

## APPENDIX 1. Characters used in phylogenetic analysis.

### Characters from Dodson et al. (2004)

1. Rostral, size and shape: triangular in lateral view with short dorsal and ventral processes (0); enlarged with deeply concave caudal margin and hypertrophied dorsal and ventral processes (1).
2. External naris, size and position: small, restricted to dorsal one-third of snout (0); large, expanded to occupy most of the depth of the snout (1), Brown and Schlaikjer (1940b).
3. Premaxillary septum: absent (0); present, rostral premaxillae lie directly on one another (1).
4. Premaxillary septum, shape: subcircular (0); rostrally elongate (1).
5. Premaxilla, thickened narial strut along caudal margin of the premaxillary septum: absent (0); present (1), Forster et al. (1993).
6. Premaxilla, narial strut orientation: rostrally inclined (0); caudally inclined (1), Forster et al. (1993).
7. Premaxilla, narial strut with a bony flange on caudal margin: present (0); reduced (1), absent [state added] (2) ORDERED
8. Premaxilla, interpremaxillary fossa perforating premaxillary septum: absent (0); present (1), Forster (1996a).
9. Premaxilla, recess in ventral portion of septum: absent (0); present (1), Forster et al. (1993).
10. Premaxilla, size of recess in septum: small, slight in-pocketing along ventral aspect of septal fossa (0); large, deeply recessed into premaxilla (1), Forster et al. (1993).
11. Premaxilla, premaxillary (narial) process extending into the external naris from the caudoventral margin of the premaxillary septum: absent (0); present (1), Forster (1990).
12. Premaxilla, recess on lateral surface of the premaxillary (narial) process: absent (0); present (1), Forster (1990).
13. Premaxilla, ventral expansion of the caudoventral oral margin: absent, caudoventral oral margin of premaxilla level with alveolar margin of the maxilla (0); present, expanded ventrally to extend well below alveolar margin of the maxilla (1), Forster (1990).

14. Premaxilla, caudal tip of caudoventral process inserts into an embayment in the nasal and is surrounded by the nasal: present (0); absent (1), Forster et al. (1993).
15. Premaxilla, forked distal end of caudoventral process: absent (0); present (1), Forster et al. (1993).
16. External antorbital fenestra, size : large, 20% or more length of body of maxilla (0); greatly reduced to less than 10% length of body of maxilla, or absent (1), Granger and Gregory (1923), Chinnery and Weishampel (1998).
17. Nasal, ornamentation: absent (0); horncore (1); pachyostotic boss (2), Sampson (1995).
18. Nasal, ornamentation position: centered caudal or caudodorsal to internal naris (0); shifted forward, centered dorsal or rostrodorsal to endonaris (1), Forster (1990).
19. Nasal, horncore length: small, length of horncore less than 15% basal skull length (0); moderate to large, length of horncore 20% or more of basal skull length (1), Forster (1990).
20. Lacrimal, size: large, forms 50% or more of the rostral orbital margin (0); small, forms 40% or less of the rostral orbital margin (1), Brown and Schlaikjer (1940b).
21. Postorbital, supraorbital ornamentation: absent (0); present (1).
22. Postorbital, supraorbital ornamentation: horncore (0) rugose boss (1).
23. Postorbital, position of supraorbital ornamentation: centered rostrodorsal or dorsal to orbit (0); centered caudodorsal or caudal to orbit (1), Lehman (1996).
24. Postorbital, length of supraorbital horncore: elongate, greater than 35% basal skull length (0); short, less than 15% basal skull length (1), Forster (1990).
25. Postorbital, curvature of supraorbital horncore in adults: caudally recurved (0); straight or rostrally curved (1), Forster et al. (1993).
26. Prefrontal-prefrontal contact: absent (0); present (1), Lambe (1915), Forster (1990), Sampson (1995).
27. Jugal infratemporal flange: absent (0); present, contacts jugal process of squamosal below the infratemporal fenestra (1), Brown and Schlaikjer (1940b), Forster (1990).
28. Quadratojugal, position of contact with jugal and quadrate: jugal, quadratojugal, quadrate contact in a rostral to caudal order (0); jugal, quadratojugal, quadrate contact in a lateral to medial order (1), Forster (1990).

29. Supracranial cavity complex: absent (0); present, supracranial cavities narrow and shallow, do not underlie supraorbital ornamentation (1); present, supracranial cavities broad, underlie supraorbital ornamentation and may be confluent with extensive cornual sinuses (2), Brown and Schlaikjer (1940b), Forster (1990), Sampson (1995), Forster (1996a).
30. Frontal, contribution to orbital margin: present (0); absent (1), Brown and Schlaikjer (1940b).
31. Frontal fontanelle, shape: rostrocaudally long and uniformly narrow transversely (0); key-hole shaped with a broad rostral half (1); broadly oval to circular (2), Forster (1996a).
32. Parietosquamosal frill, length relative to basal skull length: elongate, 0.80 or more (0); shortened, 0.70 or less (1), Hatcher et al. (1907), Lehman (1990).
33. Parietosquamosal frill, marginal undulations: absent (0); present (1), Gilmore (1917).
34. Parietal, imbrication effect on lateral margin of frill in adults: absent (0); present (1), Sampson et al. (1997).
35. Squamosal, length relative to parietal: equal or subequal in length (0); squamosal much shorter than parietal (1).
36. Squamosal, rostromedial lamina forming the caudolateral floor of dorsotemporal fossa: absent (0); present (1), Dodson (1986).
37. Squamosal-quadratus contact: socketlike cotylus on squamosal for ball-like quadratus head (0); elongate groove on squamosal to receive lamina of quadratus (1), Forster (1990).
38. Parietal fenestra, orientation: long axis directed transversely (0); long axis directed axially (1), Forster (1990).
39. Parietal fenestra, maximum proximodistal diameter: 40% or less total parietal length (0); 45% or more total parietal length (1), adapted from Forster et al. (1993).
40. Parietal, accessory fenestra medial to the rostral end of the infratemporal fenestra: absent (0); present (1), Hatcher et al. (1907), Forster (1996b).
41. Parietal, median bar: narrow and straplike, width less than .05 total parietal length (0); wide, 0.15 or more total parietal length (1).
42. Epoccipitals on parietal and squamosal: absent (0); present (1).
43. Epoccipital crossing squamosal-parietal contact: absent (0); present (1).

44. Epoccipitals, pattern of fusion to frill margin: occurs from rostral to caudal (0); occurs from caudal to rostral (1), Lehman (1990).
45. Squamosal epoccipital, shape: crescentic or ellipsoidal (0); triangular (1), or low, spindle-shaped and barely distinct from squamosal margin in adults (2) ORDERED
46. Parietal epoccipitals, number per side: one to three (0); six to eight (1).
47. Parietal epoccipital, most median epoccipital (locus 1) developed into a curved process with pronounced external sulci and ridges: absent (0); present (1).
48. Parietal epoccipital, orientation at locus 1 relative to parietal: caudally directed (0) dorsal to rostrally directed (1).
49. Parietal epoccipital, locus 2 developed into a curved process, with pronounced external sulci and ridges: absent (0); present (1).
50. Parietal epoccipital, orientation at locus 2: caudally directed from and perpendicular to parietal margin (0); medially directed, come off the parietal at an angle (0).
51. Parietal epoccipital, locus 3 modified into a large hornlike process: absent (0); present (1).
52. Basioccipital, contribution to occipital condyle: large, forms more than one-third of condyle (0); reduced, forms ventral one-third of condyle only (1), Brown and Schlaikjer (1940b).
53. Frontal, contribution to exit for c.n. I: present (0); absent, enclosed entirely by ossifications of the interorbital septum (1), Forster (1990).
54. Supraoccipital, contribution to foramen magnum: present (0); absent, eliminated from margin by exoccipital-exoccipital contact on midline (1), Brown and Schlaikjer (1940b).
55. Exoccipital, number of exits for c.nn. X, XI, XII: three (0); two (1), Brown and Schlaikjer (1940b), Forster (1990).
56. Lower jaw, level of articulation with quadrate: same as occlusal surface of tooth row (0); substantially ventral to tooth row (1), Ostrom (1964a), Forster (1990).
57. Predentary, orientation of triturating surface: nearly horizontal (0); inclined steeply laterally (1), Lehman (1990), Forster (1990).
58. Dentary, caudal extent of tooth row: terminates medial to the coronoid process (0); terminates caudal to the coronoid process (1), Brown and Schlaikjer (1940b).

59. Dentary, shape of the coronoid process: low, with gently convex apex and no neck (0); high, expanded into a rostrally projecting hook at apex, constricted neck present (1), Lull (1933).
60. Tooth, number of roots: one (0); two (1).
61. Tooth vertical replacement series: one or two replacement teeth (0); more than two replacement teeth (1).
62. Tooth ornamentation: subsidiary ridges present, extend from margin to base of tooth (0); subsidiary ridges reduced, present only at margin of teeth (1).
63. Atlas, neural arch orientation: nearly vertical (0); steeply inclined caudally (1), Brown and Schlaikjer (1940b).
64. Sacrum, number of fused vertebrae: eight or less (0); ten or more (1).
65. Sacrum, deep longitudinal channel on ventral surface: present (0); absent (1), Lambe (1915), Lehman (1990).
66. Sternum, shape: elongate and narrow (0); short and broad (1), Brown and Schlaikjer (1940b).
67. Manual and pedal unguals, shape: clawlike (0); hooflike (1), Brown (1914, Chinnery and Weishampel (1998).
68. Ilium, laterally everted shelf on dorsal margin: absent (0); present (1), Hatcher et al. (1907).
69. Ilium, supracetabular process on dorsal margin over caudal part of acetabulum: absent (0); present (1).
70. Ischium, cross-sectional shape of shaft: ovoid (0); laterally compressed and bladelike, narrow along dorsal margin (1).
71. Ischium, orientation of shaft: nearly straight (0); slightly decurved (1); broadly and continuously curved (2), Brown and Schlaikjer (1940b).
72. Femur, coalescence of greater and cranial trochanters: absent (0); present (1), Brown and Schlaikjer (1940b).
73. Femur-tibia proportion: tibia longer than femur (0); femur longer than tibia (1), Brown and Schlaikjer (1940b).

**Characters added by Wu et al. (2007)**

74. Position of nasal horn: posterior (0) over front of nares (1) (Forster, 1990).
75. Transversely arched vascular traces across the anterior surface of the nasal horn core:  
absent (0) or present (1) (Wu et al., 2007)
76. Process projecting into the intermaxillary fossa/fenestra: absent (0) or present (1).  
ORDERED (Wu et al., 2007).

## New Characters

77. Premaxilla, Premaxilla: height exceeds length (0), at least as long as tall (1)
78. Premaxilla, does not contact lacrimal (0) or extends caudally to contact lacrimal (1)
79. Premaxilla: anteroventral margin of narial fossa bounded by a raised rim: absent (0) or present (1)
80. Premaxilla, extension of the buccal fossa of the maxilla onto the caudoventral surface of the premaxilla: absent (0) or present (1)
81. Premaxilla, maxillary process broad and spatulate (0) or slender and splint-like (1),
82. Premaxilla, narial fossa broadly U-shaped (0) or tapering anteriorly and subtriangular (1)
83. Premaxilla, caudodorsal ramus straight in lateral view (0) or distinctly upturned relative to main body of premaxilla in lateral view (1)
84. Narial strut of premaxilla: relatively narrow along its length (0) or subtriangular, base of narial strut broad, about 50% the length of the narial strut (1) Premaxilla, premaxillary fossa a simple depression, little or no posteroventral excavation of maxilla (0) or with extensive posteroventral excavation hollowing the premaxilla and narial strut and creating a medial pocket (1)
85. Premaxilla, premaxillary fossa a simple depression (0) or extending posteroventrally to excavate the interior of the narial strut and premaxilla.
86. Premaxilla, descending process extending from dorsal margin of premaxillary fossa into the premaxillary fossa: absent (0) or present (1)
87. Squamosals with limited lateral expansion (0) or squamosals with a prominent lateral wing contributing to frill (1)
88. Squamosal, surface of caudal ramus flat (0) or dorsally concave (1)
89. Squamosal, caudalmost epoccipital small (0) or enlarged (1)
90. Parietal with tall, bladelike sagittal keel extending to the caudal margin of the parietal (0) or sagittal crest absent (1)
91. Parietal fenestrae extended laterally to squamosals: absent (0) or present (1),
92. Parietal, caudal margin weakly notched or convex (0) or strongly notched, angle between lateral rami of parietal posterior bar less than 120° (1)
93. Parietal, epoccipital 1 prominent (0), low, reduced (1)
94. Parietal posterior bar: platelike or straplike in cross-section (0), rodlike, thickness approaching anteroposterior width (1)

95. Nasals and frontals unfused in adults (0) or coossified in adults (1)
96. Postorbital horns dorsally directed in anterior view (0) or dorsolaterally directed (1),
97. Palpebral, free (0), or incorporated into orbital rim and forming a thick boss along the anterodorsal margin of the orbit (1)
98. Jugal postorbital process slender (0) or broad, subequal to ventral ramus of jugal in width, postorbital bar broad (1)
99. Jugal, thickened boss along ventral margin of orbit weakly developed or absent (0) or prominent (1)
100. Supraoccipital with prominent depression dorsal to foramen magnum: absent (0) or present (1)
101. Exoccipitals long and strap-like (0) or terminally expanded and subtriangular (1),
102. Epijugal large and horn-like (0) or low and blunt (1)
103. Predentary: edges sharp (0) or with a broad, concave triturating surface extending to the tip of the predentary (1)
104. Predentary caudodorsal processes short (0) or elongate (1)
105. Dentary short and deep (0) or elongate (1)
106. Dentary: rostral hook of coronoid process weakly developed or absent (0) or hook prominent (1),
107. Splenial tall and covering much of medial surface of dentary (0) or long and low, covering ventral part of dentary (1)
108. Teeth: at least 20 teeth in dentary and maxilla: absent (0) or present (1)
109. Axis vertebra, axis centrum short (0) or elongate, length of centrum subequal to height (1)
110. Sacral vertebrae: sacral transverse processes short (0) or elongate (1)
111. Sacral vertebrae: sacrum strongly arched in lateral view: absent (0) or present (1),
112. Caudal vertebrae: caudal neural spines elongate (0) or short (1)
113. Scapula, lateral ridge extending the length of the scapular blade: absent (0) or present (1)
114. Scapula, lateral ridge terminates on anterior margin of scapular blade (0) or ends on lateral surface of the blade (1)
115. Coracoid, coracoid and scapula make equal contributions to glenoid (0) or coracoid contribution to glenoid reduced (1) (Brown and Schlaikjer, 1940)
116. Humerus, deltopectoral crest short (0) or deltopectoral crest elongate, apex of crest extended at least to midlength of shaft (1),
117. Femur, fourth trochanter with a distally projecting hook (0) or reduced to a low ridge (1) (Makovicky and Norell, 2006)
118. Pubis, distal end of prepubis weakly expanded (0) or strongly expanded, more than 200% the width of the shaft (1)
119. Prepubic process short (0) or elongate, subequal to preacetabular blade of ilium in length (1) (Makovicky and Norell, 2006)

#### **DATA MATRIX**

“!” = coded as inapplicable.

Character 10 was recoded as '1' for *Eotriceratops*; character 45 was recoded as '2' for *Triceratops* and *Torosaurus*; character 22 was recoded as '0&1' for *Chasmosaurus*;

*Protoceratops andrewsi*

## Leptoceratopsidae

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### *Zuniceratops christopheri*

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## *Turanoceratops tardabilis*

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### *Avaceratops lammersi*

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*Centrosaurus apertus*

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0!1110000!!!1001000010110111111111111010111

*Styracosaurus albertensis*

01100!!00!0!110110111001!1111101111111001111010111111111111110111101110  
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## *Einiosaurus procurvicornis*

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*Achelousaurus horneri*

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Pachyrhinosaurus spp.

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0!1110000!!!!100100101!110??11111111??1?????111

*Chasmosaurus* spp.

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## *Mojoceratops peritania*

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## *Agujaceratops mariscalensis*

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*Pentaceratops sternbergii*  
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*Anchiceratops ornatus*

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## *Arrhinoceratops brachyops*

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*Torosaurus* spp.

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*Triceratops* spp.

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## *Eotriceratops xerinsularis*

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