
Supplementary information

Extreme armour in the world's oldest ankylosaur

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Supplementary Material

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Phylogenetic data matrix: SI_Spicomellus_matrix.tnt	Separate file

1. Systematic Palaeontology

Dinosauria Owen, 1842

Ornithischia Seeley, 1888

Ankylosauria Osborn, 1923

Spicomellus afer Maidment *et al.*, 2021

Holotype. NHMUK (Natural History Museum, London, UK) PV R 37412, a partial rib bearing four co-ossified spikes (Maidment *et al.* 2021).

Referred material. A partial skeleton, USMBA (Université Sidi Mohamed Ben Abdellah) 5 to USMBA 84, comprising a left quadrate, cervical, dorsal, sacral and caudal vertebrae, dorsal ribs, scapulocoracoids, partial ilia, ischia and pubes, and a variety of dermal armour including a cervical half-ring and parts of a sacral shield. A description of this material is provided below.

Revised diagnosis. Modified from Maidment *et al.* (2021): differs from all other dinosaurs in possessing ‘T’-shaped dorsal ribs with a fused, rod-like osteoderm on the dorsal surface, from which projects a series of co-ossified conical dermal spikes, and an elaborate cervical half-ring comprising a horse shoe-shaped basal band with five fused spikes, at least two of which were extremely elongate (approaching 1 m in length), and two small plates.

Locality and horizon. The holotype and referred specimens are from the Bathonian (Middle Jurassic) El Mers III Formation of Boulahfa Plain, south of Boulemane, Fez-Meknes, Morocco. Detailed locality information and a stratigraphic log can be found in Maidment *et al.* (2020). Although Maidment *et al.* (2020) originally reported that the El Mers Group might extend to the Callovian, further biostratigraphic work by our team has indicated a Bathonian age for the Group.

2. Anatomical Description

Quadrate (Fig. S1)

The left quadrate (USMBA 34) is partially preserved, missing its anteromedial portion (Fig. S1). In anterior view, the lateral margin of the quadrate is sinuous, being outwardly convex in its dorsal part, and concave just before the distal condyle. Medially, the pterygoid flange of the quadrate is incomplete but is widest transversely in its dorsal part and thins ventrally. The anterior surface of the quadrate is concave and bears a dorsoventrally extending ridge in the middle of the surface which reaches neither the dorsal nor the ventral margins, merging with the surface dorsally and ventrally. Medial to this ridge, there is a fossa bounded laterally by the ridge and medially by the medially projecting pterygoid flange. The fossa opens dorsally and is narrower ventrally. A second, more prominent ridge extends from the medial margin of the pterygoid flange towards the distal condyles, merging with the smooth anterior surface before it reaches them. This ridge causes the pterygoid flange to deflect medially. Medial to this ridge is a second fossa which opens ventrally towards the condyles and is bounded by the medial edge of the distal end.

The distal condyle is roughly rectangular with the long axis transverse. The anterior and posterior margins converge medially so that the medial side is shorter than the lateral side. There is no distinction between medial and lateral condyles but the surface is not well preserved. In anterior view, the quadrate condyles are roughly horizontal.

In posterior view, the surface is smooth and flat to shallowly concave. Immediately dorsal to the condyles, there is a fossa that is situated on the medial side of the element, and has a short ridge extending vertically bounding its lateral side. The pterygoid flange deflects somewhat medially.

The head of the quadrate is located on the dorsolateral surface and is anteroposteriorly thicker than the rest of the element with the exception of the distal condyles.

Maximum length = 21 cm

Maximum width as preserved = 14.5 cm



Fig. S1. Left quadrate, USMBA 34 in a, anterior and b, posterior view.

Possible cranial fragments (Fig. S2)

USMBA 38 is a large fragment that is T-shaped in outline. On the presumed lateral surface, the downstroke of the 'T' is a convex bar. Dorsally, where the downstroke and cross-stroke of the T meet, the element is shallowly concave. The top part of the T cross-stroke is convex and tapers towards one end. The ends are all broken. In medial view, the downstroke bears a distinct ridge which is developed into a flange that is angled towards the tapering side of the cross stroke, and this and a second ridge that extends along the top of the T-stroke delimit the margins of a deep fossa. The untapered end of the cross-stroke is flat medially.

Length of cross stroke = 17.5 cm

Length of downstroke = 16 cm.

USMBA 66 is a D-shaped element that could be a paroccipital process. The lateral margins of the D, with the curved outline, are smooth and taper towards the curved edge. Medially, close to the vertical downstroke of the 'D', the element is anteroposteriorly thicker, and bears three ridges that delimit shallow fossae. Dorsally in this part is another, dorsally facing shallow fossa. On the other side of the element, close to the downstroke of the 'D', a prominent, curved ridge delimits a deep, D-shaped fossa whose flat margin parallels the downstroke of the D. Medial to this, the element is broken.

Maximum height of the element = 8 cm

Maximum width of the element = 6 cm



Fig. S2. Possible cranial fragments, views unknown. a, b, USMBA 38; c, d, USMBA 66.

Vertebrae

Eight isolated vertebrae are preserved, in addition to the fused sacral vertebrae and two fused handle vertebrae. The isolated vertebrae represent the cervical (USMBA 52, 55), anterior dorsal (USMBA 51), sacrodorsal (USMBA 54) and caudal (USMBA 61, 64, 65, 71) regions. Neurocentral sutures are completely closed (indistinguishable) in all specimens.

Cervical vertebrae (Fig. S3)

USMBA 52 and 55 appear to represent mid to posterior cervicals based on their anteroposteriorly elongate centra. USMBA 52 (Fig. S3) is the better preserved of the two with a complete centrum and a partial neural arch, although the latter is still largely obscured by matrix. It is missing the prezygapophyses, transverse processes, neural spine and left

postzygapophysis. The centrum is anteroposteriorly elongate, being almost twice as long as dorsoventrally high, with anteroposteriorly concave lateral surfaces that give it a spool-shape in ventral view and a concave ventral surface in lateral view. The anterior and posterior articular surfaces are oval, being wider transversely than high dorsoventrally, and strongly concave. Only the bases of the parapophyses are preserved, positioned on the neurocentral suture similar to the anterior dorsal (see below). They are deeply concave with well developed rims. The postzygapophysis extends only a short distance posterior to the posterior margin of the centrum and has a weakly convex articular surface that faces primarily ventrally.

Centrum, anteroposterior length = 99 mm

Anterior articular face, dorsoventral height = 57 mm.

Anterior articular face, transverse width = 66 mm.

Posterior articular face, dorsoventral height = 53 mm.

Posterior articular face, transverse width = 68 mm.

Anteroposterior width of left parapophysis = 32.5 mm.

USMBA 55 is the centrum only, missing all of the neural arch and spine. The base of the parapophysis is not preserved but it is otherwise similar in morphology to USMBA 52.

Centrum, anteroposterior length = 90 mm

Anterior articular face, dorsoventral height = 58 mm

Anterior articular face, transverse width = 63 mm

Posterior articular face, dorsoventral height = 49.5 mm

Posterior articular face, transverse width = 65 mm.

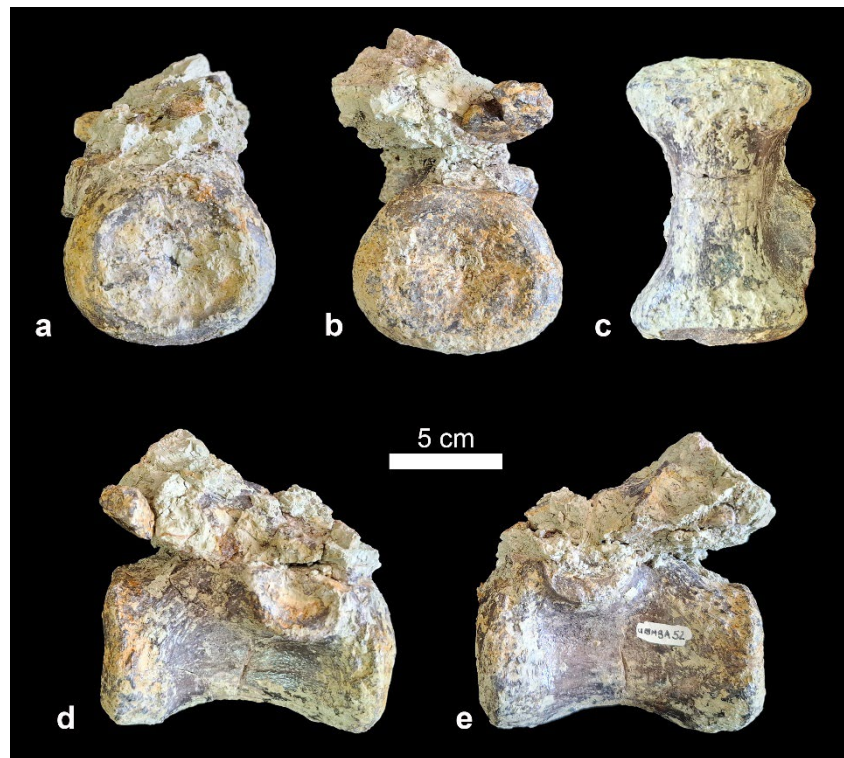


Fig S3. USMBA 52, cervical vertebra in a, anterior, b, posterior, c, ventral, d, right lateral and e, left lateral views.

Dorsal vertebrae (Fig. S4)

USMBA 51 is a relatively anterior dorsal missing its neural spine and the right prezygapophysis (Fig. S4). The para- and diapophyses fit well with the anterior dorsal rib USMBA 15, supporting the anterior dorsal position of this vertebra. The centrum is longer anteroposteriorly than tall dorsoventrally and in lateral view the posterior articular face is set slightly ventral to the anterior facet, giving it a slightly parallelogram-shaped outline. The anterior and posterior articular facets are both roughly oval in outline, being wider than high, with central concavities. In ventral view the lateral surfaces of the centrum are anteroposteriorly concave giving it a spool-shape, and the ventral surface is concave in lateral view. There are no fossae or foramina on the lateral surface. Above the centrum is the small, subcircular neural canal. The parapophysis is very large, with a deep oval concavity (long access of the oval extending dorsoventrally) surrounded by a prominent raised rim which is raised to its greatest extent ventrally. The parapophysis is positioned on the neurocentral contact at the anterior end of the vertebra. The elongate transverse processes are directed laterally and dorsally, at an angle of approximately 45 degrees to the horizontal in anterior view. Their diapophyseal surfaces are positioned directly dorsal to the parapophyses and are strongly convex. The prezygapophysis projects strongly

anteriorly well anterior to the anterior surface of the centrum. Its articular surface faces nearly entirely dorsally and slightly medially. There are weak postzygodiapophyseal and paradiapophyseal laminae which form the dorsal and anterior margins of an unusual, deep fossa on the lateral surface of the neural arch, posterior to the transverse process and posterodorsal to the parapophysis.

There is a pathology on the right lateral and ventral margins of the posterior margin of the centrum, extending slightly posteriorly beyond the centrum. This has a roughened external surface.

Centrum, anteroposterior length = 81 mm

Anterior articular face, dorsoventral height = 50 mm

Anterior articular face, transverse width = 61 mm

Posterior articular face, dorsoventral height = 51 mm

Posterior articular face, transverse width = 56 mm

Anteroposterior width of left parapophysis = 37 mm

Dorsoventral height to base of neural spine = 85 mm

Length of left transverse process from base to tip = 42 mm.

USMBA 54 is a partial vertebra identified as a sacrodorsal. It is missing the posterior end of the centrum and most of the neural arch and spine, including the pre- and postzygapophyses. Transverse processes appear to have been absent, with instead a large single concavity on the lateral surface representing the conjoined para- and diapophyses. The centrum is strongly compressed along its length relative to the anterior articular surface, with strongly concave lateral surfaces in ventral view and a strongly concave ventral margin in lateral view. The anterior articular surface has an oval outline and is concave, but with the long axis of the oval oriented dorsoventrally (i.e. taller than wide) rather than transversely as in the more anterior dorsal and cervicals. The neural canal is also oval and dorsoventrally higher than wide, as opposed to subcircular. The single rib facet is very large and anteriorly placed and appears to be positioned primarily on the neural arch but with the base extending onto the anterodorsal margin of the centrum. It is very deeply concave with a pronounced raised rim. The facet is anteroposteriorly wider ventrally than dorsally, with a subtle suggestion of subdivision into

para- and diapophyseal areas. The base of a postzygadiapophyseal lamina is preserved but there is no indication of a deep fossa as seen in the anterior dorsal.

This vertebra does not fit onto the anterior end of the preserved sacrum and the rib that would have attached to it probably articulated with the medial surface of the preacetabular process.

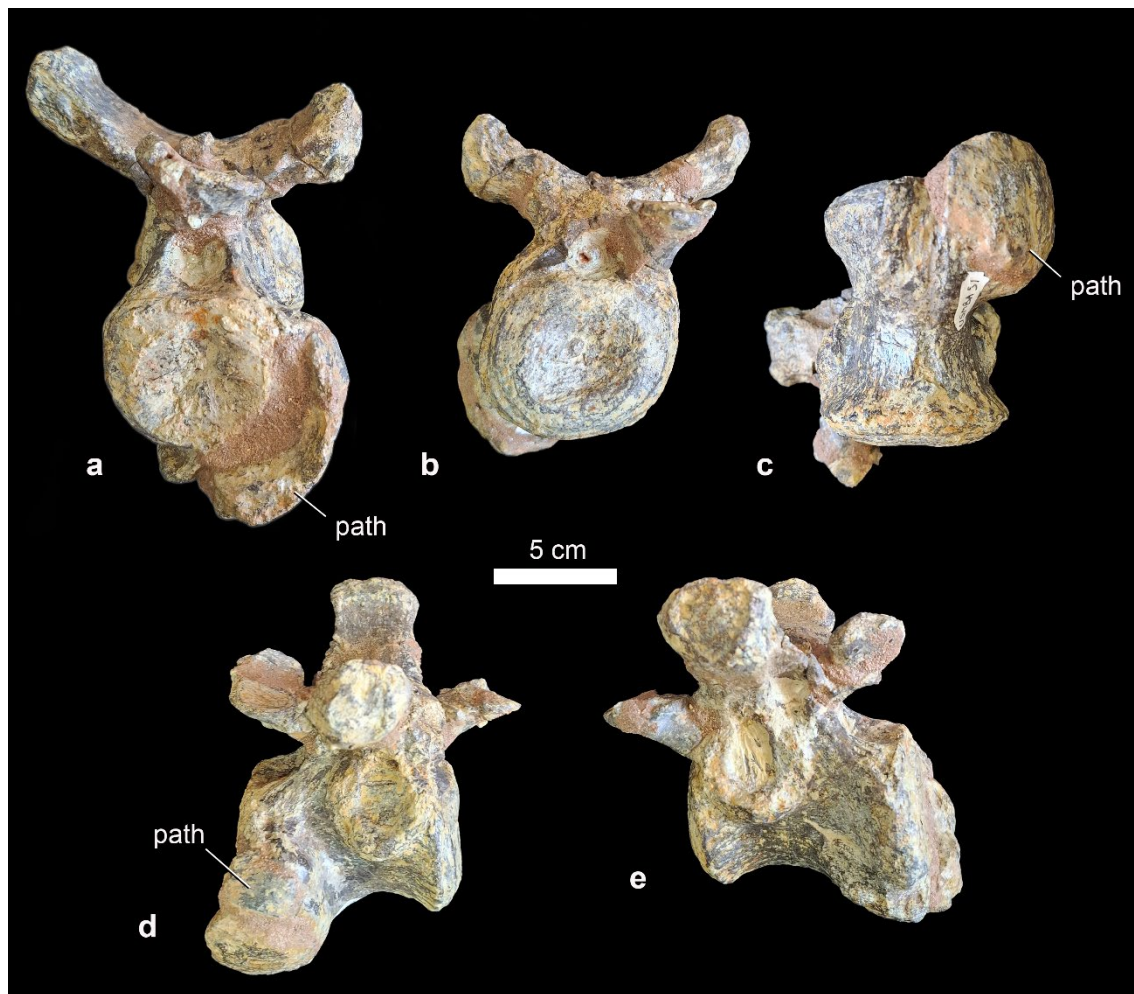


Fig. S4. Dorsal vertebra, USMBA 51, in a, anterior, b, posterior, c, ventral, d, right lateral and e, left lateral views. **path**, pathology.

Sacrum (Fig. S5)

USMBA 13 is a fused sacrum including the posterior part of the centrum of sacral 1 and complete sacra 2–4. All of these vertebrae are fused together although the contacts between the centra are visible. Dorsally, the neural spines are indistinguishably fused together into a single plate. Fine, rod-like ossified tendons extend anteroposteriorly along the neural spines in various places. On the left side the sacral ribs are not in articulation and the scars for their attachment are visible. On the right side, sacral rib 2 is missing but the bases of sacral ribs 3

and 4 are present in articulation with the vertebrae. The cross section of the neural canal is dorsoventrally deep and ellipsoid anteriorly, but dorsoventrally shorter and subcircular posteriorly.

The centra are robust and approximately subequal in anteroposterior length and transverse width. The length of sacral 1 is unclear because it is broken, sacral 2 and 3 have centra that are subequal in length, whereas sacral 4 is slightly shorter. The ventral surfaces of the centra are broadly and smoothly convex with no central ridge or groove present. The posterior face of sacral 4 has a flattened heart-shaped outline and its surface is flat to gently convex.

The facet for sacral rib 2 is the largest of the three preserved and is positioned on the contact between the centra of sacral 1 and 2. It has a teardrop shaped outline with the apex pointing dorsally. The facet for sacral rib 3 is positioned primarily on the centrum of sacral 3, but partially supported by an expansion of the posterior end of the centrum of sacral 2. The facet for sacral rib 3 has a trapezoid shaped outline, being anteroposteriorly broader ventrally and tapering dorsally. The facet for sacral rib 4 is sub-circular and is positioned entirely on the lateral surface of the centrum of sacral 4. It is the smallest of the three.

The postzygapophyses of sacral 4 are partially preserved but their articular surfaces are missing. They are separated from one another on the posterior midline by a narrow, dorsoventrally extending groove.

Sacral 2, centrum length = 74 mm

Sacral 2, centrum width = 63 mm

Sacral 2, height from centrum to top of neural spine = 112 mm

Sacral 3, centrum length = 77 mm

Sacral 3, centrum width = 64 mm

Sacral 3, height from centrum to top of neural spine = 120 mm

Sacral 4, centrum length = 60 mm

Sacral 4, centrum width = 70 mm.

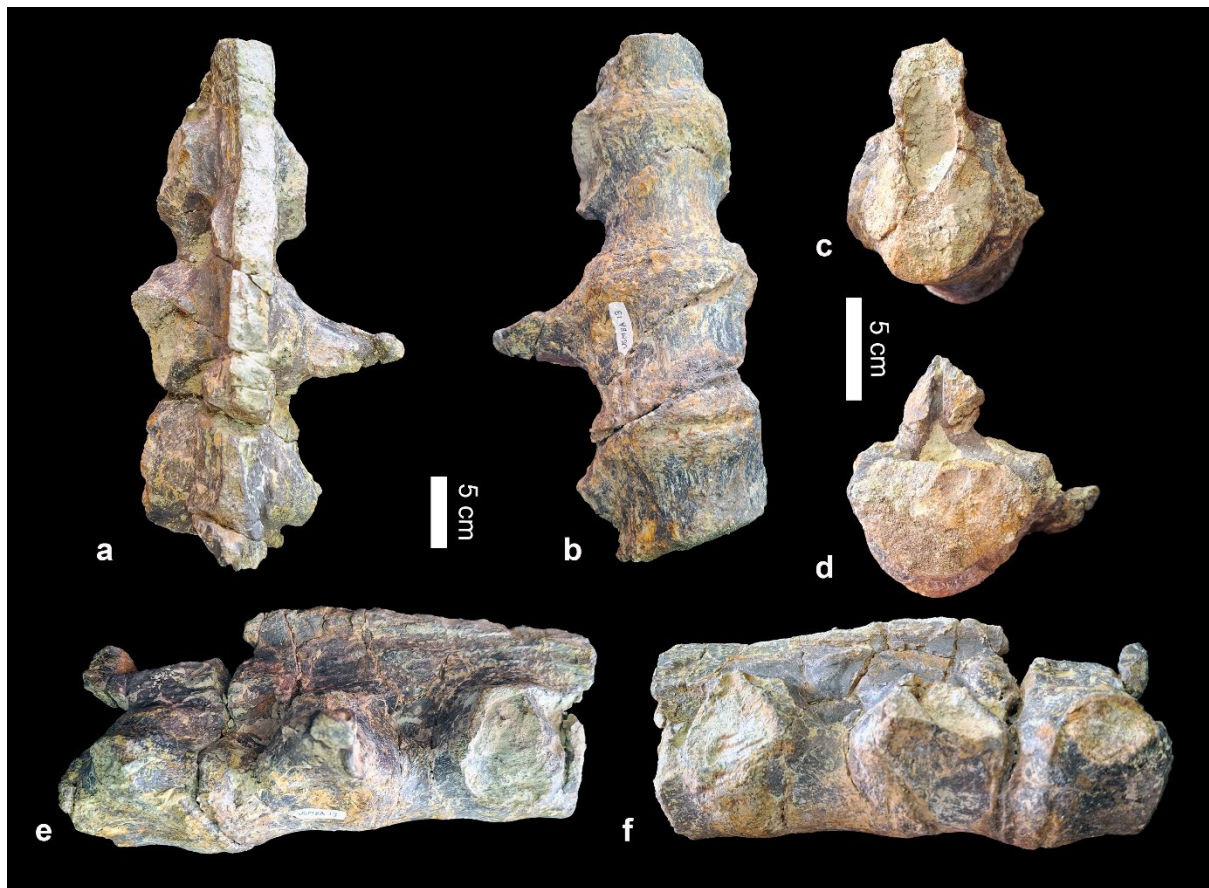


Fig. S5. Sacrum, USMBA 13, in a, dorsal, b, ventral, c, anterior, d, posterior, e, right lateral and f, left lateral views.

Free caudal vertebrae (Fig. S6)

The four caudal vertebrae appear to be in this proximal to distal sequence based on size: USMBA 71 (anterior caudal), USMBA 61, USMBA 65, USMBA 64.

USMBA 71 is a proximal caudal based on its large size and elongate transverse processes (Fig. S6). It is relatively complete but lacks the distal end of the left transverse process, while the right transverse process is broken and the distal most part may not be preserved. The spine has broken off but is mostly preserved adjacent to the left prezygapophysis. This vertebra has been somewhat dorsoventrally compressed and deformed. The anterior articular surface of the centrum is heart-shaped, transversely wider than dorsoventrally tall and deeply concave. The ventral surface of the centrum is concave anteroposteriorly with a groove along the midline. A chevron facet is present posteriorly. The lateral surfaces are anteroposteriorly concave. The posterior surface of the centrum is similarly transversely wider than tall with an oval outline and very deeply concave. Transverse processes are very broad, with their bases positioned on the

neurocentral contact and extending along the anterior 70% of the length of the centrum. They extend laterally and perhaps slightly ventrally, although this is difficult to assess because of the compression. Prezygapophyses extend well beyond the anterior surface of the centrum and have flat to gently concave articular surfaces that face dorsally and medially at approximately 45 degrees to the horizontal. The postzygapophyses only slightly overhang the posterior surface of the centrum and their very broad articular surfaces are at a very low angle to the horizontal. The spine is not well preserved but appears to have been broad in lateral view with a subquadrate outline. No obvious laminae or fossae are present on the vertebra.

Centrum, anteroposterior length = 57 mm

Anterior articular face, dorsoventral height = 40 mm

Anterior articular face, transverse width = 58 mm

Posterior articular face, dorsoventral height = 41 mm

Posterior articular face, transverse width = 68 mm

Length of right transverse process from base = 103 mm (incomplete).

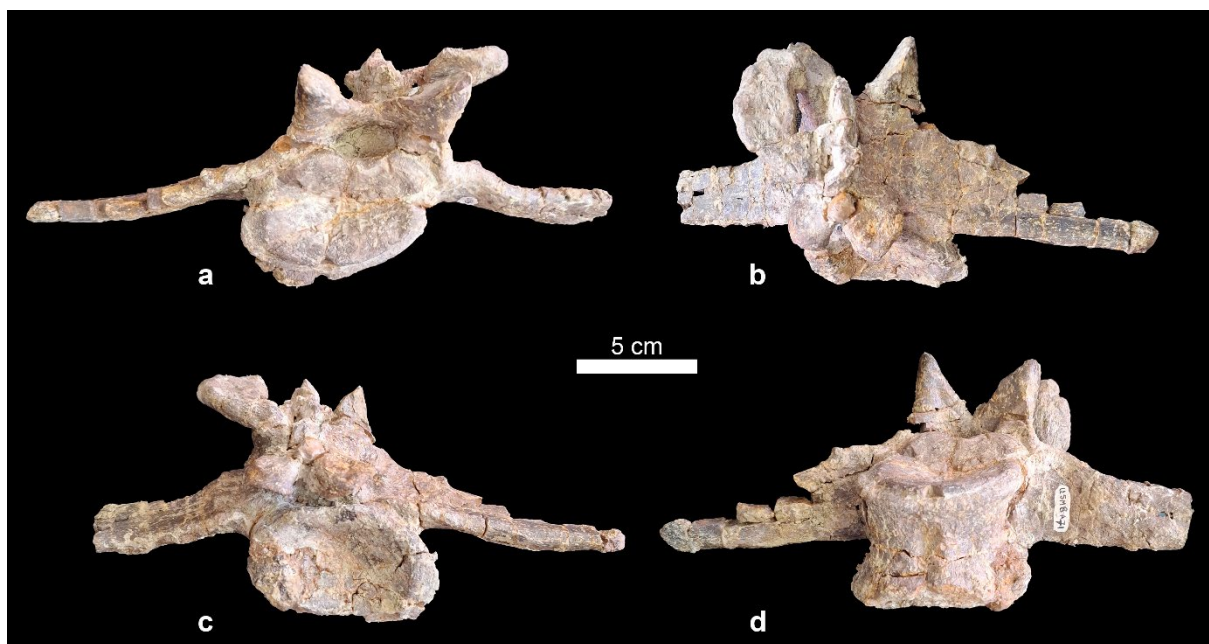


Fig. S6. Anterior caudal, USMBA 71, in a, anterior, b, dorsal, c, posterior and d, ventral views.

USMBA 61 is a centrum with the base of the transverse process preserved on the left side. The centrum is approximately as anteroposteriorly long as dorsoventrally tall in lateral view, with

anteroposteriorly concave lateral surfaces and a concave ventral margin. The anterior face of the centrum is sub-oval in outline, wider than high, and gently concave. The posterior face is similar but has a flattened ventral margin as a result of the chevron facets that are present on the posterior end of the ventral surface. The base of the transverse process is anteriorly placed on the neurocentral contact and extends over ~60% of the length of the centrum.

Centrum, anteroposterior length = 52 mm

Anterior articular face, dorsoventral height = 49 mm

Anterior articular face, transverse width = 66 mm

Posterior articular face, dorsoventral height = 50 mm

Posterior articular face, transverse width = 65 mm.

USMBA 65 is a more distal caudal which is lacking its left transverse process, most of the neural spine, and all zygapophyses except the left postzygapophysis. It has also been crushed and distorted and has substantial matrix remaining. The ventral margin of the centrum is broken posteriorly where the chevron facets would be expected to be present. Centrum articular faces are wider transversely than high with an oval outline and concave articular surfaces. The lateral and ventral surfaces of the centrum are smoothly concave anteroposteriorly and the ventral margin is smoothly rounded without a keel or groove. The transverse process arises from midlength of the neurocentral contact and projects laterally and slightly posteriorly. It is proportionately shorter and anteroposteriorly shorter than in the more anterior vertebra. There are no fossae or laminae present on the neural arch.

Centrum, anteroposterior length = 56 mm

Anterior articular face, dorsoventral height = 41 mm

Anterior articular face, transverse width = 54 mm

Posterior articular face, dorsoventral height = 40 mm

Posterior articular face, transverse width = 54 mm.

USMBA 64 is a partial centrum only, missing all of the neural arch, spine and transverse process and with parts of the right side of the centrum missing, including part of the anterior articular face. It is similar in morphology to the centra of the preceding caudals.

Centrum, anteroposterior length = 45.5 mm

Anterior articular face, dorsoventral height = 38 mm

Anterior articular face, transverse width = ? (at least 46 mm)

Posterior articular face, dorsoventral height = 44 mm

Posterior articular face, transverse width = 57 mm.

Handle vertebrae (Fig. 1A)

Associated with the left ilium (USMBA 12) are two vertebrae that appear to be handle vertebrae. They are fused together and the morphology of their dorsal surfaces cannot be seen because they are firmly wedged between the acetabulum and preacetabular process. The posterior articular facet of the first centrum is sub-rounded in outline and gently concave. A very small, circular neural canal is present dorsal to the centrum. The neural spine is broken dorsally, but an elongate, relatively robust left prezygapophysis extends from the posterior surface of the centrum where its posteriormost part is broken anteriorly and slightly laterally. Its anterior extend is also broken off. Ventrally, the centra appear to be slightly flattened on the midline, and bear a series of strong anteroposteriorly extending ridges, which are probably ossified tendons. There are at least two on each side of the midline. The area of fusion between the two vertebrae is transversely expanded, and a robust, thickened area that could be a chevron is fused to the ventral surface. It possesses two struts that extend anteriorly and dorsally either side of the haemal canal, and are fused to the ventral surfaces of the centra. The body of the chevron extends somewhat ventrally but strongly anteriorly parallel to the ventral surface of the second centrum, and is anteroposteriorly elongate, but dorsoventrally quite narrow. It is transversely compressed and broken at its distalmost extent. The second vertebra has similar ossified tendons to the first, although they only extend as far anteriorly as the middle of the centrum. At this level, two small nubbin-like processes extend laterally and probably represent the transverse processes. On the anteroventral surface, there is an anterior chevron facet to which a chevron is not fused. The anterior articular surface is dorsoventrally compressed and flat to slightly convex. There is no indication that these two vertebrae were fused to any others.

Dorsoventral height of articular surface of first centrum = 2.9 cm

Transverse width of articular surface = 4.1 cm

Length of first centrum = 4.4 cm

Length of second centrum = 4.9 cm

Transverse width of articular facet of second centrum = 4.3 cm

Dorsal ribs (Figs 1B; S7)

Six ribs with fused spikes are preserved. Based on the shape of the proximal ends and the length of the ribs, all represent dorsal ribs. All of the ribs are T-shaped in cross section, as in the holotype, and all bear dermal armour comprising a flat base and rounded spikes extending dorsally from the basal plate. The three longest and best preserved ribs all bear six spikes, the third of which is the longest. Where they are complete, the other spikes appear to be roughly similar in size to each other

One rib, which is incomplete distally, appears to be an anterior dorsal based on its curvature and the fact that only two spikes extend from its dorsal surface (USMBA 15). The tuberculum is anteroposteriorly compressed and lacks a distinctly clear articular facet for the parapophysis. Instead, its outline is gently rounded in anterior view. The rounded and gently concave capitulum is located on the dorsal surface of the tuberculum, set back from the articular surface of the latter, and is transversely broader. Dorsal and lateral to the parapophysis, the basal plate of the armour is attached to the dorsal surface of the rib. In anterior view, the basal plate is separated from the dorsal surface by a distinct notch. Level with this notch, the rib curves strongly ventrally. On one side of the rib, the basal plate can be distinguished from the dorsal surface of the rib by a groove, but on the other side a similar groove is absent and the basal plate and rib are confluent. Two spikes project from the dorsal surface of the basal plate. The medialmost is rounded in cross section and short, being less than double the height of the diameter of the base. The second spike is oval in cross section with the long axis transverse, although this could have been accentuated slightly by crushing. It is roughly double the height of the first spike. Ventrolateral to the second, longer spike, the basal plate tapers to a point, and the flat dorsal surface of the rib extends ventrally from this point without adornment.

The other three ribs (USMBA 16, 6 and 8) are similar in morphology, except that the basal plate is longer, extending further down the rib shafts, but in each case it can be seen to have a notch

at the proximal end and taper to a point distally. Grooves separating the basal plate from the dorsal surface of the rib are less distinct in these specimens, and are not continuous down the length of the ribs.

USMBA 7 is fragmentary rib which preserves the proximal part only and is offset by a large fracture.

USMBA 84 is broken and has four spikes along its dorsal surface. The height of the spikes varies along the rib. The smallest is the medialmost one and they become higher until the third, which is the highest, and then the then the spikes become The spikes are similar in morphology to each other: they have a rounded base and are pointed distally.

USMBA 48 is a large, flat, broken element that may have been part of a rib or possibly a piece of dermal armour. Associated with it is a rounded, small spike similar to those found on the ribs. It is 13 cm long.

	Length as preserved	Length of longest spike	Length of medialmost spike
USMBA 6	47 cm	14 cm	3.5 (broken tip)
USMBA 8	62 cm	10 cm	5.5 cm
USMBA 16	63 cm	11 cm	3.5 cm
USMBA 15	35 cm	14 cm	6 cm
USMBA 7	26 cm	6cm	5 cm (broken tip)
USMBA 84	40 cm	9,5 cm	5 cm



Fig. S7. Ribs of *Spicomellus afer*.

Scapulocoracoids (Fig. S8)

Both scapulocoracoids are preserved, but neither is complete. In the left, the ventral part of the coracoid and glenoid fossa are well preserved, but the scapulocoracoid is broken dorsally, the acromial process is broken, and the shaft is rotated slightly. In the right, the dorsal part of the coracoid is better preserved, and the acromial process is complete, but the glenoid is not as well preserved. Neither scapula blade is complete so the total length of the elements is unknown.

The scapulae and coracoids are indistinguishably fused. The coracoid appears to be anteroposteriorly slightly shorter than it was dorsoventrally high, but because neither are complete dorsally, it is difficult to be certain. The anterior margin of the coracoid describes a gently convex curve, which terminates ventrally in a poorly developed sternal process that does not extend further ventrally than the glenoid and is strongly convex on its lateral surface. A shallow fossa separates the sternal process from the glenoid. The lateral surface of the coracoid is convex, and pierced by a small coracoid foramen, which is only clearly preserved on the right. The coracoid foramen is set some distance anterior to the presumed location of the scapulocoracoid suture. The medial surface of the coracoid is strongly concave, especially anteriorly. The coracoid foramen opens as an anteroposteriorly elongate channel, the posterior part of which presumably extended onto the medial surface of the scapula. The coracoid's contribution to the glenoid is D-shaped, with the flat margin of the D facing posteriorly. It is flat, transversely thicker than the rest of the coracoid, and has an everted margin.

The acromial process of the scapula is very prominent, and is present as a laterally and anteriorly projecting ridge that extends ventrally from the anterodorsal margin of the scapula for a short distance before turning posteriorly to extend along the scapula blade level with the dorsal margin. In this region it is thickened dorsoventrally, and gives the impression that the dorsal margin of the scapula has folded laterally to form a shelf. The distal extent of the ridge extending posteriorly from the acromium cannot be determined because both scapulae are broken in this region. Ventral to the anterior part of the acromial ridge, where it extends ventrally, the lateral surface of the scapula is a shallow fossa bounded posteriorly by a ridge that supports the corner of the acromial process, and the posterior part of the glenoid fossa. The scapula's contribution to the glenoid is approximately equal in size to that of the coracoid, and is also D-shaped, with the straight margin facing the coracoid. It is gently concave. It is also rimmed by an everted margin, and there is a large and rugose muscle scar on its ventrolateral part. Posterior to the proximal plate, the blade of the scapula is smooth and flat, as far as can

be determined. Medially, the surface of the proximal plate of the scapula is not well preserved in either specimen, but may have been convex. On the blade, situated at mid-height and posterior to the glenoid is a pointed tubercle-like muscle scar.

Total length as preserved => R = 33 cm; L = 35 cm

Maximum height of the coracoid, as preserved => R = 17 cm; L = 15 cm

Coracoid anteroposterior width, right = 11.5

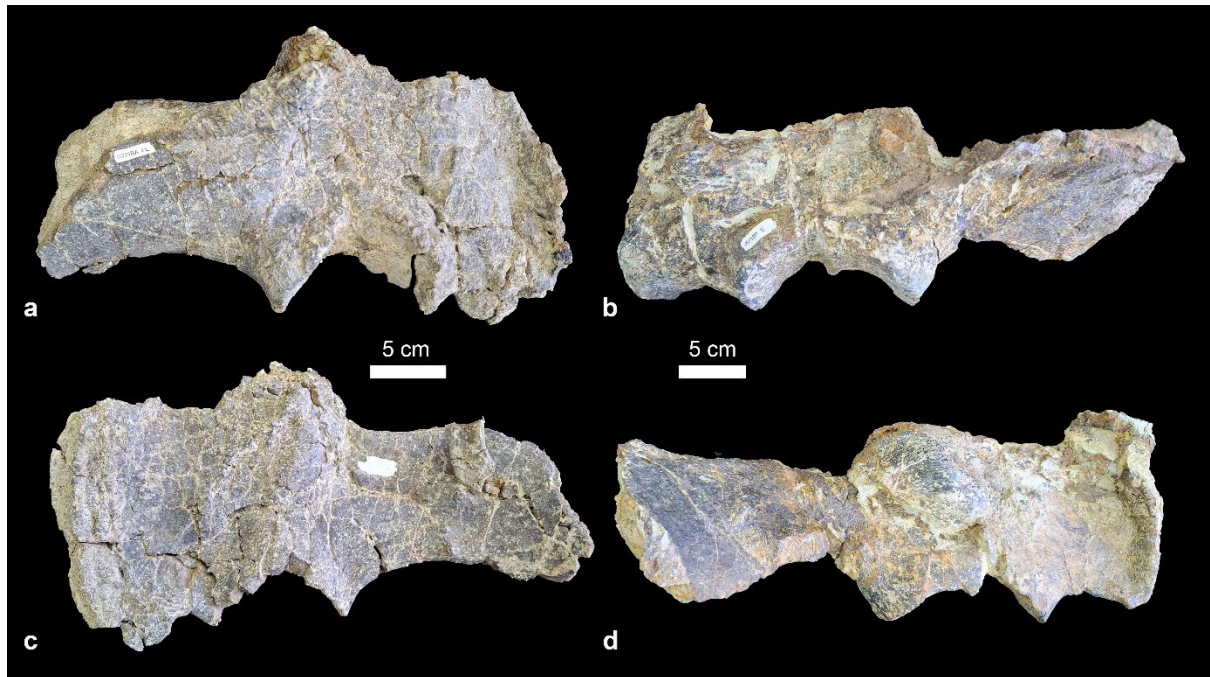


Fig. S8. Right scapulocoracoid, USMBA 72 (a, c), and left scapulocoracoid, USMBA 5 (b, d) in a, b, lateral and c, d, medial views.

Pelvis (Figs 1G, S9)

Posterior parts of both ilia are preserved, including robust postacetabular processes, and the acetabular regions. Both pubes are preserved fused to the anterior margin of the acetabulum, and the proximal part of the right ischium is also fused. Sutures between these elements are not visible. The right ilium is in one piece and is USMBA 10. The left ilium is preserved in two pieces and is USMBA 12.

In ventral view, the postacetabular processes extend posteriorly for about the same distance as the anteroposterior length of the acetabulum. An extremely robust postacetabular ridge extends posteriorly along the ventral surface of the postacetabular process, terminating in a

transversely expanded, blunt ended knob. This expansion appears to be due to a caudosacral rib that would have articulated with the medial surface of this ridge, and this is clearer on the left side, where the distal end of this rib can be seen fused to the knob. Based on this distal end, the rib was probably slender relative to the sacral ribs.

The postacetabular ridge demarcates a medial fossa, probably corresponding to the brevis fossa. The medial surface of the brevis fossa is broken. Lateral to the postacetabular ridge is a supraacetabular flange, whose margin extends anteriorly and laterally in a continuous curve from the distal end of the postacetabular process. It is thickened dorsoventrally and in lateral view is folded somewhat ventrally. This thickening is entirely posterior to the acetabulum. The ventral surface of the supracetabular flange and the postacetabular process lateral to the postacetabular ridge is shallowly concave.

The lateral side of the ilium lateral to the acetabulum is broken on both sides. The acetabulum is a deeply concave cup-like structure that is closed medially by fusion of the ischium. The ischiadic peduncle is C-shaped in outline with the opening anterior, and rises posteroventrally. The ischium is indistinguishably fused to the posterior and medial surface of the ischiadic peduncle, and presumably formed part of the peduncle itself. The proximal part of the ischium is deeply concave, and the pubic peduncle of the ischium extends anteriorly, presumably to contact the pubis, but whether it contacts the pubic peduncle is unclear. The shape of the proximal margin of the ischium cannot be determined because of fusion of the sutures. The dorsal and ventral margins of the ischium converge ventrally towards the ischiadic blade, which is broken. The medial surface of the ischium is strongly convex.

Medially, three sacral ribs (sacrals 2-4) are fused to the medial surface of the acetabulum and possibly the ischium. Sacral rib 2 attaches medial to the anterodorsal corner of the acetabulum, and this contact is dorsoventrally very deep. Sacral rib 3 is medial to the anterior part of the ischiadic peduncle and is poorly preserved on both sides. Sacral rib four is located medially to the posteroventral corner of the ischiadic peduncle and extends to contact the proximal part of the brevis shelf. The rib is angled anteroventrally and compressed anterodorsally-posteroventrally. One sacral rib is lying out of place attached to the broken medial surface of right sacral rib four. It has an elongate articular facet for the vertebra, but it is not totally clear which rib this is.

The pubis is more-or-less- complete on both sides and fused indistinguishably to the pubic peduncle of the ilium and ischium. The pubes appear to retain both thin slender postpubes and a short, robust prepubis. The body of the pubis is concave dorsally where it is fused to the

acetabulum and convex ventrally. On the left, a short, robust prepubis extends anterolaterally, and projects anterior to the anterior margin of the pubis. It is dorsoventrally compressed and terminates in a rounded distal end. On the right, the prepubis is missing due to damage in this region. Both postpubes are present. The postpubis is a very slender strut that extends ventrally from the centre of the body of the pubis and turns to extend medially. The obturator foramen is open on both sides and is roofed dorsally by the ischium. The postpubis extends onto the pubic peduncle of the ischium, where it is fused to the ventral surface as a distinct ridge. The first sacral rib is fused to the posteromedial part of the body of the pubis and is delineated by a groove that extends anteromedially before curving anterolaterally towards the anterior end. This sacral rib is double-headed at its distal end: the ventral process articulates with the pubis and the dorsal process articulates with the medial surface of the preacetabular process. This rib is complete on the left side, and is short, robust, anteroposteriorly compressed and has an ellipsoidal single articular facet.

In dorsal view, the sacral shield appears to be directly fused to the surface of the ilium, and was continuous across the sacral ribs. A large spike was situated medial to the supraacetabular flange. It is dorsomedially to ventrolaterally compressed with strongly developed anterior and posterior ridges, and projects posterolaterally and dorsally. The distal end is missing. Over the acetabulum and further anteriorly there are several evenly spaced small spikes. One is located directly over the acetabulum, and another lies medially to this. A second and third row of spikes extends parallel to these more anteriorly, and they are arranged in a grid pattern in parasagittal and transverse rows. There are no clear junctions between osteoderms, no rosette-like structures around the spikes, and no scales.

Length of right acetabulum = 20 cm

Length of right postacetabular process = 18 cm

Length of left postacetabular process = 15 cm

Length of spike as preserved = 24 cm

Largest diameter at the base = 9.8 cm

Smallest diameter at the base = 4.4 cm

Largest diameter at broken end = 6.2 cm

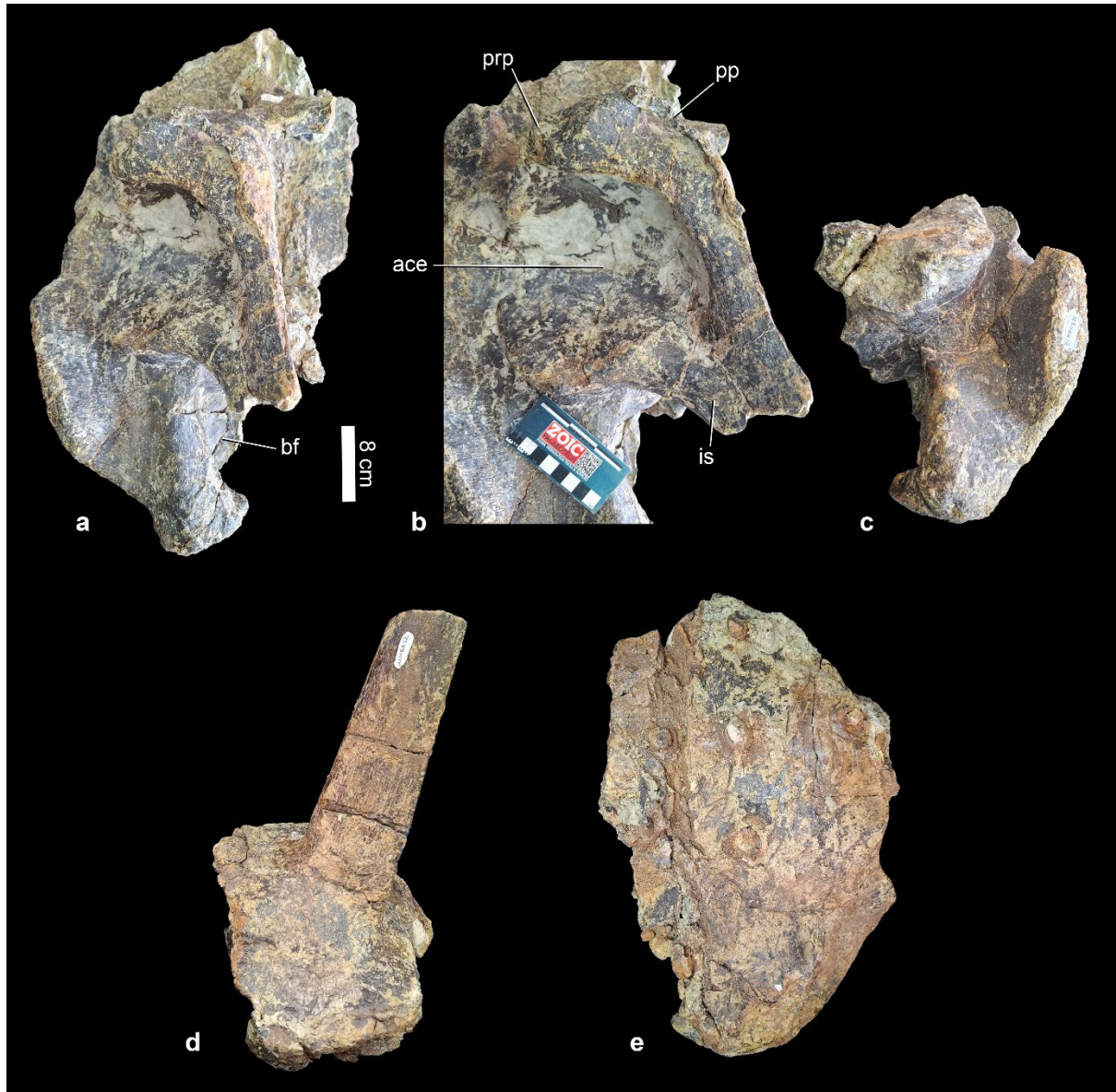


Fig. S9. a, right ilium, USMBA 12 in ventral view; b, detail of right acetabular region showing pubis and ischium in dorsolateral view; c, left ilium, USMBA 10 in ventral view; d, left ilium, USMBA 10, in anterodorsal view showing large spike located over the supracetabular flange; e, right ilium, USMBA 12, in dorsal view. **ace**, acetabulum; **bf**, brevis fossa; **is**, ischium; **pp**, postpubis; **prp**, prepubis.

Metatarsals (Fig. S10)

Two metatarsals are preserved. USMBA 50 is a right metatarsal II. USMBA 53 is a metatarsal IV, which also appears to be from the right side although the proximal end is incomplete, complicating identification.

The right metatarsal II (USMBA 50) is relatively short and robust in dorsal and lateral views. The proximal end is slightly transversely expanded relative to the shaft in dorsal view but strongly expanded dorsoventrally in lateral view. In proximal view the proximal end of the bone is deeper dorsoventrally than transversely wide, as is typical of MTII in ornithischians, with a flattened lateral surface, a flat to gently convex ventral surface and a broadly and continuously rounded margin medial and dorsally. There is no sign of an articular facet for MTI. The surface of the proximal end is flat and somewhat rugose. The shaft has a similar cross section, being flattened laterally and ventrally and rounded medially and dorsally. Distally, the distal end is gently expanded transversely and dorsoventrally relative to the shaft in dorsal and lateral views. The distal articular surface is sub-rectangular in distal view, with nearly straight medial and lateral margins, a convex dorsal margin and a concave ventral margin. The surface is transversely concave, roughened, and extends onto the dorsal surface of the distal part of the element.

Maximum length = 106 mm

Maximum dorsoventral height, proximal end = 76 mm

Maximum transverse width, proximal end = 53 mm

Transverse width at midshaft = 40 mm

Dorsoventral height at midshaft = 42 mm

Maximum transverse width, distal end = 57 mm

Maximum dorsoventral height, distal end = 55 mm.

Metatarsal IV (USMBA 53) is slightly longer than metatarsal II and is strongly expanded at proximal and distal ends in dorsal view. In lateral view it is strongly expanded ventrally at the proximal end but there is little dorsoventral expansion distally. The proximal end is damaged and incomplete medially, but the outline appears to be subequal in transverse width and dorsoventral height, with flattened medial and ventral margins and broadly and continuously curved lateral and dorsal margins. The proximal end is therefore dorsoventrally deepest medially and tapers laterally. At midshaft the cross section is similar to that of the proximal end. The distal end of the bone is not well preserved but has a subrectangular outline, with gently convex lateral and distal margins and a flat ventral margin. The medial margin of the distal end of the bone is poorly preserved but might bear a small concavity on its surface.

Maximum length = 127 mm

Maximum dorsoventral height, proximal end = 60 mm

Maximum transverse width, proximal end = 61 mm

Transverse width at midshaft = 39 mm

Dorsoventral height at midshaft = 41 mm

Maximum transverse width, distal end = 65 mm

Maximum dorsoventral height, distal end = 42 mm.



Fig S10. a–f, metatarsal IV, probably from the right side; g–l, right metatarsal II. a, g, dorsal; b, h, medial; c, i, ventral; d, j, lateral; e, k, proximal; f, l, ventral.

Dermal armour

Cervical half-ring (Figs 1F, 2F)

USMBA 14 is a compound osteoderm that, given its size and shape, must have been a cervical half ring. It originally would have comprised five spikes and two plates. The basal plate is fused together into a horseshoe shape and is angled so that posteriorly it is slightly wider than anteriorly. Ventrally, the basal plate is uneven, probably where the bases of individual spikes

fused to form the ring. Centrally, on the midline, there was a single spike with a diamond cross section. This was the smallest spike of the half-ring and its tip is missing. Extending towards its apex, it was rounded in cross-section. Immediately ventral to this spike, the basal plate has a ventral bulge. Lateral to this midline spike are two very large, flat spikes. On the left, the spike is broken, but on the right the spike is 87 cm long, and missing a few cm of its distal tip. At the base of these extremely long spikes, the spikes have a sharp ridge extending up the front, while the remainder of the cross section is broadly convex. The ridge is not central, but slightly offset medially. The ridge merges to become the medial margin of the spike about $\frac{1}{4}$ of the way along its length; from there to the apex it has a rectangular cross-section with the long axis transverse. Lying lateral to these large spikes were two more. The base is preserved on the left hand side, but on the right this area is crushed and there is no sign of the base of this second large spike. It is possible that this second spike was not fused on the right. Although poorly preserved, it appears that this second set of spikes approached the first in size, at least at the base, and had a similar morphology with a prominent ridge extending up the anterior surface. Ventral to the second set of spikes, the basal plate ends on each side in a rounded apex. Extending ventrally and laterally from this apex is a small plate, preserved on the right but not on the left. The plate is similar in morphology to others on the body; it is convex on its posterior surface and flatter on its anterior surface, and has a slightly posteriorly offset apex.

The half-ring is 34 cm around its internal surface. The plate is 14 cm from apex to base.

Sacral shield (Figs 1J, 2H)

A flat piece of bone (USMBA 9) that measures 37 cm by 25 cm at its maximum appears to be part of a sacral shield. The dorsal surface is flat and smooth, and unadorned bearing no scales or rosette-like structures. Instead, five evenly spaced short spikes project from its dorsal surface. The spikes are rounded in cross-section and have diameters of 3-4 cm. They are approximately double the height of their diameters. The longest spike appears to have been dislodged and is now angled; it is 9.5 cm long, while the shortest is 5 cm long. Slightly longer spikes appear to have been located laterally. Ventrally, a rib, which presumably would have extended from a dorsal vertebra to contact the preacetabular process of the ilium, is present, but indistinguishably fused to the surrounding bone. It is identifiable because it is elongate, convex in ventral view, and flattens towards what presumably was the lateral surface of the shield. The anterior margin of the rib is horizontal transversely and the edge of the sacral shield appears to be finished/complete in this region. Three of the spikes project from the dorsal

surface level with this rib. Dorsoventrally, the block of bone is around 5 cm thick (including the rib) and it appears that it was firmly co-ossified with any underlying bone, or that connective tissue that roofed the space between the long dorsosacral ribs and the ilium was ossified and the sacral shield was indistinguishably fused to it. Laterally (based on the morphology of the rib), the ventral part of the block appears complete, and smoothly curves laterally, however, the dorsal surface, which presumably formed the shield, is broken, so would have extended further laterally than the underlying bone. In ventral view, the ventral surface of the element is smooth and gently concave, and thickened laterally. In places there is evidence of the cross-hatched structural fibres characteristic of ankylosaur dermal armour (Maidment et al. 2021).

A second piece of sacral shield (USMBA 11) is similar triangular in shape and has three spikes projecting from its dorsal surface (one is broken and only the base remains). Ventrally, the element is similar to the larger block: there are thicker areas that may have corresponded to parts of the ilium or ribs, and one edge is smoothly convex and finished. It does not articulate with the larger block.

Two smaller pieces of sacral shield were associated with the sacrum (USMBA 73 and USMBA 74). Both bear small spikes.

Plates (Figs 1H, 2K)

Eight plates are preserved (USMBA 23, 26, 24, 27, 20, 28, 29, 42). The first seven are very similar in morphology. They are all transversely compressed, except at the base. All terminate in a point, which is offset from the centre of the base, with one convex margin and one concave margin. The convex margin is here regarded to lie anteriorly, such that the apices are swept posteriorly. The plates differ from each other in their size, and in some other details.

USMBA 23 is the largest of the plates, and is 34 cm in maximum height. One side of the plate (interpreted to be the dorsal side) is flat, while the other side is gently convex. At the base, the plate is slightly expanded on the convex side and smooth. In contrast, on the flat side, it is more expanded, and the broken base of a spine, which was oval with sharp points in cross section, was fused to the base of the plate, indicating that the original structure of the osteoderm would have been compound, with a large plate lying ventral to a substantial spike. This means that the plate came from the right side of the body.

USMBA 24 and 26 (Fig. 2K) are identical in shape and size. They are 24 cm in maximum height. One side, interpreted as the ventral side, is slightly more convex than the other, which is still

has a slight anteroposterior convexity. Anteriorly, ventral to the convex margin of the plate, the bases are only slightly expanded, but posteriorly, ventral to the concave plate margin, the bases are more expanded, and there is a clear line where they likely embedded in the skin.

Identification of the more convex surface of the plate as lying ventrally based on USMBA 23 indicates that both of these plates were from the right side of the body.

USMBA 27 (Fig. 1H) is the next smallest plate, being 21 cm in maximum height. The plate is convex on one side and slightly concave on the other. The convex side bears two strong ridges that extend from the base of the plate towards the apex, merging with the surface just before the apex is reached. As in USMBA 24 and 26, the base is more expanded on concave surface, and more expanded posteriorly, under the concave margin. Assuming the slightly concave surface was dorsal, this plate was from the left side of the body.

USMBA 20 is not as well preserved as the other plates, missing parts of the edges and the dorsal apex, but it appears similar in overall morphology, and again has a thickened base lying posteriorly. This plate appears to have been from the left hand side of the body.

USMBA 28 is a small plate, 20 cm tall, and missing the tip of its apex. It is also anteroposteriorly narrower than the others, with less a less pronounced posterior concave margin. Both sides of the plate are convex, but one is more so. The basal expansion is well developed, similar to that of USMBA 23, and is asymmetric, being more greatly expanded on the less convex side of the plate, indicating that the greater part of the expansion lay dorsally. The plate is from the right side of the body.

USMBA 29 is a small plate, 16 cm in maximum height. Unlike USMBA 28, it does have a strongly concave posterior margin. Both surfaces are convex, but one much more so than the other. The base of the plate is expanded laterally approximately equally on both sides, and in contrast to all of the other plates, it is hollow-based. It also does not lie ventral to the posterior margin of the plate. This plate appears to be from the left side.

USMBA 42 is different in morphology from the other plates, and is not as well preserved. It is much thicker dorsoventrally, and is more elongate relative to its width. It has approximately straight anterior and posterior margins, and its apex is only slightly offset posteriorly. One surface is much more convex than the other, and the convex surface currently has some nodule material attached that needs to be prepped off. It is unclear if the base of the plate is complete, but it appears transversely thickened.

Slender rounded spines with expanded bases (Figs 1D, 2G)

USMBA 30 (Fig. 2G) and 31 are slender spines with rounded cross-sections and greatly expanded bases that are ventrally flat. USMBA 30 is 10 cm long, with a cross-section at the top of the basal plate that is 2.5 cm in diameter. It is very slightly curved along its length. The basal plate expands horizontally and is roughly circular in outline. The basal plate is 6 cm in diameter. Ventrally, the basal plate is flat. USMBA 31 is similar but slightly longer, being 14 cm long. Its basal plate is incomplete but appears to have been tear-drop shaped and very slightly concave, and has rugose margins. A third spike, USMBA 46, is similar in morphology, but its base is broken.

USMBA 37 is a more elongate spike with a slightly less expanded base. It is about 30 cm long, although it is missing its distal tip. Close to the apex, the spine is rounded in cross section, but ventrally it develops sharp anterior and posterior ridges which give the spine an oval cross section. The base of the spine, prior to its expansion, is 3.7 cm in diameter. The basal plate is expanded and ball-like, being convex on all surfaces. It has a maximum diameter of 5.7 cm. It is slightly angled, indicating that the spike may have projected backwards on the body. However the spike itself has been plastically deformed.

USMBA 18 (Fig. 1D) is a very elongate and slender spine with an expanded base. It has a maximum length of 52 cm. As in USMBA 37, it is rounded in cross section near its apex, but moving proximally it develops ridges anteriorly and posteriorly. The cross-sectional diameter just above the basal plate is a maximum of 5.7 cm. The osteoderm has a slight curvature, probably posteriorly. The basal plate is roughly square, with a transverse width of 12 cm and an anteroposterior width of 11 cm. It is strongly concave ventrally, with a subtle ridge that extends anteroposteriorly along the midline. The anterior and posterior margins of the basal plate are dorsoventrally compressed, but the lateral margins are expanded and ellipsoidal in outline, probably indicating that the basal plate articulated with, and could have been fused to, other, similar osteoderms around it. The symmetrical shape of the basal plate indicates the spike was on the midline of the body. A second, very similar spike is present but only the distal tip is preserved (USMBA 21). However, this suggests that the animal likely had more than one of these spikes on its body.

Flat, blade-like spines (Figs 1E, 2C, M)

Four spines, USMBA 22, 19, 75 and 17 represent elongate spines that are transversely flattened and blade-like. USMBA 22 (Fig. 1E) is the smallest and most slender. It is 39 cm long, 4.6 cm in its largest diameter just dorsal to the basal plate, and 2.3 cm in its smallest diameter just dorsal to the basal plate. The apex of the spine is slightly swept back, so that the posterior margin of the spine is slightly concave along its length. The basal plate is broken but does not appear to have been greatly expanded; however, it does seem to have been concave at its base, or possibly pup-tent shaped. The anterior and posterior margins are smoothly rounded and are not sharp ridges.

USMBA 19 (Fig. 2C) is wider than USMBA 22 and not as slender. It has longitudinal striations on its surface and its distal tip is missing. It is 43 cm long and the diameters above the basal part are 6.3 and 3.5 cm. The basal plate is expanded either side of the flat surfaces of the spine. It is poorly preserved but appears to have been hollow-based. Laterally, the basal plate is dorsoventrally thick and oval in outline, suggesting that it may have articulated with another spine.

USMBA 17 (Fig. 2M) is a transversely compressed, blade-like spike with a small base. The spike is 27 cm long. Its posterior margin is broken, so the preserved anteroposterior width is 5.9 cm and the spike measures 2.3 cm in its transverse width. The base of the spine is laterally expanded and is asymmetric with one side extending further ventrolaterally. The base of the plate is pup-tent shaped with flat internal surfaces. Triangular facets are present on the distal ends of either side of the basal plate. These ends probably articulated with another osteoderm.

USMBA 75 is poorly preserved and in many fragments. It is 35 cm long. It is strongly transversely compressed, and flat on one side but convex on the other. It appears to have been straight, without an offset apex. The base is somewhat squashed, but it appears to have been transversely expanded relative to the width of the osteoderm and could have been offset slightly to one sharp (posterior?) margin, although this is difficult to determine. Near the base of the spine, one margin is sharper and more compressed than the other. The transverse width of the base of the spine just dorsal to the base is 2.1 cm and the anteroposterior width is 5.9 cm.

Three-spiked osteoderms (Figs 1C, 2N)

USMBA 40 (Fig. 1C) and USMBA 63 (Fig. 2N) are three-spiked osteoderms. USMBA 40 comprises three small, slender spikes with rounded cross sections fused basally to an elongate osteoderm. The osteoderm is rectangular in outline. It is probably broken along both the short

margins. One of the long margins of the rectangle is concave, while the other is flat, giving the element a slight curvature. The concave margin is dorsoventrally thicker than the straight margin, which is scalloped ventrally. The osteoderm is gently concave ventrally, both along its short dimension and its long dimension. On the dorsal surface, the osteoderm is strongly convex, and three, equally sized and spaced short spikes with a rounded cross section project from it. The curvature of the armour suggests that it fitted around a relatively narrow portion of the body.

Total length = 14 cm

Max width = 7.5 cm

Height of spike = 3.7 cm

USMBA 63 (Fig. 2N) is similar to USMBA 40, and the basal plate is incompletely preserved. It was likely the same morphology originally but has broken. The three spikes project dorsally and are evenly spaced.

Total length of basal plate as preserved = 11.4 cm

Max width as preserved = 3 cm

Height of spike = 3.5 cm

Compound osteoderms (Figs 1I, 2D, L)

USMBA 62 has a rectangular basal plate with two spines projecting from its dorsal surface. The basal plate is dorsoventrally deep, rugose and irregular, and curved so that its ventral margin is concave and its dorsal margin is convex. As preserved it is 26 cm long. It is rectangular in outline with the long axis transverse to the curvature, so that it would have wrapped around the body transversely. Its maximum anteroposterior diameter is 9 cm. One short side is broken and distorted. Two spikes project dorsally from the basal plate. One is relatively small, 6.8 cm long, and has a ellipsoidal cross-section at the base. The apex of the spike is very slightly offset posteriorly so that the anterior margin is convex while the posterior margin is very slightly concave. A second spike clearly projected from the dorsal surface as well, but was broken at the base, and only the tip is preserved. The cross-section of the base is ellipsoidal in cross

section and was much larger than the first; the maximum anteroposterior diameter of the small spike at its base is 2.8 cm, while of the large one where it is broken, it is 7.5 cm.

USMBA 44 (Fig. 1I) has an oval basal plate with two spines projecting from it, one large and one small. The basal plate is strongly convex and smooth on its dorsal surface, and is concave on its ventral surface so that the whole osteoderm is curved. Dorsally, there is a small spike that is rounded in cross-section and that is located close to the narrower point of the oval. Ventrally the basal plate in this region is concave. Laterally, the basal plate in this region has an oval dorsoventral thickening, probably for articulation with another osteoderm. A second, much larger spike, whose tip was probably USMBA 43, although this does not fit exactly is located in the centre of the oval basal plate. The spike is much larger and has ellipsoidal cross-section with sharp anterior and posterior margins. Ventral to this spike, the basal plate is also concave, and where the two concavities of the two basal plates of each spike meet there is a ridge, indicating where they fused together. The other side of the basal plate of the large spike is dorsoventrally deep and has an oval facet, perhaps where it articulated with another osteoderm.

Total length of the basal plate = 20 cm

Total length of small spike = 10 cm

Anteroposterior diameter of small spike at base = 2.6 cm

Length of the large spike, with USMBA 43, as preserved = 39.5 cm

Anteroposterior diameter of large spike at base = 7 cm

Transverse diameter of large spike at base = 4.2 cm

USMBA 70 (Fig. 2D) is very similar to USMBA 44, with an oval base plate and two spines, one large and one small, projecting from its dorsal surface. The base plate is flatter ventrally than in USMBA 44, lacks the curvature around the body, and it is less clear that the osteoderm bases were concave. The oval base plate also lacks dorsoventrally thickened facets laterally, so it is not evident that it articulated with other osteoderms. The base plate is broken lateral to the smaller spine. The smaller spine is rounded in cross-section and is 8 cm long and is complete. It has a diameter at its base of 3 cm. It is slightly posteriorly inclined, so that the apex is slightly offset posteriorly. The longer spine projects from the centre of base plate and is angled away from the smaller spine, in contrast to USMBA 44 in which both spines project in the same direction. It has an ellipsoidal cross section with sharp anterior and posterior ridges. It is 35 cm

long but its tip is broken. Its anteroposterior diameter at the base is about 5.8 cm, while its transverse cross section is 4.3 cm. Relative to the base plate, the spines are inclined posteriorly at an angle of around 40 degrees.

USMBA 25 (Fig. 2L) is another compound osteoderm with two spines, one of which is broken. One spine is elongate and slender and ellipsoidal in cross-section with prominent ridges extending dorsoventrally. It has a basal plate that extended laterally a small amount and was concave ventrally. Offset from this spine, slightly to one side both laterally and anteriorly (orientations are estimated), a second spine, apparently slightly larger based on the ventral dimensions, projected, but only the base is preserved. The spine is more transversely compressed and blade-like, at least at its base. The offset of the two spines gives the osteoderm the impression that the spines were set *en echelon*. This second, larger spine had a basal plate with a transverse expansion and was flat ventrally; the basal plates of the two spines are now indistinguishably fused to each other to produce an ellipsoidal structure. A oval dorsoventral thickening lateral to the smaller spine perhaps indicates articulation with a second osteoderm.

Total length of basal plate = 15.5 cm.

Total length of smaller spine, as preserved = 34.5 cm

Maximum diameter at base of smaller spine = 4.5 cm

Minimum diameter at base of smaller spine = 3.3 cm

Maximum diameter at base of larger spine = 6.2 cm

Minimum diameter at base of larger spine = 2.9 cm

USMBA 58 is a large and robust osteoderm that appears to have originally had at least two spines, one very large, robust and transversely compressed, and one small, rounded spike, projecting from its dorsal surface. The rounded spike is broken and not preserved.

The basal plate is elongate, presumably transversely. At its widest, it is 9.2 cm. At one end, the end with the broken base of the smaller spine, the margin of the base plate is gently rounded in dorsal view. The other end is broken, lateral to the robust spike. The basal plate is extremely deep dorsoventrally, measuring at least 6 cm in dorsoventral height. It appears to comprise two layers that were fused together; a thick ventral portion that is flat to convex and irregular (and broken) on its surface, and a dorsal portion that has fused to it and is thinner, around 2 cm in

thickness, and on one side is separated from the ventral portion by a distinct groove. The dorsal portion projects further anteriorly than the ventral portion, so it overhangs the ventral part. Its dorsal surface bears cross-hatched structural fibres. The base of the small spike was rounded in cross section and was 3 cm in maximum diameter. The large and robust spike is broken into two pieces which do not fit together but which were restored in the field by Mohamed; these do appear to go together although there is a bit missing. The maximum length of the two preserved portions is 33 cm but the spike would have been considerably longer. It is anteroposteriorly compressed and slightly flatter on one side than the other. It angles laterally towards the smaller spine at an angle of about 80 degrees. It has a sharp lateral margin (the margin facing away from the small spike).

Single large spines with robust base plates (Fig. 2J)

USMBA 12 (Fig. 2J) is a large spine with an ellipsoidal plate that is poorly preserved posteriorly. Its base has an irregular surface ventrally. The spike projects posteriorly from the dorsal surface of the plate. The spike is elongate and relatively slender. In cross section, the spike is ellipsoidal with long axis anteroposterior. The spike is angled posteriorly at about 40 degrees. The base plate is 23 cm long and 13 cm wide. The preserved part of the spike is 23 cm long, 3.5 cm in transverse width, and 6.8 cm in anteroposterior width at the base of the spike.

USMBA 70 has an ellipsoidal basal plate with a spike projecting from its dorsal surface and angled posteriorly. Its base is concave ventrally and convex dorsally. It is broken around its margins, and is dorsoventrally thick, with a maximum thickness of 6 cm. The preserved part of the base plate is around 22 cm long and 13 cm in maximum width. The preserved part of the spike is about 22 cm long. It is transversely compressed, being 8.7 cm wide anteroposteriorly and 3.7 cm wide transversely at its base. The spike is angled posteriorly at about 30 degrees. The surface of the basal plate has two orientations of structural fibres intersecting at 90 degrees. The spike also has a very narrow striations extending proximodistally along its surface.



Fig. S11. Armour of *Spicomellus*. RJB, KE, AO and AP for scale (and the scale bar on the table is 8 cm long).

3. Phylogenetic analysis

Methods

Methods are provided in the main manuscript. The character list used was that of Raven et al. (2023). One character was modified: #146. Dorsal vertebrae, excluding anteriormost one or two: dorsal neural arch pedicle not elongated (0); greatly elongated to give the vertebra a stretched appearance (1). This was previously a continuous character in Raven & Maidment (2017) and was re-discretized by Raven et al. (2023). However, the discretization did not reflect the variation the character was designed to account for and thus has been modified to a qualitative character here. All taxa in the character-taxon matrix were rescored for this character.

Equally-weighted analysis

Iterative PCR (Pol & Escapa 2009) applied to a subset of 10 000 MPTs identified the following taxa as unstable, and these were pruned *a posteriori* to give a strict reduced consensus tree (the PCR tree; Fig. S12): *Acantholipan*, *Adratiklit*, *Alcovasaurus*, *Anoplosaurus*, *Dongyangopelta*, *Hylaeosaurus*, *Invictarx*, *Jiangjunosaurus*, *Loricatosaurus*, *Minmi*, *Mongolostegus*, *Nodocephalosaurus*, *Paranthodon*, *Pawpawsaurus*, *Sarcolestes*, *Stegopelta*, *Struthiosaurus austriacus*, *Thyreosaurus* and *Baiyinosaurus*.

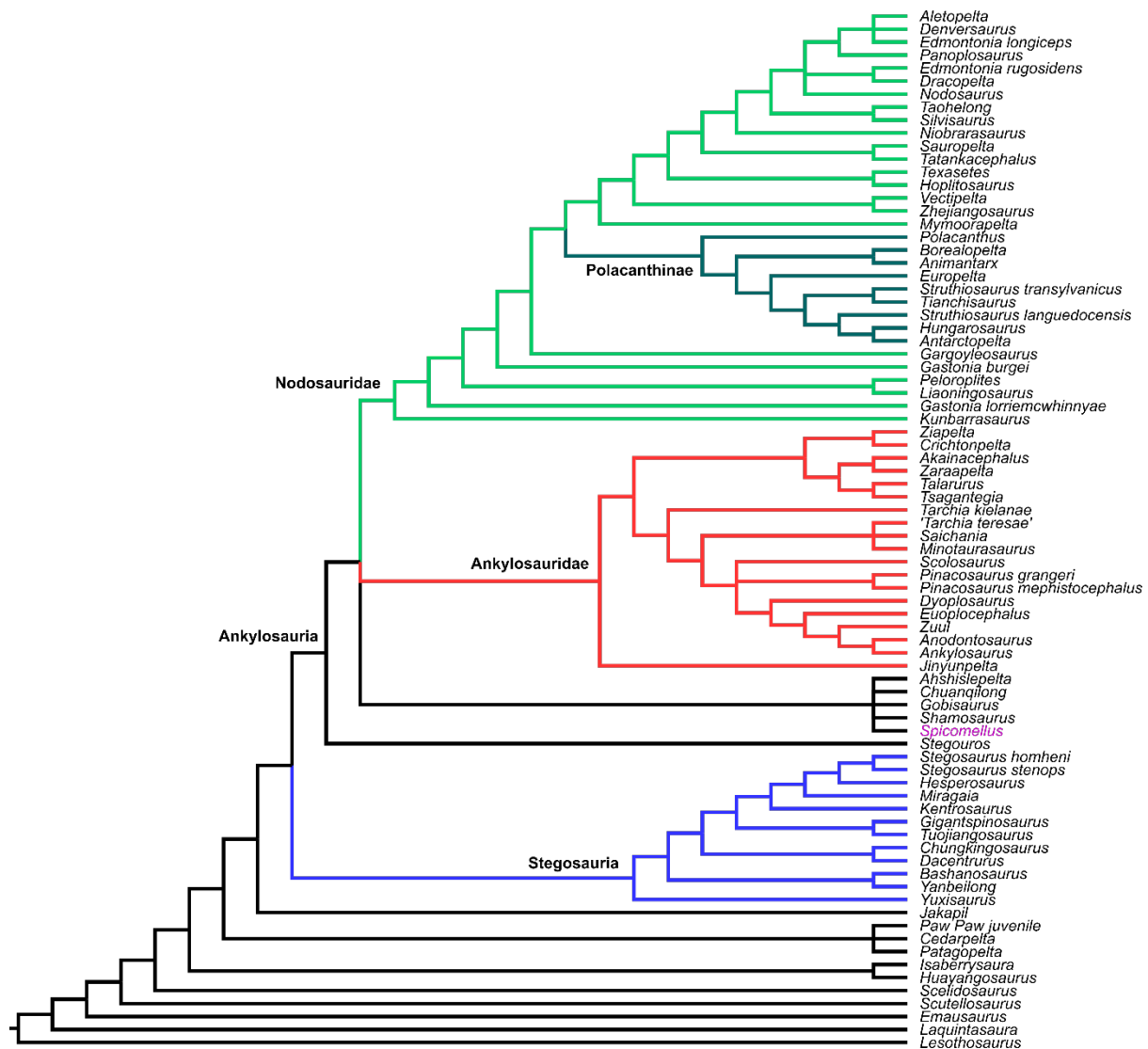


Fig. S12. Strict reduced consensus tree derived from *a posteriori* deletion of 19 taxa. Major clades are coloured and labelled for ease of viewing. In this phylogenetic scheme, clade names follow Madzia et al. (2021). Stegosauria are shown in blue, Ankylosauridae in red and Nodosauridae in green. Polacanthinae are found within Nodosaurinae and are highlighted in dark green. *Spicomellus* is highlighted in pink.

Spicomellus is found in a clade containing *Shamosaurus*, *Gobisaurus*, *Chuanqilong* and *Ahshislepelta*, which forms a polytomy outside with Ankylosauridae and Nodosauridae. *Shamosaurus* and *Gobisaurus* are usually resolved as ankylosaurids (Thompson et al. 2012; Arbour & Currie 2016). The unusual Argentinian taxon *Stegouros* is found as the most basal ankylosaur, outside of the Ankylosauridae-Nodosauridae split. *Jakapil* is resolved as a basal thyreophoran, as is *Patagopelta*. The other Southern Hemisphere ankylosaurs, *Antarctopelta* and *Kunbarrasaurus*, are found within Nodosauridae. A simplified, time-calibrated PCR tree is presented in Fig. 3 of the main manuscript.

The following characters support the clade

(*Spicomellus*+*Shamosaurus*+*Gobisaurus*+*Chuanqilong*+*Ahshislapelta*):

- 9 (1): Dorsal surface of the antorbital region of the skull anteroposteriorly arched. Convergent in all ankylosaurids except *Jinyunpelta*, and also in the nodosaurids *Gastonia burgei*, *Panoplosaurus* and *Edmontonia*. Unknown in *Spicomellus*.
- 15 (1): Deep longitudinal furrow on the anterodorsal margin of the premaxilla in dorsal view. Unknown in *Spicomellus*.
- 70 (0): Dorsoventral height of the pterygoid process of the quadrate greater than 0.5 times the height of the entire quadrate. Convergent in *Ankylosaurus* and *Gastonia burgei*.
- 190 (1): Coracoid glenoid length is 0.5 to 1 times as long as scapula glenoid length. Convergent in some polacanthines, *Texastes*, *Scelidosaurus*, *Tuojiangosaurus* and *Stegosaurus stenops*.
- 297 (1): Squamosal/postorbital horn with a continuous keel with supraorbitals. Unknown in *Spicomellus*; convergent in some ankylosaurids, *Tarchia*, and *Talarurus*.

Extended implied weights analysis

The 19 unstable taxa identified through IterPCR (see above) were deactivated, and the analysis run again but using extended implied weighting with a concavity constant of 3. The strict consensus of three most parsimonious trees (MPTs), the EIW tree, is shown in Fig. S13.



Fig S13. Strict consensus of three MPTs found in the extended implied weighted analysis. Major clades are coloured for ease of viewing. Here, clade names follow Raven et al. (2023). Stegosauria are shown in blue, Ankylosauridae in red, Polacanthidae in green, and Panoplosauridae in purple. Values below nodes are bootstrap values, carried out using 1000 pseudoreplicates. Only those clades with a bootstrap support of >50% are shown. *Spicomellus* is highlighted in pink.

Spicomellus is found as an early-diverging ankylosaurid in a clade with *Shamosaurus* and *Gobisaurus*. *Jinyunpelta* bears a tail club and is generally considered to be a basal ankylosaurine (ankylosaurs more closely related to *Ankylosaurus* than *Shamosaurus*; Raven et al. 2023), but here it is found as an early-diverging ankylosaurid. If this phylogenetic position is correct, it would suggest that tail clubs were basal for ankylosaurids. However, relationships are weakly supported in this analysis and require further testing with future discoveries. As in Raven et al. (2023), which also used extended implied weighting, Nodosauridae is not resolved.

In this analysis, *Jakapil* is found within Stegosauria, *Patagopelta* is an early-diverging ankylosaur in a clade with *Struthiosaurus languedocensis* and *Animantarx* and *Stegouros* also falls outside of the major clades but is sister taxon to *Europelta*. *Kunbarrasaurus* and *Antarctopelta* are polacanthids.

Characters that unite the clade containing the common ancestor of *Spicomellus* and *Ankylosaurus* are as follows:

- 2 (1): closure of lateral temporal fenestrae. Unknown in most ankylosaurids including *Spicomellus*; convergent in *Kunbarrasaurus*.
- 7 (0): Transverse width of posterior margin of skull greater than the width across the orbits. Convergent in *Scelidosaurus*, *Animantarx*, *Cedarpelta*, *Dracopelta* and *Huayangosaurus*; unknown in *Spicomellus*
- 96 (0): jaw articulation posterior to adductor fossa. Convergent in basal thyreophorans and stegosaurs; unknown in *Spicomellus*.
- 160 (0): No groove on the ventral surface of the sacral vertebrae. Convergent in basal thyreophorans and stegosaurs, as well as *Peloroplites*, *Zhejiangosaurus*, and *Silvisaurus*.
- 180 (1): Postzygapophyses on posterior caudal vertebrae extend over more than half the length of the adjacent centrum. Convergent in *Liaoningosaurus*.
- 185 (0): Interlocking neural arches on tail club vertebrae have a 'V' shaped divergence. Unknown in *Spicomellus*.
- 237 (0): postpubis shorter than acetabulum. Convergent in *Gargoyleosaurus*; unknown in most ankylosaurs.
- 302 (1): Jugal/quadratojugal horn has a distinct neck at its base. Convergent in *Silvisaurus*; unknown in *Spicomellus*.
- 304 (1): Jugal/quadratojugal horn is equal to or longer than the squamosal horn. Unknown in *Spicomellus*.

A single character unites *Spicomellus* with *Gobisaurus* and *Shamosaurus*:

- 70 (0): Dorsoventral height of the pterygoid process of the quadrate greater than 0.5 times the height of the entire quadrate. Convergent in *Ankylosaurus* and *Gastonia burgei*.

4. Time calibration data and code

Taxon ages

Paste the below into a text file and save as 'Ages.txt'

Taxon	FAD	LAD	
Lesothosaurus	201.4	182.2	#Hettangian-Pliensbachian, upper Elliot Formation, Baron et al 2017
Ahshislepelta	75.0	73.8	#upper Campanian, Hunter Wash Member of Kirtland Fm, Arbour and Currie 2016, Fowler 2017
Akainacephalus	76.0	75.5	#upper Campanian, middle unit of Kaiparowits Formation, Wiersma and Irmis 2018
Aletopelta	80.0	72.2	#upper Campanian, Point Loma Formation, Arbour and Currie 2016
Animantax	96.0	94.0	#Cenomanian, Mussentuchit Member of Cedar Mountain Formation, Carpenter et al 1999, Tucker et al 2020
Ankylosaurus	70.6	66.0	#late Maastrichtian, Hell Creek Formation, Arbour and Currie 2016
Anodontosaurus	72.5	71.5	#upper Campanian to lower Maastrichtian, Horsethief Member of Horseshoe Canyon Formation, A&C 2016, Fowler 2017
Antarctopelta	80.0	70.6	#upper Campanian-lower Maastrichtian, Snow Hill Island Formation, Arbour and Currie 2016
Borealopelta	121.4	113.2	#Aptian, Wabiskaw Member, Clearwater Formation, Brown et al 2017
Liaoningosaurus	123.2	122.5	#Barremian, Dawangzhangzi Bed of Yixian Formation, Arbour and Currie 2016; Chang et al 2017
Cedarpelta	96.0	94.0	#Cenomanian, Mussentuchit Member of Cedar Mountain Formation, Arbour and Currie 2016, Tucker et al 2020
Chuanqilong	121.4	113.2	#Aptian, Jiufotang Formation, Arbour and Currie 2016
Chungkingosaurus	154.8	143.1	#Kimmeridgian-Tithonian, Upper Shaximiao Formation, Maidment et al 2008, Wang et al 2018
Crichtonpelta	113.2	100.5	#Albian, Sunjiawan Formation, Arbour and Currie 2016, Jiang and Sha 2006
Dacentrurus	154.8	149.2	#Kimmeridgian, Kimmeridge Clay, Maidment et al 2008
Denversaurus	72.2	66.0	#Maastrichtian, Hell Creek Formation, Burns 2015
Dracopelta	154.8	143.1	#Kimmeridgian to Tithonian, ?Farta Pao Formation, Galton 1980
Dyoplosaurus	77.0	75.5	#Campanian, lower part of Dinosaur Park Formation, Arbour and Currie 2016, Fowler 2017
Edmontonia_longiceps	75.5	66.9	#Campanian-Maastrichtian, Horseshoe Canyon Fm, Burns 2015, Fowler 2017

Edmontonia_rugosidens	83.6	72.2	#Campanian, Two Medicine Formation, Burns 2015
Emausaurus	182.7	182.0	#Toarcian, Tenuicostatum of Ciechocinek Formation,
Haubold 1990, Barth et al	2018		
Euoplocephalus	77.0	75.5	#Campanian, lower part of Dinosaur Park Formation,
Arbour and Currie 2016, Fowler 2017			
Europelta	112.0	109.0	#early Albian, Escucha Formation, Kirkland et al 2013
Gargoyleosaurus	154.8	143.1	#Kimmeridgian to Tithonian, upper part of
Morrison Fm, Kilbourne and Carpenter 2005			
Gastonia_burgei	139.0	134.6	#Berriasian, Yellow Cat Member of Cedar Mountain
Formation, Kinneer et al 2016, Joeckel et al 2023			
Gastonia_lorriemcwhinnyae	115.0	109.9	#Aptian-Albian, Ruby Ranch Member of Cedar
Mountain Formation, Kinneer et al 2016, Tucker et al 2020			
Gigantospinosaurus	154.8	143.1	#Kimmeridgian-Tithonian Upper Shaximiao Formation,
Maidment et al 2008, Wang et al 2018			
Gobisaurus	93.9	89.8	#Turonian, Ulansuhai Formation, Arbour and Currie
2016			
Hesperosaurus	154.8	143.1	#Kimmeridgian-Tithonian, Morrison Fm, Maidment et
al 2008			
Hoplitosaurus	125.8	121.4	#Barremian, Calico Canyon of Lakota Formation,
Lucas 1901			
Huayangosaurus	161.5	154.8	#Oxfordian, Lower Shaximiao Formation,
Maidment et al 2008, Wang et al 2018			
Hungarosaurus	85.7	83.6	#Santonian, Csehbanya Formation, Osi 2005
Isaberrysaura	170.3	168.3	#early Bajocian, Los Molles Formation, Salgado et al
2017			
Jinyunpelta	113.2	93.9	#Albian-Cenomanian, Liangtoutang Formation, Zheng
et al 2018			
Kentrosaurus	154.8	143.1	#upper Kimmeridgian - Tithonian, Middle Reptile Bed
of Tendaguru Beds, Maidment et al 2008			
Kunbarrasaurus	105.3	99.6	#Upper Albian-lower Cenomanian, Allaru Mudstone,
Leahey et al 2015			
Laquintasaura	201.4	199.5	#Hettangian, La Quinta Formation, Barrett et al 2014
Minotaurasaurus	83.6	72.2	#provenence unknown? or same as T.
kielane? mid to upper Campanian, Baryuungoyot Formation, Arbour & Currie 2016			
Miragaia	154.8	143.1	#upper Kimmeridgian-lower Tithonian, Miragaia Unit of
Lourinha Formation, Mateus et al 2009			
Mymoorapelta	154.8	143.1	#Kimmeridgian-Tithonian, Brushy Basin Member of
Morrison Fm, Kirkland and Carpenter 1994			
Niobrarasaurus	89.3	83.5	#Upper Coniacian-lower Campanian, Smoky Hill
Chalk Member of Niobrara Chalk Formation, Carpenter et al 1995			
Nodosaurus	100.5	93.9	#Cenomanian, Frontier Formation, Marsh 1889

Panoplosaurus	77.0	75.5		#Campanian, lower part of Dinosaur Park Formation, Burns 2015, Fowler 2017
Paw_Paw_juvenile	105.3	100.5		#upper Albian, Paw Paw Formation, Jacobs 1994
Peloroplites	96.0	94.0		#Cenomanian, Mussentuchit Member of Cedar Mountain Formation, Carpenter et al 1999, Tucker et al 2020
Pinacosaurus_grangeri	83.6	72.2		#late Campanian, Bayn Dzak Member, Djadokhta Formation, Arbour and Currie 2016
Pinacosaurus_mephistocephalus		83.6	72.2	#late Campanian, Bayan Mandahu Formation, Arbour and Currie 2016
Polacanthus	125.8	121.4		#Barremian, Wessex Formation, Raven et al 2020
Vectipelta	125.8	121.4		#Barremian, Wessex Formation, Raven et al 2020
Saichania	83.6	72.2		#mid to upper Campanian, Barun Goyot Formation, Arbour and Currie 2016
Sauropelta	113.2	100.5		#upper Aptian to lower Albian, Cloverly Formation, Arbour and Currie 2016
Scelidosaurus	199.3	184.2		#Sinemurian-Pliensbachian, Charmouth Mudstone Formation, Norman 2020
Scolosaurus	77.0	75.5		#Campanian, lower part of Dinosaur Park Formation, Arbour and Currie 2016, Fowler 2017
Scutellosaurus	199.6	174.7		#Sinemurian-Toarcian, Kayenta Formation, Breeden and Rowe 2020
Shamosaurus	121.4	100.5		#Aptian-Albian, Zuunbayan Formation, Arbour and Currie 2016
Silvisaurus	113.2	100.5		#Albian, Terra Cotta Clay Member of Dakota Formation, Eaton 1960, Wang and Dilcher 2018
Stegosaurus_homheni	137.1	100.5		#Valanginian-Albian, Lianmuging Formation, Maidment et al 2008
Stegosaurus_stenops	154.8	143.1		#Kimmerdigian-Tithonian, Morrison Fm, Maidment et al 2008
Struthiosaurus_languedocensis	83.6	72.2		#Campanian, L'Olivet Quarry, Garcia and Pereda Suberbiola 2003
Struthiosaurus_transylvanicus	72.2	66.0		#Maastrichtian, Hateg Basin, Osi 2015
Talarurus	100.5	83.6		#Cenomanian-latest Santonian, Bayanshiree Formation, Arbour and Currie 2016
Taohelong	145.0	100.5		#Valanginian-Albian, Hekou Group, Arbour and Currie 2016, Xi et al 2018
Tarchia_kielanae	83.6	72.2		#mid to upper Campanian, Baryuungoyot Formation, Arbour and Currie 2016
Tarchia_teresae	72.2	66.0		#Maastrichtian, Nemegt Formation, Penkalski and Tumanova 2017
Tatankacephalus	113.2	100.5		#upper Aptian to lower Albian, Cloverly Formation, Arbour and Currie 2016

Texasetes	105.3	100.5	#upper Albian, Paw Paw Formation, Coombs 1995
Tianchisaurus	161.5	149.2	#Oxfordian to Kimmeridgian, Toutunhe Formation, Huang 2019
Tsagantegia	100.5	83.6	#Cenomanian-latest Santonian, Bayanshiree Formation, Arbour and Currie 2016
Tuojiangosaurus	154.8	143.1	#Kimmeridgian-Tithonian Upper Shaximiao Formation, Maidment et al 2008 Wang et al 2018
Zaraapelta	83.6	72.2	#mid to upper Campanian, Baryuungoyot Formation, Arbour and Currie 2016
Zhejiangosaurus	100.5	93.9	#Cenomanian, Chaochuan Formation, Arbour and Currie 2016
Ziapelta	75.0	73.5	#upper Campanian, De-na-zin Member and Hunter Wash Members of Kirtland Formation, Arbour and Currie 2016, Fowler 2017
Zuul	76.2	75.2	#Campanian, Coal Ridge Member of Judith River Formation, Arbour and Evans 2017
Jakapil	97	94	#Upper part of Candeleros Formation; Riguetti et al. 2022a
Yuxisaurus	195	174.7	#Late Sinemurian to Toarchian, Fengjiahe Formation, Yao et al. 2022
Stegouros	74.9	71.7	#Lower section of Dorotea Formation, Soto-Acuna et al. 2021
Yanbeilong	113.2	100.5	#Albian, Lower part of Zuoyun Formation, Jia et al. 2024
Bashanosaurus	170.9	168.2	#Bajocian, Lower Shaximiao Formation, Dai et al 2022
Patagopelta	75	69	#Late Campanian to Early Maastrichtian, Allen Formation, Riguetti et al. 2022b
Spicomellus	168.2	165.3	#Bathonian, El Mers III Formation, Maidment et al. 2021

Tree file

Paste the following into text file and save as “pcr_tree.nex”

#NEXUS

BEGIN TREES;

Title PCR_tree;

LINK Taxa = Taxa;

TRANSLATE

[0] 1 Lesothosaurus,

[1]	2 Acantholipan,
[2]	3 Adratiklit,
[3]	4 Ahshislepelta,
[4]	5 Akainacephalus,
[5]	6 Alcovasaurus,
[6]	7 Aletopelta,
[7]	8 Animantarx,
[8]	9 Ankylosaurus,
[9]	10 Anodontosaurus,
[10]	11 Anoplosaurus,
[11]	12 Antarctopelta,
[12]	13 Borealopelta,
[13]	14 Liaoningosaurus,
[14]	15 Cedarpelta,
[15]	16 Chuanqilong,
[16]	17 Chungkingosaurus,
[17]	18 Crichtonpelta,
[18]	19 Dacentrurus,
[19]	20 Denversaurus,
[20]	21 Dongyangopelta,
[21]	22 Dracopelta,
[22]	23 Dyoplosaurus,
[23]	24 Edmontonia_longiceps,
[24]	25 Edmontonia_rugosidens,
[25]	26 Emausaurus,
[26]	27 Euoplocephalus,
[27]	28 Europelta,
[28]	29 Gargoyleosaurus,
[29]	30 Gastonia_burgei,
[30]	31 Gastonia_lorriemcwhinnyae,
[31]	32 Gigantspinosaurus,
[32]	33 Gobisaurus,
[33]	34 Hesperosaurus,
[34]	35 Hoplitosaurus,

[35]	36 Huayangosaurus,
[36]	37 Hungarosaurus,
[37]	38 Hylaeosaurus,
[38]	39 Invictarx,
[39]	40 Isaberrysaura,
[40]	41 Jiangunosaurus,
[41]	42 Jinyunpelta,
[42]	43 Kentrosaurus,
[43]	44 Kunbarrasaurus,
[44]	45 Laquintasaura,
[45]	46 Loricatosaurus,
[46]	47 Minmi,
[47]	48 Minotaurasaurus,
[48]	49 Miragaia,
[49]	50 Mongolostegus,
[50]	51 Mymoorapelta,
[51]	52 Niobrarasaurus,
[52]	53 Nodocephalosaurus,
[53]	54 Nodosaurus,
[54]	55 Panoplosaurus,
[55]	56 Paranthodon,
[56]	57 Pawpawsaurus,
[57]	58 Paw_Paw_juvenile,
[58]	59 Peloroplites,
[59]	60 Pinacosaurus_grangeri,
[60]	61 Pinacosaurus_mephistocephalus,
[61]	62 Polacanthus,
[62]	63 Vectipelta,
[63]	64 Saichania,
[64]	65 Sarcolestes,
[65]	66 Sauropelta,
[66]	67 Scelidosaurus,
[67]	68 Scolosaurus,
[68]	69 Scutellosaurus,

[69] 70 Shamosaurus,
 [70] 71 Silvisaurus,
 [71] 72 Stegopelta,
 [72] 73 Stegosaurus_homheni,
 [73] 74 Stegosaurus_stenops,
 [74] 75 Struthiosaurus_austriacus,
 [75] 76 Struthiosaurus_languedocensis,
 [76] 77 Struthiosaurus_transylvanicus,
 [77] 78 Talarurus,
 [78] 79 Taohelong,
 [79] 80 Tarchia_kielanae,
 [80] 81 Tarchia_teresae,
 [81] 82 Tatankacephalus,
 [82] 83 Texasetes,
 [83] 84 Tianchisaurus,
 [84] 85 Tsagantegia,
 [85] 86 Tuojiangosaurus,
 [86] 87 Zaraapelta,
 [87] 88 Zhejiangosaurus,
 [88] 89 Ziapelta,
 [89] 90 Zuul,
 [90] 91 Jakapil,
 [91] 92 Yuxisaurus,
 [92] 93 Stegouros,
 [93] 94 Thyreosaurus,
 [94] 95 Yanbeilong,
 [95] 96 Bashanosaurus,
 [96] 97 Patagopelta,
 [97] 98 Spicomellus,
 [98] 99 Baiyinosaurus;

TREE PCR_tree =
 (((((((((((((((((((((7,20,24),55),(25,22),54),(79,71)),52),(66,82)),(83,35)),(63,88)),51),(62,((13,8),(28,((77,84),
 (76,(37,12)))))),29),30),(59,14)),31),44),(((89,18),((5,87),(78,85))),80),((81,64,48),(68,(60,61),(23,(27,(90,
 (10,9)))))),42),(4,16,33,70,98)),93),(((((((73,74),34),49),43),(32,86)),(17,19)),96,95)),92)),91),(58,15,97)),(40,36)),67,69,26),45),1);

END;

Code for time-calibration in using TimePaleoPhy

```
##Time-calibrated ankylosaur phylogeny##
```

```
##Susannah Maidment##
```

```
## 28th March 2025##
```

```
library(tidyverse)
```

```
library(ape)
```

```
library(phytools)
```

```
library(paleotree)
```

```
#Import tree
```

```
tree <- read.nexus("pcr_tree.nex")
```

```
#Check whether importing worked.
```

```
plot(ladderize(tree), cex=0.5)
```

```
#Import the ages table.
```

```
ages <- read.table("Ages.txt", header=T)
```

```
#Check whether importing worked.
```

```
ages
```

```
#make rownames taxon names
```

```
names<-ages$Taxon
```

```
rownames(ages) <- names
```

```
rownames(ages)
```

```
ages<-select(ages, -c(Taxon))
```

```
ages
```

```
#timescale the tree
```

```
calibrated.tree <- timePaleoPhy(tree=tree, timeData=ages, type="mb", vartime=0.5)
```

```
plot(ladderize(calibrated.tree), cex=0.5, font=1)
```

```
axisPhylo()
```

5. References

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