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Supporting Online Material for

A Basal Dromaeosaurid and Size Evolution Preceding Avian Flight

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A BASAL DROMAEOSAURID AND SIZE EVOLUTION PRECEDING AVIAN FLIGHT

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1. CHARACTER LIST

The character list below is the most recent version of the Theropod Working Group (TWiG) matrix. The character list is a modification of that used by Turner et al., (2007). Nine characters were added to or modified: 27, 101, 110, 121, 136, 148, 151, 156, and 225. An electronic version of this character set can be downloaded from <https://research.amnh.org/users/turner.html> or <http://research.amnh.org/vertpaleo/norell.html>.

1. Vaned feathers on forelimb symmetric (0) or asymmetric (1). The barbs on opposite sides of the rachis differ in length; in extant birds, the barbs on the leading edge of flight feathers are shorter than those on the trailing edge.

Skull

2. Orbit round in lateral or dorsolateral view (0) or dorsoventrally elongate (1). It is improbable that the eye occupied the entire orbit of those taxa in which it is keyhole shaped.
3. Anterior process of postorbital projects into orbit (0) or does not project into orbit (1).
4. Postorbital in lateral view with straight anterior (frontal) process (0) or frontal process curves anterodorsally and dorsal border of temporal bar is dorsally concave (1).
5. Postorbital bar parallels quadrate, lower temporal fenestra rectangular in shape (0) or jugal and postorbital approach or contact quadratojugal to constrict lower temporal fenestra (1).
6. Otosphenoidal crest vertical on basisphenoid and prootic, and does not border an enlarged pneumatic recess (0) or well developed, crescent shaped, thin crest forms anterior edge of enlarged pneumatic recess (1). This structure forms the anterior, and most distinct, border of the “lateral depression” of the middle ear region (Currie, 1985; Currie and Zhao, 1993) of troodontids and some extant avians.
7. Crista interfenestralis confluent with lateral surface of prootic and opisthotic (0) or distinctly depressed within middle ear opening (1).
8. Subotic recess (pneumatic fossa ventral to fenestra ovalis) absent (0) or present (1)
9. Basisphenoid recess present between basisphenoid and basioccipital (0) or entirely within basisphenoid (1) or absent (2).
10. Posterior opening of basisphenoid recess single (0) or divided into two small, circular foramina by a thin bar of bone (1).
11. Base of cultriform process not highly pneumatized (0) or base of cultriform process (parasphenoid rostrum) expanded and pneumatic (parasphenoid bulla present) (1).
12. Basipterygoid processes ventral or anteroventrally projecting (0) or lateroventrally projecting (1).
13. Basipterygoid processes well developed, extending as a distinct process from the base of the basisphenoid (0) or processes abbreviated or absent (1).
14. Basipterygoid processes solid (0) or processes hollow (1).
15. Basipterygoid recesses on dorsolateral surfaces of basipterygoid processes absent (0) or present (1).
16. Depression for pneumatic recess on prootic absent (0) or present as dorsally open fossa on prootic/opisthotic (1) or present as deep, posterolaterally directed concavity (2). The dorsal tympanic recess referred to here is the depression anterodorsal to the middle ear on the opisthotic, not the recess dorsal to the crista interfenestralis within the middle ear as seen in *Archaeopteryx lithographica*, *Shuvuuia deserti* and Aves.
17. Accessory tympanic recess dorsal to crista interfenestralis absent (0) small pocket present (1) or extensive with indirect pneumatization (2). According to (Witmer, 1990), this structure may be an extension from the caudal tympanic recess, although it has been interpreted as the main part of the caudal tympanic recess by some previous authors.
18. Caudal (posterior) tympanic recess absent (0) present as opening on anterior surface of paroccipital process (1) or extends into opisthotic posterodorsal to fenestra ovalis, confluent with this fenestra (2).
19. Exits of C. N. X-XII flush with surface of exoccipital (0) or cranial nerve exits located together in a bowl-like depression (1).
20. Maxillary process of premaxilla contacts nasal to form posterior border of nares (0) or maxillary process reduced so that maxilla participates broadly in external naris (1) or maxillary process of premaxilla extends posteriorly to separate maxilla from nasal posterior to nares (2).
21. Internarial bar rounded (0) or flat (1).
22. Crenulate margin on buccal edge of premaxilla absent (0) or present (1).

23. Caudal margin of naris farther rostral than (0), or nearly reaching or overlapping (1), the rostral border of the antorbital fossa (Chiappe et al., 1998).
24. Premaxillary symphysis acute, V-shaped (0) or rounded, U-shaped (1).
25. Secondary palate short (0) or long, with extensive palatal shelves on maxilla (1) Redefined by Makovicky et al., 2005.
26. Palatal shelf of maxilla flat (0) or with midline ventral 'tooth-like' projection (1)
27. Pronounced, round accessory antorbital fenestra absent (0) or present, fenestra occupies less than half of the depressed area between the anterior margins of the antorbital fossa and antorbital fenestra (1), or present, fenestra large and takes up most of the space between the anterior margins of the antorbital fenestra and fossa (2). [MODIFIED] A small fenestra, variously termed the accessory antorbital fenestra or maxillary fenestra, penetrates the medial wall of the antorbital fossa anterior to the antorbital fenestra in a variety of coelurosaurs and other theropods.
28. Accessory antorbital fossa situated at rostral border of antorbital fossa (0) or situated posterior to rostral border of fossa (1).
29. Tertiary antorbital fenestra (fenestra promaxillaris) absent (0) or present (1).
30. Narial region apneumatic or poorly pneumatized (0) or with extensive pneumatic fossae, especially along posterodorsal rim of naris (1).
31. Jugal and postorbital contribute equally to postorbital bar (0) or ascending process of jugal reduced and descending process of postorbital ventrally elongate (1).
32. Jugal tall beneath lower temporal fenestra, twice or more as tall dorsoventrally as it is wide transversely (0) or rod-like (1).
33. Jugal pneumatic recess in posteroventral corner of antorbital fossa present (0) or absent (1).
34. Medial jugal foramen present on medial surface ventral to postorbital bar (0) or absent (1).
35. Quadratojugal without horizontal process posterior to ascending process (reversed "L" shape) (0) or with process (i.e., inverted 'T' or 'Y' shape) (1).
36. Jugal and quadratojugal separate (0) or quadratojugal and jugal fused and not distinguishable from one another (1).
37. Supraorbital crests on lacrimal in adult individuals absent (0) or dorsal crest above orbit (1) or lateral expansion anterior and dorsal to orbit (2).
38. Enlarged foramen or foramina opening laterally at the angle of the lacrimal above antorbital fenestra absent (0) or present (1).
39. Lacrimal anterodorsal process absent (inverted 'L' shaped) (0) or lacrimal 'T' shaped in lateral view (1) or anterodorsal process much longer than posterior process (2).
40. Prefrontal large, dorsal exposure similar to that of lacrimal (0) or greatly reduced in size (1) or absent (2).
41. Frontals narrow anteriorly as a wedge between nasals (0) or end abruptly anteriorly, suture with nasal transversely oriented (1).
42. Anterior emargination of supratemporal fossa on frontal straight or slightly curved (0) or strongly sinusoidal and reaching onto postorbital process (1) (Currie, 1995)
43. Frontal postorbital process (dorsal view): smooth transition from orbital margin (0) or sharply demarcated from orbital margin (1) (Currie, 1995)
44. Frontal edge smooth in region of lacrimal suture (0) or edge notched (1) (Currie, 1995).
45. Dorsal surface of parietals flat, lateral ridge borders supratemporal fenestra (0) or parietals dorsally convex with very low sagittal crest along midline (1) or dorsally convex with well developed sagittal crest (2).
46. Parietals separate (0) or fused (1).
47. Descending process of squamosal parallels quadrate shaft (0) or nearly perpendicular to quadrate shaft (1).
48. Descending process of squamosal contacts quadratojugal (0) or does not contact quadratojugal (1).
49. Posterolateral shelf on squamosal overhanging quadrate head absent (0) or present (1) (Currie, 1995).
50. Dorsal process of quadrate single headed (0) or with two distinct heads, a lateral one contacting the squamosal and a medial head contacting the braincase (1).
51. Quadrate vertical (0) or strongly inclined anteroventrally so that distal end lies far forward of proximal end (1).
52. Quadrate solid (0) or hollow, with foramen on posterior surface (1).

53. Lateral border of quadrate shaft straight (0) or with broad, triangular process along lateral edge of shaft contacting squamosal and quadratojugal above an enlarged quadrate foramen (1)(Currie, 1995).
54. Foramen magnum subcircular, slightly wider than tall (0) or oval, taller than wide (1) (Makovicky and Sues, 1998).
55. Occipital condyle without constricted neck (0) or subspherical with constricted neck (1).
56. Paroccipital process elongate and slender, with dorsal and ventral edges nearly parallel (0) or process short, deep with convex distal end (1).
57. Paroccipital process straight, projects laterally or posterolaterally (0) or distal end curves ventrally, pendant (1).
58. Paroccipital process with straight dorsal edge (0) or with dorsal edge twisted rostrally at distal end (1) (Currie 1995).
59. Ectopterygoid with constricted opening into fossa (0) or with open ventral fossa in the main body of the element (1).
60. Dorsal recess on ectopterygoid absent (0) or present (1).
61. Flange of pterygoid well developed (0) or reduced in size or absent (1).
62. Palatine and ectopterygoid separated by pterygoid (0) or contact (1) (Currie 1995).
63. Palatine tetrad, with jugal process (0) or palatine triradiate, jugal process absent (1)(Elzanowski and Wellnhofer, 1996).
64. Suborbital fenestra similar in length to orbit (0) or reduced in size (less than one quarter orbital length) or absent (1)(Clark et al., 1994).

Mandible

65. Symphyseal region of dentary broad and straight, paralleling lateral margin (0) or medially recurved slightly (1) or strongly recurved medially (2).
66. Dentary symphyseal region in line with main part of buccal edge (0) or symphyseal end downturned (1).
67. Mandible without coronoid prominence (0) or with coronoid prominence (1).
68. Posterior end of dentary without posterodorsal process dorsal to mandibular fenestra (0) or with dorsal process above anterior end of mandibular fenestra (1) or with elongate dorsal process extending over most of fenestra (2)
69. Labial face of dentary flat (0) or with lateral ridge and inset tooth row (1)(Russell and Dong, 1993).
70. Dentary subtriangular in lateral view (0) or with subparallel dorsal and ventral edges (1) (Currie 1995).
71. Nutrient foramina on external surface of dentary superficial (0) or lie within deep groove (1)(Currie, 1987).
72. External mandibular fenestra oval (0) or subdivided by a spinous rostral process of the surangular (1).
73. Internal mandibular fenestra small and slit-like (0) or large and rounded (1) (Currie 1995).
74. Foramen in lateral surface of surangular rostral to mandibular articulation, absent (0) or present (1).
75. Splenial not widely exposed on lateral surface of mandible (0) or exposed as a broad triangle between dentary and angular on lateral surface of mandible (1).
76. Coronoid ossification large (0) or only a thin splint (1) or absent (2).
77. Articular without elongate, slender medial, posteromedial, or mediodorsal process from retroarticular process (0) or with process (1).
78. Retroarticular process short, stout (0) or elongate and slender (1).
79. Mandibular articulation surface as long as distal end of quadrate (0) or twice or more as long as quadrate surface, allowing anteroposterior movement of mandible (1).

Dentition

80. Premaxilla toothed (0) or edentulous (1).
81. Second premaxillary tooth approximately equivalent in size to other premaxillary teeth (0) or second tooth markedly larger than third and fourth premaxillary teeth (1) (Currie 1995).
82. Maxilla toothed (0) or edentulous (1).
83. Maxillary and dentary teeth serrated (0) or some without serrations anteriorly (except at base in *S. mongoliensis*) (1) or all without serrations (2).

84. Dentary and maxillary teeth large (0) or small (25-30 in dentary) (1).
85. Dentary teeth in separate alveoli (0) or set in open groove (1) (Currie, 1987).
86. Serration denticles large (0) or small (1)(Farlow et al., 1991)quantify this difference.
87. Serrations simple, denticles convex (0) or distal and often mesial edges of teeth with large, hooked denticles that point toward the tip of the crown (1).
88. Teeth constricted between root and crown (0) or root and crown confluent (1).
89. Dentary teeth evenly spaced (0) or anterior dentary teeth smaller, more numerous, and more closely appressed than those in middle of tooth row (1).
90. Dentaries lack distinct interdental plates (0) or with interdental plates medially between teeth (1). Currie (1995) suggests the interdental plates of dromaeosaurids are present but fused to the medial surface of the dentary, whereas they are absent in troodontids. In the absence of a definitive, non-destructive method for parsing between fusion/ loss we do not recognize this distinction, and code all taxa that lack distinct interdental plates with State 1.
91. In cross section, premaxillary tooth crowns sub-oval to sub-circular (0) or asymmetrical (D-shaped in cross section) with flat lingual surface (1).

Axial skeleton

92. Number of cervical vertebrae: ≤ 10 (0) or 12 or more (1)
93. Axial epiphyses absent or poorly developed, not extending past posterior rim of postzygapophyses (0) or large and posteriorly directed, extend beyond postzygapophyses (1).
94. Axial neural spine flared transversely (0) or compressed mediolaterally (1).
95. Epiphyses of cervical vertebrae placed distally on postzygapophyses, above postzygapophyseal facets (0) or placed proximally, proximal to postzygapophyseal facets (1).
96. Anterior cervical centra level with or shorter than posterior extent of neural arch (0) or centra extending beyond posterior limit of neural arch (1).
97. Carotid process on posterior cervical vertebrae absent (0) or present (1).
98. Anterior cervical centra subcircular or square in anterior view (0) or distinctly wider than high, kidney shaped (1)(Gauthier, 1986).
99. Cervical neural spines anteroposteriorly long (0) or short and centered on neural arch, giving arch an "X" shape in dorsal view (1)(Makovicky and Sues, 1998).
100. Cervical centra with one pair of pneumatic openings (0) or with two pairs of pneumatic openings (1) (Gauthier, 1986).
101. Cervical and anterior trunk vertebrae amphiplatyan (0) or opisthocoelous (1) or heterocoelous (2). [NEW STATE ADDED].
102. Anterior trunk vertebrae without prominent hypapophyses (0) or with large hypapophyses (1)(Gauthier, 1986).
103. Parapophyses of posterior trunk vertebrae flush with neural arch (0) or distinctly projected on pedicels (1) (Norell and Makovicky, 1999).
104. Hyosphene-hypantrum articulations in trunk vertebrae absent (0) or present (1).
105. Zygapophyses of trunk vertebrae abutting one another above neural canal, opposite hyosphenes meet to form lamina (0), or zygapophyses placed lateral to neural canal and separated by groove for interspinuous ligaments, hyosphens separated (1).
106. Cervical vertebrae but not dorsal vertebrae pneumatic (0) or all presacral vertebrae pneumatic (1).
107. Transverse processes of anterior dorsal vertebrae long and thin (0) or short, wide, and only slightly inclined (1).
108. Neural spines of dorsal vertebrae not expanded distally (0) or expanded to form 'spine table' (1).
109. Scars for interspinous ligaments terminate at apex of neural spine in dorsal vertebrae (0) or terminate below apex of neural spine (1).
110. Number of sacral vertebrae: 5 (0) or 6 (1) or 7 (2) or 8 (3) or 9 (4). [NEW STATES ADDED]. Additional states added to reflect diversity within added avialans.
111. Sacral vertebrae with unfused zygapophyses (0) or with fused zygapophyses forming a sinuous ridge in dorsal view (1).
112. Ventral surface of posterior sacral centra gently rounded, convex (0) or ventrally flattened, sometimes with shallow sulcus (1) or centrum strongly constricted transversely, ventral surface keeled (2). Note

that in *Alvarezsaurus calvoi* it is only the fifth sacral that is keeled, unlike other alvarezsaurids (Novas, 1997).

113. Pleurocoels absent on sacral vertebrae (0) or present on anterior sacrals only (1) or present on all sacrals (2).
114. Last sacral centrum with flat posterior articulation surface (0) or convex articulation surface (1).
115. Caudal vertebrae with distinct transition point, from shorter centra with long transverse processes proximally to longer centra with small or no transverse processes distally (0) or vertebrae homogeneous in shape, without transition point (1).
116. Transition point in caudal series begins distal to the 10th caudal (0) or between the 7th and 10th caudal vertebra (1) or proximal to the 7th caudal vertebra (2). A second state for having the transition point proximal to the 6th vertebra was added specifically to test the purported avialan relationships of *Rahonavis*.
117. Anterior caudal centra tall, oval in cross section (0) or with box-like centra in caudals I-V (1) or anterior caudal centra laterally compressed with ventral keel (2). Modified from (Gauthier, 1986).
118. Neural spines of caudal vertebrae simple, undivided (0) or separated into anterior and posterior alae throughout much of caudal sequence (1)(Russell and Dong, 1993).
119. Neural spines on distal caudals form a low ridge (0) or spine absent (1) or midline sulcus in center of neural arch (2)(Russell and Dong, 1993).
120. Prezygapophyses of distal caudal vertebrae between 1/3 and whole centrum length (0) or with extremely long extensions of the prezygapophyses (up to 10 vertebral segments long in some taxa) (1) or strongly reduced as in *Archaeopteryx lithographica* (2).
121. More than 40 caudal vertebrae (0) or 25-40 caudal vertebrae (1) or no more than 25 caudal vertebrae (2) or very short, fused into pygostyle (2). [NEW STATE ADDED]
122. Proximal end of chevrons of proximal caudals short anteroposteriorly, shaft cylindrical (0) or proximal end elongate anteroposteriorly, flattened and plate-like (1).
123. Distal caudal chevrons are simple (0) or anteriorly bifurcate (1) or bifurcate at both ends (2).
124. Shaft of cervical ribs slender and longer than vertebra to which they articulate (0) or broad and shorter than vertebra (1).
125. Ossified uncinat processes absent (0) or present (1).
126. Ossified ventral (sternal) rib segments absent (0) or present (1).
127. Lateral gastral segment shorter than medial one in each arch (0) or distal segment longer than proximal segment (1).
128. Ossified sternal plates separate in adults (0) or fused (1).
129. Sternum without distinct lateral xiphoid process posterior to costal margin (0) or with lateral xiphoid process (1).
130. Anterior edge of sternum grooved for reception of coracoids (0) or sternum without grooves (1).
131. Articular facet of coracoid on sternum (conditions may be determined by the articular facet on coracoid in taxa without ossified sternum): anterolateral or more lateral than anterior (0); almost anterior (1)(Xu et al., 1999).

Pectoral Girdle

132. Hypocleideum on furcula absent (0) or present (1). The hypocleideum is a process extending from the ventral midline of the furcula, and is attached to the sternum by a ligament in extant birds. Although a number of taxa such as advanced tyrannosaurids display a slight midline ridge (Makovicky and Currie, 1998) this is considered state 0 here. Only a full process as occurs in e.g. *Oviraptor* is considered state 1 in our analysis.
133. Acromion margin of scapula continuous with blade (0) or anterior edge laterally everted (1).
134. Posterolateral surface of coracoid ventral to glenoid fossa unexpanded (0) or posterolateral edge of coracoid expanded to form triangular subglenoid fossa bounded laterally by enlarged coracoid tuber (1).
135. Scapula and coracoid separate (0) or fused into scapulacoracoid (1).
136. Coracoid in lateral view subcircular, with shallow ventral blade (0) or subquadrangular with extensive ventral blade (1) or shallow ventral blade with elongate posteroventral process (2) or ‘strut’-like (3). [NEW STATE ADDED]

- 137. Scapula and coracoid form a continuous arc in posterior and anterior views (0) or coracoid inflected medially, scapulocoracoid 'L' shaped in lateral view (1).
- 138. Glenoid fossa faces posteriorly or posterolaterally (0) or laterally (1).
- 139. Scapula longer than humerus (0) or humerus longer than scapula (1).

Forelimb

- 140. Deltopectoral crest large and distinct, proximal end of humerus quadrangular in anterior view (0) or deltopectoral crest less pronounced, forming an arc rather than being quadrangular (1) or deltopectoral crest very weakly developed, proximal end of humerus with rounded edges (2) or deltopectoral crest extremely long and rectangular (3) or proximal end of humerus extremely broad, triangular in anterior view (4).
- 141. Anterior surface of deltopectoral crest smooth (0) or with distinct muscle scar near lateral edge along distal end of crest for insertion of biceps muscle(1).
- 142. Olecranon process weakly developed (0) or distinct and large (1).
- 143. Distal articular surface of ulna flat (0) or convex, semilunate surface (1).
- 144. Proximal surface of ulna a single continuous articular facet (0) or divided into two distinct fossae (one convex, the other concave) separated by a median ridge (1).
- 145. Lateral proximal carpal (ulnare?) quadrangular (0) or triangular in proximal view (1). The homology of the carpal elements of coelurosaurs is unclear (see, e.g., (Padian and Chiappe, 1998)), but the large, triangular lateral element of some taxa most likely corresponds to the lateral proximal carpal of basal tetanurans.
- 146. Two distal carpals in contact with metacarpals, one covering the base of metacarpal I (and perhaps contacting metacarpal II) the other covering the base of metacarpal II (0) or a single distal carpal capping metacarpals I and II (1). In the absence of ontogenetic data, it is not possible to determine whether the single large semilunate carpal of birds and many other coelurosaurs is formed by fusion of the two distal carpals or is, instead, an enlarged distal carpal 1 or 2.
- 147. Distal carpals not fused to metacarpals (0) or fused to metacarpals, forming carpometacarpus (1).
- 148. Semilunate distal carpal well developed, covering all of proximal ends of metacarpals I and II (0) or small, covers about half of base of metacarpals I and II (1) or covers bases of all metacarpals (2) or covers metacarpals II and III (3). In modern birds, the semilunate covers MC II and MC III. [NEW STATE ADDED]
- 149. Metacarpal I half or less than half the length of metacarpal II, and longer proximodistally than wide transversely (0) or subequal in length to metacarpal II (1) or very short and wider transversely than long proximodistally (2).
- 150. Third manual digit present, phalanges present (0) or reduced to no more than metacarpal splint (1).
- 151. Manual unguals strongly curved, with large flexor tubercles (0) or weakly curved with weak flexor tubercles displaced distally from articular end (1) or straight with weak flexor tubercles displaced distally from articular end (2) or absent (3). [NEW STATE ADDED]
- 152. Unguals on all digits generally similar in size (0) or digit I bearing large ungual and unguals of other digits distinctly smaller (1).
- 153. Proximodorsal 'lip' on some manual unguals - a transverse ridge immediately dorsal to the articulating surface - absent (0) or present (1). In *Velociraptor mongoliensis* and *Deinonychus antirrhopus* a lip is present, contrary to previous contentions.

Pelvic Girdle

- 154. Ventral edge of anterior ala of ilium straight or gently curved (0) or ventral edge with shallow, obtuse process (1) or process strongly hooked (2).
- 155. Preacetabular part of ilium roughly as long as postacetabular part of ilium (0) or preacetabular portion of ilium markedly longer (more than 2/3 of total ilium length) than postacetabular part (1).
- 156. Anterior end of ilium gently rounded or straight (0) or anterior end strongly convex, lobate (1) or pointed at anterodorsal corner with concave anteroventral edge (2) or distinctly concave dorsally (3). [NEW STATE ADDED based on Rauhut, 2003: char 173]
- 157. Supraacetabular crest on ilium as a separate process from antitrochanter, forms "hood" over femoral head present (0) reduced, not forming hood (1) or absent (2).

158. Postacetabular ala of ilium in lateral view squared (0) or acuminate (1).
159. Postacetabular blades of ilia in dorsal view subparallel (0) or diverge posteriorly (1).
160. Tuber along dorsal edge of ilium, dorsal or slightly posterior to acetabulum absent (0) or present (1).
161. Brevis fossa shelf-like (0) or deeply concave with lateral overhang (1).
162. Antitrochanter posterior to acetabulum absent or poorly developed (0) or prominent (1).
163. Ridge bounding cuppedicus fossa terminates rostral to acetabulum or curves ventrally onto anterior end of pubic peduncle (0), or rim extends far posteriorly and is confluent or almost confluent with acetabular rim (1). Redefined by Makovicky et al., (2005) following description of condition in *Unenlagia* and *Rahonavis* by Novas (2004) as confirmed by personal observation.
164. Cuppedicus fossa deep, ventrally concave (0) or fossa shallow or flat, with little or no lateral overhang (1) or absent (2). See (Hutchinson, 2001b) for explanation of related changes in pelvic musculature.
165. Posterior edge of ischium straight (0) or with proximal median posterior process (1).
166. Ischium with rodlike shaft [i.e. part distal to acetabular portion](0) or with wide, flat, and plate-like shaft (1) Added by Makovicky et al., 2005.
167. Ischiadic shaft straight (0) or ventrodistally curved anteriorly (1) or hooked posteriorly (2) Redefined by Makovicky et al., 2005.
168. Lateral face of ischiadic blade flat [or round in rodlike ischia] (0) or laterally concave (1) or with longitudinal ridge subdividing lateral surface into anterior (including obturator process) and posterior parts (2). Some dromaeosaurids have a distinct ridge (i.e. *Sinornithosaurus* and *Buitreraptor*) whereas other the ridge is subtle and forms a slight medial flexure of the obturator process (e.g. *Velociraptor* and *Deinonychus*). We consider these to be homologous. New character added by Makovicky et al., 2005.
169. Obturator process of ischium absent (0) or proximal in position (1) or located near middle of ischiadic shaft (2) or located at distal end of ischium (3).
170. Obturator process does not contact pubis (0) or contacts pubis (1).
171. Obturator notch present (0) or or notch or foramen absent (1).
172. Semicircular scar on posterior part of the proximal end of the ischium, absent (0) or present (1).
173. Ischium more than two-thirds (0) or two-thirds or less of pubis length (1).
174. Distal ends of ischia form symphysis (0) or approach one another but do not form symphysis (1) or widely separated (2).
175. Ischial boot (expanded distal end) present (0) or absent (1).
176. Tubercle on anterior edge of ischium absent (0) or present (1). A small tuber occurring along the rostral edge of the ischium between the pubic peduncle and obturator process was described in *Velociraptor* (Norell and Makovicky, 1997) and is also present in *Deinonychus*. (Hutchinson, 2001b) termed this structure the obturator tuberosity.
177. Pubis propubic (0) or pubis vertical (1) or pubis posteriorly oriented (opisthopubic) (2). The oviraptorid condition, in which the proximal end of the pubis is vertical and the distal end curves anteriorly, is considered to be state 1.
178. Pubic boot projects anteriorly and posteriorly (0) or with little or no anterior process (1) or no anteroposterior projections (2).
179. Shelf on pubic shaft proximal to symphysis ('pubic apron') extends medially from middle of cylindrical pubic shaft (0) or shelf extends medially from anterior edge of anteroposteriorly flattened shaft (1).
180. Pubic shaft straight (0) or distal end curves anteriorly, anterior surface of shaft concave (1) or shaft curves posteriorly, anteriorly convex curvature (2). See also (Calvo et al., 2004).
181. Pubic apron about half of pubic shaft length (0) or less than 1/3 of shaft length (1).
182. Contact between pubic apron contributions of both pubes meet extensively (0) contact disrupted by a slit (1) or no contact (2). Character added by Makovicky et al., 2005.

Hindlimb

183. Femoral head without fovea capitalis (for attachment of capital ligament) (0) or circular fovea present in center of medial surface of head (1).
184. Lesser trochanter separated from greater trochanter by deep cleft (0) or trochanters separated by small groove (1) or completely fused (or absent) to form a trochanteric crest (2).
185. Lesser trochanter of femur alariform (0) or cylindrical in cross section (1).

186. Lateral ridge absent or represented only by faint rugosity (0) or distinctly raised from shaft, mound-like (1). (Hutchinson, 2001a) clarified the terminological confusion surrounding this structure and considered it a derived homolog of the trochanteric shelf of more basal theropods and dinosaurimorphs.
187. Fourth trochanter on femur present (0) or absent (1).
188. Accessory trochanteric crest distal to lesser trochanter absent (0) or present (1). This character was identified as an autapomorphy of *Microvenator celer* (Makovicky and Sues, 1998), but it is more widespread.
189. Anterior surface of femur proximal to medial distal condyle without longitudinal crest (0) or crest present extending proximally from medial condyle on anterior surface of shaft (1).
190. Popliteal fossa between end of femur open distally (0) or closed off distally by contact between distal condyles (1).
191. Fibula reaches proximal tarsals (0) or short, tapering distally, and not in contact with proximal tarsals (1).
192. Medial surface of proximal end of fibula concave along long axis (0) or flat (1).
193. Deep oval fossa on medial surface of fibula near proximal end absent (0) or present (1).
194. Distal end of astragalus and calcaneum with condyles separated by shallow, indefinite sulcus (0) or with distinct condyles separated by prominent tendinal groove on anterior surface (1).
195. Medial cnemial crest absent (0) or present on proximal end of tibia (1).
196. Ascending process of the astragalus tall and broad, covering most of anterior surface of distal end of tibia (0) or process short and slender, covering only lateral half of anterior surface of tibia (1) or ascending process tall, but with medial notch that restricts it to lateral side of anterior face of distal tibia (2).
197. Ascending process of astragalus confluent with condylar portion (0) or separated by transverse groove or fossa across base (1).
198. Astragalus and calcaneum separate from tibia (0) or fused to each other and to the tibia in late ontogeny (1).
199. Distal tarsals separate, not fused to metatarsals (0) or form metatarsal cap with intercondylar prominence that fuses to metatarsal early in postnatal ontogeny (1).
200. Metatarsals not co-ossified (0) or co-ossification of metatarsals begins proximally (1) or distally (2).
201. Distal end of metatarsal II smooth, not ginglymoid (0) or with developed ginglymus (1).
202. Distal end of metatarsal III smooth, not ginglymoid (0) or with developed ginglymus (1).
203. MT III proximal shaft prominently exposed between MT II and MT IV along entire metapodium (0) or MT III proximal shaft constricted and much narrower than either II or IV, but still exposed along most of metapodium, subarcotometatarsal (1) or very pinched, not exposed along proximal section of metapodium, arcotometatarsal (2) or proximal part of MT III lost (3). Redefined by Makovicky et al., 2005 to follow Novas and Pol (2005: their character 200).
204. Ungual and penultimate phalanx of pedal digit II similar to those of III (0) or penultimate phalanx highly modified for extreme hyper-extension, ungual more strongly curved and significantly larger than that of digit III (1).
205. Metatarsal I articulates with the middle of the medial surface of metatarsal II (0) or metatarsal I attaches to posterior surface of distal quarter of metatarsal II (1) or metatarsal I articulates to medial surface of metatarsal II near its proximal end (2) or metatarsal I absent (3).
206. Metatarsal I attenuates proximally, without proximal articulating surface (0) or proximal end of metatarsal I similar to that of metatarsals II-IV (1).
207. Shaft of MT IV round or thicker dorsoventrally than wide in cross section (0) or shaft of MT IV mediolaterally widened and flat in cross section (1).
208. Foot symmetrical (0) or asymmetrical with slender MTII and very robust MT IV, excluding flange (1). (Senter et al., 2004) consider the foot of *Sinovenator* to be symmetric *contra* (Xu et al., 2002), but examination of the holotype as well as several referred specimens confirms that the proximal part of MT II is mediolaterally compressed while the proximal section of Metatarsal IV is broadened, reflecting an incipient stage of asymmetry. Therefore we follow Xu et al. (2002) in coding the foot of *Sinovenator* asymmetric (state 1). Although we acknowledge the difficulties in parsing states when characters display a more continuous range of expressions than originally defined, the asymmetric conditions is derived and the homology of even an incipient form of this state needs to be

acknowledged and subjected to the test of congruence. If future discoveries reveal more taxa with the incipient condition a separate state may be warranted for it.

Characters added by (Makovicky and Norell, 2004; Makovicky et al., 2003), (Novas, 2004), (Novas and Pol, 2005) and others.

209. Neural spines on posterior dorsal vertebrae in lateral view rectangular or square (0) or anteroposteriorly expanded distally, fan-shaped (1).
210. Shaft diameter of phalanx I-1 less (0) or greater (1) than shaft diameter of radius.
211. Angular exposed almost to end of mandible in lateral view, reaches or almost reaches articular (0) or excluded from posterior end angular suture turns ventrally and meets ventral border of mandible rostral to glenoid (1).
212. Laterally inclined flange along dorsal edge of surangular for articulation with lateral process of lateral quadrate condyle absent (0) or present (1).
213. Distal articular ends of metacarpals I + II ginglymoid (0) or rounded, smooth (1).
214. Radius and ulna well separated (0) or with distinct adherence or syndesmosis distally (1).
215. Jaws occlude for their full length (0) or diverge rostrally due to kink and downward deflection in dentary buccal margin (1).
216. Quadrate head covered by squamosal in lateral view (0) or quadrate cotyle of squamosal open laterally exposing quadrate head (1).
217. Brevis fossa poorly developed adjacent to ischial peduncle and without lateral overhang, medial edge of brevis fossa visible in lateral view (0), or fossa well developed along full length of postacetabular blade, lateral overhang extends along full length of fossa, medial edge completely covered in lateral view (1).
218. Vertical ridge on lesser trochanter present (0) or absent (1).
219. Supratemporal fenestra bounded laterally and posteriorly by the squamosal (0) or supratemporal fenestra extended as a fossa on to the dorsal surface of the squamosal (1).
220. Dentary fully toothed (0) or only with teeth rostrally (1) or edentulous (2).
221. Posterior edge of coracoid not or only shallowly indented below glenoid (0), or posterior edge of coracoid deeply notched just ventral to glenoid, glenoid lip everted (1).
222. Retroarticular process points caudally (0) or curves gently dorsocaudally (1)
223. Flange on supraglenoid buttress on scapula absent (0) or present (1) (Nicholls and Russell, 1985).
224. Depression (possibly pneumatic) on ventral surface of postorbital process of laterosphenoid absent (0) or present (1)(Makovicky et al., 2003).
225. Basal tubera set far apart, level with or beyond lateral edge of occipital condyle and/or foramen magnum (may connected by a web of bone or separated by a large notch) (0) or tubera small, directly below condyle and foramen magnum, and separated by a narrow notch (1) or absent (2). (Makovicky et al., 2003). [NEW STATE ADDED]
226. Dorsal edge of postacetabular blade convex or straight (0) or concave, brevis shelf extending caudal to vertical face of ilium giving ilium a dorsally concave outline in lateral view (1) (Novas 2004).
227. Postacetabular end of ilium terminating in rounded or square end in dorsal view (0) or with lobate brevis shelf projecting from end of ilium and beyond end of postacetabular lamina (1) Character added by Makovicky et al. (2005) – State 0 occurs in basal dromaeosaurs and basal troodontids whereas *Buitreraptor* and *Microraptor* have a lobate brevis shelf. The reduced brevis shelf of *Unenlagia* also appears to be slightly expanded.
228. Flexor heel on phalanx II-2 small and asymmetrically developed only on medial side of vertical ridge subdividing proximal articulation (0) or heel long and lobate, with extension of midline ridge extending onto its dorsal surface (1). Character added by Makovicky et al., 2005. Advanced troodontids and dromaeosaurids have a well developed, more symmetric heel, but more basal taxa within each clade including *Sinovenator*, *Microraptor*, *Buitreraptor*, *Rahonavis* and *Neuquenraptor* display state 0 with a weak, medially skewed heel (see also Senter et al., 2004).
229. Large, longitudinal flange along caudal or lateral face of metatarsal IV absent (0) or present (1). Modified from Novas and Pol (2005). A low, rugose muscle scar is evident along the metaphysis of Metatarsal IV in many theropods and is probably a precursor to the flange considered here. Presence of the rugose scar does not constitute a distinct flange, however, here and is considered to fall under the conditions of state 0 here. Unlike Novas and Pol (2005) we consider the laterally directed flange of *Velociraptor* as homologous with the caudally directed flange in other paravians, because these

structure occupy identical topological positions. Likewise, we consider this flange to be present in *Sinornithosaurus*.

230. Proximodorsal process of ischium small, tab-like or pointed process along caudal edge of ischium (0) or process large proximodorsally hooked and separated from iliac peduncle of the ischium by a notch (Chiappe et al., 1999). Character added by Makovicky et al., 2005- State 1 occurs in *Unenlagia*, *Rahonavis*, *Confuciusornis* and in some specimens of *Archeopteryx* (Berlin, Solnhofen). Other basal paravian taxa that possess a proximodorsal process generally display state 0 including *Buitreraptor*, *Microraptor*, *Sinornithosaurus* and *Sinovenator*.
231. Lateral face of pubic shaft smooth (0) or with prominent lateral tubercle about halfway down the shaft (1) (Senter et al. 2004). State (1) is observed exclusively in the Yixian Fm. dromaeosaurids *Microraptor* and *Sinornithosaurus*.
232. Distally placed dorsal process along caudal edge of ischidial shaft absent (0) or present (1)(Forster et al., 1998).
233. Obturator process square (i.e. with distinct caudal edge or notch) (0) or triangular with caudal end confluent with shaft (1).
234. Triangular obturator process with short rostral projection and wide base along ischial shaft (0) or with short base, long process extending rostrally (1). State 1 occurs in a number of basal paravians including *Microraptor*, *Sinornithosaurus*, *Sinovenator*, *Rahonavis* and *Buitreraptor*. Due to incomplete preservations of the ischiadic margin in *Unenlagia*, the condition is difficult to determine, but we view this taxon as having state 1 based on firsthand observation of the holotype.
235. Tuber along extensor surface of MT II absent (0) or present (1)(Chiappe, 2002).
236. Ulna/Femoral length ratio: significantly less than one (0) or equal or greater than one (1).

Characters added by Turner et al., (2007).

- Character 237: Dorsal displacement of accessory (maxillary) fenestra: absent (0) or present (1). *In all dromaeosaurids with known cranial material, the maxillary fenestra is displaced dorsally within the antorbital fossa. In other theropods, this displacement is absent with the fenestra positioned more ventrally or central on the medial lamina of the maxilla. (modified from Senter et al., 2004: char. 5).*
- Character 238: Jugal process of maxilla, ventral to the external antorbital fenestra dorsoventrally narrow (0) or dorsoventrally wide (1). *In some dromaeosaurids, such as Tsaagan mangas (IGM 100/1015) the jugal process of the maxilla is dorsoventrally wide. In other dromaeosaurids, such as Velociraptor mongoliensis (AMNH FR 6515) the jugal process of the maxilla is dorsoventrally narrow. (modified from Senter et al., 2004: char. 14).*
- Character 239: Accessory antorbital (maxillary) fenestra recessed within a shallow, caudally or caudodorsally open fossa, which is itself located within the maxillary antorbital fossa: absent (0) or present (1). *All dromaeosaurids with known cranial material exhibit state 1. Witmer (1997: p43) discusses this morphology in detail.*
- Character 240: Nasal process of maxilla, dorsal ramus (ascending ramus of maxilla): prominent, exposed medially and laterally (0) or absent or reduced to slight medial, and no lateral exposure (1). *Most theropods, including Velociraptor mongoliensis, have a prominent ascending ramus of the maxilla. In derived avialans this lamina becomes reduced or absent. (modified from Gauthier, 1986 and Cracraft, 1986 by Chiappe, 1996: char. 6 by Clarke and Norell, 2002: char. 10).*
- Character 241: + In lateral view, participation of the ventral ramus of the nasal process of the maxilla in the anterior margin of the internal antorbital fenestra: present extensively (0) or small dorsal projection of the maxilla participates in the anterior margin (1) or no dorsal projection of maxilla participates in the anterior margin (2). *In most theropods, the ventral ramus of the nasal process of the maxilla forms the anterior margin of the internal antorbital fenestra. A reduction and loss of this ramus is a trend within avialans. (modified from Clarke and Norell, 2002: char. 11).*
- Character 242: In lateral view, dorsal border of the internal antorbital fenestra formed by lacrimal and maxilla (0) or by lacrimal and nasal (1). *In all basal avialans, except Archaeopteryx lithographica, the nasal forms the dorsal border of the internal antorbital fenestra. In non-avialan theropods, including Archaeopteryx lithographica, the dorsal border is formed from the medial lamina of the ascending process of the maxilla.*
- Character 243: In lateral view, dorsal border of the antorbital fossa formed by the lacrimal and maxilla (0) or by the lacrimal and nasal (1) or by maxilla, premaxilla, and lacrimal (2). *In all basal avialans,*

including *Archaeopteryx lithographica*, the nasal forms the dorsal border of the antorbital fossa. This is because the ascending process of the maxilla in *Archaeopteryx lithographica* is recessed medially slightly.

- Character 244: In lateral view, lateral lamina of the ventral ramus of nasal process of maxilla: present, large broad exposure (0), or present, reduced to small triangular exposure (1). *The derived state is found in basal dromaeosaurids such as Sinornithosaurus millenii, basal troodontids like Mei long, and in the new taxon Shanag ashile.*
- Character 245: Supratemporal fossa with limited extension onto dorsal surfaces of frontal and postorbital (0) or covers most of frontal process of the postorbital and extends anteriorly onto dorsal surface of frontal (1). *A number of large theropods, dromaeosaurids, and some oviraptorosaurians exhibit state 1. This character is distinguished from character 42, which codes for the shape of the fossa on the frontal and postorbital. (modified from Currie 1995, by Currie and Varricchio, 2004: char. 14).*
- Character 246: Jugal does not particulate in margin of antorbital fenestra (0) or participates in antorbital fenestra (1). *In Allosaurus fragilis and Oviraptor philoceratops the jugal does not participate in the margin of the antorbital fenestra.*
- Character 247: Anterior and posterior denticles of teeth not significantly different in size (0) or anterior denticles, when present, significantly smaller than posterior denticles (1). *The anterior and posterior denticles in most theropods as well as Dromaeosaurus albertensis exhibit state 0. Most dromaeosaurids exhibit state 1. (see Ostrom, 1969).*
- Character 248: Maxillary teeth almost perpendicular to jaw margin (0) or inclined strongly posteroventrally (1). *Bambiraptor feinbergorum and Atrociraptor marshalli exhibit state 1. (modified from Currie and Varricchio, 2004: char. 40).*
- Character 249: Maxillary tooth height highly variable with gaps evident for replacement (0) or almost isodont with no replacement gaps (1). *State 1 usually depicts no more than a 30% difference in height between adjacent teeth. (Currie and Varricchio, 2004: char. 41).*
- Character 250: Splenial forms notched anterior margin of internal mandibular fenestra: absent (0) or present (1). *State 1 is present in Allosaurus fragilis and Tyrannosaurus rex. (Currie and Varricchio, 2004: char. 35).*
- Character 251: First premaxillary tooth size compared with crowns of premaxillary teeth 2 and 3: slightly smaller or same size (0) or much smaller (1) or much larger (2). *(modified from Currie, 1995; Currie and Varricchio, 2004: char. 42).*

Dromaeosaurus albertensis

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Deinonychus antirrhopus

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Velociraptor mongoliensis

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Utahraptor ostrommaysorum

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Adasaurus mongoliensis

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Achillobator giganticus

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Tsaagan mangas

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Saurornitholestes langstoni

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Sinornithosaurus millenii

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Microraptor zhaoianus

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Microraptor gui

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Rahonavis ostromi

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Mononykus olecranus

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Patagonykus puertai

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Alvarezsaurus calvoi

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Ornitholestes hermanni

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Coelurus fragilis

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Archaeopteryx lithographica

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Avimimus portentosus

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Caudipteryx zoui

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Confuciusornis sanctus

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Struthiomimus altus

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Gallimimus bullatus

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Garudimimus brevipes

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Pelecanimimus polydon

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Harpymimus okladnikov

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Troodon formosus

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Saurornithoides mongoliensis

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Saurornithoides junior

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Byronosaurus jaffei

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Sinornithoides youngi

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Sinovenator changii

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Mei long

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EK troodontid (IGM 100/44)

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Segnosaurus galbinensis

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Erlikosaurus andrewsi

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Alxasaurus elesitaiensis

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Tyrannosaurus rex

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Albertosaurus libratus

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0110100000?000101000000100000010000?10001000000001000000?01000100100010000000101100
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Mahakala

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Apsaravis ukhaana

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?010?????1?111[12]0100?00000?00??1?20?0?????0?00?01????????????????

Yixianornis

101?????2?????????2?0?01?????1????????????????????1?????????????????000?0?0?????00?0?120??10?01??
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Sapeornis

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Jinfengopteryx

?0?????????????????1?01??1100?????????1?00?0?0??01?????100?????00?00?0?1?0?000?1??0???1?
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3. ANALYSIS PROTOCOL AND RESULTS

To test the phylogenetic placement of *Mahakala* we have expanded the Turner et al. (2007) study by adding 11 additional taxa and modifying nine characters. A total of 69 coelurosaurian taxa and 251 characters (18 ordered) were used in the analysis, with *Allosaurus fragilis* and *Sinraptor dongi* used to root the most parsimonious trees. Characters 9, 16, 17, 18, 27, 37, 39, 40, 68, 76, 113, 157, 164, 169, 174, 182, 184, and 220 were ordered because they either represent potentially nested statements of primary homology or include presence/absence states. The dataset was treated with equally-weighted parsimony analysis implemented in TNT v. 1.0 (Goloboff et al., 2003). A heuristic tree search strategy was conducted performing 1000 replicates of Wagner trees (using random addition sequences) followed by TBR branch swapping (holding 10 trees per replicate). The best trees obtained at the end of the replicates were subjected to a final round of TBR branch swapping. Zero length branches were collapsed if they lack support under any of the most parsimonious reconstructions (i.e., rule 1 of Coddington and Scharff, 1994). This analysis resulted in 1296 most parsimonious trees of 867 steps (CI= 0.3541, RI=0.7167) found in 439 out of the 1000 replicates (fig. S1). For the purpose of the phylogenetic analysis, we followed Makovicky et al., (2005), and tentatively considered *Neuquenraptor argentinus* a junior synonym of *Unenlagia comahuensis*.

4. DIAGNOSES FOR SELECTED CLADES AND DEFINITION OF DROMAEOSAURIDAE AND UNENLAGIINAE

Coelurosauria

Caudal tympanic recess present as opening on anterior surface of paroccipital process (18: 0 → 1); Secondary palate present (25: 0 → 1); QJ L shaped (35: 1 → 0); Nasofrontal suture wedge shaped (41: 1 → 0); Quadrate hollow with foramen on the posterior surface (52: 0 → 1); PMX tooth crown D-shaped (91: 0 → 1); Cervical centrum articulations amphiplatyan (101: 1 → 0); Groove separating ascending process from astragalar

condyles (197: 0 → 1); Obturator process of ischium triangular (233: 0 → 1); Dorsal border of the antorbital fossa formed by the lacrimal and maxilla (243: 1 → 0).

Maniraptora

Pneumatic recess in posteroventral corner of antorbital fossa absent (33: 0 → 1); Quadrate vertical (51: 1 → 0); Coronoid ossification absent (76: 0 → 2); Dentaries lack interdental plates (90: 1 → 0); Epipophyses of cervical vertebrae placed proximal to postzygapophyseal facets (95: 0 → 1); Shaft of cervical ribs broad and shorter than vertebra (124: 0 → 1); Coracoid with shallow ventral blade with elongate posteroventral process (136: 0 → 2).

Paraves

Promaxillary fenestra position (28: 0 → 1); T-shaped lacrimal (39: 0 → 1); distal chevrons bifurcate (123: 0 → 1); acromion laterally everted (133: 0 → 1); L-shaped scapulocoracoid (137: 0 → 1); proximal ulnar facet subdivided (144: 0 → 1); Rostral edge of ilium convex & lobate (156: 0 → 1); Supraacetabular tuber along dorsal edge of ilium (160: 0 → 1); Ischium > 70% of pubis (173: 0 → 1); pubic shaft anteriorly convex (180: 0 → 2); Posterior trochanter present (186: 0 → 1).

Deinonychosauria

Pterygoid palatal flange large (61: 1 → 0); Foramen in lateral surface of mandible absent (74: 0 → 1); Splenial exposed in lateral view (75: 0 → 1); Maxillary and dentary teeth all without serrations (83: 0 → 1); Deltopectoral crest with muscle scar (141: 0 → 1); Enlarged, raptorial ungual on pedal digit II (204: 0 → 1).

Dromaeosauridae (here we follow the stem-based definition of Sereno, 1998:

Dromaeosaurus albertensis but not *Troodon formosus*, *Ornithomimus edmonticus*, *Passer domesticus*)

Accessory tympanic recess absent (17: 1 → 0); Paroccipital process elongate and slender, with dorsal and ventral edges nearly parallel (56: 1 → 0); Paroccipital process with straight dorsal edge (58: 0 → 1); MTII with ginglymoid articulation (201: 0 → 1).

Unenlagiinae (given the phylogenetic hypothesis of this study, we here amend the definition of Unenlagiinae given by Makovicky et al. (2005) in order to preserve the closest approximation of the aforementioned authors' original taxonomic content and prevent conflict and definitional redundancy with Microraptorinae. Therefore, we here provide the amended definition of Unenlagiinae as all taxa closer to *Unenlagia comahuensis* than to *Velociraptor mongoliensis* and *Microraptor zhaoianus*).

Unenlagiinae + Shanag

Nutrient foramina on external surface of dentary lie within a deep groove (71: 0 → 1).

Microraptorinae + Unenlagiinae

Distal caudal chevrons bifurcate at both ends (123: 1 → 2); Humerus longer than scapula (139: 0 → 1); Distal articular surface of ulna convex (143: 0 → 1); Subarctometarsal metapodium (203: 0 → 1); Longitudinal flange along caudal of metatarsal IV (229: 0 → 1); Triangular obturator process with short base, long process extending rostrally (234: 0 → 1); Lateral lamina of the ventral ramus of nasal process of maxilla small with narrow triangular exposure (244: 0 → 1).

Dromaeosaurinae + Velociraptorinae

Frontal postorbital process sharply demarcated from orbital margin (43: 0 → 1); Frontal edge notched (44: 0 → 1); Internal mandibular fenestra large and rounded (73: 0 → 1); All presacral vertebrae pneumatic (106: 0 → 1); Anterior end of ilium pointed at

anterodorsal corner with concave anteroventral edge (156: 1 → 2); Flexor heel on phalanx II-2 long and lobate (228: 0 → 1).

5. ANCESTRAL STATE ANALYSIS

Previous discussions of dromaeosaurid and paravian body size evolution were non-analytical and/or restricted in taxonomic scope (Serenó, 1999; Xu et al., 2000; Xu et al., 2002; Xu and Norell, 2004; Carrano, 2006). Although increased body size has been cited as a trend within dromaeosaurids (Xu et al., 2002), this trend remained untested and uncharacterized. Moreover, previous hypotheses of dromaeosaurid relationships provided, at best, ambiguous optimization of ancestral body size. A species-rich, large bodied Laurasian clade was sister to a species-poor, small-bodied microraptorine clade. Additionally, a species-rich troodontid clade was known to have only one or two small basal members but otherwise was represented by large bodied species. This provided, at best, ambiguous optimization of ancestral body size at the base of Dromaeosauridae and Troodontidae and therefore Deinonychosauria. Therefore, it was uncertain if both miniaturization and gigantism trends were present within Paraves and the Dromaeosauridae.

Femoral length has been shown to be reliable mass predictor in theropod dinosaurs (Christiansen and Fariña, 2004). Hindlimb proportions are similar across almost all clades of non-avian theropods, with exception of the largest non-avian theropods, which exhibit a degree of positive allometry between femur length versus hindlimb length (Gatesy, 1991; Gatesy and Middleton, 1997). The theropods considered in the present analysis do not constitute these largest theropods and have proportional femur to hindlimb ratios (Gatesy, 1991). Therefore, femoral length provides a reliable proxy for body size—both in mass and in overall length. Femur lengths from 26 paravian taxa were measured by the authors or taken from the literature (see Section 8). The body mass estimation equation of Christiansen and Fariña (2004) was employed. This is used because circumference measurements were not obtainable for many paravian taxa given the frequent crushing in many of the Jehol taxa. Ancestral size was estimated by optimizing estimated body mass across the set of most parsimonious trees.

Body mass was treated as a continuous additive character and mapped as such using TNT v1.0 (Goloboff et al., 2003). This procedure uses a modification of Wagner parsimony where the cost of transformation between any two values is set as the module of their algebraic difference. Given the type of character and the assigned transformation costs, this procedure is equivalent to Sankoff optimization (Felsenstein, 2004), but is implemented in a simpler manner and with the added advantage of the 65,001 states allowed by TNT v1.0. Values for internal nodes (ancestral reconstructions) are assigned so that cost of transformation is minimized over the entire tree. No binning of measurements is necessary as in squared-change parsimony (Maddison, 1991) and neither is it required that the inferred change occur evenly across branches (Goloboff et al., 2006). This in effect allows the data to imply a rate and allows this rate to vary across the tree. Application of a parsimony method over a likelihood (i.e. Brownian motion) method is preferred in this analysis. When rates of change are slow or when branch lengths are short, parsimony-based methods have been shown to perform well (Hillis et al., 1992; Pol and Siddall, 2001). Further, both Brownian motion and squared-change

parsimony can mask directional trends (Pagel, 1999a, b) and has been shown to produce less reliable results than parsimony (Webster and Purvis, 2002).

Figure S2 depicts the optimization of estimated body mass of paravians along their evolutionary history. The evolutionary tree is shown horizontally with the root placed to the left and the successively more derived nodes and terminals are displayed to the right. Internal nodes are labeled with the single most parsimonious assignment or with the range of possible values that are equally most optimal. Taxa considered in this analysis are a subset of all paravian taxa used in the phylogenetic analysis. Terminal taxa from which there was no reliable information are excluded from this analysis. Figure S2 shows *Sinornithosaurus milleni* as the sister taxon of *Microraptor* + *Graciliraptor* although in the phylogenetic analysis its position among microraptorines or unenlagiines was unresolved. Resolving *Sinornithosaurus milleni* as either the sister taxon to *Microraptor* + *Graciliraptor* or the sister taxon to Unenlagiinae + *Shanag* does not affect the optimal ancestral reconstructions for the tree. Due to the important phylogenetic position and small size of *Shanag*, an estimated femur length was used in the analysis. Exclusion of *Shanag*, however, does not change the reconstructed ancestral state. Additionally, optimization of femur length or log-transformed femur length (not shown) as a proxy for body length does not change the observed pattern of body size change.

Although small taxa have been found previous to *Mahakala* (e.g., *Sinovenator*, *Mei*, *Sinornithosaurus*, *Buitreraptor*), most of these taxa are still twice as long as *Mahakala* and nearly an order of magnitude more massive. Consequently, inclusion of *Mahakala* has critical impact on the reconstruction of the basal dromaeosaurid, troodontid, deinonychosaur, and paravian conditions. With the exclusion of *Mahakala*, optimization of the continuous character changes markedly and the reconstructed basal conditions for the above clades becomes larger and the range of possible reconstructions increases (fig. S3). The Deinonychosauria node is reconstructed with a range of 2.4 to 4.2 kilograms as opposed to 700 grams; and that the Paraves node is extremely ambiguous with equally parsimonious reconstruction varying between 0.6 kilograms to 4.2 kilograms—nearly an order of magnitude variation, the mean of which being demonstrably larger than all basal avialans. Thus *Mahakala* is decisive for inferring extreme miniaturization at the base of Paraves and Deinonychosauria.

The pattern of ghost lineage duration and phylogenetic placement for all basal paravians reveals that the small paravian taxa, regardless of their temporal occurrence, are recovered basally in their respective clades. Given their delicate construction, small taxa such as these are typically preserved only in exceptional circumstances, often requiring Lagerstätten conditions (e.g., Jehol deposits, Solnhofen, Ukhaa Tolgod, etc). Therefore, the duration of the ghost lineages for these small taxa are best viewed as indicators of the temporal distribution of paravian-preserving Lagerstätte. It is, therefore, unsurprising that the first dromaeosaurids and troodontids discovered were the large-bodied members of the currently recognized clades. Their early discovery and shorter ghost lineages are certainly reflections of their higher preservation potential. If large-bodied taxa were present along the ghost lineages of the small-bodied paravians, then we view it as unlikely that representatives would not already have been sampled. [That being said, it is true that part of the early radiation of paravians is documented from Early Cretaceous deposits in Asia that show a bias toward preserving small-bodied taxa.](#) [Notable exceptions, however, are the occurrence of *Shenzhousaurus* and *Beipaiosaurus*](#)

and the Early Cretaceous Öösh deposits from Mongolia, which does not show such a taphonomic bias. The converse is true for Early Cretaceous deposits from North America, which tend to preferentially preserve larger-bodied taxa. Therefore, it is conceivable that an improved sampling from other taphonomic settings in North America and Asia could alter the current hypotheses of phylogeny and body size evolution.

6. HISTOLOGICAL ANALYSIS AND AGE ESTIMATION

The femur has very thin cortices, so the majority of the earlier formed bone has been reabsorbed (Fig. S4). All of the tissues are primary fibrolamellar woven bone (inner 3/4) parallel-fibered (outer 1/4) with longitudinal vascularization. There is no sign of Haversian reconstruction or endosteal deposits. The endosteal surfaces show extensive osteoclastic erosion. Two definitive lines of arrested growth are evident. The degree of vascularization diminishes slightly as one moves toward the periphery of the cross-section. Also the osteocyte lacunae become more flattened in the same direction. Given the width of the zone that is present back-calculating to the centroid would make the animal five years old. These indicators place the animal at the beginning of the transition to the asymptotic growth phase (i.e., the animal is either a very young adult or an older sub-adult). This is consistent with the presence of diminishing vascularization and the development of the parallel-fibered bone. This is also consistent with numerous osteological indicators. The cranial sutures are coossified and the astragalocalcaneum is fused. The neurocentral sutures are closed in all preserved caudal vertebrae and cervical vertebrae. Additionally, the odontoid process appears fused to the axis. This pattern is consistent with that found in mature individuals of derived maniraptorans such as the dromaeosaurids *Velociraptor* (IGM 100/981) and *Deinonychus* (YPM 5204) as well as the oviraptorid *Khaan* (IGM 100/1002).

7. SUPPLEMENT DISCUSSION

Character state optimization changes for characters 203, 227, 229, and 234 resulted in the grouping of unenlagiine dromaeosaurids with Jehol microraptorines. In the most recent phylogenetic analyses utilizing the TWiG matrix (Makovicky et al., 2005; Norell et al., 2006; Turner et al., 2007) found character state 203.1 (possession of the subarctometatarsal condition) as independently derived in Unenlagiinae and *Sinornithosaurus* + *Microraptor*. Here it is found as a synapomorphy for a clade containing unenlagiine and microraptorine dromaeosaurids. Likewise, character state 227.1 (dorsocaudal edge of ilium concave) was previously an unenlagiine synapomorphy, paralleled in *Microraptor zhaoianus*. In the present analysis, it is an ambiguous Microraptorinae + Unenlagiinae synapomorphy—it is either synapomorphic for the clade or is paralleled in *Microraptor zhaoianus*, *Buitreraptor gonzalezorum*, and *Unenlagia*. Character state 229.1 (longitudinal flange along caudal of metatarsal IV) was recovered as synapomorphic for Deinonychosauria by Makovicky et al. (2005) and Turner et al. (2007). Here it is a Microraptorinae + Unenlagiinae synapomorphy. The laterally directed flange on metatarsal IV in *Velociraptor mongoliensis* is a parallelism. Lastly, the broad-based, triangular obturator process (character 234.1) in *Sinornithosaurus*, *Microraptor*, *Rahonavis*, and *Buitreraptor* is considered synapomorphic, not independently derived as found by previous analyses.

Previous phylogenetic hypotheses supporting monophyly of Gondwanan dromaeosaurids (Unenlagiinae) corroborated vicariance hypotheses for the distribution of maniraptoran lineages such as alvarezsaurids and dromaeosaurids. However, given the phylogenetic hypothesis presented here Unenlagiinae may include the Asian taxon *Shanag*. Additionally, the Unenlagiinae are no longer depicted as the basalmost dromaeosaurid clade. This rejects the pattern of a basal split between Gondwanan dromaeosaurids for all Laurasian dromaeosaurids. It is, instead, suggestive of a pattern of regional extinction and/or dispersal within a widespread Dromaeosauridae in the Late Jurassic.

8. SELECT MEASUREMENTS (in mm) OF MAHAKALA (IGM 100/1033).

Elements	
Frontal (anteroposterior length)	25.2
Occiput width (b/w paroccipital processes)	22
Caudal series (caudal 1-13)	171
Humerus (right)	26*/35-40 ^e
Radius (left)	36*
Ulna (left)	32*/40 ^e
MC II (left)	18
MC III (left)	15*
Ilium (left)	52.5
Femur (left)	79
Tibia (left)	110
Metatarsus	82
Pedal ungual, digit II (anteroposterior length)	17
Pedal ungual, digit II (length of outside curve)	19

*indicates partial length based on nearly complete element.

^e indicates the estimated complete length of partial element.

9. PARAVIAN FEMUR LENGTHS, ESTIMATED BODY LENGTHS AND BODY MASS.

See Supplemental Figure 5 for regression used to estimate body lengths, whereas the table below shows the estimated body masses used in the ancestral state analysis. The bivariate equation of Christiansen and Fariña (2004) utilizing femur length was used:

$$\log_{10}body\ mass = -6.288 \pm 0.500 + 3.222 \pm 0.181 \times \log_{10}femur\ length$$

Measurements in millimeter; estimates rounded to two significant digits for taxa under a meter or three significant digits for taxa over a meter in length. Sharp decrease in body length in *Sapeornis*, *Confuciusornis*, *Yixianornis*, and *Apsaravis* reflects the presence of a pygostyle in these taxa instead of long tails.

^e Indicates body length taken from data source in previous column.

* Indicates an estimated (underestimate) length based on nearly complete elements.

Taxon	Femur Length	DATA SOURCE	BODY LENGTH EST. (mm)	MASS (kg)
<i>Mahakala</i>	80	IGM 100/1033	650	0.700
<i>Buitreraptor</i>	145*	Makovicky et al., 2005	1250	4.700
<i>Unenlagia</i>	380*	Novas, 1997	2000 ^e	105.700
<i>Rahonavis</i>	88	Forster et al., 1998	700 ^e	0.900
<i>Sinornithosaurus</i>	148*	Xu et al. 1999	1280	5.000
<i>Microraptor zhaoianus</i>	75	Hwang et al. 2002	630	0.600
<i>Microraptor zhaoianus</i>	53	Xu et al., 2001	470	0.200
<i>Microraptor gui</i>	100	IVPP V13352	770	1.400
<i>Graciliraptor</i>	130*	IVPP V13474	1100	3.300
<i>Velociraptor</i>	238	Norell and Makovicky, 1999	1500 ^e	23.406
<i>Deinonychus</i>	440	Holtz, 1994	3000 ^e	169.500
<i>Saurornitholestes</i>	225	MOR 660	1950	19.500
<i>Adasaurus</i>	273	IGM 100/20	2390	36.400
<i>Achillobator</i>	550	Perle et al., 1999	4850	347.900
<i>S. mongliensis</i>	200*	cast of AMNH 6515	1740	13.300
<i>Troodon</i>	300*	NMC 12340	2600	49.350
<i>Sinornithoides</i>	140	Xu et al., 2000	1200	4.200
<i>Jinfengopteryx</i>	70	Ji et al., 2005	548 ^e	0.500
<i>Mei long</i>	81	Xu and Norell, 2004	530 ^e	0.700
<i>Sinovenator</i>	118	Xu et al., 2002	1000	2.400
<i>Archaeopteryx</i>	70	Zhou and Zhang, 2002	580	0.500
<i>Jeholornis</i>	75	Zhou and Zhang, 2002	688 ^e	0.600
<i>Sapeornis</i>	81	Zhou and Zhang, 2002	400 ^e	0.726
<i>Confuciusornis</i>	42	Chiappe et al., 1999	250 ^e	0.100
<i>Yixianornis</i>	41	Clarke et al., 2006	234 ^e	0.100
<i>Apsaravis</i>	41*	IGM 100/1017	175 ^e	0.100
<i>Shanag</i>	55	Est. from <i>M. zhaoianus</i>	450	0.200

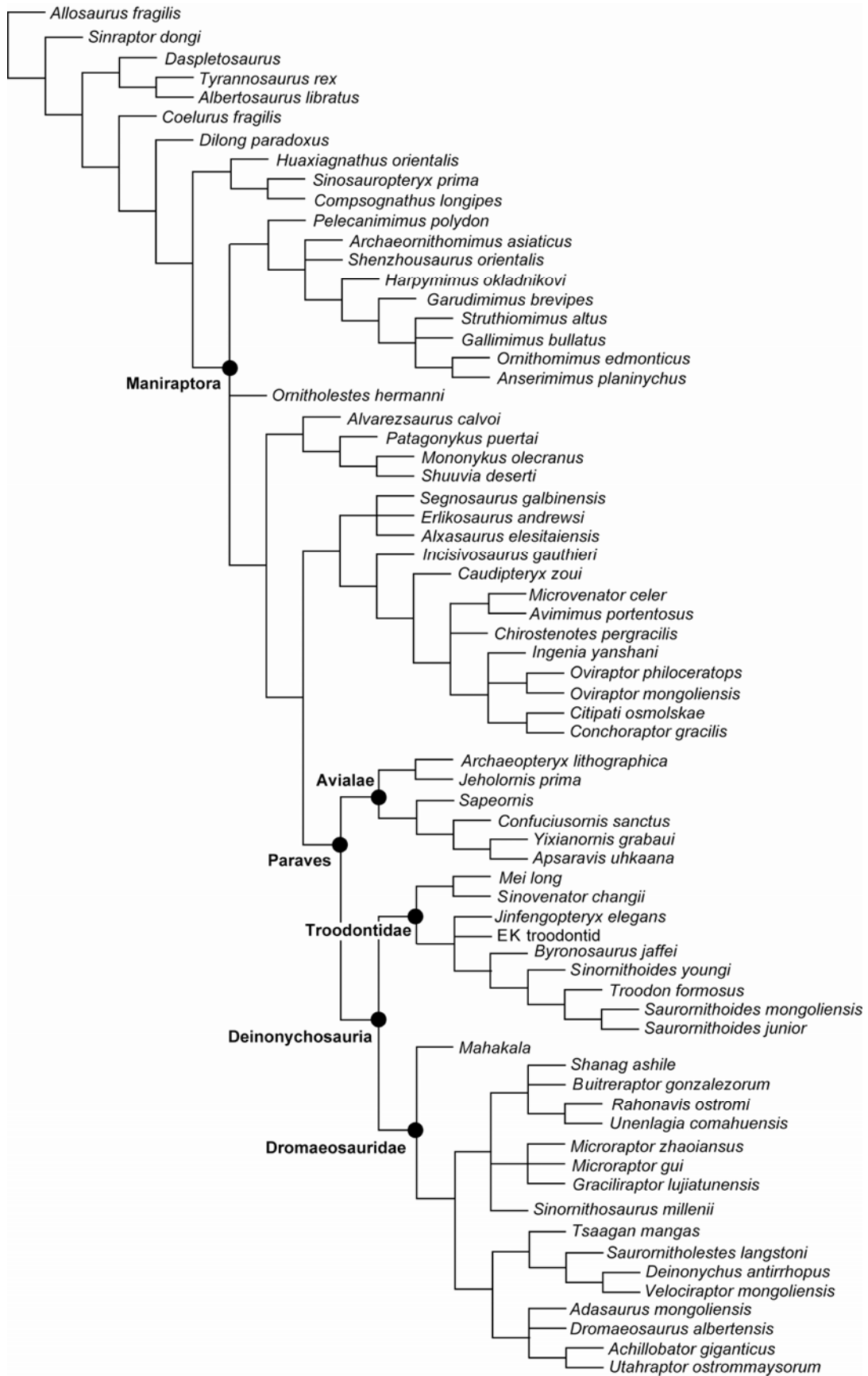


Fig. S1. Phylogenetic relationships of *Mahakala omnogovae* within Coelurosauria. Adams consensus of 1296 trees depicting the phylogenetic placement of *Mahakala omnogovae* within the Coelurosauria as the basal most dromaeosaurid. This topology is based on a maximum parsimony analysis of 251 characters in 69 taxa resulting in 1296 most parsimonious trees of 867 steps (CI= 0.3541, RI=0.7167) found in 439 out of the 1000 replicates.

Strict consensus differs in reduced resolution within the *Adasaurus*, *Dromaeosaurus*, *Achillobator*, *Utahraptor* clade due to lability in placement of *Dromaeosaurus*; reduced resolution within the *Unenlagia*, *Rahonavis*, *Buitreraptor*, *Shanag* clade due to lability in placement of *Shanag*; and reduced resolution within oviraptorosaurs more derived than *Incisivosaurus gauthieri*.

Characters uniting *Mahakala* with other dromaeosaurids include the absence of an accessory tympanic recess dorsal to the crista interfenestralis, elongate paroccipital process with parallel dorsal and ventral edges that twist rostrally distally, and the presence of a distinct ginglymus on the distal end of metatarsal II.

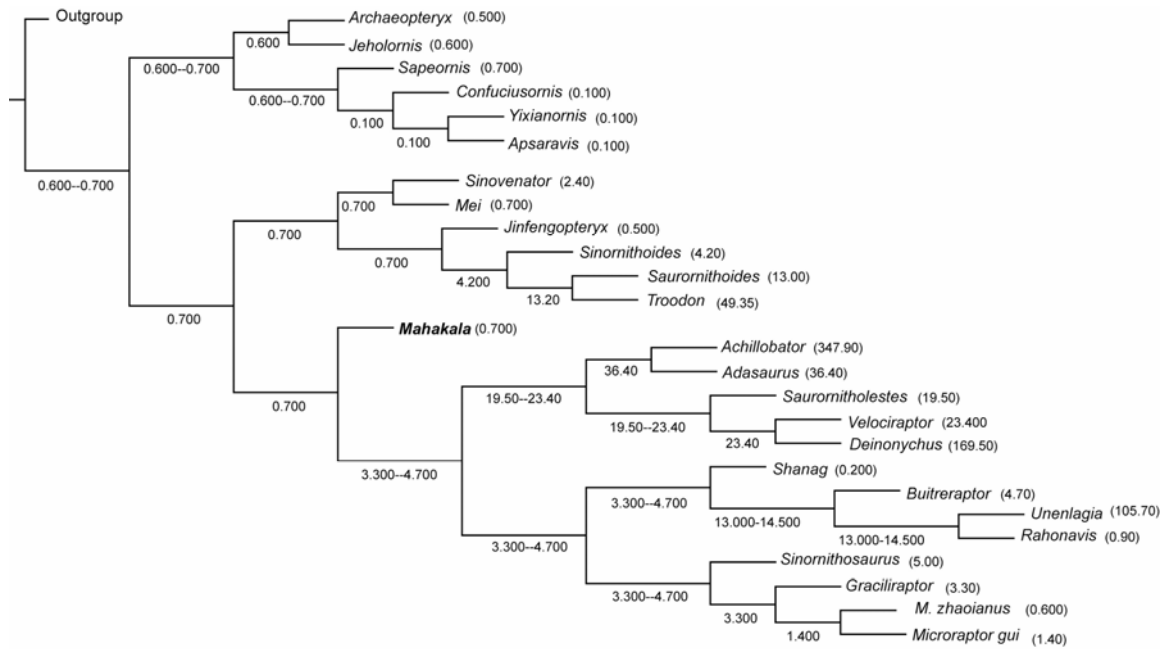


Fig. S2. Body mass optimization. The above tree shows the most parsimonious reconstructions of the ancestral states used for the tree shown in Figure 3. Internal nodes are labeled either with the single most parsimonious assignment or with the range of possible values that are equally optimal. Values represent body mass estimates in kilograms.

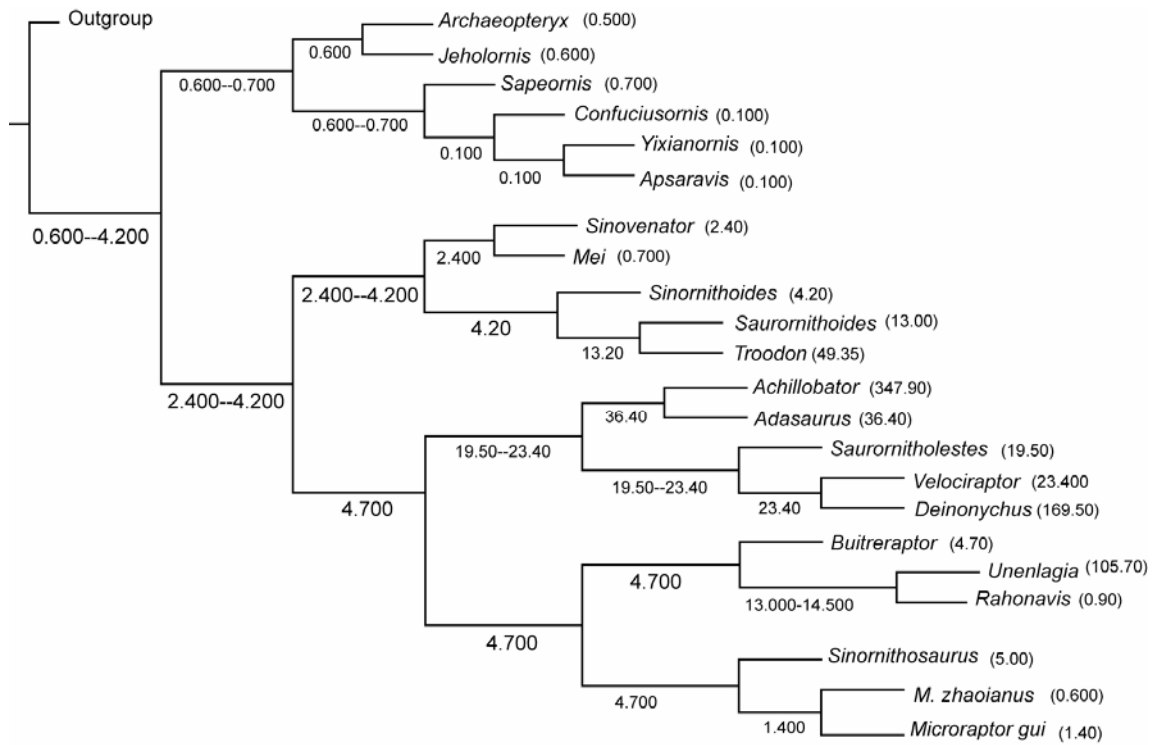


Fig. S3. Decisiveness of *Mahakala* and the present study for understanding paravian body size evolution: effects of inclusion of *Mahakala*, discovery of *Jinfengopteryx* as a troodontid and current phylogenetic hypothesis. The above tree shows the most parsimonious reconstructions of the ancestral states as they would have been reconstructed prior the discovery of *Mahakala* and the results of this study and phylogenetic analysis. *Mahakala*, *Shanag*, *Graciliraptor* and *Jinfengopteryx* are excluded. Internal nodes are labeled either with the single most parsimonious assignment or with the range of possible values that are equally optimal. Values represent body mass in kilograms. Note that the Deinonychosauria node is reconstructed with a range of 2.4 to 4.2 kilograms as opposed to 700 grams; and that the Paraves node is extremely ambiguous with equally parsimonious reconstructions varying between 0.6 kilograms to 4.2 kilograms—nearly an order of magnitude variation the mean of which being demonstrably larger than all basal avialans.

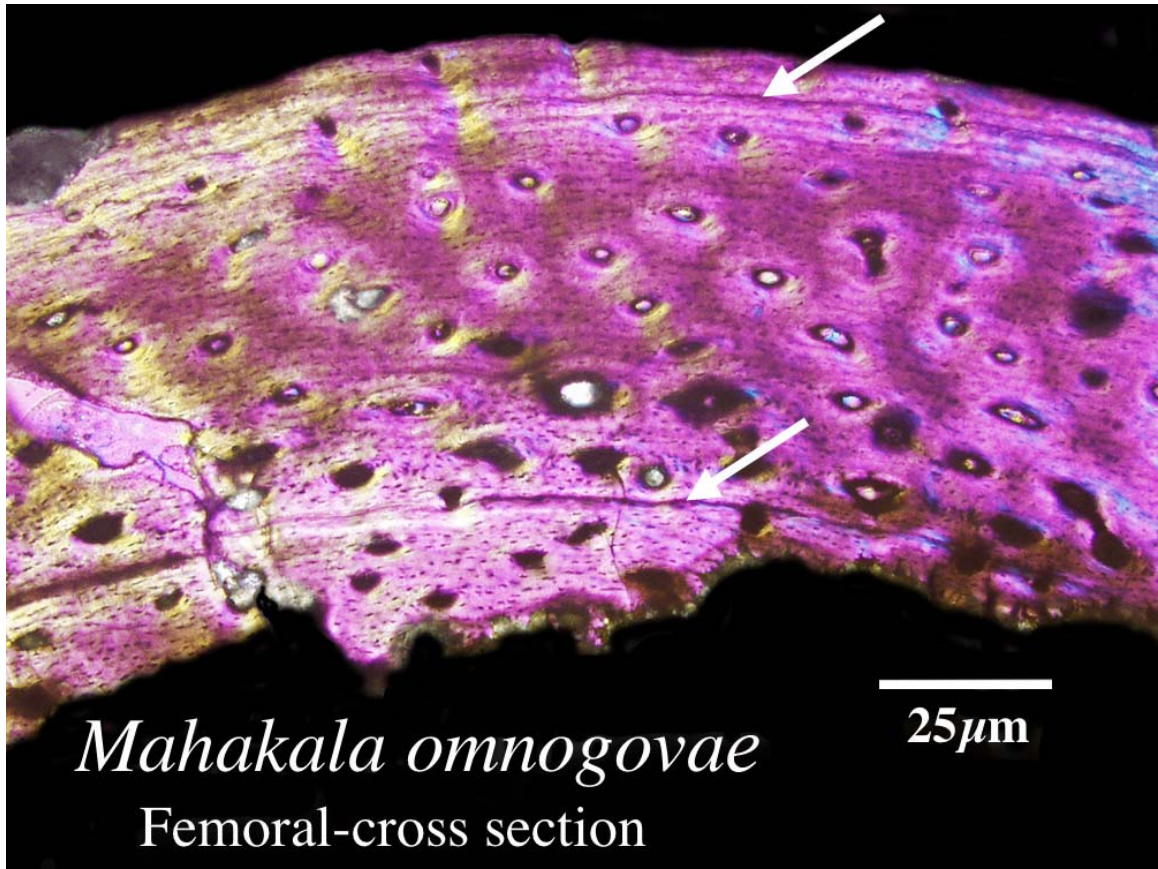


Fig. S4. Histological section from the femoral shaft of *Mahakala omnogovae* (IGM 100/1033), shown in polarized microscopy. Arrows point to lines of arrested growth (LAGs).

PARAVIAN LENGTH ESTIMATION

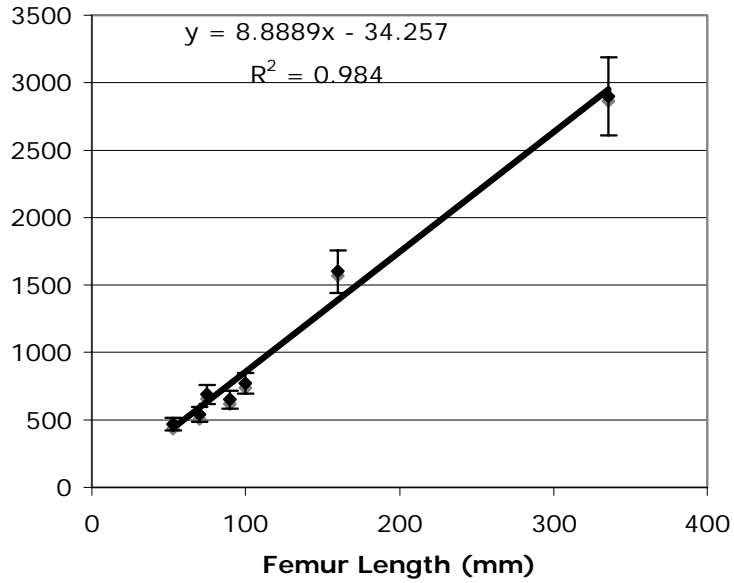


Fig. S5. Body length estimation. Regression used to estimate body length from femoral length. Taxa used in the regression are: *Deinonychus antirrhopus* (Holtz, 1994), *Sinornithosaurus milleni* (Xu et al., 1999), *Jeholornis prima* (Zhou and Zhang, 2002), *Microraptor zhaoianus* (Xu et al., 2001), *Microraptor gui* (IVPP V13352), *Velociraptor mongoliensis* (IGM 100/982), and *Jinfengopteryx elegans* (Ji et al., 2005). Taxa were selected to because they are either complete individuals or represent near endpoints in body length.

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