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SUPPLEMENTARY ONLINE MATERIAL FOR

A new pliosaurid from the Oxford Clay Formation of Oxfordshire, UK

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Supplementary Online Material

SOM 1. Description of the postcranial skeleton of *Eardasaurus powelli* gen. et sp. nov.

References

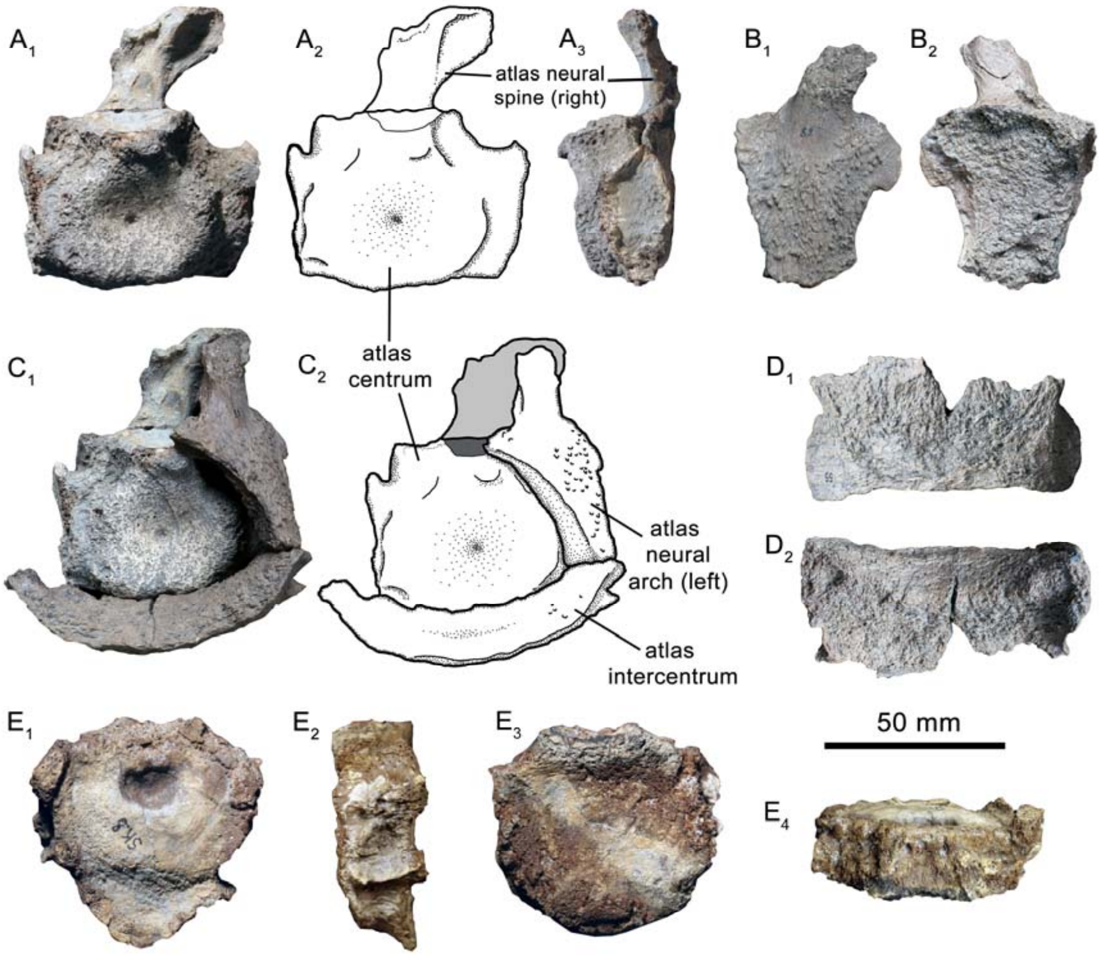
SOM 2. The batch file for phylogenetic analysis, including the data matrix in Nexus format and full analytical specifications available at http://app.pan.pl/SOM/app67-Ketchum_Benson_SOM/SOM_2.txt.

SOM 1. Description of the postcranial skeleton of *Eardasaurus powelli* gen. et sp. nov.

Institutional abbreviations.—CAMSM, Sedgwick Museum of Earth Sciences, University of Cambridge, UK; GPIT, Palaeontological Collection of Tübingen University, Tübingen, Germany; NHMUK, the Natural History Museum, London, UK; OUMNH, Oxford University Museum of Natural History, Oxford, UK.

Axial skeleton.—A partial atlas-axis complex and 56 postaxial vertebrae comprising 18 cervicals, three pectorals, 24 dorsals, four sacrals, and eight caudals are preserved. The centra, neural arches and ribs are all disarticulated, including those of the cervical vertebrae. This may indicate that OUMNH PAL-J.2247 is osteologically immature, as fusion of the cervical neurocentral sutures occurs during ontogeny in most plesiosaurians, including cryptoclidids (Brown, 1981) and the closely related Middle Jurassic thalassophonean *Peloneustes philarchus* (e.g. NHMUK PV R2679; GPIT-PV-30091). In contrast, the neurocentral sutures often remain unfused even in large thalassophoneans such as *Pliosaurus* (Benson et al. 2013), and therefore may not be a reliable indicator of ontogenetic stage in all pliosaurids.

Atlas-axis complex.—The atlas-axis complex is partially preserved, missing the axial intercentrum and neural arch (SOM Fig. 1).



SOM FIG. 1. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. **A_1–A_3**, atlas centrum and attached right neural arch in **A_1– A_2**, anterior, **A_3**, left lateral views. **B_1–B_2**, left atlantal neural arch in **B_1**, lateral and **B_2**, medial views. **C_1–C_2**, articulated atlas vertebra in anterior view. In interpretive drawing (**C_2**), dark grey represents the right neural arch, which is not in articulation. **D_1–D_2**, atlas intercentrum in **D_1**, ventral, **D_2**, dorsal views. **E_1–E_4**, axis centrum in **E_1**, anterior, **E_2**, right lateral, **E_3**, posterior, **E_4**, dorsal views.

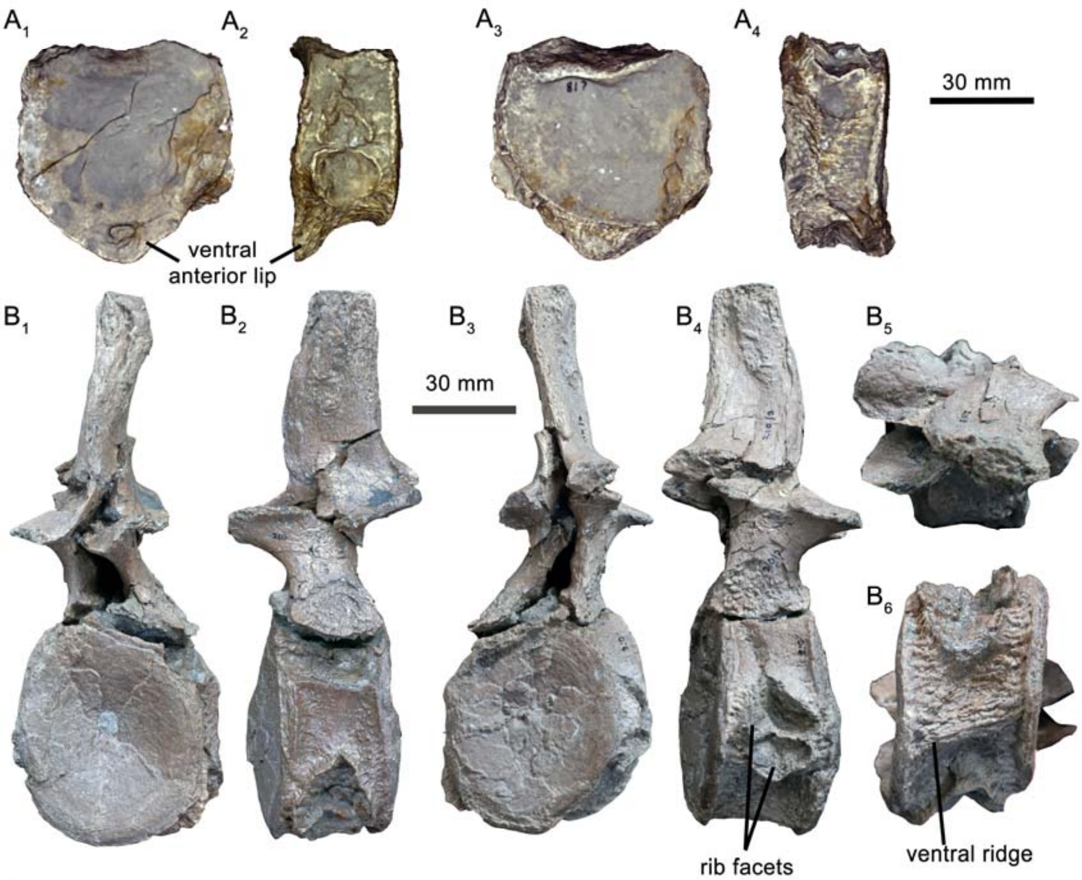
The atlantal centrum is transversely broad, and anteroposteriorly narrow. The anterior surface is concave and sub-hexagonal in outline. It is bounded laterally by the facets for the neural arches and atlantal intercentrum; thus the centrum would have been excluded from the lateral surface of the atlantal cup. The ventral surface of the atlantal centrum is abraded, and so the ventral facet for the intercentrum is not preserved.

The right atlantal neural arch has been crushed onto the posterior articular surface of the atlantal centrum. The neural spine is mediolaterally compressed with a subrectangular outline. The posteromedial surface of the neural spine is gently concave. The left neural arch is disarticulated, and its lateral surface is rugose. The atlantal intercentrum is well preserved, and is also highly rugose. It has a pair of short, rugose, posterolaterally oriented processes.

The axial centrum is slightly abraded, but it has not been crushed and its dimensions have not been significantly affected by its state of preservation. It is slightly narrower than the atlantal centrum in anteroposterior length (axial centrum anteroposterior length = 16.6 mm; atlantal centrum anteroposterior length = 24.4 mm; both measured along the neural canal). Their summed anteroposterior length (including the anterior projection of the atlantal intercentrum = 13 mm) gives a length:height ratio of that atlas-axis complex of 1.05 (using the dorsoventral height of the posterior surface of the axial centrum = 51.3 mm). This is similar to the ratios seen in *Liopleurodon* (ratio = 1.06; NHMUK PV R3536) and *Simolestes* (ratio = 1.14; NHMUK PV R3319), but is proportionally short compared to the ratio in other Middle Jurassic pliosaurids including *Marmornectes* (ratio = 1.3; Ketchum and Benson 2011b), *Peloneustes philarchus* (ratio = 1.4; Andrews 1913), '*Pliosaurus*' *andrewsi* (ratio = 1.58; NHMUK PV R3891). It is also short compared to the atlas-axis complex of the holotype of '*Peloneustes*' *evansi* (ratio = 1.6; CAMSM J.46910; Seeley 1877). These differences largely result from the anteroposteriorly short morphology of the axial centrum of *Eardasaurus*.

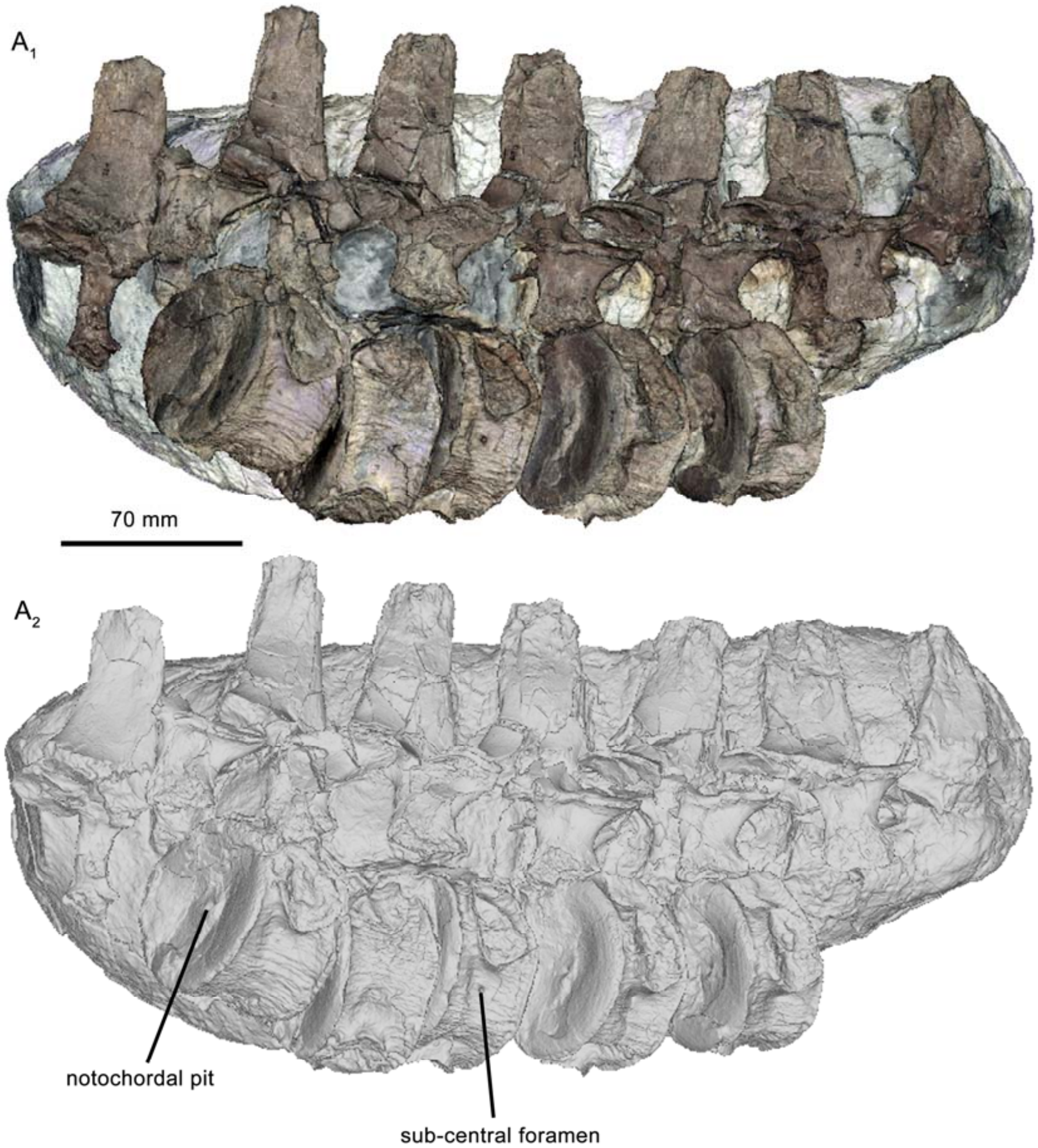
The axial centrum of *Eardasaurus* bears a large notochordal pit on the anterior surface. There is a prominent ventral lip, which would have articulated with the axial intercentrum anteriorly. The axial rib facets are poorly preserved so it is not possible to tell if the axial rib would have been single or double-headed

Postaxial cervical vertebrae.—There are 18 postaxial cervical vertebrae preserved with their associated ribs and unfused neural arches (SOM Fig. 2–4). Thus, the cervical count is 20, including the atlas-axis complex, similar to other Middle Jurassic pliosaurids (e.g. Andrews 1913). The third cervical centrum has a large, ventral lip on the anterior margin, similar to the axial centrum (SOM Fig. A_1-A_2). Subsequent cervical centra have a much smaller ventral lip that is absent in mid–posterior cervicals (SOM Fig. 2B, 3). This ventral lip is also present in anterior cervicals of *Peloneustes philarchus* (e.g. Tarlo 1960, plate 25) and the holotype of '*Peloneustes*' *evansi* (CAMSM J.46910), as well as many other pliosaurids including *Liopleurodon* (NHMUK PV R3536), '*Pliosaurus*' *andrewsi* (NHMUK PV R3891) and *Marmornectes* (Ketchum and Benson 2011b) from the Oxford Clay Formation.



SOM FIG. 2. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. **A_1–A_4**, anterior cervical vertebra in **A_1**, anterior, **A_2**, left lateral, **A_3**, posterior, **A_4**, ventral views, from structured light surface scan. **B_1–B_6**, mid cervical vertebra in **B_1**, left lateral, **B_2**, anterior, **B_3** right lateral, **B_4**, posterior **B_5** dorsal, **B_6** ventral views.

The lateral surfaces of the anterior to mid-cervical centra have double-headed rib facets (SOM Fig. 2A, B). These become single-headed in the posteriormost cervicals (SOM Fig. 3). All cervical vertebrae of *Eardasaurus* are crushed slightly transversely. As preserved, they are about half as long anteroposteriorly as they are wide, and slightly wider than they are tall. The articular surfaces bear a small notochordal pit. Subcentral foramina are usually absent, and only present on a few cervicals. Even where they are present, they are small, and there is often only one. The ventral surfaces of the cervical centra are rugose, and the anterior cervicals bear a low, midline ventral ridge (SOM Fig. 2B_6). Posteriorly along the cervical series, the ventral ridge flattens and becomes indistinct (SOM Fig. 3). A ventral midline ridge is also present in *Peloneustes philarchus* (e.g. Andrews 1913; Tarlo 1960) and the holotype of '*Peloneustes*' *evansi* (CAMSM J. 46910; Seeley 1877; regarded as a synonym of *Peloneustes philarchus* by Tarlo 1960), but is absent in other pliosaurids from the Oxford Clay Formation (Andrews 1913; Tarlo 1960).



SOM FIG. 3. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. **A$_1$–A$_2$**, block of posterior cervical vertebrae in right lateral view, from 3D digital renderings of surface scan. **A$_1$**, with texture, **A$_2$**, with texture removed to show structure.

The cervical neural arches are crushed mediolaterally; therefore the presence or absence of medial rugose excrescences (which are present in *Marmornectes*; Ketchum and Benson 2011b) cannot be determined. The pre-and post-zygapophyses are angled dorsomedially (prezygapophyses) and ventromedially (postzygapophyses) at approximately 45 degrees. The cervical neural spines are transversely compressed, and sub-rectangular in lateral view. This is similar to the neural spine morphology of *Peloneustes philarchus* (Andrews 1913) and *Liopleurodon* (NHMUK PV R3536), which also have mediolaterally narrow cross-sections. However, it differs from the morphology of most other pliosaurids, including *Marmornectes* (Ketchum and Benson 2011b), '*Pliosaurus*' *andrewsi* (Andrew 1913; NHMUK PV R3891), *Simolestes* (NHMUK PV R3319), and the holotype of '*Peloneustes*' *evansi* (broken cervical neural spine: CAMSM J.46910bg), in which the cervical neural spines are proportionally much broader.

The lateral surfaces of the cervical neural spines are rugose, particularly near the dorsal tips. The posterior margins bear a low, narrow, dorsoventrally oriented ridge. The neural spines widen very slightly transversely towards the dorsal tips. This is similar to *Peloneustes philarchus* and *Liopleurodon ferox* (Andrews, 1913), but differs from *Marmornectes* (Ketchum & Benson 2011b), *Simolestes* (NHMUK PV R3319) '*Pliosaurus*' *andrewsi* (NHMUK PV R 3891) in which the neural spines are strongly transversely expanded at the tip.

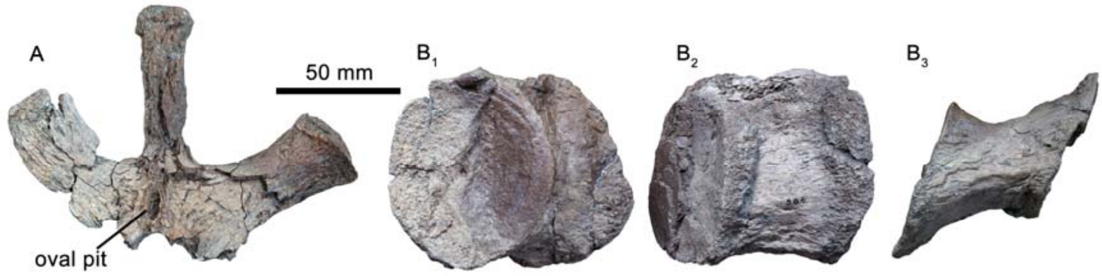
The anterior-mid cervical ribs (SOM Fig. 4A) have two tightly co-joined rib heads on the medial surface, with only a shallow, narrow groove separating them. The rib-heads are separated by a short, narrow slot on the posterior or anterior margins of the rib shaft; rarely both. Where two rib heads are present, the dorsal rib head is larger, and taller dorsoventrally than the ventral rib head. The posterior cervical ribs are single-headed.

The distal ends of the anterior-mid cervical ribs are expanded to form prominent, rounded anterior and posterior processes. The anterior process is rugose, whereas the posterior process is relatively smooth. In the anterior cervical ribs, the processes are subequal in size. Posteriorly, towards the pectoral region the posterior process increases in size relative to the anterior process (SOM Fig. 4B).

SOM FIG. 4. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. **A_1–A_4**, left mid cervical rib in **A_1**, ventral, **A_2**, dorsal, **A_3**, anterior, **A_4**, proximal views. **B_1–B_3**, pectoral rib in **B_1**, ventral, **B_2**, dorsal, **B_3**, anterior views.

Pectoral vertebrae.—Three centra are preserved in which the rib facet overlies the articulation between the neural arch and the centrum. The pectoral ribs are single headed, with a dorsoventrally tall rib head (SOM Fig. 4B). The shaft is elongate and tapers distally. Approximately two-thirds of the way along the shaft, on the dorsal margin, is a rugose excrescence, which is homologous with the anterior process of the cervical ribs.

Dorsal vertebrae.—24 dorsal vertebrae are preserved (SOM Fig. 5). Some are still preserved inside nodules, and are relatively three-dimensional. As with the cervical vertebrae, all isolated dorsal vertebrae are crushed, and so the exact dimensions in life are difficult to determine. However, as preserved, the centra are almost as long anteroposteriorly as they are transversely wide. The articular faces have a central notochordal pit. The neural arches have also been crushed anteroposteriorly. There is a dorsoventrally oriented oval pit or foramen present on the anterior midline of the neural arch, immediately dorsal to the zygapophyses (SOM Fig. 5A). The shape of the neural spine is difficult to determine with certainty, due to crushing. As preserved, the dorsal tip is wider mediolaterally than long, anteroposteriorly.



SOM FIG. 5. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. **A,** dorsal neural arch in anterior view. **B_1–B_4**, dorsal centrum in **B_1**, anterior, **B_2**, left lateral, **B_3**, ventral views.

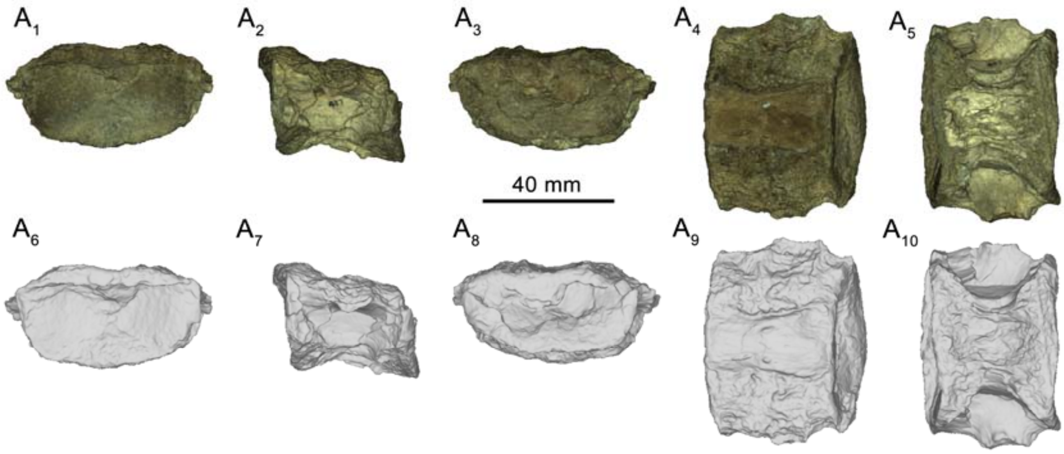
The dorsal rib heads are single-headed, with an articulation facet that is shaped like a figure-of-eight. The shafts taper distally, and are anteroposteriorly compressed, with a central groove that extends along the entire length of the anterior and posterior surfaces (SOM Fig. 6). The dorsal and ventral margins of the shaft are almost uniformly convex. However, a few centimetres lateral to the rib head, the dorsal margin is interrupted by a short, obliquely oriented groove.

SOM FIG. 6. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. Close up of skeleton on display showing six dorsal ribs, laid out as discovered in the quarry.

Sacral vertebrae.—There are four centra preserved near the tail in which the rib facet overlies the suture between the neural arch and the centrum and are interpreted as sacrals. The sacral rib heads are dorsoventrally tall for articulation with both the neural arch and the centrum (SOM Fig. 7). Proximally, the ventral surface of the rib shaft is strongly convex. Distally the shaft becomes dorsoventrally compressed and expands anteroposteriorlly, as in other pliosaurids. The shaft curves gently ventrally towards the distal end.

SOM FIG. 7. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. $\mathbf{A_1}$–$\mathbf{A_4}$, sacral rib in $\mathbf{A_1}$, dorsal, $\mathbf{A_2}$, anterior or posterior, $\mathbf{A_3}$, ventral, $\mathbf{A_4}$, proximal views, produced from 3D digital rendering of structured light scan with texture. $\mathbf{A_5}$–$\mathbf{A_8}$, same views as $\mathbf{A_1}$–$\mathbf{A_4}$ with texture removed to reveal structure more clearly.

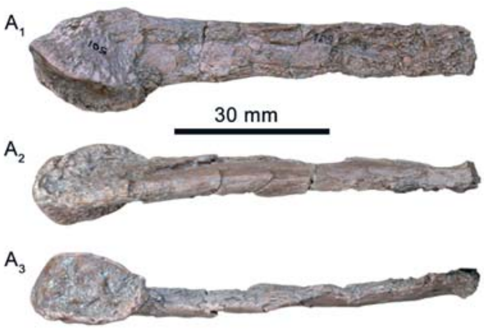
Caudal vertebrae.—Eight caudal vertebrae are preserved (SOM Fig. 8). They are crushed dorsoventrally, and their width is therefore exaggerated artificially, relative to their height. The rib facets are situated closely ventral to the facets for the neural arches. There are paired, triangular-shaped chevron facets on the anterior and posterior margins of the ventral surface, but they are poorly preserved. No subcentral foramina are present.



SOM FIG. 8. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. $\mathbf{A_1}$–$\mathbf{A_5}$, caudal centrum in $\mathbf{A_1}$, anterior, $\mathbf{A_2}$, left lateral, $\mathbf{A_3}$, posterior, $\mathbf{A_4}$, dorsal, $\mathbf{A_5}$, ventral views, produced from 3D digital rendering from structured light scan with texture. $\mathbf{A_6}$–$\mathbf{A_{10}}$, same views as $\mathbf{A_1}$–$\mathbf{A_5}$ with texture removed to show structure more clearly.

SOM FIG. 9. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. Close-up of skeleton on display showing posterior dorsal, sacral and caudal series.

Numerous caudal ribs, or possibly chevrons are preserved (SOM Figs. 9–10). The shafts are long, slender and gently curved. There is a small, oval facet at the distal end. At the proximal end, the head of the rib or chevron is sub-oval in shape, and oriented at 45 degrees to the main axis of the shaft.

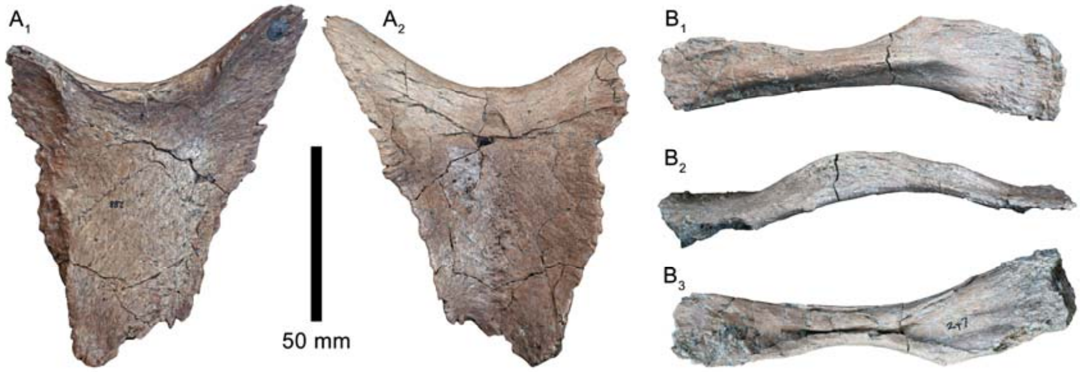


SOM FIG. 10. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. **A**–**C**, caudal rib or chevron.

Gastralia.—Eleven gastralia are preserved. They are unfused, and have been preserved disarticulated. They are curved, and taper at either end. They have a flattened cross section, with a groove extending longitudinally along the centre of the shaft.

Appendicular skeleton.—Of the appendicular skeleton, only the clavicle and/or interclavicle, partial left forelimb and partial left hindlimb are preserved.

Pectoral girdle.—An asymmetrical, approximately triangular-shaped element of the pectoral girdle that could either be the clavicle or the interclavicle is preserved (SOM Fig. 11A). A similar element had previously been identified in *Peloneustes philarchus* as an 'osmosternum', 'episternum' or 'interclavicle' by several authors (Lydekker, 1889; Seeley, 1892; Jaccard, 1908; Andrews, 1913), but re-identified by Ketchum & Benson (2011b) as a clavicle due to the pronounced asymmetry, strongly suggesting that it is not a midline element. However, there is still some uncertainty surrounding this identification.

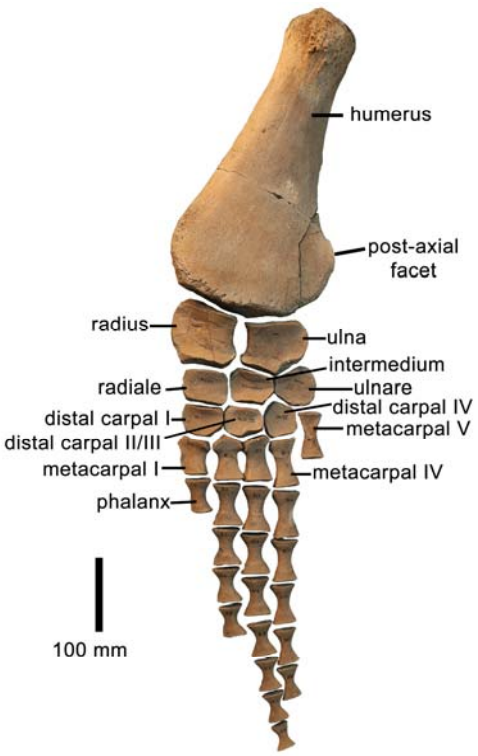


SOM FIG. 11. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. **A**, clavicle or interclavicle. **B**, unidentified element, possible clavicle.

An elongate element, found in the same general area as the triangular-shaped pectoral bone (SOM Fig. 11B) could potentially be part of the pectoral girdle. It is similar to the clavicles of *Tricleidus seeleyi* (Andrews, 1910 pl. 9 fig. 3). No definitive clavicles have ever been described in pliosaurids, and there is currently not enough evidence to be able to confidently identify this bone.

Forelimb.—The left forelimb was found preserved in articulation (SOM Fig. 12). A cast was taken while the limb was *in situ* in the field, and the position of all the individual elements can be identified with certainty.

The complete left humerus is 400 mm long proximodistally and 220 mm wide anteroposteriorly. The humeral shaft is oval in cross-section, and flattens, widens and curves dorsally towards the distal end. The distal expansion is wide and asymmetrical, and almost uniformly convex, with little differentiation between the facets for the radius and ulna. There is a distinctive, oval shaped facet on postaxial margin.



SOM FIG. 12. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. Articulated left forelimb as preserved, in dorsal view.

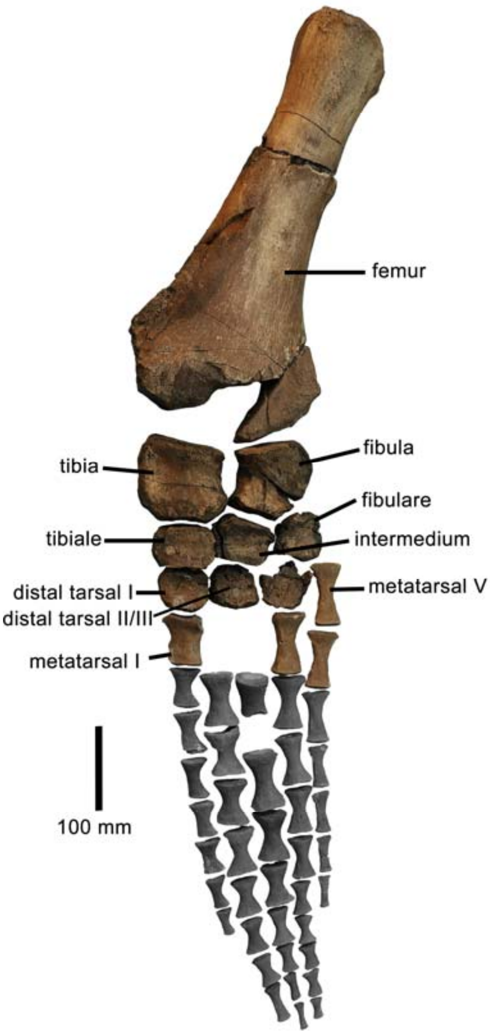
The ulna is broader anteroposteriorly than long. It is approximately pentagonal in shape, with a nearly straight proximal border. Distally there are two facets for articulation with the ulnare and intermedium. The preaxial margin is concave in dorsal view, enclosing a proximodistally elgonate epidodial foramen with the radius. The ulna becomes progressively dorsoventrally compressed towards its postaxial margin.

The left radius is approximately as wide anteroposteriorly as it is long. The preaxial margin is gently convex in dorsal view, and dorsoventrally compressed, but expands in depth towards the centre of the bone. The larger of the two distal facets articulates with the radiale, and the smaller facet articulates with the intermedium.

The proximal carpals are approximately subequal in size and are closely articulated with each other and the distal carpals. The metacarpals are in turn closely interlocked with each other and the distal carpals. The carpus and proximal manus would therefore probably have formed a relatively inflexible unit in life. The ulnare and distal carpal IV, with which the ulnare articulates are compressed dorsoventrally compared to the radiale, intermedium, and other metacarpals.

There are 17 phalanges preserved in articulation with the forelimb. It is incomplete, and so the phalangeal formula is unknown. Forty additional complete phalanges plus six partial phalanges were found disarticulated. The largest of these can confidently be assigned to the hindlimb(s), but the placement of the remainder is uncertain. As with the other elements of the limb, the preaxial and postaxial margins of the phalanges are compressed relative to the depth along the midshaft where they form the leading or trailing edges of the flipper, respectively. The shafts of the ungual phalanges taper strongly distally.

Hindlimb.—The left femur is nearly complete, except for a portion of the distal end, which is missing (SOM Fig. 13).



SOM FIG. 13. Holotype of *Eardasaurus powelli* gen. et sp. nov. (OUMNH PAL-J.2247) from the Middle Jurassic of Oxfordshire. Left hindlimb in dorsal view. Grey area represents the area of the pes reconstructed from disarticulated phalanges.

The femur is larger and more robust than the humerus. The tibia and fibula are approximately as wide as they are long, and similar in shape to the radius and ulna, respectively, only larger, as with the tarsus and pes. The hindlimb of *Eardasaurus* differs from those of most other pliosaurids from the Oxford Clay Formation in having proportionally short epipodials (SOM Fig. 13). The ratio of proximodistal length to anteroposterior width (measured at the proximal surface) of the tibia is 1.02 in *Eardasaurus*. This ratio is similar to that of '*Pliosaurus*' *andrewsi* (1.03; NHMUK PV R3891) and *Marmornectes* (1.05; Ketchum and Benson 2011b), but short compared to *Peloneustes* (1.13; Andrews 1913; NHMUK PV R2440), *Simolestes* (1.43; Andrews 1913; NHMUK PV R3170), and NHMUK PV R2443 (1.14; Andrews 1913), a specimen comprising a mandible and partial hindlimb of uncertain taxonomic status (referred to '*Pliosaurus*' *andrewsi* by Tarlo 1960).

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