1	0.250	0 ==> 1
	125	1	0.333	1 ==> 0
	138	1	0.222	0 --> 1
	140	1	0.500	0 ==> 1
	162	1	1.000	0 ==> 1
	176	1	0.200	0 ==> 1
	205	1	0.222	2 ==> 1
node_62 --> node_61	4	1	0.200	0 ==> 1
	22	1	0.500	0 ==> 1
	25	1	0.500	0 --> 1
	29	1	1.000	2 ==> 0
	50	1	0.429	0 ==> 2
	53	1	0.500	0 ==> 1
	57	1	0.333	1 ==> 0
	60	1	0.500	0 --> 1
	63	1	0.500	0 ==> 1
	65	1	0.667	0 ==> 2
	67	1	0.250	0 --> 1
	76	1	1.000	0 --> 1
	120	1	0.400	0 ==> 1
	122	1	0.200	1 ==> 0
	123	1	0.333	0 --> 1
	126	1	0.333	0 ==> 1
	136	1	0.333	1 --> 0
	143	1	0.500	0 --> 1
	149	1	0.500	0 --> 1
	151	1	0.333	0 --> 1
	152	1	0.333	1 --> 4

	156	1	0.333	0 --> 1
	163	1	0.500	1 ==> 0
	178	1	0.500	0 ==> 1
	179	1	0.250	0 ==> 1
	181	1	0.500	1 ==> 0
	189	1	0.333	0 --> 1
	192	1	0.200	0 --> 1
	198	1	0.250	0 --> 1
	203	1	0.286	1 ==> 2
	206	1	0.333	0 ==> 1
	224	1	0.667	0 ==> 2
	226	1	0.500	0 ==> 1
	239	1	0.333	0 ==> 1
	250	1	0.400	2 ==> 0
	260	1	0.333	0 ==> 1
	265	1	0.286	0 ==> 1
node_61 --> Yunguisaurus	2	1	0.143	1 ==> 0
	7	1	0.286	1 ==> 0
	32	1	0.333	0 ==> 1
	35	1	0.333	0 ==> 1
	40	1	0.500	1 ==> 0
	45	1	0.500	0 ==> 1
	103	1	0.286	0 --> 2
	130	1	1.000	0 ==> 1
	131	1	0.375	1 ==> 3
	141	1	0.333	0 ==> 1
	156	1	0.333	1 --> 0
	179	1	0.250	1 --> 2
	205	1	0.222	2 ==> 0
	231	1	0.400	1 ==> 0
node_61 --> Pistosaurus	33	1	0.200	0 ==> 1
	103	1	0.286	0 --> 2
	109	1	0.286	0 ==> 2
	153	1	0.250	1 ==> 2
	157	1	0.333	0 --> 1
	158	1	0.286	0 --> 1
	170	1	0.333	0 ==> 1
	173	1	0.125	0 ==> 1
	176	1	0.200	0 ==> 1
	180	1	0.250	1 ==> 0
	183	1	0.250	0 ==> 1
	191	1	1.000	0 --> 1
	193	1	0.333	0 ==> 1
	201	1	0.200	0 ==> 1
	225	1	0.500	0 ==> 2
	227	1	0.286	1 ==> 0
node_61 --> Augustasaurus	51	1	0.333	0 ==> 1
	70	1	0.250	1 ==> 0
	92	1	0.333	0 ==> 1
	138	1	0.222	0 --> 1
	148	1	0.667	0 ==> 2
	165	1	0.286	0 ==> 2
	177	1	0.250	0 ==> 1
	203	1	0.286	2 ==> 1
	208	1	0.333	0 ==> 2
	256	1	0.500	0 ==> 1
node_61 --> node_60	1	1	0.200	0 --> 1
	4	1	0.200	1 --> 0
	9	1	0.500	0 --> 1
	12	1	1.000	0 --> 1

	15	1	0.667	0 --> 1
	33	1	0.200	0 --> 1
	62	1	0.250	0 --> 1
	86	1	0.500	0 --> 1
	96	1	0.250	0 --> 1
	98	1	1.000	0 --> 1
	100	1	0.500	1 --> 0
	109	1	0.286	0 --> 2
	113	1	0.250	0 --> 1
	123	1	0.333	1 --> 0
	152	1	0.333	4 --> 1
	159	1	0.400	0 --> 1
	160	1	0.750	0 ==> 1
	161	1	0.400	0 ==> 1
	164	1	0.500	0 ==> 1
	165	1	0.286	0 ==> 2
	171	1	1.000	1 ==> 0
	177	1	0.250	0 ==> 1
	181	1	0.500	0 ==> 1
	190	1	0.400	0 --> 1
	196	1	0.333	0 --> 2
	199	1	1.000	0 --> 1
	205	1	0.222	2 --> 1
	214	1	0.667	0 --> 1
	216	1	0.500	1 --> 0
	251	1	0.333	0 --> 1
	254	1	1.000	0 --> 1
	258	1	0.500	0 --> 1
	267	1	1.000	0 --> 1
	268	1	1.000	0 --> 1
node_60 --> Bobosaurus	151	1	0.333	1 --> 2
	153	1	0.250	1 ==> 0
	156	1	0.333	1 --> 0
	178	1	0.500	1 ==> 2
	179	1	0.250	1 --> 2
	185	1	0.333	0 ==> 1
	188	1	0.333	0 ==> 1
	227	1	0.286	1 ==> 0
node_60 --> node_59	17	1	0.200	0 ==> 1
	136	1	0.333	0 --> 1
	137	1	0.400	2 ==> 1
	152	1	0.333	1 --> 2
	167	1	1.000	0 ==> 1
	172	1	0.429	0 ==> 3
	187	1	0.600	3 --> 1
	223	1	0.250	2 --> 0
	244	1	0.500	0 --> 1
	255	1	1.000	0 --> 1
node_59 --> node_58	2	1	0.143	1 ==> 0
	18	1	0.333	0 --> 1
	19	1	0.400	0 --> 1
	31	1	0.500	0 ==> 1
	49	1	0.500	1 --> 0
	50	1	0.429	2 ==> 1
	65	1	0.667	2 ==> 1
	68	1	0.667	0 --> 2
	71	1	0.667	0 ==> 2
	95	1	0.333	0 --> 1
	108	1	0.500	1 --> 0
	114	1	0.250	0 --> 1

	121	1	0.250	0 --> 1
	138	1	0.222	0 --> 1
	148	1	0.667	0 ==> 2
node_58 --> node_50	1	1	0.200	1 --> 0
	19	1	0.400	1 --> 2
	33	1	0.200	1 ==> 0
	43	1	1.000	0 ==> 2
	68	1	0.667	2 --> 0
	70	1	0.250	1 --> 0
	77	1	0.500	0 ==> 1
	84	1	0.667	2 ==> 0
	106	1	0.500	0 --> 1
	109	1	0.286	2 --> 0
	114	1	0.250	1 --> 0
	121	1	0.250	1 --> 0
	127	1	1.000	0 ==> 2
	142	1	0.250	0 --> 1
	152	1	0.333	2 ==> 3
	158	1	0.286	0 --> 1
	180	1	0.250	1 ==> 0
	203	1	0.286	2 ==> 0
	239	1	0.333	1 ==> 0
	252	1	0.500	1 ==> 0
node_50 --> node_39	16	1	1.000	0 ==> 1
	21	1	0.400	0 --> 1
	22	1	0.500	1 --> 0
	29	1	1.000	0 --> 1
	52	1	0.667	0 ==> 1
	62	1	0.250	1 --> 0
	83	1	0.286	2 --> 1
	96	1	0.250	1 --> 0
	101	1	1.000	0 --> 1
	131	1	0.375	1 --> 0
	143	1	0.500	1 --> 0
	172	1	0.429	3 ==> 2
	192	1	0.200	1 --> 0
	201	1	0.200	0 ==> 1
	206	1	0.333	1 --> 0
node_39 --> node_38	4	1	0.200	0 --> 2
	6	1	0.500	0 --> 1
	9	1	0.500	1 ==> 2
	17	1	0.200	1 --> 0
	34	1	1.000	0 ==> 1
	67	1	0.250	1 --> 0
	70	1	0.250	0 --> 1
	71	1	0.667	2 --> 1
	103	1	0.286	0 --> 1
	109	1	0.286	0 --> 2
	112	1	0.667	1 ==> 0
	114	1	0.250	0 --> 1
	115	1	1.000	1 --> 0
	124	1	1.000	0 --> 1
	131	1	0.375	0 --> 2
	138	1	0.222	1 ==> 2
	150	1	1.000	0 --> 1
	157	1	0.333	0 ==> 1
	165	1	0.286	2 --> 0
	205	1	0.222	1 --> 0
	214	1	0.667	1 --> 2
	216	1	0.500	0 ==> 1

	231	1	0.400	1 ==> 0
	232	1	0.333	0 --> 1
	235	1	0.333	2 --> 0
	236	1	0.250	0 --> 1
	242	1	0.429	1 --> 2
	249	1	0.200	0 ==> 1
	250	1	0.400	0 ==> 2
	263	1	0.200	0 --> 1
	264	1	0.250	0 --> 1
node_38 --> node_36	1	1	0.200	0 --> 1
	7	1	0.286	1 --> 2
	11	1	1.000	0 --> 1
	15	1	0.667	1 --> 2
	50	1	0.429	1 --> 3
	51	1	0.333	0 --> 1
	52	1	0.667	1 --> 2
	54	1	1.000	0 --> 1
	83	1	0.286	1 --> 2
	84	1	0.667	0 --> 2
	87	1	0.333	0 --> 1
	90	1	1.000	0 --> 1
	99	1	0.333	0 --> 2
	100	1	0.500	0 --> 1
	103	1	0.286	1 --> 2
	110	1	1.000	0 --> 1
	117	1	0.500	0 --> 1
	120	1	0.400	1 --> 0
	127	1	1.000	2 --> 1
	132	1	0.333	0 --> 1
	137	1	0.400	1 --> 0
	159	1	0.400	1 --> 2
	161	1	0.400	1 --> 2
	165	1	0.286	0 --> 1
	172	1	0.429	2 --> 0
	177	1	0.250	1 --> 0
	187	1	0.600	1 --> 0
	189	1	0.333	1 ==> 0
	194	1	0.500	0 --> 1
	196	1	0.333	2 --> 0
	207	1	0.500	0 --> 1
	220	1	0.250	0 --> 1
	224	1	0.667	2 --> 0
	232	1	0.333	1 --> 2
	244	1	0.500	1 --> 0
	251	1	0.333	1 --> 0
	255	1	1.000	1 ==> 2
	262	1	1.000	0 --> 1
	269	1	0.333	0 --> 1
node_36 --> Rhaeticosaurus	122	1	0.200	0 ==> 1
	123	1	0.333	0 ==> 1
	125	1	0.333	1 ==> 0
	126	1	0.333	1 ==> 0
	136	1	0.333	1 ==> 0
	141	1	0.333	0 ==> 2
	164	1	0.500	1 ==> 2
	172	1	0.429	0 --> 1
	188	1	0.333	0 ==> {12}
	246	1	0.250	0 ==> 1
	264	1	0.250	1 --> 0
	265	1	0.286	1 ==> 0

node_36 --> Peloneustes	152	1	0.333	3 ==> 1
	153	1	0.250	1 ==> 0
	174	1	0.500	0 ==> 1
	175	1	0.333	0 ==> 1
	179	1	0.250	1 ==> 2
	182	1	0.500	0 ==> 1
	186	1	1.000	0 ==> 1
	222	1	0.333	1 ==> 0
	223	1	0.250	0 ==> 2
	224	1	0.667	0 --> 3
	229	1	1.000	0 ==> 1
	231	1	0.400	0 ==> 2
	238	1	1.000	0 ==> 1
	241	1	1.000	1 ==> 0
	242	1	0.429	2 --> 0
	244	1	0.500	0 --> 2
	245	1	0.250	0 ==> 1
	251	1	0.333	0 --> 2
	254	1	1.000	1 ==> 2
	256	1	0.500	0 ==> 1
	259	1	0.333	0 ==> 1
	270	1	0.250	0 ==> 1
node_38 --> node_37	13	1	0.200	0 ==> 1
	14	1	0.500	0 --> 2
	25	1	0.500	1 ==> 0
	28	1	0.500	0 ==> 2
	53	1	0.500	1 ==> 0
	66	1	0.500	0 ==> 1
	73	1	0.250	0 ==> 1
	82	1	0.333	0 ==> 1
	113	1	0.250	1 ==> 0
	121	1	0.250	0 ==> 1
	130	1	1.000	0 ==> 2
	131	1	0.375	2 --> 3
	151	1	0.333	1 --> 2
	183	1	0.250	0 --> 1
	203	1	0.286	0 --> 2
	209	1	0.500	0 --> 2
	227	1	0.286	1 --> 2
	235	1	0.333	0 --> 1
	257	1	0.250	0 ==> 1
node_37 --> H. longirostris	17	1	0.200	0 --> 1
	50	1	0.429	1 ==> 2
	65	1	0.667	1 ==> 0
	99	1	0.333	0 ==> 1
node_37 -> H. tomistomimus	114	1	0.250	1 --> 0
	141	1	0.333	0 ==> 1
	259	1	0.333	0 ==> 1
	265	1	0.286	1 ==> 2
node_37 --> H. zanoni	88	1	0.333	0 ==> 1
	142	1	0.250	1 --> 0
	236	1	0.250	1 --> 0
	242	1	0.429	2 --> 1
	263	1	0.200	1 --> 0
node_39 --> Thalassiodracon	3	1	0.167	0 ==> 1
	7	1	0.286	1 ==> 0
	8	1	0.333	0 ==> 1
	46	1	0.333	1 ==> 0
	61	1	0.333	0 ==> 1
	79	1	0.250	1 ==> 0

	92	1	0.333	0 ==> 1
	141	1	0.333	0 ==> 1
	142	1	0.250	1 --> 0
	158	1	0.286	1 --> 0
	173	1	0.125	0 ==> 1
node_50 --> node_49	4	1	0.200	0 --> 1
	31	1	0.500	1 --> 0
	32	1	0.333	0 --> 1
	35	1	0.333	0 --> 1
	69	1	0.500	0 --> 1
	78	1	0.333	0 --> 1
	111	1	0.333	1 ==> 0
	126	1	0.333	1 --> 0
	128	1	1.000	0 --> 1
	140	1	0.500	0 --> 1
	141	1	0.333	0 ==> 2
	144	1	1.000	0 --> 1
	148	1	0.667	2 --> 1
	182	1	0.500	0 ==> 1
	189	1	0.333	1 --> 0
	194	1	0.500	0 ==> 1
	246	1	0.250	0 --> 1
node_49 --> Attenborosaurus	13	1	0.200	0 ==> 1
	50	1	0.429	1 ==> 2
	61	1	0.333	0 ==> 1
	208	1	0.333	0 ==> 2
	209	1	0.500	0 ==> 2
	219	1	0.500	0 ==> 3
	220	1	0.250	0 ==> 1
	235	1	0.333	2 ==> 1
	270	1	0.250	0 ==> 1
node_49 --> node_48	3	1	0.167	0 --> 1
	7	1	0.286	1 --> 0
	17	1	0.200	1 --> 0
	113	1	0.250	1 --> 0
	133	1	0.250	1 --> 0
	152	1	0.333	3 ==> 4
	161	1	0.400	1 --> 0
	190	1	0.400	1 ==> 0
	197	1	0.333	0 --> 1
	232	1	0.333	0 --> 1
	257	1	0.250	0 --> 1
node_48 --> node_47	159	1	0.400	1 ==> 2
	165	1	0.286	2 --> 0
	227	1	0.286	1 ==> 2
	244	1	0.500	1 ==> 2
	251	1	0.333	1 ==> 2
node_47 --> Plesiosaurus	107	1	0.333	0 ==> 1
	108	1	0.500	0 --> 1
	169	1	0.500	0 ==> 1
	180	1	0.250	0 ==> 1
	201	1	0.200	0 ==> 1
	222	1	0.333	1 ==> 0
	232	1	0.333	1 --> 0
node_47 --> node_46	4	1	0.200	1 --> 0
	48	1	0.200	0 --> 1
	58	1	0.500	1 --> 0
	79	1	0.250	1 --> 0
	84	1	0.667	0 --> 1
	92	1	0.333	0 --> 1

	95	1	0.333	1 --> 0
	97	1	0.333	0 --> 1
	145	1	1.000	0 --> 1
	157	1	0.333	0 ==> 1
	158	1	0.286	1 --> 0
	176	1	0.200	0 --> 1
	185	1	0.333	0 --> 1
	187	1	0.600	1 --> 3
	203	1	0.286	0 --> 2
	216	1	0.500	0 --> 1
	228	1	0.333	1 ==> 0
	235	1	0.333	2 ==> 0
	245	1	0.250	0 --> 1
	246	1	0.250	1 --> 0
	247	1	0.500	0 --> 1
node_46 --> Eretmosaurus	165	1	0.286	0 --> 2
	265	1	0.286	1 ==> 2
node_46 --> node_45	170	1	0.333	0 --> 1
	173	1	0.125	0 ==> 1
	249	1	0.200	0 --> 1
	250	1	0.400	0 ==> 1
	264	1	0.250	0 ==> 1
	270	1	0.250	0 ==> 1
node_45 --> Westphaliasaurus	176	1	0.200	1 --> 0
	217	1	0.500	0 ==> 1
	240	1	0.500	0 ==> 1
	242	1	0.429	1 ==> 0
	247	1	0.500	1 --> 0
	251	1	0.333	2 ==> 1
node_45 --> node_44	158	1	0.286	0 --> 1
	172	1	0.429	3 ==> 0
	192	1	0.200	1 ==> 0
	198	1	0.250	1 --> 0
	207	1	0.500	0 --> 1
	209	1	0.500	0 --> 1
	210	1	1.000	0 --> 2
	212	1	1.000	0 ==> 1
	219	1	0.500	0 ==> 3
	245	1	0.250	1 --> 0
	263	1	0.200	0 ==> 1
node_44 --> node_42	3	1	0.167	1 --> 0
	14	1	0.500	0 ==> 2
	32	1	0.333	1 --> 0
	39	1	1.000	0 ==> 1
	43	1	1.000	2 ==> 1
	57	1	0.333	0 --> 1
	61	1	0.333	0 ==> 1
	66	1	0.500	0 --> 1
	67	1	0.250	1 --> 0
	91	1	0.333	1 --> 0
	96	1	0.250	1 --> 0
	99	1	0.333	0 --> 2
	100	1	0.500	0 --> 1
	103	1	0.286	0 --> 1
	109	1	0.286	0 --> 2
	122	1	0.200	0 --> 1
	138	1	0.222	1 ==> 0
	164	1	0.500	1 --> 2
	166	1	1.000	0 --> 1
	178	1	0.500	1 ==> 2

	179	1	0.250	1 ==> 0
	188	1	0.333	0 ==> 1
	193	1	0.333	0 ==> 1
	210	1	1.000	2 --> 3
	249	1	0.200	1 --> 0
	265	1	0.286	1 ==> 2
node_42 --> Seelyosaurus	152	1	0.333	4 ==> 3
	158	1	0.286	1 ==> 2
	196	1	0.333	2 ==> 1
	209	1	0.500	1 --> 0
	213	1	1.000	0 ==> 1
	236	1	0.250	0 ==> 1
	260	1	0.333	1 ==> 0
node_42 --> node_41	37	1	0.500	0 ==> 1
	38	1	1.000	0 ==> 1
	50	1	0.429	1 ==> 2
	153	1	0.250	1 ==> 2
	154	1	1.000	0 ==> 1
	183	1	0.250	0 ==> 1
	205	1	0.222	1 --> 0
	223	1	0.250	0 ==> 2
	235	1	0.333	0 --> 2
node_41 -> M. tournemirensis	10	1	0.286	1 ==> 2
	48	1	0.200	1 --> 0
	58	1	0.500	0 ==> 1
	82	1	0.333	0 ==> 1
	132	1	0.333	0 ==> 1
	197	1	0.333	1 ==> 0
	198	1	0.250	0 --> 1
	205	1	0.222	0 --> 2
	263	1	0.200	1 ==> 0
node_41 --> node_40	33	1	0.200	0 ==> 1
	151	1	0.333	1 --> 2
	180	1	0.250	0 ==> 1
	200	1	0.500	0 --> 1
	201	1	0.200	0 --> 1
	203	1	0.286	2 --> 0
	207	1	0.500	1 --> 2
	231	1	0.400	1 ==> 0
	245	1	0.250	0 ==> 1
node_40 -> M. brachypterygius	3	1	0.167	0 ==> 1
	4	1	0.200	0 ==> 1
	83	1	0.286	2 ==> 1
	103	1	0.286	1 --> 0
	152	1	0.333	4 ==> 3
	192	1	0.200	0 ==> 1
	220	1	0.250	0 ==> 1
	227	1	0.286	2 ==> 1
	258	1	0.500	1 ==> 0
	265	1	0.286	2 ==> 1
node_40 -> M. homalospondylus	25	1	0.500	1 ==> 2
	251	1	0.333	2 ==> 1
node_44 --> node_43	10	1	0.286	1 --> 0
	27	1	1.000	0 --> 1
	35	1	0.333	1 --> 0
	38	1	1.000	0 --> 2
	45	1	0.500	0 ==> 1
	46	1	0.333	1 --> 0
	60	1	0.500	1 --> 0
	68	1	0.667	0 ==> 1

	83	1	0.286	2 ==> 1
	85	1	1.000	1 --> 0
	89	1	1.000	0 ==> 1
	112	1	0.667	1 ==> 2
	125	1	0.333	1 ==> 0
	131	1	0.375	1 --> 2
	161	1	0.400	0 --> 1
	163	1	0.500	0 ==> 1
	168	1	1.000	0 --> 1
	169	1	0.500	0 --> 1
	170	1	0.333	1 --> 0
	185	1	0.333	1 --> 0
	200	1	0.500	0 --> 1
	206	1	0.333	1 --> 0
	207	1	0.500	1 --> 2
	214	1	0.667	1 --> 2
	220	1	0.250	0 --> 1
	228	1	0.333	0 --> 1
	232	1	0.333	1 --> 2
	234	1	1.000	0 --> 1
	237	1	1.000	0 --> 1
	250	1	0.400	1 --> 2
	252	1	0.500	0 --> 1
	257	1	0.250	1 ==> 0
	269	1	0.333	0 ==> 1
node_43 --> Plesiopterys	48	1	0.200	1 --> 0
	77	1	0.500	1 ==> 0
	78	1	0.333	1 --> 0
	79	1	0.250	0 --> 1
	151	1	0.333	1 ==> 2
	153	1	0.250	1 ==> 2
	196	1	0.333	2 ==> 1
	198	1	0.250	0 --> 1
	270	1	0.250	1 ==> 0
node_43 --> Cryptoclidus	14	1	0.500	0 ==> 1
	51	1	0.333	0 ==> 1
	63	1	0.500	1 ==> 0
	71	1	0.667	2 ==> 1
	72	1	0.500	0 ==> 1
	74	1	0.500	0 ==> 1
	80	1	1.000	0 ==> 1
	82	1	0.333	0 ==> 1
	152	1	0.333	4 ==> 3
	160	1	0.750	1 ==> 3
	161	1	0.400	1 --> 2
	173	1	0.125	1 ==> 0
	176	1	0.200	1 --> 0
	187	1	0.600	3 ==> 0
	190	1	0.400	0 ==> 1
	195	1	1.000	0 ==> 1
	202	1	1.000	1 ==> 0
	203	1	0.286	2 ==> 1
	216	1	0.500	1 ==> 2
	221	1	1.000	0 ==> 1
	222	1	0.333	1 ==> 0
	225	1	0.500	0 ==> 1
	226	1	0.500	1 ==> 0
	227	1	0.286	2 ==> 1
	230	1	1.000	0 ==> 1
	239	1	0.333	0 ==> 1

	240	1	0.500	0 ==> 1
	242	1	0.429	1 ==> 3
	244	1	0.500	2 ==> 3
	245	1	0.250	0 ==> 2
	255	1	1.000	1 ==> 3
	259	1	0.333	0 ==> 1
	260	1	0.333	1 ==> 0
	261	1	1.000	0 ==> {12}
	262	1	1.000	0 ==> 2
	265	1	0.286	1 ==> 0
	268	1	1.000	1 ==> 2
node_48 --> Eoplesiosaurus	193	1	0.333	0 ==> 1
	205	1	0.222	1 --> 2
node_58 --> Macroplata	2	1	0.143	0 ==> 1
	4	1	0.200	0 --> 1
	13	1	0.200	0 ==> 1
	28	1	0.500	0 ==> 1
	62	1	0.250	1 --> 0
	67	1	0.250	1 --> 0
	73	1	0.250	0 ==> 1
	83	1	0.286	2 ==> 0
	120	1	0.400	1 ==> 2
	131	1	0.375	1 ==> 2
	151	1	0.333	1 ==> 2
	153	1	0.250	1 ==> 0
	192	1	0.200	1 --> 0
	217	1	0.500	0 ==> 1
	227	1	0.286	1 ==> 2
	231	1	0.400	1 ==> 2
node_58 --> Stratesaurus	1	1	0.200	1 --> 0
	3	1	0.167	0 ==> 1
	10	1	0.286	1 ==> 0
	17	1	0.200	1 ==> 0
	21	1	0.400	0 ==> 1
	70	1	0.250	1 ==> 0
	79	1	0.250	1 ==> 0
	95	1	0.333	1 --> 0
	99	1	0.333	0 ==> 1
	133	1	0.250	1 ==> 0
	138	1	0.222	1 ==> 0
	149	1	0.500	1 ==> 0
	173	1	0.125	0 ==> 1
	175	1	0.333	0 ==> 1
	225	1	0.500	0 ==> 2
	269	1	0.333	0 ==> 1
node_58 --> node_57	7	1	0.286	1 --> 2
	8	1	0.333	0 --> 1
	9	1	0.500	1 --> 2
	10	1	0.286	1 --> 2
	13	1	0.200	0 --> 1
	21	1	0.400	0 --> 2
	49	1	0.500	0 --> 1
	87	1	0.333	0 --> 1
	99	1	0.333	0 --> 1
	100	1	0.500	0 --> 2
	102	1	1.000	0 --> 1
	111	1	0.333	1 --> 0
	120	1	0.400	1 --> 2
	124	1	1.000	0 --> 2
	159	1	0.400	1 ==> 2

	172	1	0.429	3 ==> 1
	179	1	0.250	1 --> 0
	183	1	0.250	0 ==> 1
	184	1	0.667	0 ==> 2
	208	1	0.333	0 --> 2
	210	1	1.000	0 --> 1
	218	1	1.000	0 --> 1
	228	1	0.333	1 ==> 0
	244	1	0.500	1 --> 2
	257	1	0.250	0 --> 1
node_57 --> Avalonnectes	141	1	0.333	0 ==> {12}
	173	1	0.125	0 ==> 1
node_57 --> node_56	50	1	0.429	1 ==> 2
	57	1	0.333	0 ==> 1
	164	1	0.500	1 ==> 0
	174	1	0.500	0 ==> 1
	205	1	0.222	1 --> 0
	242	1	0.429	1 --> 2
node_56 --> node_51	4	1	0.200	0 --> 1
	6	1	0.500	0 --> 1
	14	1	0.500	0 --> 2
	18	1	0.333	1 --> 0
	19	1	0.400	1 --> 0
	28	1	0.500	0 --> 1
	33	1	0.200	1 --> 0
	83	1	0.286	2 --> 0
	121	1	0.250	1 --> 0
	133	1	0.250	1 --> 0
	179	1	0.250	0 --> 1
	201	1	0.200	0 --> 1
	246	1	0.250	0 ==> 1
	249	1	0.200	0 ==> 1
node_51 --> Eurycleidus	245	1	0.250	0 ==> 1
node_51 --> R. macrocephalus	137	1	0.400	1 ==> 0
	138	1	0.222	1 ==> 2
	153	1	0.250	1 ==> 0
	190	1	0.400	1 ==> 2
	225	1	0.500	0 ==> 2
node_56 --> node_55	15	1	0.667	1 ==> 2
	20	1	0.500	0 --> 1
	52	1	0.667	0 ==> 1
	93	1	1.000	0 --> 1
	99	1	0.333	1 --> 2
	132	1	0.333	0 --> 1
	184	1	0.667	2 --> 1
	196	1	0.333	2 --> 1
	205	1	0.222	0 --> 2
	240	1	0.500	0 --> 1
	250	1	0.400	0 --> 2
	264	1	0.250	0 ==> 1
node_55 --> node_54	2	1	0.143	0 --> 1
	19	1	0.400	1 --> 2
	116	1	0.500	1 ==> 0
	137	1	0.400	1 --> 0
	153	1	0.250	1 ==> 0
	158	1	0.286	0 --> 1
	179	1	0.250	0 --> 2
	187	1	0.600	1 --> 2
	232	1	0.333	0 ==> 1
	236	1	0.250	0 --> 1

node_54 --> Meyerasaurus	2	1	0.143	1 --> 0
	7	1	0.286	2 ==> 0
	10	1	0.286	2 ==> 1
	13	1	0.200	1 ==> 0
	21	1	0.400	2 --> 0
	86	1	0.500	1 ==> 0
	88	1	0.333	0 ==> 1
	97	1	0.333	0 ==> 1
	103	1	0.286	0 ==> 1
	107	1	0.333	0 ==> 1
	109	1	0.286	2 ==> 1
	122	1	0.200	0 ==> 1
	184	1	0.667	1 --> 2
	197	1	0.333	0 ==> 1
node_54 --> Maresaurus	4	1	0.200	0 --> 1
	20	1	0.500	1 --> 0
	46	1	0.333	1 ==> 0
	48	1	0.200	0 ==> 1
	96	1	0.250	1 ==> 0
	137	1	0.400	0 --> 1
	160	1	0.750	1 ==> 2
	172	1	0.429	1 ==> 3
node_54 --> node_53	18	1	0.333	1 ==> 0
	23	1	1.000	0 ==> 1
	59	1	1.000	0 --> 1
	178	1	0.500	1 --> 0
	245	1	0.250	0 ==> 1
	263	1	0.200	0 --> 1
node_53 --> node_52	19	1	0.400	2 --> 0
	138	1	0.222	1 ==> 2
	177	1	0.250	1 --> 0
	190	1	0.400	1 --> 2
	240	1	0.500	1 --> 2
	249	1	0.200	0 ==> 1
node_52 --> R. cramptoni	2	1	0.143	1 --> 0
node_53 --> R. thorntoni	117	1	0.500	0 ==> 1
	120	1	0.400	2 ==> 1
	165	1	0.286	2 ==> 0
	223	1	0.250	0 ==> 2
node_55 --> Archaeonectrus	4	1	0.200	0 --> 2
	135	1	1.000	0 ==> 1
	138	1	0.222	1 ==> 2
	159	1	0.400	2 ==> 1
	173	1	0.125	0 ==> 1
	235	1	0.333	2 ==> 1
node_59 --> Anningasaura	3	1	0.167	0 ==> 1
	10	1	0.286	1 ==> 2
	28	1	0.500	0 ==> 1
	48	1	0.200	0 ==> 1
	69	1	0.500	0 --> 1
	72	1	0.500	0 ==> 1
	73	1	0.250	0 --> 1
	74	1	0.500	0 ==> 1
	83	1	0.286	2 ==> 0
	88	1	0.333	0 ==> 1
	91	1	0.333	1 ==> 0
	97	1	0.333	0 --> 1
	106	1	0.500	0 --> 1
	107	1	0.333	0 --> 1
	122	1	0.200	0 ==> 1

131	1	0.375	1 ==>	0
160	1	0.750	1 ==>	3
173	1	0.125	0 ==>	1
175	1	0.333	0 ==>	1

table S4. Measurements and proportions in the trunk and limbs of Eosauropterygia. References are to the major publications from which the measurements were taken, either from the text or from the illustrations. Fe, femur length; Fe.DW, distal width of femur; Fe.MW, minimal shaft width of femur; GA, glenoid-acetabular distance; Hu, humerus length; Hu.DW, distal width of humerus; Hu.MW, minimal shaft width of humerus; Ra, radius length; Ti, tibia length. Collections acronyms: FMNH, Field Museum of Natural History, Chicago, USA; GMPKU, Geological Museum of Peking University, Beijing, China; MfN, Museum für Naturkunde, Berlin, Germany; LWL-MFN, LWL-Museum für Naturkunde, Münster, Germany; NHMUK, Natural History Museum, London, UK; PIMUZ, Paläontologisches Institut und Museum Universität Zürich, Zurich, Switzerland; SMF, Senckenberg-Museum, Frankfurt, Germany; SMNS, Staatliches Museum für Naturkunde, Stuttgart, Germany; STIPB, Steinmann Institute Paleontology Collection, University of Bonn, Bonn, Germany; ZMNH, Zhejiang Museum of Natural History, Hangzhou, Zhejiang, China.

Taxon	Spec. #	*Reference*	GA	Hu	Hu.MW	Hu.DW	Fe	Fe.MW	Fe.DW	Ra	Ti	GA/Hu	GA/Fe	Hu/Ra	Fe/Ti	Hu/Ti	Hu/Fe	Fe/Fe DW
Serpianosaurus mirigiolensis	PIMUZ T 3931	Rieppel (1989) (64)	148	36	4	12	34	3	5	21	20	4.11	4.35	1.71	1.70	1.80	1.06	7.08
Neusticosaurus pusillus	PIMUZ T 3934	Sander (1989) (65)	83	21	2.7	7.3	20.0	1.4	2.3	12.0	10.0	3.95	4.15	1.75	2.00	2.10	1.05	8.70
Neusticosaurus peyeri	PIMUZ T 3615	Sander (1989) (65)	45	11	1.8	3.7	10.7	1.5	2.0	6.7	5.6	3.98	4.21	1.69	1.91	2.02	1.06	5.35
Nothosaurus marchicus	MfN I. 007.18	Rieppel & Wild (1996) (66)	227	63	12	18	68	7	13	34	36	3.60	3.34	1.85	1.89	1.75	0.93	5.44
Nothosaurus giganteus	PIMUZ T 4829	Rieppel (2000) (67)	1023	238	40	52	250	35	52	127	132	4.30	4.09	1.87	1.89	1.80	0.95	4.81
Lariosaurus calcagnii	PIMUZ T 3983	Rieppel (2000) (67)	608	162	43	47	128	14	19	74	61	3.75	4.75	2.19	2.10	2.66	1.27	6.74
Wangosaurus brevirostris	GMPKU-P-1529	Ma et al. (2015) (68)	585	163	26	47	166	16	19	86	72	3.59	3.52	1.90	2.31	2.26	0.98	8.74
Yunguisaurus liae	ZMNH M8738	Sato et al. (2014) (59)	1085	210	51	64	183	46	61	113	108	5.17	5.93	1.86	1.69	1.94	1.15	3.00
Pistosaurus longaevus	SMF R4041	Geissler (1895) (69), Sues (1987) (52)	-	178	24	57	178	31	50	114	-	-	-	1.56	-		1.00	3.56
Augustasaurus hagdorni	FMNH PR 1974	Sander et al. (1997) (53)	-	184	24	49	-	-	-	96	-	-	-	1.92	-		-	-
Bobosaurus forojuliensis	MFSN 27285	Dalla Vecchia (2006) (58), Fabbri et al. (2014) (13)	1071	258	42	-	-	-	-	-	193	4.15	-	-	-	1.34	-	-
Rhaeticosaurus mertensi	LWL-MFN P 64047	this study	484	183	32	51	185	37	66	48	43	2.64	2.62	3.81	4.30	4.26	0.99	2.80
Eoplesiosaurus antiquior	TTNCM 8348	Benson et al. (2012) (12)	665	221	54	79	219	32	75	77	81	3.01	3.04	2.87	2.70	2.73	1.01	2.92
Avalonnectes arturi	NHMUK 14550	Benson et al. (2012) (12)	547	-	-	-	207	42	91	-	77	-	2.64	-	2.69		-	2.27
Thalassiodracon hawkinsi	NHMUK 2018	pers. obs. on cast STIPB	355	145	38	70	140	29	64	60	53	2.45	2.54	2.42	2.64	2.74	1.04	2.19
Plesiosaurus dolichodirus	NHMUK 22656	Conybeare (1824) (70)	508	158	42	65	146	31	70	62	62	3.22	3.48	2.55	2.35	2.55	1.08	2.09
Westphaliasaurus simonsensii	LWL-MFN P 58091	Schwermann & Sander (2011) (71)	919	280	65	132	290	58	141	99	112	3.28	3.17	2.83	2.59	2.50	0.97	2.06
Plesiopterys wildi	SMNS 16812	O'Keefe (2004) (72)	505	154	45	87	155	28	70	60	52	3.28	3.26	2.57	2.98	2.96	0.99	2.21
Meyerasaurus victor	SMNS 12478	Smith & Vincent (2010) (73)	1179	442	83	189	411	61	167	151	139	2.67	2.87	2.93	2.96	3.18	1.08	2.46
Rhomaleosaurus thorntoni	NHMUK R4853	Smith & Benson (2014) (74)	1806	710	138	360	681	133	305	152	150	2.54	2.65	4.67	4.54	4.73	1.04	2.23

table S5. List of histological samples. Collections acronyms: LACM, Natural History Museum of Los Angeles County, Los Angeles, USA; LWL-MFN, LWL-Museum für Naturkunde, Münster, Germany; OMNH, Osaka Museum of Natural History, Osaka, Japan; SMNS, Staatliches Museum für Naturkunde, Stuttgart, Germany; STIPB, Steinmann Institute Paleontology Collection, University of Bonn, Bonn, Germany; Histological thin sections are housed in the histology slide collections of the Steinmann Institute, University of Bonn, Germany.

Taxon	Bone	Clade	Spec. Number	Age
Nothosaurus mirabilis[1]	Femur	Nothosauroidea	STIPB R 49	Middle Triassic
Anarosaurus heterodontus[2]	Humerus, femur	Pachypleurosauria	STIPB Wijk08-58	Middle Triassic
Pistosaurus longaevus[1]	Humerus	Pistosauroidea	SMNS 84825	Middle Triassic
Rhaeticosaurus mertensi	Femur	Plesiosauria	LWL-MFN P 64047	Late Triassic
Plesiosaurus dolichodirus	Humerus	Plesiosauria	STIPB R 89	Early Jurassic
Plesiosaurus dolichodirus	Femur	Plesiosauria	STIPB R 90	Early Jurassic
Plesiosauridae indet.	Humerus	Plesiosauria	SMNS 96869	Early Jurassic
Plesiosauridae indet.	Humerus	Plesiosauria	SMNS 96897	Early Jurassic
Cryptoclidus eurymerus	Humerus, femur	Plesiosauria	STIPB R 324	Middle Jurassic
Pliosaurus sp.	Propodial	Plesiosauria	SMNS 54025	Middle Jurassic
Pliosaurus sp.	Femur	Plesiosauria	SMNS 96896	Middle Jurassic
Elasmosauridae indet.	Humerus	Plesiosauria	OMNH MV 85	Late Cretaceous
Polycotylus latipinnis	Femur	Plesiosauria	LACM 129639a	Late Cretaceous

[1] See ref. (20)
[2] See ref. (75)

table S6. Local bone apposition rate to the end of the first year and relative body size at the end of the first year in selected sauropterygians. The holotype individual of *Rhaeticosaurus mertensi* did not live to the end of the second year. The sampled long bones of the non-plesiosaurian sauropterygians were incomplete, but all clearly were smaller too much smaller than the plesiosaurians as evidenced by the total cortical thickness. Cortical thickness was measured from the center of the medullary region and represents the entire thickness of cortical bone deposited by the animal during its lifetime. See text for further explanations.

	Neusticosaurus pusillus PIMUZ T 4211	*Nothosaurus* sp. SMNS 84856	*Pistosaurus grandaevus* SMNS 84825	*Rhaeticosaurus mertensi* LWL-MFN P 64047	*Plesiosaurus dolichodirus* STIPB R89	Plesiosauridae indet. SMNS 96897	*Cryptoclidus eurymerus* STIPB R324
Bone	humerus	femur	humerus	femur	humerus	humerus	femur
Length in mm	?	?	?	185	162	496	315
Number of growth marks	3	5	4	1	2	2	3
Thickness to 1st mark (mm)	1.05	3.2	7.6	16.9	12.1	66	26.5
% total	66	56	54	88	67	75	63
Thickness 1st to 2nd mark (mm)	0.44	1.5	3.3	-	3.8	22	6.5
% total	28	26	24	-	21	25	15
Total cortical thickness (mm)	1.6	5.8	14	19.3	18.1	88	42.2
% total	100	100	100	100	100	100	100
Apposition rate (µm/day) at 365 days gestation	1.4	4.4	10.4	23.2	16.6	90.4	36.3
Apposition rate (µm/day) at 50 days gestation	2.5	7.7	18.3	40.7	29.2	159.0	63.6
Apposition rate (µm/day) at 500 days gestation	1.2	3.7	8.7	19.6	14.0	76.3	30.6

table S7. Comparison of local bone apposition rates in the femur of selected amniotes compared to local bone apposition rates in the humeri and femora of plesiosaurians. All but the sauropterygians are extant taxa for which apposition rate was determined experimentally (*33*). Values for sauropterygians were taken from table S6.

	No. of species	Rate in µm/day
Mammals	3	13.10 - 40.25
Turtles	3	0.24 - 3.55
Lizards	4	1.03 - 7.6
Crocodiles	1	9.45
Birds	5	73.91 - 156.86
Neusticosaurus	1	1.4
Nothosaurus	1	4.4
Pistosaurus	1	10.4
Plesiosaurians	4	16.6 - 90.4

data file S1. Character matrix in NEXUS format for phylogenetic analysis described in Materials and Methods.