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SUPPLEMENTARY INFORMATION

External and internal structure of ankylosaur (Dinosauria, Ornithischia) osteoderms and
their systematic relevance

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RH: BURNS AND CURRIE—STRUCTURE OF ANKYLOSAUR OSTEODERMS

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APPENDIX S1. Description of characters used in phylogenetic analysis of Ankylosauria and two outgroup taxa, *Scelidosaurus* and *Huayangosaurus*. Cranial and dental characters (1–50) are modified from Hill et al. (2003). Postcranial characters (51–66) are modified from Vickaryous et al. (2004; characters 48–63). Numbering incongruities between this study and Vickaryous et al. (2004) have been noted. We also note similarities in osteoderm characters (64–91) with those of previously published analyses.

- (1) Maximum skull width relative to maximum skull length: <1 (0); >1 (1).
- (2) Highest point of skull roof: posterior to orbits (0); above orbits (1); anterior to orbits (2).
- (3) Premaxillary palate wider than long: absent (0); present (1).
- (4) Premaxillary teeth: present (0); absent (1).
- (5) External nares facing anteriorly: absent (0); present (1).
- (6) Accessory openings in the narial region: absent (0); present (1).
- (7) Fused osteoderms present on premaxilla: absent (0); present (1).
- (8) Anterior edge of premaxilla with broad ventrally concave notch in anterior view
absent (0); present (1).
- (9) Ventral margin of premaxilla in lateral view: flat (0); concave (1); convex, resulting
in a sharp premaxillary beak (2).
- (10) Continuous edge formed by the premaxillary beak and maxillary tooth rows: present
(0); absent (1).
- (11) Anterior-most maxillary teeth obscured in lateral view by processes of the
premaxilla: absent (0); present (1).

- (12) Maxillary tooth rows deeply inset from lateral edge of skull: absent (0); present (1).
- (13) Maxillary tooth rows deeply concave laterally, outlining an hourglass-shape: absent (0); present (1).
- (14) Nasal septum dividing the respiratory passage into two separate bony canals: absent (0); present (1).
- (15) Closure of antorbital fenestra: absent (0); present (1).
- (16) Accessory antorbital ossification(s) completely separating orbit and antorbital cavity: absent (0); present (1).
- (17) Median palatal keel composed of the vomer and pterygoid: absent or weakly developed (0); extending ventrally to the level of the maxillary tooth crowns (1).
- (18) Extension of the vomerine septum: incomplete (0); extending to palatal shelves (1); extending to skull roof (2).
- (19) Paired premaxillary, maxillary, and nasal sinuses: absent (0); present (1).
- (20) Secondary palate: incomplete or absent (0); present and flat, reaching as far as the second or third maxillary tooth (1); present and composed of two palatal shelves, describing 'S'-shaped respiratory route (2).
- (21) Pterygoid foramen: absent (0); present (1).
- (22) Space between palate and braincase (interpterygoid vacuity): open (0); closed (1).
- (23) Dorsoventrally narrow pterygoids ramus of the quadrate: absent (0); present (1).
- (24) Quadrate shaft angled strongly rostroventrally: absent (0); present (1).
- (25) Quadrate excavated anteriorly: absent (0); present (1).
- (26) Quadrate fused to paroccipital process: absent (0); present (1).
- (27) Paroccipital process projecting posterolaterally: absent (0); present (1).

- (28) Occiput rectangular and wider than high: absent (0); present (1).
- (29) Hemispherical occipital condyle: absent (0); present (1).
- (30) Occipital condyle formed exclusively by the basioccipital: absent (0); present (1).
- (31) Occipital condyle set off from the ventral braincase by a distinct neck: absent (0); present (1).
- (32) Occipital condyle angled ventrally from place of maxillary tooth rows: absent (0); present (1).
- (33) Occipital condyle and paroccipital processes obscured in dorsal view by overhanging skull roof: absent (0); present (1).
- (34) Closure of supratemporal fenestra: absent (0); present (1).
- (35) Lateral temporal fenestra: open (0); closed (1).
- (36) Obliteration of cranial sutures in adults, involving fusion and dermal sculpturing of the outer surfaces of most of the dermal skull roof: absent (0); present (1).
- (37) Large subcircular dermal ossification covering most of the skull roof between the orbits: absent (0); present (1).
- (38) Anteroposteriorly narrow dermal ossification along the posterior border of the skull roof: absent (0); present (1).
- (39) Pair of large, sub-rectangular osteoderms at posterior edge of skull roof: absent (0); present (1).
- (40) Raised, polyhedral dermal ossifications on skull roof: absent (0); present (1).
- (41) Secondary dermal ossification, projecting ventrolaterally from the quadratojugal region: absent (0); present and rounded (1); present and wedge-shaped (2).

- (42) Secondary dermal ossification, projecting posterolaterally from the squamosal region: absent (0); present as weakly developed pyramid (1); present as prominent, wedge-shaped or pyramidal structure (2); present as narrow, elongated spines (3).
- (43) Median dermal ossification overlying dorsum of nasal region: absent (0); present (1).
- (44) Two pairs of dermal ossifications bordering the external nares: absent (0); present (1).
- (45) Tooth crown with cingulum: absent (0); present (1).
- (46) Closure of external mandibular fenestra: absent (0); present (1).
- (47) Coronoid process low and rounded, projecting only slightly above the level of the dentary tooth row: absent (0); present (1).
- (48) Elongate osteoderm fused to the ventrolateral side of the mandible in adults: absent (0); present (1).
- (49) Sinuous ventral margin of mandible, which parallels the sinuosity of the dorsal margin in lateral view: absent (0); present (1).
- (50) Predentary ventral process short (relative to other thyreophorans): absent (0); present (1).
- (51) Atlas and axis fused to form a syncervical: absent (0); present (1). Vickaryous et al. (2004:ch.46).
- (52) One or more postaxial cervical centra in profile: anterior and posterior ends parallel and aligned (0); anterior and posterior ends parallel, anterior end dorsal to posterior end (1); anterior and posterior ends parallel, posterior end dorsal to anterior end (2). Vickaryous et al. (2004:ch.47).

(53) Fusion of dorsal ribs to centra: absent (0); present (1). Vickaryous et al.

(2004:ch.48).

(54) Acromion: absent (0); present, crest at anterior margin (1); present, blade-like flange perpendicular to long axis (2); present, knoblike process (3). Vickaryous et al.

(2004:ch.52).

(55) Ventral border of coracoid in profile: rounded (0); straight (1). Vickaryous et al.

(2004:ch.53).

(56) Length of deltopectoral crest relative to humerus: <50% (0); approximately equal to or >50% (1). Vickaryous et al. (2004:ch.54).

(57) Distal margin of ilium: oriented vertically (0); forms a horizontal shelf dorsal to the acetabulum (1); partially encircles the acetabulum laterally (2). Vickaryous et al.

(2004:ch.55).

(58) Acetabulum: open (0); closed (1). Vickaryous et al. (2004:ch.56).

(59) Shaft of ischium: little to no curvature (0); pronounced curvature (1). Vickaryous et al. (2004:ch.57).

(60) Pubis contribution to acetabulum: one-quarter or more (0); virtually excluded (1).

Vickaryous et al. (2004:ch.58).

(61) Ossified tendons in region of tail: absent (0); present (1). Vickaryous et al.

(2004:ch.59).

(62) Bilateral sternal element contact: not fused (0); fused (1). Vickaryous et al.

(2004:ch.60).

(63) Synsacrum of coossified dorsal, sacral and caudal vertebrae: absent (0); present (1).

Vickaryous et al. (2004:ch.61).

- (64) Cranial osteoderms: absent (0); present (1). Estes et al. (1988:ch.128); Hill (2005:ch.302).
- (65) Gular osteoderms: absent (0); present (1). Hill (2005:305).
- (66) Osteoderms on proximal limb segments: absent (0); present (1). deBraga and Rieppel (1997:ch.167); Lee (1996:ch.127); Heckert and Lucas (1999:ch.60); Hill (2005:ch.306).
- (67) Caudal osteoderms: absent (0); present on dorsal or dorsolateral surfaces of tail only (1); completely surrounding tail (2). Hill (2005:ch.307).
- (68) Dimensions of largest osteoderm: smaller than a dorsal centrum (0); equal to or larger than a dorsal centrum (1). Lee (1996:ch.125); Hill (2005:ch.309).
- (69) Maximum number of contiguous osteoderms per transverse row: two (0); four (1); six (2); eight (3); ten or more (4). Modified from Brochu (1997:ch.37); Hill (2005:ch.313).
- (70) External neurovascular grooves on osteoderms: absent or faint (0); present and random (1); present and parallel or radiate (2). Hill (2005:ch.316).
- (71) Keel height: shorter than width of osteoderm (0); taller than width of osteoderm (1). Hill (2005:ch.320).
- (72) Basal surface of osteoderms: flat or gently concave (0); deeply excavated (1); strongly convex (2). Carpenter (2001:ch.34); Hill (2005:ch.331).
- (73) Distal thoracic osteodermal spines: absent (0); present as triangular, dorsoventrally flattened elements (1), present as solid, conical spines (2). Carpenter (2001:ch.36); Hill (2005:ch.336).

(74) Margin of osteoderms: tapering or rounded (0); crenulated (1); squared-off with sutural boundary (2). Hill (2005:ch.340).

(75) Triangular caudal osteoderms with excavated basal surfaces: absent (0); present (1). Hill (2005:ch.342).

(76) Keels of caudal osteoderms taller than those of thoracic osteoderms: (0) absent (keels equal in external-basal height), present (1). Hill (2005:ch.343).

(77) Multiple parasagittal rows of osteoderms in cervical region: absent (0); present, fused together (1); present, fused to **basal bony band** (2); present, unfused (3). Vickaryous et al. (2004:ch.49).

(78) Parasagittal rows of fused osteoderms in cervical region: absent (0), two present (1), three present (2). Carpenter (2001:ch.35).

(79) Pelvic osteoderms: not coossified (0); coossified into a mosaic of small osteoderms surrounding several larger osteoderms (1); coossified into a solid mosaic of polygonal osteoderms (2).

(80) External cortical histology of skeletally mature osteoderms: lamellar bone (0); **ISFB** (1).

(81) Haversian bone: absent in core of skeletally mature osteoderms (0); may be present in in core of skeletally mature osteoderms (1).

(82) Basal **cortex of** skeletally mature osteoderms: **present (0); absent or poorly developed (1).**

(83) External rugosity profile of skeletally mature osteoderms: hummocky (0); pitted (1); smooth (2); projecting (3).

(84) External neurovascular grooves on skeletally mature osteoderms: absent (0); present (1).

(85) Distal spines on cervical half ring: absent (0); present, projecting dorsoposteriorly (1); present, projecting anteriorly (2). Carpenter (2001:ch.83).

(86) Osteoderms form posterior cranial horns: absent (0); present (1). Carpenter (2001:ch.59).

(87) Median osteoderms of the cervical half rings: absent (0); present, flat with a low keel (1); present, tall and conical (2).

(88) Anteroposteriorly elongate osteoderm fused to the ventrolateral side of the mandible in adults: absent (0); present (1). Hill et al. (2003:ch.48).

(89) Multiple parasagittal rows of post-cervical osteoderms: absent (0); present (1). Vickaryous et al. (2004:ch.50).

(90) Specialized tail club knob osteoderms: absent (0); present (1). Vickaryous et al. (2004:ch.51).

(91) **Structrural** fiber arrangement in osteoderms: **absent (0)**; reaches orthoganoal arrangment near osteoderm surfaces (**1**); diffuse throughout (**2**); highly ordered sets of orthogonally arranged fibers in the superficial cortex (**3**).

APPENDIX S2. Description of characters used in phylogenetic analysis of Ankylosauria and outgroup taxon *Scelidosaurus*. Cranial and postcranial characters (1–38) are modified from Kirkland (1998) with postcranial osteoderm characters from that study removed. Similarities in osteoderm characters (39–66) with those of other analyses are noted after their descriptions.

- (1) Skull roof wider at posterior edge of skull: absent (0); present (1).
- (2) Skull wider than long: absent (0); present (1).
- (3) Skull highest at a point anterodorsal to orbits: absent (0); present (1).
- (4) Premaxillary scoop wider than long: absent (0); present (1).
- (5) Premaxillary (= tomial) notch: absent (0); present (1).
- (6) Margin of premaxilla continuous with lateral margin of maxilla: absent (0); present (1).
- (7) False palate made up by extension of maxilla: absent (0); small (1); large (2).
- (8) Palate wide: absent (0); present (1).
- (9) Hourglass-shaped buccal emargination: absent (0); present (1).
- (10) Nasal openings placed posteriorly: absent (0); present (1).
- (11) Nasal openings directed anteriorly: absent (0); present (1).
- (12) Respiratory passages complex: absent (0); present (1).
- (13) Lower temporal fenestra not visible in lateral view: absent (0); present (1).
- (14) Quadrate angled anteroventrally: absent (0); present (1).
- (15) Occipital condyle at high angle to frontal plane of skull: absent (0); present (1).
- (16) Occipital condyle with neck: absent (0); present (1).

- (17) Basioccipital makes up entire spherical occipital condyle: absent (0); present (1).
- (18) Paraoccipital process rotated into frontal plane: absent (0); present (1).
- (19) Basispterygoid process of the basisphenoid: absent (0); shortened (1); secondarily elongate (2).
- (20) Premaxillary teeth: present (0); absent (1);
- (21) Cingula on teeth: absent (0); present (1).
- (22) Fused osteoderm(s) on premaxilla: absent (0); present (1).
- (23) Wedge-shaped posterolaterally projecting osteoderm on jugal or quadratojugal: absent (0); small (1); large (2).
- (24) Wedge-shaped posterolaterally projecting osteoderm on squamosal: absent (0); small (1); large (2).
- (25) Paraoccipital process in dorsal view: visible (0); hidden (1).
- (26) Median nasal osteoderm: absent (0); present (1).
- (27) Median osteoderm on skull roof: absent (0); present (1).
- (28) Anteroposteriorly narrow osteoderm along posterior edge of skull: absent (0); present (1).
- (29) Groove across back of skull: absent (0); present (1).
- (30) Narial openings ringed by osteoderms: absent (0); present (1).
- (31) Thick, raised osteoderms on skull roof: absent (0); present (1).
- (32) Acromion: absent (0); present, crest at anterior margin of scapula (1); present, blade-like flange perpendicular to long axis of scapula (2). Kirkland (1998:ch.32 and 33).
- (33) Anteroposteriorly elongate coracoids: absent (0); present (1). Kirkland (1998:ch.34).

- (34) Deltopectoral crest large, extending more than halfway down the shaft of the humerus: absent (0); present (1). Kirkland (1998:ch.35).
- (35) Fused anterior trochanter: absent (0); present (1). Kirkland (1998:ch.36).
- (36) Ischium ventrally flexed near midlength: absent (0); present (1). Kirkland (1998:ch.37).
- (37) Iliac directed transversely: absent (0); present (1). Kirkland (1998:ch.45).
- (38) Pubis reduced: absent (0); present (1). Kirkland (1998:ch.46).
- (39) Cranial osteoderms: absent (0); present (1). Estes et al. (1988:ch.128); Hill (2005:ch.302).
- (40) Gular osteoderms: absent (0); present (1). Hill (2005:ch.305).
- (41) Osteoderms on proximal limb segments: absent (0); present (1). deBraga and Rieppel (1997:ch.167); Lee (1996:ch.127); Heckert and Lucas (1999:ch.60); Hill (2005:ch.306).
- (42) Caudal osteoderms: absent (0); present on dorsal or dorsolateral surfaces of tail only (1); completely surrounding tail (2). Hill (2005:ch.307).
- (43) Dimensions of largest osteoderm: smaller than a dorsal centrum (0); equal to or larger than a dorsal centrum (1). Lee (1996:ch.125); Hill (2005:ch.309).
- (44) Maximum number of contiguous osteoderms per transverse row: two (0); four (1); six (2); eight (3); ten or more (4). Brochu (1997:ch.37); Hill (2005:ch.313).
- (45) External neurovascular grooves on osteoderms: absent or faint (0); present and random (1); present and parallel or radiate (2). Hill (2005:ch.316).
- (46) Keel height: shorter than width of osteoderm (0); taller than width of osteoderm (1). Hill (2005:ch.320).

- (47) Basal surface of osteoderms: flat or gently concave (0); deeply excavated (1); strongly convex (2). Carpenter (2001:ch.34); Hill (2005:ch.331).
- (48) Distal thoracic osteodermal spines: absent (0); present as triangular, dorsoventrally flattened elements (1), present as solid, conical spines (2). Carpenter (2001:ch.36); Hill (2005:ch.336).
- (49) Margin of osteoderms: tapering or rounded (0); crenulated (1); squared-off with sutural boundary (2). Hill (2005:ch.340).
- (50) Triangular caudal osteoderms with excavated basal surfaces: absent (0); present (1). Hill (2005:ch.342).
- (51) Keels of caudal osteoderms taller than those of thoracic osteoderms: (0) absent (keels equal in external-basal height), present (1). Hill (2005:ch.343).
- (52) Multiple parasagittal rows of osteoderms in cervical region: absent (0); present, fused together (1); present, fused to half ring (2); present, unfused (3). Vickaryous et al. (2004:ch.49).
- (53) Parasagittal rows of fused osteoderms in cervical region: absent (0), two present (1), three present (2). Carpenter (2001:ch.35).
- (54) Pelvic osteoderms: not coossified (0); coossified into a mosaic of small osteoderms surrounding several larger osteoderms (1); coossified into a solid mosaic of polygonal osteoderms (2).
- (55) External cortical histology of skeletally mature osteoderms: lamellar bone (0); **ISFB** (1).
- (56) Haversian bone: absent in core of skeletally mature osteoderms (0); may be present in in core of skeletally mature osteoderms (1).

- (57) Basal **cortex of** skeletally mature osteoderms: present (0); absent or poorly developed (1).
- (58) External rugosity profile of skeletally mature osteoderms: hummocky (0); pitted (1); smooth (2); projecting (3).
- (59) External neurovascular grooves on skeletally mature osteoderms: absent (0); present (1).
- (60) Distal spines on cervical half ring: absent (0); present, projecting dorsoposteriorly (1); present, projecting anteriorly (2). Carpenter (2001:ch.83).
- (61) Osteoderms form posterior cranial horns: absent (0); present (1). Carpenter (2001:ch.59).
- (62) Median osteoderms of the cervical half rings: absent (0); present, flat with a low keel (1); present, tall and conical (2).
- (63) Anteroposteriorly elongate osteoderm fused to the ventrolateral side of the mandible in adults: absent (0); present (1). Hill et al. (2003:ch.48).
- (64) Multiple parasagittal rows of post-cervical osteoderms: absent (0); present (1). Vickaryous et al. (2004:ch.50).
- (65) Specialized tail club knob osteoderms: absent (0); present (1). Vickaryous et al. (2004:ch.51).
- (66) **Structrural** fiber arrangement in osteoderms: **absent (0)**; reaches orthoganoal arrangment near osteoderm surfaces (**1**); diffuse throughout (**2**); highly ordered sets of orthoganally arranged fibers in the superficial cortex (**3**).

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