

# Supporting Information

for

## Tyrant dinosaur evolution tracks the rise and fall of Late Cretaceous oceans

Mark A. Loewen<sup>1,\*</sup>, Randall B. Irmis<sup>1</sup>, Joseph J. W. Sertich<sup>2</sup>, Philip J. Currie<sup>3</sup> Scott D. Sampson<sup>1,2</sup>

**1**Natural History Museum of Utah and Department of Geology & Geophysics, University of Utah, 301 Wakara Way, Salt Lake City, UT 84108-1214, United States of America, **2**Department of Earth Sciences, Denver Museum of Nature & Science, 2001 Colorado Blvd, Denver, CO 80205, United States of America, **3**University of Alberta, CW405 Biological Sciences, Edmonton, Alberta T6G 2E9, Canada

\*Correspondence and requests for materials should be addressed to: M.A.L. (mloewen@nhmu.utah.edu).

### Table of Contents

1. Table S1: Institutional Abbreviations	2
2. Table S2: Sources of Character Scoring	3
3. Phylogenetic Analysis Characters	4
4. Table S3: Taxon Scorings	47
5. Figure S1: Numbered Nodes for the Synapomorphy List	55
6. Table S4: Synapomorphy List	56
7. Table S5: Stratigraphic Position of Select Taxa	59
8. Table S6. Results of the Biogeographic Analysis	60
9. Additional References	68

## TABLE S1: INSTITUTIONAL ABBREVIATIONS

**AMNH**, American Museum of Natural History, New York, New York; **ANSP**, Academy of Natural Sciences of Philadelphia, Philadelphia, Pennsylvania; **BSP**; Bürgermeister-Müller-Museum in Solnhofen, Germany; **BSPAS**, Bayerische Staatsammlung für Paläontologie und historische Geologie, Munich, Germany; **BYU**, Brigham Young University Museum of Paleontology, Provo, Utah; **CEU**, Utah State University College of Eastern Utah Prehistoric Museum, Price, Utah; **CM**, Carnegie Museum of Natural History, Pittsburgh, Pennsylvania; **DNM**, Dinosaur National Monument, Jensen, Utah; **FMNH**, Field Museum of Natural History, Chicago, Illinois; **FRDC**, Fossil Research and Development Center, Gansu Bureau of Geology and Mineral Resources Exploration, Lanzhou, P. R. China; **GIN**, Institute of Geology, Mongolian Academy of Sciences, Ulaan Bataar, Mongolia; **GR**, Ghost Ranch Ruth Hall Museum of Paleontology, Ghost Ranch, New Mexico; **GVM**, (see also NGMC) National Geological Museum of China, Beijing, China; **HMN**, Humboldt Museum für Naturkunde, Humboldt, Germany; **IGM**, Mongolian Institute of Geology, Ulaan Bataar, Mongolia; **IVPP**, Institute of Vertebrate Paleontology and Paleoanthropology, Beijing, China; **JM**, Jura Museum in Eichstätt, Germany; **JME**, Jura-Museum Eichstätt, Eichstätt, Germany; **KZV**, Kazuo County Museum, western Liaoning Province, China; **LACM**, Los Angeles County Museum, Los Angeles, California; **LH**, Museo de Cuenca, Cuenca, Spain (provisionally housed at the Unidad de Paleontología of the Universidad Autónoma de Madrid, Madrid, Spain); **LH-PV**, Long Hao Institute for Stratigraphic Paleontology, Hohhot, Nei Mongol Autonomous Region, China; **MACN**, Museo Argentino de Ciencias Naturales, Buenos Aires, Argentina; **MNA**, Museum of Northern Arizona, Flagstaff, Arizona; **MNHN**, Muséum National d'Histoire Naturelle, Paris, France; **MOR**, Museum of the Rockies, Bozeman, Montana; **MWC**, Museum of Western Colorado, Fruita, Colorado; **MWIG**, Museum of Isle of Wight Geology, Sandown, Isle of Wight, United Kingdom; **NGMC**, National Geological Museum of China, Beijing, China; **NIGP**, Nanjing Institute of Geology and Palaeontology, Nanjing, China; **NHM**, Natural History Museum, London, United Kingdom; Canadian Museum of Nature (formerly National Museum of Canada), Ottawa, Ontario, Canada; **NMMNH**, New Mexico Museum of Natural History, Albuquerque, New Mexico; **OUMNH**, Oxford Museum of Natural History, Oxford, United Kingdom; **PIN**, Paleontological Institute, Moscow, Russia; **PVL**, Paleontología Vertebrados, Fundación Miguel Lillo, Tucumán, Argentina; **RMM**, McWane Science Center (formerly Red Mountain Museum) Birmingham, Alabama; **ROM**, Royal Ontario Museum, Toronto, Ontario, Canada; **SBA**, Soprintendenze per i Beni Archeologici di Salerno, Avellino Benevento e Caserta, Salerno, Italy; **TMP**, Royal Tyrell Museum of Paleontology, Drumheller, Alberta, Canada; **TPII**, Thanksgiving Point Institute, Inc. (North American Museum of Ancient Life), Lehi, Utah; **UALVP**, University of Alberta Laboratory of Vertebrate Paleontology, Edmonton, Alberta, Canada; **UCMP**, University of California Museum of Paleontology, Berkeley, California; **UMNH**, Utah Museum of Natural History, now the Natural History Museum of Utah (the previous numbering system has been retained), Salt Lake City, Utah; **USNM**, National Museum of Natural History, Smithsonian Institution, Washington, DC; **UUPV**, University of Utah Vertebrate Paleontology (now UMNH), Salt Lake City, Utah; **YPM**, Peabody Museum, Yale University, New Haven, Connecticut; **ZIN**, Paleoherpetological Collection, Zoological Institute of the Russian Academy of Sciences, Saint Petersburg, Russia; **ZPAL**, Institute of Paleobiology, Polish Academy of Sciences, Warszawa, Poland.

## TABLE S2: SOURCES OF CHARACTER SCORING

Character scorings were based upon the following specimens and references are listed if they were also used to score taxa:

<u>Taxon</u>	<u>Source</u>
<i>Tawa hallae</i>	GR 241 (holotype), 155, 242, 243, 244; Nesbitt et al., 2009
<i>Coelophysis bauri</i>	AMNH FR 7223, 7224, 7239, 7241, 7242; MNA V3315;
<i>Dilophosaurus wetherilli</i>	UCMP 37302 (holotype), 37303, 77270
<i>Ceratosaurus nasicornis</i>	USNM 4735 (holotype); BYU 12893, 13024; MWC 1, UMNH VP 5278
<i>Dubreuillosaurus valesdunensis</i>	MNHN 1998-13; Allain 2002; Allain 2005
<i>Piatnitzkysaurus floresi</i>	PVL 4073 (holotype); MACN Pv CH895; Bonaparte, 1986; Rauhut, 2004
<i>Eustreptospondylus oxoniensis</i>	OUMNH J.3311; Sadleir et al., 2008
<i>Monolophosaurus jiangi</i>	IVPP 84019; Zhao and Currie 1993; Brusatte et al., 2010; Zhao et al., 2010
<i>Sinraptor dongi</i>	IVPP 10500; Currie and Zhao, 1993
<i>Allosaurus fragilis</i>	USNM 4734 (holotype); DNM 2560; UMNH CLDQ material
<i>Tanycolagreus topwilsoni</i>	TPII 2000-09-29
<i>Coelurus fragilis</i>	YPM 1991-1995; 2010; 9162
<i>Sinosauroptryx prima</i>	GVM 2123; NIGP 127586; (holotype); NIGP 127587; Currie and Chen, 2001
<i>Compsognathus longipes</i>	Peyer, 2006
<i>Juravenator starki</i>	JME Sch 200; Chiappe and Göhlich, 2010
<i>Scipionyx samniticus</i>	SBA-SA 163760; Dal Sasso and Maganuco, 2011
<i>Ornitholestes hermanni</i>	AMNH 619
<i>Haplocheirus sollers</i>	IVPP V15988
<i>Utahraptor ostrommaysorum</i>	CEUM 1156; Senter et al., in prep
<i>Deinonychus antirrhopus</i>	AMNH 3015, 3038; YPM 5201-5265; Ostrom, 1969
<i>Linheraptor exquisitus</i>	IVPP V16923
<i>Velociraptor mongoliensis</i>	AMNH FR 6515, IGM 100/24, 25, 976, 982, 985, PIN 3143/8, ZPAL MgD-8/97; Norell and Makovicky, 1997, 1999; Barsbold and Osmólska, 1999
<i>Archaeopteryx lithographica</i>	BMNH 37001; HMN 1880; JM 2257; BSP 1999; WDC-CSG-100; Wellnhofer, 1974; Wellnhofer, 1992; Elzanowski and Wellnhofer, 1996; Mayr et al., 2007
<i>Pelecanimimus polydon</i>	LH 7777; Perez-Moreno et al., 1994
<i>Shenzhousaurus orientalis</i>	NGMC 97-4-002
<i>Harpyimimus okladnikovi</i>	IGM 100/29; Kobayashi and Barsbold, 2005
<i>Gallimimus bullatus</i>	IGM 100/1133; MgD-I/1a
<i>Proceratosaurus bradleyi</i>	NHM R 4860; Rauhut et al., 2010
<i>Kileskus aristotocus</i>	ZIN PH 5/117 etc; Averianov et al., 2010
<i>Guanlong wucaii</i>	IVPP V 14531, IVPP V 14532
<i>Sinotyrannus kazuoensis</i>	KZV-001; Ji et al., 2009
<i>Juratyrant langhami</i>	OUMNH J.3311; Benson, 2008; Brusatte et al., 2012
<i>Stokesosaurus clevelandi</i>	UMNH VP 7434 (UUPV 2938); UMNH VP 6383 (UUPV 2320)
<i>Dilong paradoxus</i>	IVPP V11579, IVPP V14242, IVPP V14243
<i>Eotyrannus lengi</i>	MIWG 1997.550
<i>Bagaraatan ostromi</i>	ZPAL MgD-1/108; Osmólska, 1996
<i>Raptorex kriegsteini</i>	LH PV18
<i>Dryptosaurus aquilunguis</i>	ANSP 9995; AMNH 2438
<i>Xiongguanlong baimoensis</i>	FRDC-GS JB16-2-1; Li et al., 2009
<i>Alectrosaurus olseni</i>	AMNH 6554
<i>Appalachiosaurus montgomeriensis</i>	RMM 6670
<i>Alioramus altai</i>	IGM 100/1844
<i>Alioramus remotus</i>	PIN 3141/1
<i>Gorgosaurus libratus</i>	ROM 1247; TMP 91.36.500, 94.12.602, 95.5.1; UALVP 10; USNM 12814
<i>Albertosaurus sarcophagus</i>	ROM 807; TMP 85.98.1; TMP 81.10.1; TMP 86.64.1
Dinosaur Park Fm. tyrannosaurid B	TMP 85.62.1; TMP 94.143.1
<i>Daspletosaurus torosus</i>	NMC 8506; NMC 1154; NMC 350
Two Medicine Fm. tyrannosaurid	MOR 590; MOR cast 093
<i>Teratophoneus curriei</i>	UMNH VP 16690; BYU 8120 (8120/9396, 8120/9397, 826/9402 & 9398)
<i>Bistahieversor sealeyi</i>	NMMNH P-27469; NMMNH P-25049; USNM 8355
<i>Lythronax argestes</i>	UMNH VP 20200
<i>Tyrannosaurus rex</i>	AMNH 5029; BHI 3033; FMNH PR 2081; MOR 008, 555; RTMP 81.6.1;
<i>Tarbosaurus bataar</i>	GIN 100/69; GIN 107/1; GIN 107/2; UMNH VPC 32.4; ZPAL MgD-I/4
<i>Zhuchengtyrannus magnus</i>	ZCDM V0031

## PHYLOGENETIC ANALYSIS CHARACTERS

The 501 characters (303 cranial and 198 postcranial) used in the phylogenetic analysis are listed below. Recent previous usage of characters is indicated by citations in parentheses. Characters presented in Brusatte et al. (2009) were largely derived from Carr and Williamson, (2010), which was in press at the time. Many of the characters of Li et al. (2009); Sereno et al. (2009); Brusatte et al. (2009); and Carr and Williamson, (2010) are restated in Brusatte et al. (2010). Citations previous to 2009 are generally not included, as many are reviewed in Sereno and Brusatte (2009). Taxa are scored for the adult condition wherever possible. New characters are indicated in red. Ordered characters are indicated as **ORDERED** and are based on either an observed ontogenetic trajectory within a species of tyrannosauroid or on inclusion of a character state within another. Ordered characters (a total of 48) include: 1, 2, 13, 39, 43, 46, 70, 94, 96, 100, 102, 108, 110, 126, 137, 147, 149, 152, 155, 160, 167, 177, 188, 200, 202, 207, 225, 269, 270, 272, 274, 276, 281, 291, 329, 351, 364, 406, 420, 425, 432, 442, 465, 470, 471, 489, and 491.

### Skull

1. Naris, size:
  - (0) – small, less than half of the length of the antorbital fenestra
  - (1) – large, greater than half but still less than the length of the antorbital fenestra
  - (2) – huge, approaching the length of the antorbital fenestra**ORDERED**  
(New Character)
2. Naris, posterior margin position:
  - (0) – anterior to antorbital fossa
  - (1) – posterior to or even with the antorbital fossa, but anterior to maxillary fenestra
  - (2) – posterior to antorbital fossa, and posterior to the anterior border of the maxillary fenestra**ORDERED**  
(Modified from Chiappe et al., 1998; Li et al., 2009:23)
3. Rostrum length compared to posterior skull length (measured from the anterior premaxilla to midpoint of the lacrimal bar divided by basal skull length to end of quadrate):
  - (0) – longirostran, rostrum more than 0.65
  - (1) – rostrum 0.55 - 0.65 of posterior skull
  - (2) – brevirostrine, rostrum 0.4 - 0.55  
(New Character)
4. Orbit, shape:
  - (0) – round
  - (1) – orbit more than 10% taller than wide but less than twice as tall
  - (2) – dorsoventrally elongate orbit twice as tall as wide  
(Modified from Li et al., 2009:2)
5. Orbit size:
  - (0) – huge, anterioposterior length at least 3 times the rostroposterior length of laterotemporal fenestra
  - (1) – small, anterioposterior length less than 3 times the rostroposterior length of laterotemporal fenestra  
(New Character)
6. Orbit orientation:
  - (0) – laterally directed, orbit is directed parallel to sagittal plane
  - (1) – sublaterally, orbit is directed from 10 to 15 degrees from sagittal plane
  - (2) – anteriorly directed, orbit is directed anteriorly at greater than 20 degrees from sagittal plane  
(New Character)
7. Laterotemporal fenestra, posterior bar:
  - (0) – ascending rami of quadrate and quadratojugal meet squamosal to form a straight posterior border
  - (1) – angled (kinked) posterior border of the laterotemporal fenestra in lateral view  
(Li et al., 2009:254).
8. Lateral temporal fenestra, orientation of long axis relative to long axis of orbit:
  - (0) – posterodorsally directed long axis of laterotemporal fenestra compared to long axis of orbit
  - (1) – the long axis of the orbit and laterotemporal fenestra are approximately parallel  
(Modified from Brusatte et al., 2010:5)
9. Skull width vs skull length:
  - (0) – narrow, 37% or less than premaxilla-quadratojugal length
  - (1) – 40% - 58% of premaxilla-quadratojugal length
  - (2) – wide, more than 63% of premaxilla-quadratojugal length  
(Modified from Holtz, 2001; Currie et al., 2003)

10. Snout width, mediolateral width of the snout at the level of the posterior-most maxillary tooth:
  - (0) – twice or less the width of nasals
  - (1) – approximately three times the width of the nasals  
(Holtz, 2001; Currie et al., 2003; Brusatte et al., 2009:2)
11. Skull height as a ratio of maximum skull height in lateral view to skull length (premaxilla-occipital condyle length):
  - (0) – short, less than 30%
  - (1) – tall, greater than 35%

(Modified from Kurzanov, 1976; Brusatte et al., 2009:3)
12. Skull, anteroposterior length compared to the length of the dorsal vertebral series:
  - (0) – skull short, less than 40% of the length of the dorsal vertebrae
  - (1) – skull long, greater than 40% of the length of the dorsal vertebrae

(Brusatte et al., 2010:3)

### Premaxilla

13. Premaxilla, premaxillary symphysis, overall shape in dorsal view:
  - (0) – acute, V-shaped
  - (1) – rounded, U-shaped
  - (2) – transverse, rostrally facing

**ORDERED**

(Modified from Li et al., 2009:24)
14. Premaxilla, maxillary process orientation in dorsal view:
  - (0) – laterally (and resultantly widely visible in lateral view)
  - (1) – rostrolaterally (facing almost equally dorsally and laterally)
  - (2) – anteriorly (and resultantly mostly hidden in lateral view)

(Brusatte et al., 2010:9)
15. Anterior margin of the premaxillary body in lateral view:
  - (0) – inclined and extends caudodorsally
  - (1) – or extends nearly vertically

(Modified from Brusatte et al., 2009:5)
16. Premaxilla, shape of anterior margin:
  - (0) – smoothly curved
  - (1) – discrete inflection point between nearly anterior region and more horizontal dorsal region

(Modified after Brusatte et al., 2010:13)
17. Premaxilla, nasal processes divergence:
  - (0) – nasal processes are appressed
  - (1) – nasal processes divergent with medial nasal process intervening in between

(Carpenter et al., 2005; Brusatte et al., 2009:6)
18. Premaxilla, subnarial process length:
  - (0) – subnarial process absent
  - (1) – present but much shorter than narial process
  - (2) – subequal to length of narial process
  - (3) – much longer than narial process

(New Character)
19. Large foramen in the lateral surface of the base of the nasal process of the premaxilla:
  - (0) – absent
  - (1) – present

(Modified from Brusatte et al., 2009:7)
20. Premaxilla, form of narial fossa ventral to internal naris:
  - (0) – shallowly excavated
  - (1) – deeply excavated, anterior margin invaginated as a deep groove

(Modified after Brusatte et al., 2010:11)
21. Premaxilla, extent of narial fossa:
  - (0) – limited to region immediately ventral to external naris
  - (1) – extensive, covers more than two thirds of the depth of the body of premaxilla near the posterior end

(Brusatte et al., 2010:12)

22. Premaxilla, main body, dorsoventral depth:
  - (0) – shallow, less than or equal to anteroposterior length
  - (1) – between 1-1.9 times anteroposterior length
  - (2) – deep, greater than 2 times anteroposterior length

(Brusatte et al., 2010:8)
23. Premaxillary interdental plates:
  - (0) – fused
  - (1) – unfused

(Brusatte et al., 2009:12)
24. Premaxilla, position of palatal process:
  - (0) – immediately above interdental plates
  - (1) – separated from interdental plates by deep lingual surface of premaxilla

(Brusatte et al., 2010:14)

### **Maxilla**

25. Maxilla, constriction between articulated premaxillae and maxillae:
  - (0) – absent
  - (1) – present

(Rauhut, 2003; Smith et al., 2007:21)
26. Maxilla and premaxilla contact along alveolar margins:
  - (0) – in contact at alveolar margins
  - (1) – alveolar margins do not contact

(Tykoski, 2005; Smith et al., 2007:22)
27. Maxilla, orientation of the maxillae towards each other in dorsal view:
  - (0) – acutely angled
  - (1) – subparallel

(Harris, 1998; Smith et al., 2007:23)
28. Maxilla, anterior margin, premaxillary suture on body of maxilla in lateral view:
  - (0) – sloping
  - (1) – vertical

(Modified from Brusatte et al., 2009:22)
29. Maxilla, anterior process possesses concave step in anterior margin of maxilla:
  - (0) – absent
  - (1) – present shallow step with relatively short anterior ramus
  - (2) – present deep step with long anterior ramus

(Modified from Brusatte et al 2010:30)
30. Maxilla, pneumatic excavation/antrum in maxillary anterior process:
  - (0) – absent
  - (1) – present

(Sereno et al., 1994; Smith et al., 2007:31)
31. Maxilla, vertical height at inflection point of anterior end of antorbital fenestra versus total height:
  - (0) – short, less than 40% total height
  - (1) – from 45% to 55% total height
  - (2) – tall, more than 60% total height

(New Character)
32. Maxilla, promaxillary fenestra:
  - (0) – absent
  - (1) – present

(Russell, 1970)
33. Maxillary fenestra:
  - (0) – absent
  - (1) – small, fenestra occupies less than half of the depressed area between the anterior margins of the antorbital fossa and antorbital fenestra
  - (2) – large, takes up greater than half up to 3/4 of the space between the anterior margins of the antorbital fenestra and fossa
  - (3) – greater than 3/4 of the length of the eyeball-bearing portion of the orbit

(Modified from Gauthier, 1986; Li et al., 2009:29; Sereno et al., 2009: 1; Carr and Williamson 2010: 17; and Brusatte et al., 2010)

34. Maxilla, maxillary fenestra, shape of posterior border:  
(0) – round or ovoid  
(1) – subrectangular or squared corner  
(New Character)
35. Maxilla, maxillary fenestra, location:  
(0) – posterior to the anterior margin of the antorbital fossa  
(1) – partially overlapped laterally by the anterior margin of the antorbital fossa  
(Carr and Williamson 2010: 15, 16; Sereno et al., 2009: 12; Brusatte et al., 2010:17)
36. Maxilla, maxillary fenestra, location:  
(0) – dorsal to ventral margin of antorbital fossa  
(1) – abuts ventral margin of antorbital fossa  
(Sereno et al. 2009: 13; Brusatte et al., 2010:18)
37. Maxilla, secondary posterior maxillary fenestra within interfenestral strut:  
(0) – absent  
(1) – present  
(New Character)
38. Maxilla, elongate secondary fossa dorsal to maxillary fenestra inside antorbital fossa on the lateral surface of the maxilla:  
(0) – absent  
(1) – present  
(New Character)
39. Maxilla, form of contact with nasal in subadult to adult specimens:  
(0) – smooth  
(1) – weakly scalloped  
(2) – deeply scalloped with interlocking transverse ridges on both elements  
**ORDERED**  
(Sereno et al. 2009: 15; Brusatte et al., 2010:31)
40. Maxilla, form of external subcutaneous surface texturing:  
(0) – random foramina and shallow grooves and ridges  
(1) – deep, prominent, dorsoventrally trending grooves and ridges  
(Brusatte et al., 2010:32)
41. Maxilla, neurovascular foramina, form:  
(0) – foramina absent  
(1) – primary row of foramina continues as a row posteriorly  
(2) – transitions into a sharp groove, paralleling the antorbital fossa rim, posteriorly  
(Modified from Brusatte et al., 2010:36)
42. Maxilla, antorbital fossa, extent on main body under midpoint of antorbital fenestra:  
(0) – covers more than 65% of the depth of the main body beneath the midpoint of the antorbital fenestra  
(1) – covers 50% to 60% of the depth of the main body beneath the midpoint of the antorbital fenestra  
(2) – covers much less than 45% of the depth of the main body beneath the midpoint of the antorbital fenestra  
(Modified from Brusatte et al., 2010:37)
43. Maxilla, ventral margin in lateral view:  
(0) – straight  
(1) – slightly convex  
(2) – highly convex  
**ORDERED**  
(Modified from Sereno et al. 2009: 14; Carr and Williamson 2010: 30; Brusatte et al., 2010:28)
44. Maxilla, palatal shelf of maxilla dorsal to interdental plates:  
(0) – unexpanded mediolaterally  
(1) – broad mediolateral expansion forming shelf subequal to or wider than alveolar body  
(New Character)
45. Maxilla, broad mediolaterally expanded palatal shelf, ventral border:  
(0) – covex below palatal suture  
(1) – concave below palatal suture  
(New Character)

46. Maxilla, depressor pits for dentary teeth in palatal shelf of maxilla dorsal to interdental plates:
- (0) – no pits
  - (1) – shallow pits along most of the ventral surface of palatal shelf of maxilla, may have deep anterior pits
  - (2) – deep pits along ventral surface of palatal shelf of maxilla
- ORDERED**  
(New Character)

## Nasal

47. Nasal, constriction just posterior to subnarial processes, in mediolateral width at posterior end of naris:
- (0) – unconstricted
  - (1) – constricted, but less than 30% of the width of widest point of nasal
  - (2) – constricted, to less than 50% of the width of widest point of nasal
- ORDERED**  
(Modified from Carr and Williamson 2010: 41; Brusatte et al 2010:42)
48. Nasals, fusion along the midline:
- (0) – unfused along entire length
  - (1) – at least partially fused
- (Holtz, 2001; Li et al., 2009:263)
49. Nasal, crest (or crests):
- (0) – absent
  - (1) – midline crest present
  - (2) – bilateral crests present along lateral margins of nasals
- (Li et al., 2009:264)
50. Nasal, crest fenestration:
- (0) – not fenestrated
  - (1) – fenestrated
- (Modified from Brusatte et al., 2009:45)
51. Nasal, crest, dorsal wing of lacrimal wraps onto side of nasal crest:
- (0) – absent
  - (1) – present
- (Smith et al., 2007; Li et al., 2009:290)
52. Nasal, dorsal surface ornamentation (excluding crests):
- (0) – smooth
  - (1) – ornamented
- (Holtz, 2001; Li et al., 2009:296)
53. Nasal, dorsal ornamentation:
- (0) – irregular rugosities
  - (1) – midline hornlets
- (New Character)
54. Nasal, dorsal surface of the nasals (excluding crest morphology):
- (0) – flat for most of length
  - (1) – dorsally convex
- (Modified from Currie et al., 2003; Brusatte et al., 2009:32)
55. Nasal, dorsal surface of the posterior end of the nasal (frontal process only):
- (0) – flat
  - (1) – convex
  - (2) – concave
- (Modified from Brusatte et al., 2009:42)
56. Nasal, dorsal surface in dorsal view, mediolateral expansion of anterior end, anterior to the maxillary fenestra:
- (0) – absent
  - (1) – present
- (New Character)
57. Nasal, in dorsal view, posterior end:
- (0) – the same width as the rest of the element
  - (1) – restricted, posterior 1/3 of element narrower than the anterior 2/3
  - (2) – expanded, posterior 1/3 of element wider than the anterior 2/3
- (New Character)

58. Nasal, dorsal surface in lateral view (excluding crests):  
(0) – straight or convex, relatively flat  
(1) – concave with ventral deflection  
(New Character)
59. Nasal, lateral wing for articulation with lacrimal:  
(0) – absent  
(1) – present  
(Modified from Smith et al., 2007:290; Carr and Williamson 2010: 40; Sereno et al. 2009:4; Brusatte et al 2010)
60. Nasal, frontal suture shape:  
(0) – simple wedge (V-shaped)  
(1) – W-shaped  
(2) – transverse or gentle U-shaped  
(New Character)

### Lacrimal

61. Lacrimal, shape in lateral view:  
(0) – inverted “L” shaped, anterior and ventral process at right angles  
(1) – “7” shaped, acute angle between anterior and ventral processes  
(Modified from Carr and Williamson 2010: 55; Brusatte et al., 2010: 48)
62. Lacrimal, anterior process length:  
(0) – longer than ventral process  
(1) – from 90% to 70% the length of the ventral process  
(2) – short less than 65% ventral process length  
(Modified from Sereno et al., 1998; Smith et al., 2007:56)
63. Lacrimal, ornamentation in adult individuals:  
(0) – absent  
(1) – manifest only as surface rugosity  
(2) – dorsal crest  
(Modified from Sereno et al. 2009: 18; Carr and Williamson 2010: 56; Brusatte et al., 2010: 49)
64. Lacrimal, dorsal crest, height in lateral view:  
(0) – low, less than the width of the anterior/posterior length of the descending process  
(1) – relatively tall, at least as tall as the anterior/posterior length of the descending process  
(New Character)
65. Lacrimal, dorsal crest, cross-section in anterior view:  
(0) – pinched or squared  
(1) – rounded  
(New Character)
66. Lacrimal, dorsal crest, shape in lateral view:  
(0) – sharp, with crest forming distinct peak  
(1) – rounded  
(2) – rounded peak  
(New Character)
67. Lacrimal, dorsal crest, position of the apex of the ornamentation in lateral view:  
(0) – apex anterior to posterior edge of antorbital fenestra  
(1) – apex posterior to posterior edge of antorbital fenestra  
(Modified from Li et al., 2009:52)
68. Lacrimal, posterior dorsal process:  
(0) – absent, or short  
(1) – present, long and gracile  
(2) – present, well-developed and robust  
(New Character)
69. Lacrimal, cornual boss on posterodorsal process:  
(0) – absent  
(1) – present, boss forms ridge or shelf so that ridge and rounded crest are sigmoidal in dorsal view  
(2) – present, forms massive rounded boss  
(New Character)

70. Lacrimal, extent of pneumaticity:
- (0) – absent
  - (1) – limited, partially hollows bone in the region where the anterior and ventral rami meet
  - (2) – extensive, completely hollows bone
- ORDERED**
- (Sereno et al. 2009: 16; Brusatte et al 2010: 52)
71. Lacrimal, accessory pneumatic recess on anterior process of lacrimal:
- (0) – absent
  - (1) – present
- (Modified from Brusatte et al., 2009:60)
72. Lacrimal, position of accessory pneumatic recess:
- (0) – posterior, much closer to ventral process than anterior end of anterior process
  - (1) – anterior, much closer to anterior end of anterior process than ventral process
- (Modified from Brusatte et al., 2009:61)
73. Lacrimal, pneumatic recess opening internally onto anteromedial surface of bone inside antorbital fossa and below anterior process and lacrimal vacuity:
- (0) – absent
  - (1) – present
- (Carr and Williamson 2010: 68; Brusatte et al 2010:57)
74. Lacrimal, posterior process, medial surface for articulation with frontal, inflated by pneumatic recess:
- (0) – no
  - (1) – yes
- (Brusatte et al 2010:62)
75. Lacrimal, lacrimal vacuity opening laterally at the angle of the lacrimal above antorbital fenestra:
- (0) – absent
  - (1) – present, large, where the vacuity extends posteriorly to the ventral process at least  $\frac{1}{2}$  width of ventral process
  - (2) – tiny, much less than  $\frac{1}{2}$  width ventral process where the vacuity ends cranial to the ventral process
- (Modified from Li et al., 2009:38)
76. Lacrimal, lacrimal vacuity, height to length ratio:
- (0) – tall, greater than 1.1
  - (1) – short, less than 0.9
  - (2) – subequal
- (Modified from Brusatte et al., 2009:55)
77. Lacrimal, lacrimal vacuity, rim of lacrimal vacuity flush with rim of the antorbital fossa:
- (0) – flush with ventral surface
  - (1) – rimmed
- (New Character)
78. Lacrimal, lacrimal vacuity, posterodorsal margin of lacrimal vacuity:
- (0) – rimmed
  - (1) – rounded
- (New Character)
79. Lacrimal, orbitonasal ridge on medial surface, position:
- (0) – anterior to posterior margin of ventral process
  - (1) – adjacent to or contacting posterior margin of ventral process
- (Carr and Williamson 2010: 69; Brusatte et al 2010:60)
80. Lacrimal, extent of antorbital fossa on ventral process:
- (0) – covers greater than 60% of anteroposterior length along the contact with the jugal
  - (1) – less than 60% of anteroposterior length along the contact with the jugal
- (Brusatte et al 2010:63)
81. Lacrimal, subocular process restricting anterior orbit margin on caudolateral margin of ventral process, and defining ocular region of orbit:
- (0) – absent
  - (1) – present
- (Modified from Sampson et al., 1998; Currie and Carpenter, 2002:31; Benson, 2009:43; Brusatte et al., 2009:63)

## Prefrontal

82. Prefrontal:  
(0) – present  
(1) – absent  
(Li et al., 2009)
83. Prefrontal, exposure on anterior rim of orbit in lateral view:  
(0) – present, with ventral process forming part of the anterior rim of the orbit  
(1) – absent, displaced posteriorly and/or medially with the ventral process absent  
(Modified from Rauhut, 2003; Smith et al., 2007: 61; Sereno et al., 2009:20; Brusatte et al., 2010:111)
84. Prefrontal, extent of exposure on orbital rim in lateral view:  
(0) – exposed with ventral process less than 20% of the diameter of the orbit  
(1) – exposed with long ventral process that extends more than halfway down the ventral process of the lacrimal, anteriorposterior length similar to that of the anterior process of the lacrimal  
(Modified from Carr and Williamson 2010:132; Brusatte et al 2010:112)
85. Prefrontal, shape of prefrontal excluded from the anterior rim of the orbit:  
(0) – ventral process absent, but dorsal exposure similar to that of lacrimal  
(1) – excluded from the anterior rim of the, being displaced posteriorly and/or medially; ventral process absent, and greatly reduced in size  
(Modified from Rauhut, 2003; Smith et al., 2007: 61; Sereno et al., 2009:20; Brusatte et al., 2010:111)
86. Anterior extent of the prefrontal position relative to lateral part of frontal process of nasal:  
(0) – anterior to frontal process of nasal  
(1) – even with or lateral to frontal process of nasal  
(2) – posterior to frontal process of nasal  
(Modified from Brusatte et al., 2009:117)
87. Prefrontal, contact with lacrimal and frontal:  
(0) – prefrontal separates lacrimal and frontal  
(1) – lacrimal and frontal contact each other behind the prefrontal  
(2) – lacrimal and frontal contact each other in front of the prefrontal  
(Modified from Brusatte et al., 2009:119)

## Frontal

88. Frontal, anterior margin:  
(0) – narrow anteriorly as an elongate wedge between nasals  
(1) – anterior end terminates abruptly even if w shaped, suture with nasal transversely oriented  
(Modified from Xu et al., 2006; Li et al., 2009:41; Sereno et al. 2009:38; Brusatte et al., 2010:113)
89. Frontal, ratio of anteroposterior length of exposed portion on skull roof to mediolateral width at midpoint of single element:  
(0) – long, greater than 2.5  
(1) – short, less than 2.0  
(Brusatte et al., 2010:114)
90. Frontal, exposure along orbital margin:  
(0) – broadly exposed along orbital margin  
(1) – present but limited to a small notch  
(2) – excluded by postorbital-lacrimal contact in large specimens  
(Li et al., 2009:271; Sereno et al., 2009:21; Carr and Williamson 2010:104; Brusatte et al., 2010:120)
91. Frontal, shape of the prefrontal articular surface on dorsal surface of skull:  
(0) – straight or rostromedial arc  
(1) – notch  
(Modified from Brusatte et al., 2009:129)
92. Frontal, expansion of supratemporal fossa onto dorsal surface:  
(0) – supratemporal fossa extends anteriorly onto dorsal surface of frontal  
(1) – supratemporal fenestra excluded from frontal  
(Modified from Currie 1995; Currie and Varricchio, 2004:14; Li et al., 245)
93. Frontal, supratemporal fossa, anterior emargination:  
(0) – straight or curved  
(1) – sinusoidal  
(Currie, 1995; Li et al., 2009:42)

94. Frontal, supratemporal fossa, anteroposterior length compared to overall length of exposed portion of frontal on skull roof:

- (0) – less than 30%
- (1) – between 30-45%
- (2) – between 45-55%
- (3) – greater than 60%

**ORDERED**

(Brusatte et al., 2009:123; Carr and Williamson 2010:136-137; Brusatte et al., 2010: 115)

95. Frontal, supratemporal fossa, medial extension:

- (0) – fossa restricted to posterolateral corner of frontal
  - (1) – meets opposing fossa at the midline
- (Sereno et al., 2009:39; Brusatte et al., 2010:116)

96. Frontal, postorbital suture:

- (0) – dorsoventrally shallow and undifferentiated
- (1) – dorsoventrally shallow (approximately 6 times longer than deep) and differentiated into a vertical region anteriorly and a horizontal region posteriorly
- (2) – dorsoventrally deep (approximately twice as long as deep) and subtly differentiated into vertical and horizontal regions

**ORDERED**

(Sereno et al. 2009:37; Carr and Williamson 2010:145; Brusatte et al., 2010:119)

97. Frontal, shape of frontal viewed between supratemporal fossa:

- (0) – flat
- (1) – low flat-topped or low bilateral sagittal crests without midline peak
- (2) – short, low pyramidal sharp sagittal crest
- (3) – long, tall, bladelike sharp sagittal crest on frontal, sometimes flat-topped
- (4) – domed with dorsally convex surface

(Modified from Brusatte et al., 2009:131; Carr and Williamson 2010:139; Carr and Williamson 2010:141; Brusatte et al., 2010:118; Brusatte et al., 2010:117)

## Parietal

98. Parietal-frontal suture, form:

- (0) – transversely smooth
  - (1) – tab-like wedge from parietal extends anteriorly to overlie frontal on midline
- (Carr and Williamson 2010:147; Brusatte et al., 2010:121)

99. Parietals, dorsal surface in transverse view:

- (0) – flat
  - (1) – comprised of two parallel crests forming flat table
  - (2) – transversely convex with single midsagittal crest
- (Modified from Xu et al., 2006; Li et al., 2009:45; Carr and Williamson 2010:150; Brusatte et al., 2009:122,123)

100. Parietals, distinct frontoparietal peak:

- (0) – absent
- (1) – low frontoparietal peak
- (2) – frontoparietal peak  $\frac{1}{2}$  to less than  $\frac{2}{3}$  height of nuchal crest
- (3) – frontoparietal peak nearly as tall as nuchal crest

**ORDERED**

(New Character)

101. Parietals, dorsal surface in lateral view:

- (0) – generally flat or concave
  - (1) – arched, dorsally convex
- (New Character)

102. Parietals, shape of flat or concave dorsal surface in lateral view:

- (0) – generally flat
- (1) – shallowly concave
- (2) – deeply concave with depth of concavity approaching  $\frac{1}{2}$  of length

**ORDERED**

(New Character)

103.Parietals, nuchal crest height:

- (0) – as low subequal to roof of the skull
- (1) – equal or shorter than tallest part of the skull
- (2) – taller than any other part of the skull

(Modified from Holtz, 2001; Brusatte et al., 2009:134; Sereno et al., 2009:41; Carr and Williamson 2010:149)

### **Postorbital**

104.Postorbital, anterior (frontal) process length:

- (0) – short, anterior process is approximately half the length of the ventral process
- (1) – long, anterior process is greater than 60% of the length of the ventral process

(Li et al. 2010:252; Brusatte et al., 2010: 88)

105.Postorbital, anterior process:

- (0) – slender process, thickness is much less than the thickness of the midpoint of the ventral process
- (1) – robust process, thickness is subequal to that of the midpoint of the ventral process

(New Character)

106.Postorbital, anterior process curvature in lateral view:

- (0) – straight anterior (frontal) process
- (1) – anterior process strongly arched anterodorsally

(Modified from Li et al., 2009:4)

107.Postorbital, descending process:

- (0) – relatively narrow and comparable to preorbital bar (lacrimal) in anterior/posterior width
- (1) – at least the midpoint of the postorbital bar (formed by descending process of postorbital and sometimes ascending process of jugal) wide and plate-like, about twice as wide as preorbital bar

(Li et al. 2010: 268)

108.Postorbital, subocular process:

- (0) – absent
- (1) – present, slight expansion into the orbit
- (2) – greatly expanded into the orbit so as to greatly restrict ventral part of orbit

**ORDERED**

(Modified from Sereno et al. 2009:30; Brusatte et al., 2009: 92; Brusatte et al., 2010: 86)

109.Postorbital, subocular process, position:

- (0) – at ventral end of ventral process
- (1) – flange-like, separated from ventral tip of ventral process by a notch

(Carr and Williamson, 2010:102; Brusatte et al., 2010: 87)

110.Postorbital, ornamentation:

- (0) – absent
- (1) – present low sculpturing
- (2) – present cornual boss of rugose grooves
- (3) – present as round knobby cornual boss

**ORDERED**

(New Character)

111.Postorbital, cornual process, position relative to caudal margin of orbit:

- (0) – cornural process positioned posterior to orbit margin
- (1) – cornual process confluent from posterior margin of orbit

(New Character)

112.Cornual process undercut at base, so that process is differentiated from the rest of the lateral surface:

- (0) – absent
- (1) – present

(Modified from Brusatte et al., 2009:88)

113.Postorbital, squamosal process, form of posterodorsal margin:

- (0) – uninterrupted convex arc
- (1) – emarginated by squamosal (discrete concave notch within the margin in lateral view)

(Brusatte et al 2009: 90; Carr and Williamson 2010:99; Brusatte et al 2010: 84)

114.Postorbital, squamosal process length:

- (0) – reaches posterior margin of the laterotemporal fenestra
- (1) – stops short of posterior margin of fenestra

(Brusatte et al 2009: 9; Sereno et al. 2009:28; Carr and Williamson 2010:100; Brusatte et al 2010: 85)

115. Postorbital, expansion of supratemporal fossa onto dorsal surface of postorbital:  
 (0) – no supratemporal fenestra on postorbital  
 (1) – covers most of frontal process of the postorbital and extends anteriorly onto dorsal surface of frontal  
 (Modified from Currie 1995; Currie and Varricchio, 2004:14; Li et al., 2009:245)
116. Postorbital, postorbito-lacrimal osteoderm:  
 (0) – absent  
 (1) – present  
 (Brusatte et al., 2009:94)

### **Squamosal**

117. Squamosal, anterior extent:  
 (0) – at or ahead of anterior margin of the fenestra  
 (1) – posterior to anterior margin of laterotemporal fenestra  
 (Modified from Brusatte et al., 2009:89)
118. Squamosal, presence of supratemporal fossa:  
 (0) – absent, fenestra bounded laterally and posteriorly by the squamosal  
 (1) – present, fossa extends onto dorsal surface of the squamosal  
 (Li et al., 2009:219)
119. Squamosal, web of bone overhangs the caudal border of the supratemporal fossa:  
 (0) – absent  
 (1) – present  
 (Modified from Brusatte et al., 2009:95)
120. Squamosal, orientation of web of bone that overhangs supratemporal fossa:  
 (0) – dorsal  
 (1) – lateral  
 (New Character)
121. Squamosal, supratemporal fossa, surface morphology:  
 (0) – flat or concave  
 (1) – convex  
 (Carr and Williamson 2010:107; Brusatte et al., 2010: 91)
122. Squamosal, descending process orientation:  
 (0) – parallels quadrate shaft  
 (1) – oblique to quadrate shaft oriented at about 45 degrees  
 (2) – nearly perpendicular to quadrate shaft  
 (Modified from Li et al., 2009:47; Brusatte et al., 2009: 98; Carr and Williamson 2010:111; Brusatte et al., 2010: 92)
123. Squamosal, non-vertical quadratojugal process, extent of constriction of the laterotemporal fenestra:  
 (0) – process constricts less than 80%  
 (1) – process constricts more than 90%  
 (New Character)
124. Squamosal, quadratojugal process, morphology of anterior tip of entire process in those taxa with horizontal processes:  
 (0) – tapered point  
 (1) – squared off  
 (Modified from Carr and Williamson 2010:110; Brusatte et al., 2010: 93)
125. Squamosal, horizontal quadratojugal process, relationship of the articulation with quadratojugal:  
 (0) – horizontal process with rod-like ridge above quadratojugal and forming lap joint medial to the quadratojugal  
 (1) – process forms a broad lap joint with quadratojugal, but visible portion of horizontal process above quadratojugal is tab-like  
 (Modified from Brusatte et al., 2009: 99; Brusatte et al., 2010: 94)
126. Squamosal, pneumaticity in the ventral surface of the dorsal portion of bone:  
 (0) – absent  
 (1) – foramen present  
 (2) – foramen and fossa present  
**ORDERED**  
 (Modified from Brusatte et al., 2009:103)

127. Squamosal, fossa in ventral surface of the dorsal ceiling of bone, shape:

- (0) – broad with rounded margin
  - (1) – rimmed with sharp margins
- (New Character)

128. Squamosal, postquadratic process thickness in lateral view measured perpendicular to long axis of the process in the dorsoventral or cranioposterior plane in lateral view:

- (0) – absent or thin
  - (1) – subequal but not thin
  - (2) – thicker than long
- (New Character)

129. Squamosal, postquadratic process:

- (0) – short
  - (1) – at least as long as quadrate cotylus
  - (2) – twice as long as quadrate cotylus
  - (3) – three or more times as long as the quadrate cotylus
- (Modified from Brusatte et al., 2009:105)

## Jugal

130. Jugal, contribution to antorbital fenestra:

- (0) – absent
  - (1) – participates along a small surface in the antorbital fenestra
  - (2) – extensive, forms the caudoventral corner of antorbital fenestra
- (Modified from Li et al., 2009:246)

131. Jugal, pneumatic recess:

- (0) – absent
  - (1) – small and round
  - (2) – large and elongate
- (Modified from Sereno et al., 1996; Smith et al., 2007:47)

132. Jugal, pneumatic recess orientation of long axis:

- (0) – axis of recess is horizontal
  - (1) – axis of foramen inclined at an angle of 45 degrees to the ventral skull margin
- (Modified from Currie et al., 2003; Li et al., 2009:33)

133. Jugal, position of pneumatic recess in antorbital fossa:

- (0) – antorbital fossa edge does not extend past the pneumatic recess
  - (1) – antorbital fossa edge is continuous caudoventral to the pneumatic recess
- (Modified from Brusatte et al., 2009: 68)

134. Jugal, maxillary process, antorbital fossa position relative to ventral process of lacrimal:

- (0) – posterior edge of fossa posterior to or directly ventral to midpoint of ventral process
  - (1) – posterior edge of fossa anterior to midpoint of ventral process
- (Modified from Brusatte et al., 2009:69)

135. Jugal, maxillary process, dorsoventral depth:

- (0) – shallow, not expanded relative to suborbital portion of bone
  - (1) – deep, expanded relative to suborbital portion of bone
- (Carr and Williamson 2010: 73; Brusatte et al., 2010: 65)

136. Jugal, suture with lacrimal, angle of the posterior half of the contact:

- (0) – low, suture sub-horizontal
- (1) – steep with posteroventral tab

(Modified from Brusatte et al., 2009: 74; Carr and Williamson 2010:81; Brusatte et al., 2010: 70)

137. Jugal, subocular process on ventral part of orbit to accept the subocular flange of the postorbital:

- (0) – absent, postorbital process confluent with suborbital margin
- (1) – present, slight notch between postorbital articulation and suborbital margin
- (2) – present, pronounced flange corresponding to subocular flange of postorbital

## ORDERED

(New Character)

138. Jugal, postorbital process width at base:

- (0) – narrow less than 1/4 length of jugal
  - (1) – wide, greater than 1/3 length of jugal
- (New Character)

139.Jugal, postorbital facet of ascending process:

- (0) – absent or shallow
- (1) – mediolaterally oriented scarf joint

(Modified from Brusatte et al., 2009:75)

140.Jugal, postorbital process, orientation relative to ventral margin of jugal in life position:

- (0) – approximately perpendicular
- (1) – posteriorly inclined 15-25 degrees from perpendicular
- (2) – strongly posteriorly inclined to 30 or more degrees

(Modified from Brusatte et al., 2010: 75)

141.Jugal, shape of orbital margin:

- (0) – weakly concave, approximately level with lacrimal-jugal suture
- (1) – U-shaped, extends ventral to lacrimal-jugal suture

(Sereno et al., 2009: 26; Brusatte et al., 2010: 79)

142.Jugal, ventral margin:

- (0) – ventral margin relatively straight or gently convex
- (1) – ventral margin convex rugose peak

(New Character)

143.Jugal, lateral jugal ornamentation:

- (0) – absent
- (1) – rugose thickening present

(New Character)

144.Jugal, dorsal prong of quadratojugal ramus, slope in lateral view:

- (0) – horizontal
- (1) – posterodorsal

(Brusatte et al., 2009: 82; Carr and Williamson 2010:91; Brusatte et al., 2010: 77)

145.Jugal, raised rim on the ventrolateral surface, paralleling the ventral margin of the bone and anteriorly confluent with the antorbital fossa rim of the maxilla:

- (0) – absent
- (1) – present

(Modified from Brusatte et al., 2010:80)

## Quadratojugal

146.Quadratojugal, form of jugal articulation:

- (0) – dorsal prong of posterior process of jugal does not approach the base of the quadratojugal
- (1) – does approach the base of the quadratojugal (the corner where the anterior and dorsal processes of the quadratojugal meet)

(Carr and Williamson 2010:120; Brusatte et al 2010: 100)

147.Quadratojugal, constriction of lateral temporal fenestra:

- (0) – absent, dorsal process is approximately vertical
- (1) – present, convex kink along the suture between the quadratojugal and squamosal that projects into the fenestra, constricting it to approximately one half of its maximum anteroposterior length
- (2) – present, dorsal region of quadratojugal moderately expanded anteroposteriorly relative to the remainder of the bone, constricting fenestra to approximately one half of its maximum anteroposterior length
- (3) – present, dorsal region of quadratojugal expanded anteroposteriorly by at least twice the minimum anteroposterior dimension of the bone, forming a flange that meets the ventral process of the squamosal to nearly divide the fenestra

## ORDERED

(Modified from Sereno et al. 2009:35; Carr and Williamson 2010:116; Brusatte et al., 2010: 98)

148.Quadratojugal, anterior process, dorsoventrally expanded so majority of process overlaps laterally onto jugal:

- (0) – absent
- (1) – present

(New Character)

149.Quadratojugal, overall form of jugal process:

- (0) – elongate tapered process
- (1) – tab-like process with rounded anterior end
- (2) – tab-like process with squared-off anterior end

## ORDERED

(Modified from Currie et al., 2003; Sereno et al., 2009:34; Carr and Williamson 2010:121; Brusatte et al., 2010: 101)

150. Quadratojugal, squamosal-quadratojugal contact:  
 (0) – at tips or absent  
 (1) – broad  
 (Carrano et al., 2002, 2005; Rauhut, 2003; Smith et al., 2007:82)
151. Quadratojugal, anteroposterior breadth of quadratojugal dorsal process:  
 (0) – narrow  
 (1) – broad  
 (Smith et al., 2007:83)
152. Quadratojugal, dorsal process, ridge along anterior margin of lateral surface:  
 (0) – absent  
 (1) – present, subtle and fades in strength dorsally  
 (2) – present, robust and extends to the dorsal margin of the bone  
**ORDERED**  
 (Brusatte et al., 2009: 107; Carr and Williamson 2010:117; Brusatte et al., 2010: 99)
153. Quadratojugal, presence of posterior process:  
 (0) – absent, without horizontal process posterior to ascending process (reversed “L” shape)  
 (1) – present, process inverted ‘T’ or ‘Y’ shape  
 (Modified from Li et al., 2009:35, 281; Brusatte et al 2010: 103)
154. Quadratojugal, orientation of posterior process:  
 (0) – lateral facing process  
 (1) –posterior facing process  
 (Modified from Li et al., 2009:35, 281; Brusatte et al 2010: 103)
- Quadrato**
155. Quadrato foramen size:  
 (0) – absent  
 (1) – small less than 3% element dorsoventral height  
 (2) – more than 5% element height but less than 40% element height  
 (3) – more than 45% element height  
**ORDERED**  
 (Modified from Holtz, 2004; Li et al., 2009:275)
156. Quadrato foramen conformation:  
 (0) – almost completely formed within the quadrato  
 (1) – 75% of foramen formed by the quadrato  
 (2) – formed equally by the quadrato and quadratojugal  
 (Modified after Rauhut, 2003)
157. Quadrato foramen orientation:  
 (0) – caudally, not visible in lateral view  
 (1) – caudolaterally, visible in lateral view  
 (New Character)
158. Quadrato foramen position:  
 (0) – at midheight or dorsal to midheight  
 (1) – ventral, near the quadrato neck  
 (New Character)
159. Quadrato, pneumaticity:  
 (0) – absent  
 (1) – present, deep recess on the anterior surface where the pterygoid wing and condyles meet  
 (Molnar, 1985; Currie et al., 2003; Carr and Williamsn 2009:126; Brusatte et al 2010: 114; Brusatte et al 2010: 106)
160. Quadrato, oval fossa on medial surface of pterygoid wing:  
 (0) – absent  
 (1) – present shallow fossa  
 (2) – present deep fossa  
**ORDERED**  
 (New Character)
161. Quadrato condyles, position relative to occipital condyle when skull is in articulation:  
 (0) – rostral to or approximately aligned  
 (1) – completely posterior  
 (Carr and Williamson 2010:127; Sereno et al. 2009:42; Brusatte et al 2010: 107)

## **Supraoccipital**

162. Supraoccipital, form of dorsal margin:  
(0) – smoothly convex and undivided  
(1) – divided into two processes (“bilobate”)  
(Brusatte et al., 2009:158; Carr and Williamson 2010:172; Brusatte et al., 2010: 149)

163. Supraoccipital, distinct dorsal process of supraoccipital:  
(0) – absent  
(1) – present  
(Brusatte et al., 2009: 155)

164. Supraoccipital, width of dorsal process of supraoccipital:  
(0) – narrow  
(1) – wide  
(Brusatte et al., 2009: 156)

165. Supraoccipital, dorsal process of supraoccipital form of dorsal surface:  
(0) – flat or peaked  
(1) – forked  
(New Character)

166. Supraoccipital, form of median posterior surface of dorsal process:  
(0) – flat  
(1) – midline peaked ridge  
(2) – midline groove present  
(New Character)

167. Supraoccipital, median ridge above dorsal process:  
(0) – absent or no differentiation between dorsal process and median ridge  
(1) – present; slight, peaked ridge  
(2) – present; well-developed, wide ridge

## **ORDERED**

(Modified from Holtz, 2001; Currie et al., 2003; Brusatte et al., 2009:157)

168. Supraoccipital, contribution to dorsal rim of foramen magnum:  
(0) – forms entire rim  
(1) – makes limited contribution to rim via triangular ventral process  
(2) – completely excluded from rim  
(Harris, 1998; Currie et al., 2003; Brusatte et al., 2009:158; Carr and Williamson 2010:158; Brusatte et al., 2010:148)

## **Prootic**

169. Prootic, depression for pneumatic recess:  
(0) – absent  
(1) – present as dorsally open fossa on prootic/opisthotic  
(Li et al., 2009; Brusatte et al., 2010: 163)

## **Opisthotic**

170. Opisthotic, posterior (caudal) tympanic recess:  
(0) – absent  
(1) – present  
(Li et al., 2009:18)

171. Opisthotic, posterior (caudal) tympanic recess position:  
(0) – posterior  
(1) – anterior  
(Modified from Brusatte et al., 2009:141)

172. Opisthotic, ventral extension:  
(0) – notch separates basal tuber from more anteroventral extension of exoccipital-basisphenoid suture  
(1) – notch absent (Currie et al., 2003; Brusatte et al., 2009:142)

173. Opisthotic, orientation of the paroccipital processes:  
(0) – directed laterally, or slightly ventrolaterally  
(1) – directed strongly ventrolaterally,  
(Modified from Rauhut, 1997; Rauhut, 2003; Smith et al., 2007:90; Li et al., 2009)

174. Opisthotic, ventral extent of the paroccipital processes:

- (0) – above or level with the dorsal border of the occipital condyle
  - (1) – situated at mid-height of occipital condyle or lower
- (Rauhut, 2003; Smith et al., 2007:91)

175. Opisthotic, curvature of the ventral surface paroccipital process:

- (0) – straight
  - (1) – curving ventrally, pendant
- (Currie et al., 2003; Brusatte et al., 2009:144)

176. Opisthotic, paroccipital process length:

- (0) – elongate and slender
  - (1) – process short, thick, 60% or more of dorsoventral height compared to mediolateral length
- (Modified from Smith et al., 2007; Li et al., 2009:56)

177. Opisthotic, exoccipital-opisthotic, paroccipital processes, deep fossa on posterior surface dorsolateral to the foramen magnum:

- (0) – absent
- (1) – present and shallow
- (2) – present and deep

#### **ORDERED**

(Modified from Brusatte et al., 2010: 151)

178. Opisthotic, exits of cranial nerves X-XII:

- (0) – flush with surface of exoccipital
  - (1) – cranial nerve exits located together in a bowl-like depression
- (Li et al., 2009:19; Brusatte et al., 2010:153)

179. Opisthotic, exoccipital-opisthotic, crista tuberalis (= metotic strut), extent in posterior view:

- (0) – crista tuberalis absent or extent very limited
  - (1) – extensive, extends subequal to the length of the paroccipital process
- (Modified from Brusatte et al., 2010:152)

### **Laterosphenoid**

180. Laterosphenoid, transverse scar on lateral surface:

- (0) – absent
  - (1) – present
- (Modified from Brusatte et al., 2009:137)

181. Laterosphenoid, dorsal suture with the parietal:

- (0) – flat
  - (1) – raised into a sharp ridge laterally
- (Brusatte et al., 2009:138)

182. Laterosphenoid, antotic crest separating lateral wall of braincase from orbital and temporal spaces:

- (0) – absent or indistinct
  - (1) – present; robust and rugose
- (Carr and Williamson 2010:152, 155; Brusatte et al., 2010:164)

183. Laterosphenoid, antotic crest, form:

- (0) – single structure
  - (1) – bifurcates ventrally
- (Brusatte et al., 2010:165)

184. Laterosphenoid, fossa on lateral surface that houses head of epitygoid:

- (0) – absent or shallow
  - (1) – present, deep and rugose
- (Brusatte et al., 2010:166)

185. Laterosphenoid, ventrolateral shelf:

- (0) – absent
  - (1) – present
- (Modified from Brusatte et al., 2009:140)

### **Basioccipital**

186. Basioccipital, orientation of occipital surface:

- (0) – faces directly posteriorly
  - (1) – faces posteroventrally
- (Holtz, 2001; Currie et al., 2003; Brusatte et al., 2009:3; Sereno et al. 2009:46; Brusatte et al., 2010:147)

187.Basioccipital, occipital condyle constriction of neck:

- (0) – lateral constriction of neck
- (1) – subspherical without constricted neck
- (Li et al., 2009:55)

188.Basioccipital, subcondylar recesses:

- (0) – absent
- (1) – shallow
- (2) – deep

**ORDERED**

(Holtz, 2004; Li et al. 2009:255; Carr and Williamson 2010:168; Brusatte et al., 2010:156)

189.Basioccipital, basicranium in ventral view:

- (0) – longer than wide, or with subequal proportions
- (1) – clearly wider than long

(Currie et al., 2003; Li et al. 2009:272; Sereno et al. 2009:49; Carr and Williamson 2010:169; Brusatte et al., 2010:161)

190.Basioccipital, basal tubera:

- (0) – equally formed by basioccipital and basisphenoid and not subdivided
- (1) – subdivided by a lateral longitudinal groove into a medial part entirely formed by the basioccipital, and a lateral part, entirely formed by the basisphenoid

(Rauhut, 2003; Smith et al., 2007:100)

191.Basioccipital, basal tubera mediolateral width:

- (0) – greater than occipital condyle width
- (1) – equal to or less than occipital condyle width

(Currie et al., 2003; Makovicky et al., 2003; Smith et al., 2007:102)

192.Basioccipital, basal tubera, dorsoventral depth:

- (0) – less than depth of occipital condyle
- (1) – greater than depth of occipital condyle

(Brusatte et al., 2010:154)

193.Basioccipital, basicranium,mediolateral width of basal tubera versus the width of the basispterygoid processes:

- (0) – subequal or basal tuber wider
- (1) – basispterygoids wider

(New Character)

194.Basioccipital, basal tubera in posterior view, concave notch ventrally between opposing tubera, dorsoventral depth:

- (0) – shallow, less than 30% depth of tubera
- (1) – deep, more than 30% depth of tubera

(Brusatte et al., 2010:155)

195.Basioccipital, ventral surface across basal tubera and basisphenoids orientation:

- (0) – oriented nearly horizontally
- (1) – oriented caudoventrally

(Harris, 1998; Currie et al., 2003:149; Brusatte et al., 2009:149)

196.Basioccipital, pneumatic openings associated with internal carotid artery:

- (0) – absent
- (1) – present

(Allain, 2002; Coria and Currie, 2006; Smith et al., 2007:106; Brusatte et al., 2009:146)

### Parabasisphenoid

197.Parabasisphenoid, with large surfaces of pronounced muscle scars flanking basisphenoid recess:

- (0) – no
- (1) – yes

(Bakker et al. 1998; Li et al., 2009:280)

198.Parabasisphenoid, basispterygoid recess (pneumatic recess above basispterygoid processes on lateral surface of braincase):

- (0) – absent or very shallow pneumatic fossa
- (1) – present as a deep fossa

(Carr and Williamson 2010:160; Brusatte et al., 2010:157)

199.Parabasisphenoid, basisphenoid recess:

- (0) – undivided
- (1) – divided

(Modified from Li et al., 2009:10)

200.Parabasisphenoid, orientation of division of basisphenoid recess:

- (0) – transversely divided so that there is an anterior and posterior recess
- (1) – divided by a single midline strut into two laterally separate chambers
- (2) – divided by a “Y” shaped strut of bone forming three recesses

**ORDERED**

(Modified from Li et al., 2009:10)

201.Parabasisphenoid, basisphenoid recess, inflation of the dorsal surface of the recess:

- (0) – absent

- (1) – present

(Carr and Williamson 2010:166; Brusatte et al., 2010:159)

202.Parabasisphenoid, basisphenoid recess, orientation of central axis:

- (0) – horizontal, recess obscured in posterior view
- (1) – posteroventral, recess partially visible in posterior view
- (2) – extremely posteroventral, recess compressed anteroposteriorly and widely visible in posterior view, and basipterygoid processes located beneath the basal tubera

**ORDERED**

(Sereno et al. 2009:50; Carr and Williamson 2010:163,165; Brusatte et al., 2010: 158)

203.Parabasisphenoid, shape of rostrum:

- (0) – anteroposteriorly expanded, ventral margin is a smooth concave arch

- (1) – dorsoventrally expanded, ventral margin is nearly vertical posteriorly and then abruptly transitions to horizontal trend anteriorly

(Brusatte et al., 2010:162)

## Palate

204.Palate, shelf-like primary palate, presence:

- (0) – absent

- (1) – present

(Currie et al., 2003; Brusatte et al., 2009:159)

205.Palate, internal choana, shape:

- (0) – anteroposteriorly elongate oval

- (1) – nearly circular

(Brusatte et al., 2010:145)

206.Palate, suborbital fenestra, shape:

- (0) – anteroposteriorly elongate oval

- (1) – nearly circular

(Brusatte et al., 2010:146)

## Vomer

207.Vomer, anterior horizontal expansion:

- (0) – absent

- (1) – present, slight expansion

- (2) – present, expanded to equilateral diamond shape

**ORDERED**

(Modified from Carr, 1999; Sereno et al. 2009:45; Bursatte et al., 2009:160; Carr and Williamson 2010:176; Brusatte et al., 2010: 128)

## Palatine

208.Palatine anterior expansion of dorsal process into a vomerine process:

- (0) – absent

- (1) – present

(New Character)

209.Palatine, vomeropterygoid process, anteroposterior length of dorsal margin ratio to length of greatest constriction of process neck:

- (0) – long, greater than 2.0

- (1) – short, or less than 2.0

(Carr and Williamson 2010:188; Brusatte et al., 2010:134)

**210. Palatine posterior expansion of dorsal process:**

- (0) – absent
  - (1) – present
- (New Character)

**211. Palatine, overall orientation of dorsal surface of vomerine process:**

- (0) – rostrodorsally directed at 45 degrees
- (1) – horizontal

(Modified from Brusatte et al., 2009:173; Carr and Williamson 2010:189; Brusatte et al., 2010:135)

**212. Palatine, dorsoventral height of the dorsal process:**

- (0) – tall, 60% or more than narrowest rostroposterior width of the neck of the dorsal process
- (1) – short, less than 50%

(Modified from Brusatte et al., 2009:171)

**213. Palatine, overall orientation of neck of dorsal process:**

- (0) – rostrodorsally directed at nearly 45 degrees
- (1) – vertically directed

(New Character)

**214. Palatine, posterior expansion of base of the neck of the dorsal process:**

- (0) – absent
- (1) – present

(New Character)

**215. Palatine, pneumatic recess, number of external pneumatic openings:**

- (0) – absent
- (1) – present, one opening
- (2) – present, two openings

(Modified from Brusatte et al., 2009:175; Carr and Williamson 2010: 190; Brusatte et al., 2010:136, 137)

**216. Palatine, anterior or primary opening of palatine recess, location of posterior margin:**

- (0) – posterior to or even with the posterior margin of the neck of the vomeroptyerygoid process
- (1) – anterior to posterior margin of the vomeroptyerygoid process neck

(Carr and Williamson 2010:194; Brusatte et al., 2010:138)

**217. Palatine, position of the posterior edge of the posterior pneumatic recess compared to the posterior edge of the dorsal process:**

- (0) – anterior to the posterior margin of dorsal process
- (1) – extends posterior to the posterior margin of the process

(Brusatte et al., 2009:177)

**218. Palatine, presence of slot on the articular surface for the maxilla:**

- (0) – absent
- (1) – present

(Brusatte et al., 2009:180)

**219. Palatine, maxillary process, form of maxillary articulation:**

- (0) – flat
- (1) – deeply excavated as a slot, demarcated dorsally by a pronounced lip of bone

(Carr and Williamson 2010:197; Brusatte et al., 2010: 141)

**220. Palatine, maxillary articulation, form:**

- (0) – maxilla abuts lateral surface of maxillary process and anterior region of jugal process
- (1) – contact reinforced by a “brace” at the anteroventral corner of the jugal process, which sits within internal antorbital fossa

(Brusatte et al., 2010:143)

**221. Palatine, morphology of maxillary articulation brace:**

- (0) – projects ventrally due to a jugal process that extends further ventrally than the maxillary process, such that there is a discrete corner between the two processes in lateral view
- (1) – projects laterally, with no discrete corner between the smoothly confluent jugal and maxillary processes in lateral view

(Brusatte et al., 2010:144)

**222. Palatine, jugal process, location of contact surface for lacrimal:**

- (0) – posterior (“distal”), separated from opening of palatine recess by wide margin
- (1) – anterior (“proximal”), closely approaches opening of palatine recess

(Carr and Williamson 2010:196; Brusatte et al., 2010:140)

223. Palatine, extension of pneumatic recess into jugal process:

- (0) – no extension
  - (1) – yes, process visibly inflated
- (Carr and Williamson 2009:199; Brusatte et al., 2010:142)

### Epipterygoid

224. Epipterygoid ventral margin:

- (0) – undivided
  - (1) – forked
- (Brusatte et al., 2009:161)

### Ectopterygoid

225. Ectopterygoid, body pneumatic:

- (0) – apneumatic
- (1) – pneumatic, uninflated
- (2) – pneumatic with inflated body

#### ORDERED

(Modified from Brusatte et al., 2009:162; Sereno et al. 2009:44; Carr and Williamson 2010:178; Brusatte et al., 2010:129)

226. Ectopterygoid, external opening of pneumatic recess, shape:

- (0) – thin ovoid slot
  - (1) – larger, round or triangular
- (Carr and Williamson 2010:183; Brusatte et al., 2010:132)

227. Ectopterygoid, surface posteriorly adjacent to external opening of pneumatic recess, form:

- (0) – flat, recess grades smoothly into the floor of the lateral temporal fenestra (=subtemporal fenestra)
  - (1) – lip, recess separated from lateral temporal fenestra (=subtemporal fenestra)
- (Carr and Williamson 2010:185; Brusatte et al., 2010:133)

228. Ectopterygoid, jugal process, external pneumatic foramina leading into jugal recess:

- (0) – absent
  - (1) – present
- (Brusatte et al., 2009:164; Carr and Williamson 2010:180; Brusatte et al., 2010:130)

229. Ectopterygoid, jugal process inflation:

- (0) – uninflated
  - (1) – inflated by internal pneumaticity
- (Carr and Williamson 2010:181; Brusatte et al., 2010:131)

230. Ectopterygoid, mediolateral length of jugal process:

- (0) – short
  - (1) – long
- (Brusatte et al., 2009:163)

231. Ectopterygoid, dorsoventral thickening of jugal process:

- (0) – thin jugal process
  - (1) – thickened
- (Brusatte et al., 2009:165)

232. Ectopterygoid, dorsal recess form:

- (0) – absent
  - (1) – present forms dorsal lip
- (Li et al., 2009:60)

### Pterygoid

233. Pterygoid, contact between pterygoid and palatine:

- (0) – continuous
  - (1) – discontinuous in the mid-region, resulting in a subsidiary palatal fenestra
- (Ostrom, 1969; Smith et al., 2007:119)

## Mandible

234. Mandible, mandibular ramus, dorsoventral depth of dentary at level of dentary-surangular contact on the dorsal margin of the lower jaw:

- (0) – shallow, less than 20% of the total anteroposterior length of the lower jaw
  - (1) – deep, greater than 20% of the total anteroposterior length of the lower jaw
- (Carr and Williamson 2010:200; Brusatte et al 2009: 183; Brusatte et al., 2010: 168)

235. External mandibular fenestra:

- (0) – absent
- (1) – present; tiny
- (2) – present; large

(Hwang et al., 2004; Peyer, 2007; Li et al., 2009: 253; Sereno et al., 2009:51; Carr and Williamson, 2010:217; Brusatte et al., 2010: 169)

236. Mandible, internal mandibular fenestra size:

- (0) – small and slit-like
  - (1) – large and rounded
- (Currie 1995; Li et al., 2009:73)

237. Mandible, madibular joint, position in lateral view:

- (0) – anterior to or even with the paroccipital process
  - (1) – posterior to the paroccipital process
- (Brusatte et al., 2009:115)

238. Mandible, lower jaw, articulation, glenoid position relative to level of alveolar margin of dentary with mandible occluded:

- (0) – level or ventral
  - (1) – dorsal
- (Sereno et al., 2009:54; Brusatte et al., 2010: 170)

239. Mandible, occlusion in lateral view:

- (0) – jaws occlude for their full length
  - (1) – jaws diverge rostrally due to kink and downward deflection in dentary buccal margin
- (Li et al., 2009:215)

## Dentary

240. Dentary, dorsal upturn of element at anterior end:

- (0) – absent
  - (1) – present
- (New Character)

241. Dentary shape in lateral view:

- (0) – with subparallel dorsal and ventral edges
  - (1) – subtriangular in lateral view, posteriorly expanded
- (Li et al., 2009:70)

242. Dentary, expansion of posterior dentary:

- (0) – posterior height of dentary two times or less than minimum dentary height
  - (1) – posterior end of dentary more than two times the minimum dentary height
- (New Character)

243. Dentary, symphysis, texture:

- (0) – generally smooth
  - (1) – strongly rugose and beveled, with interlocking ridges and convexities for articulation with the opposing symphysis
- (Brusatte et al., 2010: 173)

244. Dentary, primary neurovascular foramina, arrangement:

- (0) – distinct foramina or set into a shallow groove posteriorly
  - (1) – set into a deep and sharp groove across the middle and posterior regions of the dentary
- (Brusatte et al., 2010: 176)

245. Dentary, overall shape of dorsal surface (excluding anterior upturn if present):

- (0) – horizontal, straight
  - (1) – dorsally concave
- (Brusatte et al., 2010: 177)

246.Dentary, ventral margin of bone in lateral view, profile:

- (0) – straight
- (1) – sigmoidal
- (New Character)

247.Dentary, posterior end, presence of posterodorsal process above external mandibular fenestra:

- (0) – present
- (1) – absent

(Modified from Li et al 2009: 68)

248.Dentary, posterior end, presence surangular process on the dorsal surface of the mandible:

- (0) – absent
- (1) – present

(Modified from Li et al 2009: 68)

249.Dentary, Meckelian groove, dorsoventral depth:

- (0) – wide and shallowly inset into medial surface of bone
- (1) – narrow and deeply inset into bone, groove appears as a thin, sharp structure

(Brusatte et al., 2010: 178)

250.Dentary, position of Meckelian groove:

- (0) – closer to ventral margin of bone
- (1) – roughly at midheight

(Modified from Bursatte et al., 2009:195)

251.Dentary, anterior extent of lingual bar:

- (0) – medial to first alveolus
- (1) – medial to second (or further posterior) alveolus (Bursatte et al., 2009:196)

252.Dentary, articular surface for splenial along ventral region of dentary ramus below the Meckelian fossa, form:

- (0) – dorsoventrally shallow and smooth
- (1) – dorsoventrally deep (nearly as deep as anterior depth of fossa) and rugose

(Brusatte et al., 2010: 174)

253.Dentary, angle of the rostral end in lateral view:

- (0) – rostral end relatively vertical with transition point between dorsal and ventral surfaces below alveoli 1-3 when present
- (1) – rostral end angled with transition point between dorsal and ventral surfaces below below alveolus 4 or further back

(Bursatti et al., 2009:197; Carr and Williamson 2010:215; Brusatte et al., 2010: 171)

254.Dentary, anteriormost alveoli, size in comparison to alveoli in rostroposterior middle of tooth row:

- (0) – approximately same size
- (1) – first two alveoli substantially smaller
- (2) – first alveolus substantially smaller

(Brusatte et al., 2010: 175)

255.Dentary, distinct interdental plates:

- (0) – present
- (1) – absent

(Modified from Li et al 2009: 90)

## Coronoid and Supradentary

256.Supradentary ossification, shape:

- (0) – elongate, shallow strip
- (1) – deep, crescentic shape

(Brusatte et al., 2010: 194)

257.Supradentary and coronoid ossifications, form of contact at their zone of fusion:

- (0) – smoothly confluent
- (1) – offset by a concave notch

(Brusatte et al., 2010: 195)

## Splenial

258.Splenial, anterior margin:

- (0) – tapered point
- (1) – squared or jagged anterior end

(New Character)

259.Splenial, form of posterior end:  
(0) – straight or slightly curved  
(1) – distinctly forked  
(Sereno et al., 1996; Smith et al., 2007:131)

260.Splenial, mylohyoid foramen:  
(0) – small, smaller than dentary alveoli  
(1) – large, subequal to or larger than dentary alveoli  
(Modified from Carr and Williamson 2010:210; Brusatte et al., 2010: 191)

261.Splenial, myohyoid foramen orientation of long axis:  
(0) – horizontal  
(1) – dorsoposteriorly inclined in line with intercoronoid process  
(Modified from Carr and Williamson 2010:210; Brusatte et al., 2010: 191)

262.Splenial, mediolateral thickness of intercoronoid process:  
(0) – no thickening  
(1) – thickened mediolaterally  
(New Character)

## Angular

263.Angular, exposure in lateral view:  
(0) – exposed almost to end of mandible in lateral view, reaches or almost reaches articular  
(1) – excluded from posterior end  
(Li et al. 2009:211)

264.Angular, exclusion from posterior end:  
(0) – end of angular stops well short of glenoid  
(1) – stops near the anterior end of glenoid  
(Li et al. 2009:211)

265.Angular posterior process:  
(0) – posterior process point projects dorsally above ventral margin of mandible  
(1) – posterior process tip flush with ventral margin of mandible  
(Li et al. 2009:211)

266.Angular, ventral margin, form:  
(0) – smoothly convex  
(1) – anterior region “flexed” relative to posterior region, such that there is a discrete step between them  
(Brusatte et al., 2010: 189)

## Surangular

267.Surangular, dorsoventral depth:  
(0) – shallow, element less than 35% craniocaudal length  
(1) – deep, depth 40% or more element craniocaudal length  
(New Character)

268.Surangular, lateral surface, wide depression present for dorsal surangular process of the dentary:  
(0) – absent or narrow groove  
(1) – wide depression  
(New Character)

269.Surangular, groove on dorsolateral surface of anterior end:  
(0) – absent  
(1) – present, shallow groove faintly visible  
(2) – present, deep well-marked groove  
**ORDERED**  
(New Character)

270.Surangular, foramen in dorsolateral groove:  
(0) – absent  
(1) – present, small foramen much smaller than groove  
(2) – present, large foramen subequal to groove in diameter  
**ORDERED**  
(New Character)

271.Surangular, anteroventral extension:  
(0) – extension is absent  
(1) – encloses external mandibular fenestra by contacting the angular anteriorly  
(Currie et al., 2003; Brusatte et al., 2009:190)

272. Surangular, surangular shelf on lateral surface, form:

- (0) – absent or low ridge
- (1) – prominent, shelf present but forms a dorsoventrally thin ridge
- (2) – prominent, well-developed shelf that is dorsoventrally deep

**ORDERED**

(Holtz, 2001 in Currie et al., 2003; Xu et al., 2006; Sereno et al. 2009:53; Brusatte et al. 2009:191; Carr and Williamson 2010:209; Brusatte et al., 2010: 180)

273. Surangular, surangular shelf, orientation relative to the long axis of the lower jaw:

- (0) – ventrally inclined anteriorly or sigmoidal
- (1) – dorsally inclined anteriorly
- (2) – horizontal

(Modified from Brusatte et al., 2010: 182)

274. Surangular foramen in lateral surface of surangular anterior to mandibular articulation:

- (0) – absent
- (1) – tiny foramen, smaller or subequal to glenoid fossa
- (2) – large surangular foramen present (bigger than glenoid fossa in diameter)

**ORDERED**

(Modified from Li et al. 2009:74; Sereno et al. 2009:52; Carr and Williamson 2010:204; Brusatte et al., 2010: 179)

275. Surangular, position of surangular shelf in relation to surangular foramen:

- (0) – placed far dorsal to posterior surangular foramen
- (1) – foramen abuts shelf but shelf projects laterally and does not overhang foramen
- (2) – shelf projects ventrolaterally to overhang foramen

(Carr and Williamson 2010:208; Brusatte et al., 2010: 181)

276. Surangular, pneumatic fossa posterodorsal to posterior surangular foramen:

- (0) – absent
- (1) – present and shallow sometimes with a small foramen inside foramen
- (2) – present and deeply invaginated with large foramen

**ORDERED**

(Brusatte et al., 2010: 183)

277. Surangular, adductor muscle attachment site dorsal to surangular shelf, orientation:

- (0) – faces primarily dorsally
- (1) – faces almost equally dorsally and laterally
- (2) – faces primarily laterally

(Brusatte et al., 2010: 184)

278. Surangular, laterally inclined flange on caudodorsal surface for articulation with lateral process of lateral quadrate condyle:

- (0) – absent
- (1) – present

(Li et al., 2009:212)

## Prearticular

279. Prearticular shape:

- (0) – dorsally concave sweeping low curve in lateral view
- (1) – subcircular in lateral view, “U” shaped

(New Character)

280. Prearticular, anterior process expansion:

- (0) – unexpanded
- (1) – expanded into a paddle like shape, more than 220% the dorsoventral depth of the midshaft

(New Character)

281. Prearticular, midshaft cross-sectional shape:

- (0) – mediolaterally flattened, plate-like
- (1) – sub-round with sub-equal width and height
- (2) – round

**ORDERED**

(New Character)

282.Prearticular, ventral process or flange:

- (0) – absent
  - (1) – present
- (New Character)

283.Prearticular, ventral bar, series of tall ridges and deep grooves on lateral surface to strengthen articulation with angular:

- (0) – absent
- (1) – present

(Brusatte et al., 2010: 193)

284.Prearticular, shape of caudoventral margin:

- (0) – sweeping ventrally convex curve
  - (1) – sigmoidal with downturned articular process
- (New Character)

### Articular

285.Articular, medial process:

- (0) – absent
- (1) – present

(Li et al., 2009:77)

286.Articular, retroarticular process shape:

- (0) – rod-like, sort
- (1) – rod-like, elongate and slender
- (2) – short, wide, and with distinct posteriorly facing concavity

(Li et al., 2009:269)

287.Articular, smooth non-articular region between glenoid and attachment site for depressor mandibular muscles:

- (0) – present
- (1) – absent

(Brusatte et al., 2010: 190)

288.Articular, pneumatic foramen posterior to glenoid:

- (0) – absent
- (1) – present

(Currie et al., 2003; Brusatte et al., 2009: 185)

### Dentition

289.Premaxilla, number of teeth:

- (0) – 5 or more
- (1) – 4
- (2) – 3
- (3) – edentulous

(Modified after Li et al., 2009:80)

290.Premaxillary teeth, position of mesial carina:

- (0) – symmetrical
- (1) – offset mesial to distal carina on all teeth (teeth ziphodont)
- (2) – rotated distally on premaxillary teeth 1 and 2 (anterior teeth “D-shaped” and posterior teeth ziphodont)
- (3) – rotated distally on all teeth

(Modified from Bakker et al., 1988; Harris, 1998:46; Smith et al., 2007:19; Benson, 2009:84; Li et al. 2009:91; Sereno et al. 2009:56-58; Carr and Williamson 2010:219; Brusatte et al., 2010:196)

291.Premaxillary teeth, median vertical ridge on lingual surface:

- (0) – absent
- (1) – present as subtle structure in anterior (mesial) premaxillary teeth
- (2) – present as pronounced structure in all premaxillary teeth

### ORDERED

(Sereno et al. 2009:60; Brusatte et al., 2010:198)

292.Premaxillary teeth, curvature of caudal (posterior) teeth:

- (0) – recurved
- (1) – straight

(Brusatte et al., 2010:199)

- 293.Premaxillary teeth, size compared to rostral-most maxillary tooth:  
 (0) – subequal  
 (1) – significantly smaller  
 (Modified from Li et al., 2009: 257; Sereno et al. 2009:59; Brusatte et al., 2010: 197)
- 294.Premaxillary teeth, presence of serrations:  
 (0) – present  
 (1) – absent on at least the mesial carina or completely absent  
 (Modified after Holtz, 2004; Li et al., 2009: 256)
- 295.Maxillary teeth, presence:  
 (0) – present  
 (1) – absent edentulous  
 (Holtz, 2004; Li et al., 2009: 82)
- 296.Maxilla, position of carina on anteriormost tooth:  
 (0) – symmetrical  
 (1) – asymmetrical so that tooth is D shaped  
 (New Character)
- 297.Maxilla, position of the posteriormost tooth:  
 (0) – nearer to the posterior end of the antorbital fenestra  
 (1) – posterior to but closer to the midpoint of the antorbital fenestra  
 (2) – anterior to the midpoint of the antorbital fenestra  
 (New Character)
- 298.Maxilla, number of teeth:  
 (0) – 18 or more alveoli  
 (1) – 14 to 17 alveoli  
 (2) – 11 to 13 alveoli  
 (3) – 10 to 1 alveoli  
 (Modified from Li et al., 2009: 202; Sereno et al. 2009:61; Carr and Williamson 2010:220; Brusatte et al., 2010:200)
- 299.Dentary, portion of dentary with teeth:  
 (0) – teeth throughout to 65% of the dorsal surface of the dentary  
 (1) – teeth restricted to the rostral 33% or edentulous  
 (Modified from Li et al., 2009:220)
- 300.Dentary, number of teeth:  
 (0) – 220 or more alveoli  
 (1) – 18 to 21 alveoli  
 (2) – 15-17 alveoli  
 (3) – 14 or less alveoli  
 (Modified from Li et al., 2009:84)
- 301.Tooth spacing on maxilla and dentary:  
 (0) – closely appressed  
 (1) – widely spaced with considerable separation between alveoli  
 (New Character)
- 302.Maxillary and dentary, mid position tooth serration symmetry:  
 (0) – proximal and distal carina serrations similar in size  
 (1) – clear asymmetry in serrations on proximal and distal carina or without serrations on either surface  
 (2) – lacking serrations  
 (Modified from Holtz, 2004; Li et al., 2009:83)
- 303.Maxillary and dentary teeth, form:  
 (0) – ziphodont, transverse width of base less than 60% of mesiodistal length  
 (1) – thickened, width greater than 60% of length  
 (2) – thickened, width nearly equal to length  
 (3) – round  
 (Sereno et al. 2009:62; Brusatte et al., 2010:201)

## Axis

- 304.Axis, pleurocoel:  
 (0) – absent  
 (1) – present  
 (Modified from Rowe and Gauthier, 1990; Smith et al., 2007; Li et al., 2009:142; Brusatte et al., 2010:203)

- 305.Axis, pleurocoel position:  
 (0) – midheight of centrum  
 (1) – dorsally located, directly underneath neurocentral suture and directly posterior to diapophysis  
 (Modified from Rowe and Gauthier, 1990; Smith et al., 2007; Li et al., 2009:142; Brusatte et al., 2010:203)
- 306.Axis, pneumatic foramen, extent of surrounding fossa:  
 (0) – limited to margins of foramen  
 (1) – extensive, occupies most of lateral surface of centrum  
 (Brusatte et al., 2010:204)
- 307.Axis, anteroposterior length of centrum compared to dorsoventral height of posterior centrum face:  
 (0) – longer than tall  
 (1) – shorter than tall, or subequal  
 (Modified from Holtz, 2001; Brusatte et al., 2010:202)
- 308.Axis, ridge on ventral surface of centrum:  
 (0) – absent  
 (1) – present  
 (Brusatte et al., 2010:205)
- 309.Axis, axial parapophyses and diapophyses:  
 (0) – moderate/prominent  
 (1) – reduced/absent  
 (Rowe, 1989; Smith et al., 2007:143)
- 310.Axis, neural spine form in lateral view:  
 (0) – sheet-like  
 (1) – anteroposteriorly reduced and rod-like  
 (Molnar et al., 1990; Smith et al., 2007:145)
- 311.Axis, neural spine in cranial view:  
 (0) – flared transversely  
 (1) – compressed mediolaterally  
 (Li et al., 2009:94)
- 312.Axis, pneumatic foramina and fossae on each side of the anterior ridge on the neural spine:  
 (0) – absent  
 (1) – present  
 (Brusatte et al., 2010:206)
- 313.Axis, neural spine, texture of dorsal region of anterior surface:  
 (0) – generally smooth or with subtle texture  
 (1) – highly rugose, with series of grooves, ridges, and eminences  
 (Brusatte et al., 2010:207)
- 314.Axis, epineurapophyseal processes on axis neural spine:  
 (0) – absent  
 (1) – present  
 (Li et al., 2009:277)
- 315.Axis, epiphyses, posterior extent:  
 (0) – absent or terminates well anterior to postzygapophysis  
 (1) – extends to, or only slightly posterior to, the posterior margin of the postzygapophysis  
 (2) – large, rugose flange that extends posterior to postzygapophysis  
 (3) – elongate flange that extends posteriorly 75% or more than the anteroposterior length of the postzygapophysis  
 (Modified from Brusatte et al., 2010:210)

### Cervical Vertebrae

- 316.Cervical vertebrae, number of pneumatic openings in anterior centra:  
 (0) – one pair of pneumatic openings  
 (1) – two pairs of pneumatic openings  
 (Gauthier, 1986; Li et al., 2009:100)

317.Cervical vertebrae, form of centra:

- (0) – amphiceolous to platyceolous
- (1) – strongly opisthocoelous

(Gauthier, 1986; Smith et al., 2007:151)

318.Cervical vertebrae, epiphyses of C3-5, form:

- (0) – absent or terminates well anterior to postzygapophysis
- (1) – extends to, or only slightly posterior to, the posterior margin of the postzygapophysis
- (2) – large, rugose flange that extends posterior to postzygapophysis

(Modified from Brusatte et al., 2010:210)

319.Cervical vertebrae, position of posterior edge of anterior cervical centra:

- (0) – level with or anterior to the posterior extent of neural arch
- (1) – extending beyond posterior limit of neural arch.

(Li et al., 2009:96)

320.Cervical vertebrae, anterior cervical centra, shape in anterior view:

- (0) – subcircular or square
- (1) – distinctly wider than high; kidney shaped

(Gauthier, 1986; Li et al., 2009:98)

321.Cervical vertebrae, anteroposterior length of centrum compared to dorsoventral height of posterior centrum face:

- (0) – longer than tall
- (1) – shorter than tall, or subequal

(Modified from Holtz, 2001; Brusatte et al., 2010:202)

322.Cervical vertebrae, neural spine positon:

- (0) – centroid of neural spine positioned on anterior half of vertebrae
- (1) – centroid of neural spine positioned posterior to the midpoint of vertebrae

(New Character)

323.Cervical vertebrae, neural spine anterioposterior minimum width:

- (0) – wide,  $\frac{1}{2}$  or more than the length of the centrum
- (1) – narrow, less than  $\frac{1}{2}$  the length of the centrum

(New Character)

324.Cervical vertebrae, neural spine dorsoventral height:

- (0) – short, less than the height of the centrum
- (1) – low and centered on neural arch, giving arch an “X” shape in dorsal view
- (2) – approximately the same height as the posterior centrum face
- (3) – tall, 1.5 or more than the height of the centrum face

(Modified from Makovicky and Sues, 1998; Holtz, 2001; Li et al., 2009:99; Brusatte et al., 2010:212)

325.Cervical vertebrae, neural spine mediolateral thickness:

- (0) – thin
- (1) – anteroposteriorly tapering thin to thick
- (2) – thick, stout rectangle, base is nearly square with nearly equal anteroposterior and transverse dimensions

(Modified from Holtz, 2004; Benson, 2008; Brusatte et al., 2010:211)

326.Cervical vertebrae, rugose ligament attachment scars on anterior and posterior surfaces of neural spine:

- (0) – absent or weakly developed
- (1) – present as prominent, flanges visible in lateral view

(New Character)

327.Cervical vertebrae, orientation of posterior centrodiapophyseal lamina in C3-5:

- (0) – nearly horizontal, fossa located primarily dorsal to lamina
- (1) – projects posteroventrally, infrapostzygapophyseal fossa located primarily posterior to lamina

(Modified from Brusatte et al., 2010:216)

328.Cervical vertebrae, position of prezygapophysis in middle cervicals:

- (0) – slightly overhangs centrum laterally
- (1) – strongly overhangs centrum laterally, entire prezygapophyseal facet placed lateral to centrum (Brusatte et al., 2010:215)

## Dorsal Vertebrae

329.Dorsal centra pneumaticity:

- (0) – apneumatic
- (1) – pneumaticity limited to anterior dorsals
- (2) – present throughout dorsal column

### ORDERED

(Modified from Li et al., 2009:106 and Brusatte et al., 2010:218)

330.Dorsal vertebrae, ratio of dorsoventral height of posterior centrum face to anteroposterior length of middle-posterior dorsal centra:

- (0) – long and low, less than 75%
- (1) – short and tall greater than 75%

(Carpenter et al., 2005; Brusatte et al., 2009:210; Carr and Williamson 2010: 228; Brusatte et al., 2010:220)

331.Dorsal vertebrae, anterior dorsal neural spines, level of posterior termination:

- (0) – at approximately the same level as the posterior centrum face
- (1) – far posterior to the posterior centrum face

(Modified from Brusatte et al., 2009:209; Carr and Williamson 2010:227; Brusatte et al., 2010:219)

332.Dorsal vertebrae, mid- posterior dorsal neural spines, level of posterior termination:

- (0) – at approximately the same level as the posterior centrum face
- (1) – far posterior to the posterior centrum face

(Modified from Brusatte et al., 2009:209; Carr and Williamson 2010:227; Brusatte et al., 2010:219)

333.Dorsal vertebrae, anterioposterior minimum width of mid-dorsal neural spine in lateral view:

- (0) – wide, subequal to centrum length
  - (1) – narrow,  $\frac{1}{2}$  centrum length or less
- (New Character)

334.Dorsal vertebrae, dorsoventral height of mid-dorsal neural spine:

- (0) – short, subequal to or less than centrum height
  - (1) – tall,  $1.5 \times$  centrum height or more
- (New Character)

335.Dorsal vertebrae, rugose ligament attachment scars on anterior and posterior surfaces of neural spine:

- (0) – absent or weakly developed
  - (1) – present as prominent, flanges visible in lateral view
- (New Character)

336.Neural spines on posterior dorsal vertebrae, shape in lateral view:

- (0) – rectangular or square
  - (1) – anteroposteriorly expanded distally, fan-shaped
- (Li et al., 2009:209)

337.Ventral keel in anterior dorsals:

- (0) – absent or very poorly developed
  - (1) – pronounced
- (Rauhut, 2003; Smith et al., 2007:170)

338.Posteriormost dorsals, parapophyses position:

- (0) – on the same level as transverse process
  - (1) – distinctly below transverse process
- (Makovicky, 1995; Smith et al., 2007:179)

## Sacral Vertebrae

339.Sacral vertebrae, number of sacral vertebrae:

- (0) – 5 or less
  - (1) – 6
- (Li et al., 2009:110)

340.Sacral vertebrae, length of anterior sacrals and posterior dorsal centrum length:

- (0) – subequal in length
  - (1) – sacrals substantively longer than posterior dorsal centra.
- (Dal Sasso and Maganuco, 2011)

341.Sacral vertebrae, pleurocoels or foramina on lateral surfaces of centra:

- (0) – absent on sacral vertebrae
  - (1) – present on anterior sacrals only
- (Li et al., 2009:113; Carr and Williamson 2010:229; Brusatte et al., 2010:223)

342. Sacral vertebrae, fenestrae between fused neural spines:

- (0) – neural spines unfused
- (1) – spines fused but fenestrae absent
- (2) – spines fused and fenestrae present

(Brusatte et al., 2010:224)

343. Sacral ribs, position of ribs on sacrum:

- (0) – span two sacrals
- (1) – limited to a single sacral

(Brusatte et al., 2010:225)

344. Sacral ribs, position of rib attachment for ribs on individual sacrals:

- (0) – span centrum and neural arch
- (1) – limited to neural arch only

(Brusatte et al., 2010:226)

345. Sacral vertebra five, position of ventral margin of posterior articular face in lateral view:

- (0) – at same level as ventral margin of anterior articular face
- (1) – positioned ventral to ventral margin of anterior articular face

(Brusatte et al., 2010:227)

## Caudal Vertebrae

346. Caudal vertebrae: presence of transverse processes:

- (0) – on more than 16 posteriors
- (1) – on 12 to 16
- (2) – on fewer than 12 posteriors

(Holtz, 2004; Brusatte et al., 2009:214)

347. Caudal vertebrae, transition point in caudal series at which transverse processes end:

- (0) – begins distal to the 10th posterior
- (1) – between the 5th and 10th posterior vertebra

(Li et al., 2009:116)

348. Caudal vertebrae, anterior caudal centra shape:

- (0) – tall, oval or round in cross section
- (1) – with box-like centra in posteriors I-V

(Gauthier, 1986; Li et al., 2009:117)

349. Caudal vertebrae, anterior caudals, position of posterior end of base of neural spine:

- (0) – anterior to posterior surface of centrum
- (1) – or level with or posterior to posterior surface of centrum

(Brusatte et al., 2010:229)

350. Caudal vertebrae, anterior caudals, shape of transverse processes in dorsal view:

- (0) – rectangular, with parallel anterior and posterior sides, or slightly ovoid with a gradual expansion in width distally
- (1) – distal end expanded into a spatulate bulb

(Brusatte et al., 2010:230)

351. Caudal vertebrae, anterior caudals, two laminae linking prezygapophysis and transverse process, between which is a triangular fossa:

- (0) – absent
- (1) – present, shallow fossa
- (2) – present, deep fossa

## ORDERED

(Modified from Brusatte et al., 2010:231)

352. Caudal vertebrae, neural spines:

- (0) – simple, undivided
- (1) – separated into anterior and posterior alae throughout much of caudal sequence

(Russell and Dong, 1993; Li et al., 2009:118)

353. Caudal vertebrae, anterior spur in front of neural spine in mid-caudals:

- (0) – absent
- (1) – present

(Makovicky, 1995; Smith et al., 2007:198)

354.Caudal vertebrae, distal caudal neural spine shape:

- (0) – form a low ridge
- (1) – spine absent

(Modified from Russell and Dong, 1993; Li et al., 2009:119)

355.Caudal vertebrae, mid to distal caudal postzygapophyses length:

- (0) – short between 20% to 100% centrum length
- (1) – extremely long, between 150% to 1000% centrum length

(Modified Li et al., 2009:120)

### Chevrons

356.Chevrons, anterior process of chevron base:

- (0) – absent/weak
- (1) – large

(Molnar et al., 1990; Smith et al., 2007:199)

357.Chevrons of anterior caudals, form of distal end:

- (0) – short anteroposteriorly, shaft cylindrical
- (1) – distal end elongate anteroposteriorly, flattened and plate-like

(Modified from Smith et al., 2007:200)

358.Chevrons, form of mid-caudal chevrons:

- (0) – rod-like or only slightly expanded ventrally
- (1) – L-shaped

(Sereno et al., 1996; Smith et al., 2007:201)

359.Chevrons, form of distal caudal chevrons:

- (0) – rod-like or L-shaped
- (1) – skid-like or T-shaped

(Rauhut, 2003; Smith et al., 2007:202)

### Ribs and Gastralia

360.Pneumatic excavations in cervical or dorsal rib heads:

- (0) – absent
- (1) – present

(Harris, 1998; Smith et al., 2007:165)

### Forelimb

361.Scapula, length relative to humerus:

- (0) – longer than humerus
- (1) – shorter than humerus

(Li et al., 2009:139)

362.Radius and ulna separation:

- (0) – radius and ulna clearly separate elements
- (1) – distinct adherence or syndesmosis distally

(Li et al., 2009:214)

### Scapula

363.Scapula general form:

- (0) – short and broad (ratio length/minimal height of shaft <9)
- (1) – slender and elongate (ratio >10)

(Perez-Moreno et al., 1993; Smith et al., 2007:212)

364.Scapula, dorsal expansion of proximal blade measured from the dorsal surface at the scapulocoracoid suture to the most ventrally displaced dorsal surface of the scapular blade:

- (0) – not more than twice the minimum scapular blade width
- (1) – twice to 2.5 times the minimum scapular blade width
- (2) – expanded more than three times the minimum scapular width
- (3) – expanded more than four times the minimum scapular width

**ORDERED**

(New Character)

- 365.Scapula, angle between dorsal arcromion process and dorsal surface of scapular blade:
- (0) – sweeping curve
  - (1) – distinct angle greater than 100 degrees
  - (2) – distinct angle less than 95 degrees
- (Modified from Brusatte et al 2009:216; Sereno et al. 2009: 68; Carr and Williamson 2010: 234; Brusatte et al., 2010:232)
- 366.Scapula, distal end expansion relative to proximal portion of scapula:
- (0) – markedly expanded
  - (1) – not expanded
- (Gauthier, 1986; Smith et al., 2007:213)
- 367.Scapula, ratio of dorsoventral depth of distal expansion to minimum dorsoventral depth of blade:
- (0) – less than 2.5
  - (1) – greater than 2.5
- (Sereno et al. 2009: 70; Brusatte et al., 2010:235)
- 368.Scapula, acromion margin in rostrodorsal view:
- (0) – continuous with blade in anterior aspect
  - (1) – anterior edge laterally everted relative to plane of scapular blade
- (Li et al., 2009:133)
- 369.Scapula, acromion margin length:
- (0) – long, either tapering or horizontal triangle
  - (1) – truncated with deep base but short reach beyond scapular blade and squared-off profile
- (Li et al., 2009:279)
- 370.Scapula and coracoid form in posterior and anterior views:
- (0) – continuous arc
  - (1) – coracoid inflected medially, scapulocoracoid ‘L’ shaped in lateral view
- (Li et al., 2009:137)

## **Coracoid**

- 371.Coracoid in lateral view:
- (0) – subcircular, with shallow ventral process
  - (1) – subquadrangular with extensive ventral process
  - (2) – shallow ventral blade with elongate ventral process
- (Li et al., 2009:136)
- 372.Coracoid, anteroposterior length at midpoint:
- (0) – long, 200% or greater than the length of the scapular acromion at midheight
  - (1) – short, less than 150% of the length of the scapular acromion at midheight
- (Modified from Sereno et al. 2009: 71; Brusatte et al., 2010:237)
- 373.Posterolateral surface of coracoid ventral to glenoid fossa:
- (0) – unexpanded
  - (1) – posterolateral edge of coracoids expanded to form triangular subglenoid fossa bounded laterally by enlarged coracoid tuber
- (Li et al., 2009:134)
- 374.Ventral part of coracoid anterior to the glenoid facet:
- (0) – approximately level with the rim of the facet
  - (1) – with tapering posteroventral process
- (Gauthier, 1986; Smith et al., 2007:217)
- 375.Glenoid fossa orientation:
- (0) – faces posteriorly or posterolaterally
  - (1) – faces laterally
- (Li et al., 2009:138)
- 376.Ossified sternal plates in adults:
- (0) – ossified sternal plates absent
  - (1) – plates ossified, but separate in adults
- (Modified from Li et al., 2009: 128)

## Humerus

377.Humerus, form of shaft:

- (0) – straight
- (1) – sigmoid

(Carpenter et al., 2005; Brusatte et al., 2009:218)

378.Humerus, proximal head, morphology:

- (0) – low, poorly differentiated, crescentic shaped in proximal view, overhangs posterior surface and does not overhang anterior surface
  - (1) – enlarged, occupies the majority of the proximal end, bulbous in proximal view, overhangs both posterior and anterior surfaces
- (Sereno et al. 2009:73; Brusatte et al., 2010:240)

379.Deltopectoral crest form:

- (0) – long, makes up more than 40% or more of the element length
- (1) – makes up 30-38% of element length
- (2) – short, less than 25% element length, deltopectoral crest less pronounced, forming an arc rather than being quadrangular

(Modified from Li et al., 2009:140 and Brusatte el al., 2010:)

380.Humerus, rotation along shaft, orientation of long axis of proximal end relative to that of distal end:

- (0) – approximately 30-45 degree angle
  - (1) – approximately parallel, shaft rotation absent
- (Carr and Williamson 2010:236; Brusatte et al., 2010:242)

381.Humerus, additional muscle attachment tubera at the corner of the anterior and lateral surfaces distal to the deltopectoral crest:

- (0) – absent
  - (1) – present
- (Brusatte et al., 2010:243)

382.Humerus, form of distal condyles:

- (0) – medial condyle expanded further medially than the lateral condyle is laterally
  - (1) – lateral and medial condyles expanded equally (offset from shaft in anterior or posterior view is equal)
- (Brusatte et al., 2010:245)

383.Humerus, length relative to the femur:

- (0) – 45% or more
- (1) – 40-30%
- (2) – 25-30%

(Carr and Williamson 2010: 235; Sereno et al. 2009: 72; Brusatte et al., 2010:239)

## Ulna

384.Ulna, shaft axis, form:

- (0) – bowed
- (1) – straight

(Li et al., 2009; Sereno et al. 2009:75; Brusatte et al., 2010:246)

385.Ulna, distal articular surface, form:

- (0) – convex
  - (1) – flat
- (Sereno et al. 2009:76; Brusatte et al., 2010:247)

## Manus

386.Distal carpal, principal distal carpal shape:

- (0) – semilunate in lateral view with trochlear proximal surface
  - (1) – discoid with flat proximal surface
- (Li et al. 2010:276; Carr and Williamson 2010:238; Brusatte et al., 2010:248)

387.Manus, number of metacarpals present:

- (0) – 5
- (1) – 4
- (2) – 3

(Modified from after Li et al., 2009:150)

388. Manus, number of digits with phalanges:

- (0) – 4
- (1) – 3
- (2) – 2

(Modified from Li et al., 2009: 270; Sereno et al. 2009:82; Brusatte et al., 2010:249)

389. Metacarpal I, medial distal condyle, size:

- (0) – well-developed and large
- (1) – rudimentary

(Sereno et al. 2009:78; Brusatte et al., 2010:250)

390. Metacarpal II, ratio of the length of metacarpal II to the length of metacarpal I:

- (0) – metacarpal II is 2 or more times the length of metacarpal I
- (1) – metacarpal II is less than 1.8 times the length of metacarpal I

(Modified from Sereno et al. 2009:79; Brusatte et al., 2010:252)

391. Metacarpal II, mediolateral width at midpoint:

- (0) – equal to or narrower than metacarpal I
- (1) – more robust than metacarpal I

(Carr and Williamson 2010: 253)

392. Metacarpal III, length:

- (0) – subequal in length to MC II
- (1) – much shorter than MC II

(Holtz, 2004; Brusatte et al., 2009:223)

393. Manual phalanx II-1, shaft diameter:

- (0) – less than shaft diameter of radius
- (1) – greater than shaft diameter of radius

(Li et al., 2009: 210)

394. Manual phalanx II-1, length:

- (0) – longer than metacarpal I
- (1) – subequal to metacarpal I
- (2) – shorter than metacarpal I

(Sereno et al. 2009:81; Brusatte et al., 2010:254)

395. Manual unguals, flexor tubercle, form:

- (0) – large, robust, rugose, conical structure
- (1) – reduced to a small convexity

(Brusatte et al., 2010:255)

396. Manual unguals, degree of recurvature:

- (0) – extensive, flexor margin deeply concave
- (1) – thin and reduced, flexor margin shallowly concave
- (2) – robust and reduced, flexor margin shallowly concave

(Modified after Brusatte et al., 2010:256)

397. Manual unguals, proximodorsal lip on some manual unguals, a transverse ridge immediately dorsal to the articulating surface:

- (0) – absent
- (1) – present

(Li et al., 2009: 153)

## Ilium

398. Ilium, overall shape of blade:

- (0) – sub-quadrangular or trapezoidal in lateral view
- (1) – semi-oval outline in lateral view

(Modified from Benson, 2008)

399. Ilium, dorsal margin, shape:

- (0) – smoothly convex or flat across entire length
- (1) – convex anteriorly and straightens out posteriorly
- (2) – straight anteriorly and transitions to convex posteriorly

(Modified from Brusatte et al., 2010:266)

400.Ilium, length compared to length of femur:

- (0) – ilium significantly shorter than the femur (70-85%)
  - (1) – almost the same length (95-105%)
  - (2) – ilium significantly longer (105-115%)
- (Xu et al., 2004; Brusatte et al., 2009:233; Sereno et al. 2009: 83; Brusatte et al., 2010:257)

401.Ilium, blade height vs. length:

- (0) – low and long
  - (1) – tall and short
- (New Character)

402.Ilium, iliac blade orientation:

- (0) – roughly vertical
  - (1) – dorsomedially inclined, dorsal edges of ilia approach or meet each other above sacrum
- (Modified from Li et al., 2009:265)

403.Ilium, dorsal margin of blade, position relative to sacral neural spines:

- (0) – separated by a gap
  - (1) – lies against neural spines and opposing iliac blades may make contact above neural spines
- (Sereno et al. 2009: 85; Brusatte et al., 2010:260)

404.Ilium, postacetabular blade orientation in dorsal view:

- (0) – subparallel
  - (1) – diverge posteriorly
- (Li et al., 2009:159)

405.Ilium, notch on anterodorsal edge of ilium:

- (0) – absent
  - (1) – notch at rostrodorsal corner
- (Holtz, 2004; Li et al., 2009:262)

406.Ilium, pronounced anteroventral ‘hook’ on anterior expansion of ilium:

- (0) – absent preacetabular blade subtriangular
- (1) – ventral edge pendant projection
- (2) – process strongly hooked with recurved posterior margin,

**ORDERED**

(Gauthier, 1986; Rauhut, 2003; Smith et al., 2007:253; Li et al., 2009:154; Sereno et al. 2009: 87; Brusatte et al., 2010:259)

407.Ilium, preacetabular part of ilium length relative to postacetabular ilium:

- (0) – preacetabular ilium shorter
  - (1) – roughly as long as postacetabular part of ilium
  - (2) – longer than postacetabular ilium
- (Li et al., 2009:155)

408.Ilium, notch between pubic peduncle and pre-acetabular process:

- (0) – wide, with semicircular or tear-drop outline
  - (1) – narrow and slit-like
- (Modified from Benson, 2008)

409.Ilium, dorsoventrally oriented midline supraacetabular ridge on lateral face of ilium above acetabulum:

- (0) – absent
  - (1) – present posterodorsally inclined
  - (2) – present and vertical or anterodorsally oriented
- (Rauhut, 2003; Benson 2008; Li et al., 2009:266; Brusatte et al., 2009:228; Sereno et al. 2009: 84; Carr and Williamson 2010: 246-248; Brusatte et al., 2010:258)

410.Ilium, dorsal extent of supraacetabular ridge:

- (0) – short, does not extend into the m. iliofibularis scar
  - (1) – tall, extend onto the m. iliofibularis scar
- (New Character)

411.Ilium, postacetabular process shape in lateral view:

- (0) – tapering or rounded, posterior margin convex
  - (1) – squared
  - (2) – acuminate (pointy)
- (Modified from Li et al., 2009:158 and Brusatte et al., 2010:267)

412.Ilium, supraacetabular crest on ilium as a separate process from antitrochanter:

- (0) – present, forms “hood” over femoral head
- (1) – reduced, not forming hood
- (2) – absent

(Li et al., 2009:157)

413.Ilium, acetabular crest, extent on pubic peduncle:

- (0) – extensive, extends along most or all of the edge of the peduncle
- (1) – limited, discretely offset from acetabular edge of pubic peduncle

(Li et al. 2009: 278; Brusatte et al., 2010:263)

414.Ilium, acetabular crest, maximum lateral projection relative to ischial peduncle:

- (0) – significantly greater
- (1) – subequal

(Sereno et al. 2009: 91; Brusatte et al., 2010:262)

415.Ilium, pubic peduncle articular facet:

- (0) – flat or concave
- (1) – convex
- (2) – flexed with two facets set at obtuse angle to each other

(Modified from Tykoski and Rowe, 2004; Li et al., 2009:291)

416.Ilium, pubic peduncle articular facet orientation:

- (0) – facet is sub-horizontal
- (1) – facet faces anteroventrally

(New Character)

417.Ilium, pubic peduncle width in lateral view:

- (0) – uniform in width (i.e. unexpanded)
- (1) – broadly flared toward pubic articular surface

(Rauhut, 2003; Smith et al., 2007:265).

418.Ilium, pubic and ischial peduncles relative dorsoventral length:

- (0) – comparable dorsoventral length
- (1) – pubic peduncle expanded and twice or more as long as ischiatric peduncle

(Sereno et al., 1994; Smith et al., 2007:266)

419.Ilium, pubic and ischial peduncles, anteroposterior width at dorsal neck:

- (0) – pubic peduncle much larger than ischial peduncle
- (1) – both peduncles approximately the same length

(Li et al., 2009: 292; Brusatte et al., 2010:264)

420.Ilium, cuppedicus fossa (‘preacetabular fossa’ of Hutchinson, 2001a):

- (0) – absent
- (1) – present, formed as antiliac shelf anterior to acetabulum, extends posteriorly to above anterior end of acetabulum
- (2) – present, posterior end of fossa on anterior end of pubic peduncle, anterior to acetabulum

**ORDERED**

(Modified from Hutchinson, 2001a; Smith et al., 2007:264).

421.Ilium, brevis fossa lateral exposure:

- (0) – entire length of fossa visible in lateral view, including caudal portion
- (1) – only the anterior portion of the fossa is visible, the caudal portion of the fossa is hidden by posterior blade of the ilium
- (2) – nearly completely hidden by posterior blade of the ilium

(New Character)

## Pubis

422.Pubis, orientation:

- (0) – propubic
- (1) – pubis vertical or pubis posteriorly oriented (opisthopubic)

(Li et al., 2009:177; Brusatte et al., 2010:275)

423.Pubis, shaft curvature:

- (0) – shaft curves posteriorly, anteriorly convex curvature
- (1) – straight
- (2) – distal end curves anteriorly, anterior surface of shaft concave

(Calvo et al., 2004; Li et al., 2009:180; Carr and Williamson 2010: 252; Brusatte et al., 2010:269)

424.Pubis, pubic boot, posterior expansion:

- (0) – present
- (1) – little or no posterior process
- (Li et al., 2009:178)

425.Pubis, pubic boot, anterior expansion:

- (0) – absent
- (1) – present, short
- (2) – present, long

**ORDERED**

(Brusatte et al., 2009:238,239)

426.Pubis, pubic boot, anterior process, length relative to posterior process, measured from line down the middle of the shaft:

- (0) – posterior process much longer
- (1) – subequal

(Carr and Williamson 2010: 256-258; Sereno et al. 2009: 97; Brusatte et al., 2010:273)

427.Pubis, entire pubic boot, anteroposterior length relative to total long axis length of pubis:

- (0) – less than 25%
- (1) – 30-35%
- (2) – 40-55%
- (3) – 60-70%
- (4) – greater than 75%

(Modified from Brusatte et al., 2010:272)

428.Pubis, ventral margin of boot in lateral view:

- (0) – convex
- (1) – straight

(Carpenter et al., 2005a; Bursatti et al., 2009:241; Brusatte et al., 2010:274)

429.Pubis, obturator foramen:

- (0) – present
- (1) – open notch present between pubic shaft and ischiadic peduncle
- (2) – neither notch or foramen present

(Li et al., 2009:273)

430.Pubis, pubic shaft shape:

- (0) – rounded
- (1) – mediolaterally flattened

(New Character)

431.Pubis, contact between pubes:

- (0) – both pubes meet extensively
- (1) – contact disrupted by a slit-like opening

(Makovicky et al., 2005; Li et al., 2009:182)

432.Pubis, pubic tubercle on anterior margin just ventral to contact with ilium:

- (0) – absent
- (1) – present as a convexity on the anterior margin of the pubis
- (2) – present as a rugose flange discretely offset from the anterior margin of the pubis and is bordered posteriorly by heavy rugosities on the lateral surface on the obturator region of the pubis

**ORDERED**

(Brusatte et al., 2009:237; Carr and Williamson 2010: 255; Brusatte et al., 2010:270)

433.Pubis, pubic tubercle, position:

- (0) – distally positioned, located ventral to the level of the obturator notch
- (1) – proximally positioned, located level with or dorsal to the obturator notch

(Brusatte et al., 2010:271)

## Ischium

434.Ischium, length compared to the length of the pubis:

- (0) – more than two-thirds
- (1) – two-thirds or less of pubis length

(Li et al., 2009:173)

435. Ischium, midshaft thickness at compared to pubis midshaft thickness:
- (0) – about as thick or thicker than pubic shaft
  - (1) – thin, half the thickness or less than the pubic shaft
- (Modified from Brusatte et al., 2009:247; Sereno et al. 2009: 94; Carr and Williamson 2010: 265; Brusatte et al., 2010:280)
436. Ischium, shaft curvature:
- (0) – roughly straight or only gently curved
  - (1) – curved, ventrally concave
  - (2) – curved, dorsally concave
- (Modified from Makovicky et al., 2005; Li et al., 2009:167)
437. Ischium, ilio-ischiadic contact:
- (0) – ischium with slightly concave or flat proximal articular surface that contacts ilium
  - (1) – with deep socket for reception of peg-like ischial peduncle of ilium
- (Li et al., 2009:261)
438. Ischium, transverse cross-section of acetabular rim:
- (0) – convex or beveled
  - (1) – broad shelf with longitudinal sulcus or depression
- (Benson, 2008; Li et al., 2009:274)
439. Ischium, ischial boot (expanded distal end relative to midshaft):
- (0) – present
  - (1) – absent
- (Li et al., 2009:175; Sereno et al. 2009: 95; Carr and Williamson 2010: 264; Brusatte et al., 2010:279)
440. Ischium, obturator foramen and flange:
- (0) – present
  - (1) – reduced to notch, flange confluent with pubic peduncle
  - (2) – notch or foramen absent, U-shaped gap between pubic peduncle and obturator process
- (Li et al., 2009:171; Rauhut, 2003; Smith et al., 2007:287)
441. Ischium, position of apex of obturator flange, distance between apex and proximal end of ischium:
- (0) – proximal flange, position at less than 20% of ischium length
  - (1) – flange positioned at approximately 25-30% of ischium length
  - (2) – flange position at approximately 35% of ischium length
  - (3) – distal flange, position further distal than 50% of ischium length
- (Modified after Brusatte et al., 2010:281)
- 442. Ischium, broad medially deflected apron from obturator flange to distal end of ischium:**
- (0) – absent
  - (1) – present, covers 1/3 to 1/2 the ventral surface between obturator flange to distal end of ischium
  - (2) – present, covers more than 1/2 the ventral surface between obturator flange to distal end of ischium
- ORDERED**  
(New Character)
443. Ischium, scar on posterior edge of the proximal end of the ischium:
- (0) – absent
  - (1) – present
- (Holtz, 1994; Li et al., 2009:172)
- ## Femur
444. Femur, femoral head orientation:
- (0) – directed ventrally
  - (1) – directed horizontally
  - (2) – directed dorsally
- (Modified from Molnar et al., 1990; Smith et al., 2007:294)
445. Femur, femoral head orientation relative to the distal femoral condyles:
- (0) – directed anteromedially
  - (1) – directed strictly medially
- (Holtz, 1994; Smith et al., 2007:293)
- 446. Femur, fossa on the posterior surface of the femoral head, just lateral to the articular surface:**
- (0) – absent or shallow
  - (1) – narrow channel
  - (2) – deep, wide fossa
- (New Character)

447.Femur, anterior trochanter, presence and separation from shaft:

- (0) – absent
- (1) – separated from greater trochanter by deep cleft
- (2) – trochanters separated by small groove

**ORDERED**

(Modified from Li et al., 2009:184)

448.Femur form of anterior trochanter:

- (0) – alariform
- (1) – cylindrical in cross section
- (Li et al., 2009:185)

449.Femur, height of anterior trochanter:

- (0) – shorter, terminates further distally ends distal to the height of greater trochanter
- (1) – subequal or slightly taller, the two structures extend to approximately the same level proximally
- (Li et al., 2009:260; Sereno et al. 2009: 98; Carr and Williamson 2010: 269; Brusatte et al., 2010:284)

450.Femur, vertical ridge on lateral face of anterior trochanter:

- (0) – present
- (1) – absent
- (Norell and Makovicky, 1999; Li et al., 2009:218)

451.Femur, fourth trochanter, position, measurement from proximal margin of head to midpoint of fourth trochanter relative to total length of the femur:

- (0) – proximally located, distance 25% or less femoral length
- (1) – distally located, distance 30% of greater femoral length

(Modified from Brusatte et al., 2010:288)

452.Femur, circular scar (*M. adductor femoralis I*) on posterior surface of shaft distal to fourth trochanter, mediolateral position:

- (0) – scar absent
- (1) – positioned closer to the medial edge of shaft
- (2) – positioned closer to the shaft midline

(Modified from Carrano and Hutchinson, 2002; Brusatte et al., 2010:283)

453.Femur, anteromedial crest on anterior surface proximal to medial distal condyle:

- (0) – without longitudinal crest
- (1) – crest present extending proximally from medial condyle on anterior surface of shaft
- (Li et al., 2009:189)

454.Femur, depression (for *M. extensor digitalium longus*) on anterior surface of distal femur.

- (0) – absent or extremely shallow, anterior surface relatively flat
- (1) – shallow depression present
- (2) – deep depression present

(Modified from Molnar et al., 1990; Smith et al., 2007:303; Brusatte et al., 2010:290)

455.Femur, well-developed extensor groove (for *M. extensor digitalium longus*) present on the distal end of anterior surface of the distal femur constricting distal end of the EDL depression:

- (0) – groove absent, expressed as a broad concave anterior margin
- (1) – groove present and constricted to a wide, deep, U-shaped cleft in distal view
- (2) – groove present and constricted to a narrow, deep, U-shaped cleft in distal view and present as an extensive depression on the anterior surface of the femur

(Modified from Molnar et al., 1990; Smith et al., 2007:303; Brusatte et al., 2010:290)

456.Femur, depression between distal condyles in anterior view:

- (0) – relatively flat between condyles
- (1) – shallow depression between condyles
- (2) – deep depression confluent with extensor groove on anterior surface

(New Character)

457.Femur, deep channel between condyles for *M. gastrocnemius* and *flexor digitorum longus* group in distal view:

- (0) – no discrete channel present between condyles
- (1) – wide channel, wider than deep
- (2) – channel deeper than wide

(New Character)

458.Femur, crista tibiofibularis on lateral condyle in distal view:

- (0) – no distinct lateral separation in lateral condyle
  - (1) – distinct lateral constriction into crista tibiofibularis larger than half the mediolateral width of the lateral condyle
  - (2) – crista tibiofibularis restricted to medial half lateral condyle
- (Modified from Brochu, 2002 and Brusatte et al., 2010:289)

## Tibia

459.Tibia, length relative to the femur:

- (0) – tibia longer (1.05 or greater)
  - (1) – tibia subequal or shorter (less than 1.00)
- (Sereno et al. 2009: 99; Brusatte et al., 2010:292)

460.Tibia, proximal end, anterior process of lateral condyle:

- (0) – absent
- (1) – present

(Brusatte et al., 2009:252; Carr and Williamson 2010: 270; Brusatte et al., 2010:293)

461.Tibia, lateral ridge on the lateral side of the tibia for connection with fibula:

- (0) – extending from the proximal articular surface distally
  - (1) – clearly separated from proximal articular surface
- (Gauthier, 1986 Smith et al., 2007:308)

462.Tibia, lateral condyle on proximal end of tibia:

- (0) – confluent with cnemial crest anteriorly in proximal view, or only slightly offset
  - (1) – strongly offset from cnemial crest
- (Rauhut, 2003; Smith et al., 2007:305)

463.Tibia, lateral malleolus, lateral extent:

- (0) – limited, mediolateral measure is less than 40% of mediolateral width of adjacent shaft
  - (1) – extensive, mediolateral measure greater than 40% of mediolateral width of adjacent shaft
- (Carr and Williamson 2010: 271; Brusatte et al., 2010:294)

464.Tibia, lateral malleolus, position relative to medial malleolus:

- (0) – extend to approximately the same level distally
  - (1) – lateral malleolus extends significantly further distally than medial malleolus
- (Brusatte et al., 2010:295)

## Fibula

465.Fibula, excavated medial fossa on the proximal end of the fibula:

- (0) – absent
- (1) – present, shallow
- (2) – present, deep

### ORDERED

(Modified from Smith et al., 200; Li et al, 2009:193)

466.Fibula, position of medial fossa:

- (0) – not extensive, proximal border starts about 1/3 the distance between the proximal surface and the iliofibularis tubercle
  - (1) – fills most of the proximal end of the fibula
- (New Character)

467.Fibula, proximodistal cleft in the iliofibularis tubercle:

- (0) – absent
  - (1) – present, resulting in two crests separated by a depressed fossa
- (Brochu, 2002; Carr and Williamson 2010: 272; Brusatte et al., 2010:296)

468.Fibula, elongate groove on medial surface distal to iliofibularis tubercle:

- (0) – absent
  - (1) – present, distal fibula medially concave
- (New Character)

## Astragalus

469.Astragalus, ascending process, form of base:

- (0) – confluent with condylar portion
- (1) – separated by deep transverse groove
- (2) – separated by fossa across base

(Modified after Welles and Long, 1974; Li et al., 2009:197; Brusatte et al., 2010:298)

470.Astragalus, height of ascending process of astragalus (height vs. height of body):

- (0) – lower than astragalar body
- (1) – higher than the astragalar body, typically covering only lateral half of anterior surface of distal tibia
- (2) – more than twice the height of astragalar body

### ORDERED

(Welles and Long, 1974; Smith et al., 2007:321)

471.Astragalus, ascending process height (height vs. width):

- (0) – less than half the width of the bone
- (1) – half the width of the bone to equal to the width of the bone
- (2) – greater than the width of the bone

### ORDERED

(Carpenter et al., 2005b; Brusatte et al., 2009:255)

472.Astragalus, basal extent of ascending process:

- (0) – arising out of the lateral part of the astragalar body
- (1) – arising out of the complete breadth of the astragalar body

(Welles and Long, 1974; Smith et al., 2007:320; Brusatte et al., 2010:297)

473.Astragaus, anteroposterior thickness of ascending process:

- (0) – wedge-shaped/blocky
- (1) – plate-like/laminar

(Sereno et al., 1994; Smith et al., 2007:323)

474.Astragalus, ascending process contact with fibula:

- (0) – absent or limited
- (1) – extensive

(New Character)

475.Astragalus, fibular facet on body of astragalus:

- (0) – large and facing partially proximally
- (1) – reduced and confined to anterior half of lateral side of astragalus
- (2) – strongly reduced, facing laterally or absent

(Holtz, 1994; Carrano et al., 2002; Rauhut, 2003; Smith et al., 2007:319)

476.Astragalar condyles:

- (0) – almost entirely below tibia and face distally
- (1) – significantly expanded proximally on anterior side of tibia and face anterodistally

(Sereno et al., 1996; Smith et al., 2007:324)

477.Astragalus, horizontal groove across astragalar condyles anteriorly:

- (0) – absent
- (1) – present

(Welles and Long, 1974; Smith et al., 2007:325)

478.Astragalus, posterior process:

- (0) – completely caps distal tibia
- (1) – curves only slightly proximally, but not strongly covering the posterior side of the tibia
- (2) – significant portion of distal surface exposed on articular facet so that astragalas and cancanum do not cover entire distal tibia

(Allain, 2001; Smith et al., 2007:326)

## Calcaneum

479.Calcaneum, articulation with tibia:

- (0) – without facet for tibia
- (1) – with tibial facet on posteromedial corner or posterior surface

(Sereno et al., 1996; Tykoski, 2005; Smith et al., 2007:328)

## **Distal tarsals**

480.Distal tarsal fusion:

- (0) – separate, not fused to metatarsals
  - (1) – fused, forming metatarsal cap with intercondylar prominence that fuses to metatarsal early in postnatal ontogeny
- (Li et al., 2009:199)

## **Metatarsals**

481.Metatarsals, appression of major metatarsal shafts:

- (0) – not appressed against each other beyond proximal half of shaft
  - (1) – appressed throughout most or all of metatarsus, adjacent surfaces of shafts flattened for contact between metatarsals metatarsals closely appressed and distance between II-III and III-IV is approximately equal
  - (2) –distance between mt III- mt IV greater than that between mt II- mt III
- (Modified from Zanno, 2008; Li et al., 2009:287; Brusatte et al., 2010:302)

482.Metatarsals II and IV, relative length when in articulation:

- (0) – metatarsals II and IV subequal in length
  - (1) – mt II longer than mt IV
  - (2) – mt II shorter than mt IV
- (New Character)

483.Metatarsal II, articular scar for metatarsal III on distal portion of lateral surface of shaft, form:

- (0) – smooth or subtle texture
  - (1) – heavily rugose fossa
- (Modified from Brusatte et al., 2010:303)

484.Metatarsal II, tear drop shaped articular surface for metatarsal III:

- (0) – absent
  - (1) – present
- (New Character)

485.Metatarsal II, relative size of midshaft compared to metatarsal IV:

- (0) – subequal
  - (1) – metatarsal II more robust than metatarsal IV
- (New Character)

486.Metatarsal II, lateral surface in proximal view, shape:

- (0) – flat or weakly concave
  - (1) – strongly concave
- (Brusatte et al., 2010:304)

487.Metatarsal III, outline of proximal articular surface:

- (0) – rectangular
  - (1) – hourglass-shaped
  - (2) – wedge-shaped with no exposure on plantar surface
- (Paul, 1984; Smith et al., 2007:335)

488.Metatarsal III, form of midshaft shaft medial border:

- (0) – straight or subtly convex medial border in anterior view
  - (1) – medial expansion forming a convexity or bulge along the distal part of the shaft
- (Kobayashi and Barsbold, 2005; Li et al., 2009:289; Brusatte et al., 2010:300)

489.Metatarsal III, proximal shaft exposure:

- (0) – prominently exposed between MT II and MT IV along entire metapodium
- (1) – MT III proximal shaft constricted and much narrower than either II or IV, but still exposed along most of metapodium, subarcrometatarsal
- (2) – very pinched, poorly exposed exposed along proximal section of metapodium, arctometatarsal condition, mt III wedge-shaped with proximal end covered anteriorly by contact between metatarsals II and IV

## **ORDERED**

(Novas and Pol, 2005: 200; Makovicky et al., 2005; Li et al., 2009:203; Sereno et al. 2009: 100)

490.Metatarsal III, ventral non-articular surface immediately proximal to the distal condyles:

- (0) – concave
  - (1) – raised subtriangular platform
- (Sereno et al. 2009: 101; Brusatte et al., 2010:301)

491. Metatarsal IV, proximal end, medial notch for articulation with metatarsal III:

- (0) – absent
- (1) – present, shallow notch
- (2) – present, deep notch

**ORDERED**

(New Character)

492. Metatarsal IV, well-developed posteromedial flange on proximal end for articulation with metatarsal III:

- (0) – absent
  - (1) – present
- (Smith et al., 2005:339)

493. Metatarsal IV, midshaft, articular surface for metatarsal III:

- (0) – flat
  - (1) – concave
- (New Character)

494. Metatarsal IV, articular surface for metatarsal III tear drop shaped:

- (0) – absent
  - (1) – present
- (New Character)

495. Metatarsal IV, scar for the insertion of *M. gastrocnemius lateralis* covering medial third of posterior surface on metatarsal IV:

- (0) – absent or elongate scar
  - (1) – narrow oval rugosity
- (New Character)

496. Metatarsal IV, surface between metatarsal III articulation and scar for *M. gastrocnemius lateralis*:

- (0) – flat
  - (1) – concave
  - (2) – slender plantar ridge between metatarsal III articulation and *M. gastrocnemius lateralis* scar
- (New Character)

497. Metatarsal IV, depth of medial collateral ligament fossa:

- (0) – shallow, not rimmed
  - (1) – deep and rimmed
- (New Character)

## Pedal Phalanx

498. Pedal phalanges, proximal phalanges of digit II and III, ratio of length to midshaft width:

- (0) – greater than 3.0
  - (1) – 2.0 to 3.0
  - (2) – less than 2.0
- (Modified from Brusatte et al., 2010:306)

499. Pedal unguals, relative size of unguals II and III:

- (0) – subequal
  - (1) – II much larger forming sickle claw
- (New Character)

500. Pedal unguals, lip overhanging proximal articular surface dorsally (on extensor surface):

- (0) – present
  - (1) – absent or reduced to a subtle tuber
- (Brusatte et al., 2010:307)

501. Pedal unguals, curvature of flexor surface:

- (0) – curved
  - (1) – relatively straight
- (Li et al., 2009:282)

**TABLE S3: TAXON SCORINGS**

A = (1/2)

***Tawa hallae***

1010001100000000?10010?0110020100???00000100?0000??0?00000?0010?????0?00?000????00000?00100  
0000000?0????10000?0??000000?00??0?0010??1100011000000001100?10000?0?0?0??000?00000?000  
0000000000000000000000????0000?????????????0?0?0000?0200000?0000010000000?0?1000?10000?  
0100??000000010000100000000201000?????????00?00000000000000000000000?0?000?0000?0?20  
00100100000?000010000?000?000000000000000000000?000020000000000000000000000000?0?0?0??0000?0?  
0000?00000?0000?000

***Coelophysis bauri***

0100001100000000000000000?011000000???0000000?0000??0?000000010?????0?00?000????1000?00100  
00000000000000000000?0??000000?00?????0100??000001000000000000?1000000?0?0?0?000?0000000?  
?????0000000000000000?0??0000?0?00?0?????0?0?0000?02000010?00000000000000?0?000?1000?  
0100??0000000000000001000000000000000?00101000  
00  
0000?000000000000?000

***Dilophosaurus wetherilli***

00021000000000000110000001?000000?0?0001010?00?2010???0?0?011?????0?00?000????00000?00??0  
?0?????????00000?1?????00000?00??0?0110??0100010000000000?1000000?0?0?0?000?00001000?  
?????00000000000000??????????????0?0?0000?02??00110?010000000000?00000?100??  
0100??000000000000001000000002020000?001000003102000100000000000000000?0000100100000000  
00  
1100?0011000000?000100

***Ceratosaurus nasicornis***

0012100000010001000100000000200000001010?001100?11020001121000?10?0010001000?00101  
0000000001000100000?1??0000000?00??0?0200??10000010000000000?0??00101001000?011001000  
0000000000000000000000?00000000010000??00000?0??00000?02010010?0010010000000?1000000?00021  
0100??0000000000002100000012030000000000000003102000112110001001000000?0000100100000001  
000001000  
11010011100010100001001011101002000

***Dubreuillosaurus valesdunensis***

0012100000000000000010001?00?00?00200000001100?00????????0?01?????0?10?000???0000100??100  
0000000000000000000?0??0000000?00??0?02?????00?0???00001000?????1?000?000?001010100  
000000000000000000000100?????000?????????00?00000?0?1?0010?01011000000?110001000?????  
?????000000000000000000000?000?00000203000?????0001?  
?000000000?????????????????????000?  
?00?0?10?00?1?00????0?01?????????????00?  
?0?0?0?11?????0?01?????????????00?

***Piatnitzkysaurus floresi***

?????0?0?0?????????????02110100000001100?0?????????0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?000?001?001?  
00000000000000000000?000?  
?????00000000000100?????000?  
?????0?  
000000000000000010010000000?????000  
0101001?1011100?01?????????000

***Eustreptospondylus oxoniensis***

?0?21000000000000?00000011002110200100?0110?0?????????0?01?????0?10?0001000000?????100  
?0000?000000?1000?1??010000?00??0?01?????????0?0?1?0?0?0??011?????10?001000100  
0000000000000000000001010?000?????????0?0?1?0?0?0?0?1?0?0?0?0?0?0?0?0?0?0?0?0?0?0?  
?????0000000000000000000000?0?0?0001010011000030120001000000011110000000?0010001000000?  
?0?10010000?????000000000?????0000000000?1000?  
?100?112101111001110001112100

***Monolophosaurus jiangi***

1102101010000010110000?00100100100100001100?001111010120120120010?10?000?????10010000111  
00010?000000001000?1??0110000?0101??0221?10100000100000001100?2020?1011000010?000000100  
000000000011000100?????000?0011000?????????????020100110?010010?000?1100010100011  
00?110000000?0001100000020100010000010000101200011210000110101011000?0?00100?????????  
???10?10000000?00002001012010000?0010?0000000000?0?????  
???

***Sinraptor dongi***

0012100010000010101000100010010010000001010?0000??0?000200112210010?10?001100001010000111  
0000000000000101000?1??0010001000?????02120101000001000000001101010000110111000?011011100  
000000000110001000?????00001001100010?00000001000000002010001000100100000000001100010000011  
11011000000000000000110000000010200010000010000301200011211000110011011?00000?00110????????1  
??11110000?1?00?????????11??00?????100100?01010?000010010110101000001100000001000111000  
11101110111100101001011101000000100001000001000

***Allosaurus fragilis***

00121010000000100000000010011100200000001000?0000??0?000201112210010?10?001000011010000111  
00000000000001000101000?1??001000?00??0?0201?0010000010000000001101010000010111000?011001100  
0000000000110000100?????0000000110000?000000010000000001000001000101100000000011000?100011  
1101101000000000000010100000011010001100001000010120001121100011101101100000010001101100101  
001111000001010010000010002101000000100100001010?1000200101101010301010?0000002000111000  
111011101111001110010111010100000100001000001000

***Tanycolagreus topwilsoni***

0??21011??0000000?1001000?0?????????????????????????0?200100?1??0011000010100?0???  
?????????????11000?1?????0?????????????0?00?????00001100?201000?????????????????11000?????????  
?????????????020011????00????00?????????0010?010210?00000000?00?????0000?00100??  
00111100000101000000000000121000?00000?????????????001031?01?????????1101000  
0?1101110011001101021010211010100000100001000010000

***Coelurus fragilis***

???  
??0?????000?00000001?????????0000000100?????  
????????????????????????0?0?????????0021000000000000000011?????????0000000100?????  
?0110?0000?0???000000000?????????????????????????001103?1010?????????1101000  
01100110011000?0?1200101101?01?0000100001000000000

***Sinosauroptryx prima***

012000010?0001002?010?00?01?0?210000000?0??0?00?0?00????021????0?10?000?????01?000?00  
?????0?????1100?1?0?0?01101000?02?????0?00?0000?0????????0?00?10?????????????????????  
?????????????0?????????????????????000?0000?000????00?00000?000?????00?00000?000????????000?  
?0?????0?????100010001000202010?????????0010?001000000000001?????????00000011101111?  
000001000000100000000000012100001001000000?00100?02??201101011010?01?000?022001??100?  
1?????00?1?000?0?122111?1?01012000010000000000000

***Compsognathus longipes***

0120001100000000010000?00?00?012000000010?0000?0?00020?021????0?1?001000?01001??0100  
01????000101?01100?1??01001011?????0220??000000000010000?00?????00?000000?01????00?00000101?000?  
?????00000?????0?????0?????0?????0000100?00000000?0000?001????00?00000101?000?  
?0?1?000000000?10010000100000101010000?0??0?0020?000000?0000001??00000?0000000101010010  
000111000000?100000000000012110001001000000?00100?02??201101011010?01?000?022001??100?  
0?1????00?11000?0012001110?1010?000100?000000000000

***Juravenator starki***

002000010?010010030110??0?0110110000000010??000??0?0002011011????0?10?000?????00001?22110  
01?????0?01?011100?1??010001101000?0220?0000010000100000000?????????????????????????????  
?????????????????????????10101000?????????????00?0000?000?0?????00?0?????00?0?????0000?  
?0?????0?0?0????2000010013?010?????????002??01?000??1000001???1?0?????00000010100000  
0012100000?10002?0?011?211001001000000?0000?100021011101?????????0?????????????????  
?????0?0?0????0?????1012?????0?????????

***Scipionyx samniticus***

112000010?110000120101?000?0010110000100010??000??0?0002002021????0?10?000?????0001?00100  
01?????0?01?011100?1??010010111010?????20?000001000010000000?????????????????01?????  
?????????????????????0100110000?????????000100000?0000?000?1?????00?0?????00?0?????0000?  
?0?????0?0?0????0000010003??0101000?0?00000020?010000?01010000?0100?????000000001010?00  
00100000000110002?0?0111210001001000000?0220?10002010011010000?0?000?02210????10???  
?????0?0???

***Ornitholestes hermanni***

1110001100000000?11011100010010111000001000?00?0?0?010?00?120????0?1?001110?11010000?0?  
00000??0101?001000?0?000000?00?????1210??01110000000000101?00?2010000?0?????1?01?1010?  
?????0000?100000?????0?000?1000001?????????1000010??0200000?00?0?000001?000001?000001?  
10?0?000000?0??110000022030?0?????????002110011000000000000011?????????000000101?11?  
?0?????????????000000010?21??10000000100?0100?20000011021001?00?101100101101010?111?0?  
010100110?????0?00?????????012000110000100001???

***Haplocheirus sollers***

0110011100000010?01010?000100101110000001000?000??0?1002101121????1010?000?????001?????100  
?0?00?00101?000100?1??001000?00??0?0310??110000000000000000?10200?0?11?000?????01010100  
000000000000000011010?00?000?1001001?????????1000000110200000?00?00?????01000101000?  
0211100000000000200110001000000013?????????0?0?????????000000?000?000120?????0?01??  
0011110001001100000??0000210001?00010?00001??20?????????00?000?20??110?1200?11?????  
?0?????0?????????????????1?????1000?????????

***Utahraptor ostrommaysorum***

0?????0?0????000113100000???  
?????????????????????????011110000?13?????????????00000010?????????????????????????????????  
?????????????????????????0?????????????????11111?111?10010?1?????????1?????0?01?1??  
?????????????????????????01100????1211101102?????????????100

***Deinonychus antirrhopus***

00100000000000001131111000?00101200000001?00?000??0?1?1001?021????1010?000?????0?????????  
?????????????11100?1??0010?01111000?1220?000001100000001000010?????????????????????????  
?????????????????1100?10110?0000?0?10000010020?0000?0001??0010001??1000??00??  
?0?1?0001000012101100000?1020101000011100020020101011012111001011?????21100001111111  
010010101001?1?00100000021100000001002100101200?12??2001012?????????1?0001231011121010  
000?1100011000?0012211121021010??00100000000000100

***Linheraptor exquisitus***

001001100000010?21010?000100?011000000100?00?0?0?1?0?10?11????1010?000?????001????????  
?0?????000000110?1??0010001111000?1310??1000001000000000100103120?0?????????????????  
?????????????????02?00000?0111?1?????????101000?  
01111010010?????????0?12021?0?????1?0?0?1110111000?00000?????????211010001111111  
1010?10??1101111002??00002110000001?????????????10100?21?????????112?01  
?0?????0?100?0?1221112102111?0000100000000000100

***Velociraptor mongoliensis***

001001000000010021010?0001001011000000100?000?0?1000110021????1010?000?0?0101?????100  
?00000000000000000110?1?00101011010000?1310??000000000000000001031200?0011010011101000100  
00000000001000000112000000110011110?00????10000001102000001000110100?0001?110001010000?  
0211101001000012001100000012021101000?110000001010111?0002100000?001100021101000111111  
10100101011011110000000002110000001002000101200?22?011022101000?211110000123101112101  
0000?1000011000?0012211121021112000010000000000100

***Archaeopteryx lithographica***

1110010111100000?01000?000001101201000000100?000?0?1002000010????0?10?000?0?0001?????100  
?1????000001?00?200?0?0?100?????03120?000000000000000000?0?????000?0?0111?01110000  
000001?00?10?0?200?0?0?00010011010?000????100000011000?00010000?00010000?000000?10000?  
?0?0?00010000?0??210000002303110?????111?000011?0001000000000000?0001??0211000001011111  
10100101011011110110000002110000000000000101200?22?011022101000?2111100001200011?1111  
?000?1000?100?00122111?102111200001010000000000000000

***Pelecanimimus polydon***

000000??0?001011?3?112?00000?011????000100??000??0?0002001100????20?0?000?0?11001?221?0  
01????4?101?000100?????0?????0?????0?02120000000?00000?0?????????0?0?????11?0011?????  
?????01?????????????1101010?????????0?02000100?00011????101?????0?0?00?10????  
00?????010?????3?????012000023?????0?00?0?1?0?0100?000?000?0?????????????0?0?0?10?????  
011????0000211100002??01??21020002020?????????????0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?  
?????????????????????????????0?

***Shenzhousaurus orientalis***

000000??00001001031110??00000?0111000000100??000?0?100200?100????2010?000????11?????00  
?????????0101?????????10?00?????021200000?0?000?0?????????0?0?0?0?0?0?0?0?0?0?0?0?  
?????????1101010?????0?  
00?0?0?010?????13113?????0?0000001?11001??100?000?0001?00?00?00?00?00?00?00?00?00?00?  
?????????21???0?0?020000011?01201?01001?11000010010010?0?000?00200111?1100  
11????21?????????????????????????0?

***Harpyimus okladnikovi***

000000??00001001031110??00000?0?????000100??000??0?1002001100????20?0?000?0?0?1001?22100  
01????00101?000100?0??0100110?00????12?????????0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?  
?????????0?  
00?0?0?010?00?0?0?3?????1????130?????0?0011000100?001000001011001??0001?0000?010?  
0110000010??11000021??1?12101100202000?011?0?0?201011001??0?201?1??010?0?0?0?0?0?0?0?  
?????????01????01111021021012????20100?????00001

***Gallimimus bullatus***

0010001?000010110?0112??00000?0111000000100??000??0?1002001100????2010?000????1001?20010  
01????40101?000100?0??0100110?00????121????0?00?000000?0?????10?????00????0111?0011000?  
?????0111000110?01??00?????1101010?????0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?0?  
00?0?0?010100?002??3?????1????13????10?????1?????0?0?11000100?01100100001100100?00010000000111  
01111??0102111000020??0?0?2102000202000?0110200101100100100201001001011000010020111?0??  
??122221?111????0??1????1?2?012????21200?????00001

***Proceratosaurus bradleyi***

22000011000?11110311111?0010110110000002200?0?01??0????????????1?????????0????0?????  
?????????0?  
?????????01??0?0?01001000?????0?10000?????0?02000000?110010??110?????11100110  
00?100000000?020112100000001010?????0?  
?????????0?

***Kileskus aristotocus***

220?????????????111?31111?000?02101201000002200?0??  
??  
????????????????????????12???0?01??00??  
????????????????????????????01????10000?????1000

***Guanlong wucaii***

220000110001111?3111100010210120000002200?001100?0010011011????0?10?001110001000?00100  
00000000100001000?1??0010?00?010100?1222000100020010101001100?????0?0011000201101010110  
0000001100000001111001010001?0?000?????????10000000?02?000010?110?100?????0?????11100???  
00?100000000000????1210000011??000100000010000000000000000000110001001?000?00?010??1  
00110000000?010000000000021000100000000000010002000010110120002020101100011010100111100  
0111011100111010002111210110120010100000000001000

***Sinotyrannus kazuoensis***

12?????????1111?3?111??001011??10100000??00??  
??  
??0??0?????????0?0?????????0????????????  
????????????????????1000????000?????????????????110001?0????????????????????????????????  
????????????????????00010?1?????1200000101101????????????????????????????????  
???

***Juratyrant langhami***

??  
??  
??00000010010001000000001000?001?00000?0101??  
????????????????????1001000?10110000001101200??0??10110?01111100??????  
??110011001111?????????1?????????????????????????????????

***Stokesosaurus clevelandi***

??  
??  
????????????????????????????????????00000010010001000000001000?001?00000?0101??  
????????????????????1001000?10110000001101200??0??10110?01111100??????  
??110011001111?????????1?????????????????????????????????????

***Dilong paradoxus***

1100001100011111310011100100101211000001100?001A100?001001101200100?10?001110001000?00100  
00000000100001000?1??0010100?010110?12220001100020010001001100?20001?00100102010101000010  
00000011000000011000010100?????????????1000000?0110000100010000010001110011100110  
011100100000002111211000220300010000001001000000100?000?0000001?????????00000000010101  
000100100010100100000000?210011000001001????0??1000?????2010001?1010?000?1210?110100  
01110011001110?0?021?????0110000100000000000000

***Eotyrannus lengi***

?????????????1?1????001?000?0010?1?10???0??0??010??1010100110?200????1??101110000??0??????  
??0?????00?00?0?0?0000010?????????0??  
?1111000?????????132??0?00????000?????00?????0?0?0?????2????????????????????????????????  
0?111??0000101000011001??0?10?????000?????000?????10?????0?????0?????0?????0?????0?????0?????  
?????????????????????01?00001000000000?0000

***Bagaraatan ostromi***

??  
??  
??0???000??0010??1100010?????111?????  
?2110000?????0211?????????000?????????00??0?????1?????????01??1001000001000?  
?????????????????????????120?????????????????02?????1010????1?2???2101000  
??010121?11100100021112101?????????????????????????

***Raptorex kriegsteini***

001000?100?1111??110011000100101210001101110?0010??0?001001211200??0?211?011100000?????110  
0?010011?????????000?0100121??22000010001000000100??0?0?????????????????????????????  
????????0???0?1?????0?0?0?????????????0?????0?1?000100011011100010?????1110111  
?1121110001010????132110002202000100000110011101000100200121100000010000101?0010000?????11  
0012101000010100012100200?221???00120000011012200?1111?111010020????1010??1011?20111101000  
01010111011111002211121011012000?01010000000000

***Dryptosaurus aquilunguis***

?????????????????000?0?????????0?0?????????????0???  
???  
????????????????????????????????????0?????????0?????0?????0?????0?????0?????0?????  
1211010?????????01?????000???00?????  
?????????????10100?1?????????120?????????????02?????010?10?????121?10000  
?11111?1?11111102221112101?01?????01?100000?????

***Xiongguanlong baimoensis***

0000001100011110?1?001?000100?0?1?000?10111101010??0?001001201200??0??0??0?0?0001?1??001  
000101111000210000?1??01000?01011??1222000000011000000201110102000??00110111?????01000?0?  
?????01100001001000001?1?00?????????????10000001?????????????????????????????????????  
?????????????1321000121??01010000010001110100010020012110010011?????????????????????????  
?????????????????????00?11?????0201111?????????????????????????????2101010  
0?111221?01100?????22?????????????????????????????????

***Alectrosaurus olsoni***

???  
???  
???  
???  
020112210011001110222111210110100100112010110011000

***Appalachiosaurus montgomeriensis***

000?????01?????0?????00?001011?0000101110??010??0?1?1???0120110?02100011100?0?????????  
?????????????????????????????????22?????????????21111010?????????????????????????????  
?????????????????100?100100011?00000101000100?111?001000110??100110??11100?????  
?????????????0?1102000???  
?0?????????????1100??11?????????????????????????????0201?1?10111010??1201121?1000  
1212122111111111222111210110100101112020111011010

***Alioramus altai***

000110110001????0?????0010110120000110111101010??1110100010121121112111111000001?121001  
000101112101210000?1??0010101011001212122100101011011003111111020111110110211010101101100  
00110111000100111112110100?101100121111100102010101011010011011100110001110011110111  
01121110001011?????????0?21010001101101010111010001102101211?1100110112100??101?0?0??11  
?????????????????????????????00?011?????201111?????0?1?????????????0111201121010  
1?122111????00??1222111210110??1??1112?20?????0010

***Alioramus remotus***

00011011000?????????????0010??0??????10111101010??1110100010?21121112??1111100?001?1??001  
000101112101210000?1??010101011001212122???01011011000311111020111101102110101101100  
0011011100010011111211?100?1011?0021001???02010101011010010011011100110001110011110111  
011211100010??1211?????01?101000??  
??  
????????????????????????????1101??11?020?0?????

***Gorgosaurus libratus***

0011101110011110111001100010011110000010102102010??10101000101211202121001100000001?111011  
000111112101201020011100010021101?112210001201001100311111020111?101102110101101100  
001100110001010100120101001111011?11101111000101011110000100011111101100?1110011110111  
0222111010101112111321000121020011101?010?1120020011022111211111011011??110010000010111  
001210100000010001110121112211110012001001101220201111111011020202010111010111212121?1010  
1?122111011112111221112101102211111212011021001

***Albertosaurus sarcophagus***

0011101110011110111001100010011110000010102102010??10101000101211202121001110000001?111011  
000211112101201020011100010021101?112210011201001100311111020111101112110101101100  
0011001100010111001101001101111011?111011110101011110000100011111101100?1110011110111  
0222111010101112111321000121020011101101011?0020011122111211111011011110110010000010111  
001210100000010001110121112211110012001001101220201111111011020202010111010111212121010  
11122111011112111221112101102211111212011121001

**Dinosaur Park Formation tyrannosaurid B**

00121011100122101110011001112000001010212110??101211001102112121211121010001?1110120  
103112122022010110301101010021101?1122110002010011003121121201111101001110101011121011  
1111112000100111120111??1101110211111111211101011??010?1000?111110110?21110?????01110  
2221210?????12111321111101000??  
??  
??

***Daspletosaurus torosus***

0012101110012210011001??0010011120010011102102110??1012110111121120212110121111001?111012  
0002112122022010111311101010021112?2122110112010011001312112120111?11111?1?????????????1  
11111012100100?11111011100110110002101111102110101?111010011111?1?1000?????11111111  
022211101010111211132110001102001110100101112?20011122111211101101?2?????110011100010111  
001220100000010001111121112211110112001111101210201111?111111020213110121010111212121?1010  
1?122??21111121112211121011022111112120?0211010

**Two Medicine Formation tyrannosaurid (Landslide Butte Area)**

0002101110012210?11001??00100111201001110210??10??1012100?112211102121001110011001?1??011  
00021121220220101103001010100211021212211011201001100131211212011111111221010101112101  
1?111012?0010?111?????1??111110101??11?111?2111110?111010011111100110??111011110111  
02221110101?1211132110001102001?????????0?0?1?????????????????????????0?1??0?010111  
??12201000?0100?????????????011?1??121020111?1111110202?31101210101112121?1010  
1?????0111?????????????02011111212011?11010

***Teratophoneus curriei***

0?1211111011?????????0010011111000011102102?????00?102211202121011120001001?111112  
0013122123022010121301101010121?12011?????00??01??11001312112120111211111221011101102100  
111111110011011101102?1?????????1???02???110?11110100110011111110020?????11111122  
022222000111?1211?????001203001?????????0020011132111211011101101?11110011100010111  
00132??000?0100012111211?????????0121110???02?1111111111020212110121010111212121010  
11122220111112111?211?1?????????????????1010

**UMNH VP 16690 *Teratophoneus curriei***

0?12111101????????????0010011110000110210?????????00?102211202121011120001001?11112  
0013122123022010121301101010121?12011?????????????131211211201112111122101101102100  
111111110011011101102?1?????????????1????02??110?1111010?????????????????11111122  
0222222000111?1211?????001203001?????????00200111321112110111011011?111100111000010111  
?????????????????????????0121110???02?1111111111020212110121010111212121010  
1112222011112111?211?1?????????????????1010

**BYU 8120 *Teratophoneus curriei* (type)**

0?12111101????????????0010011110000110210?????????00?1022112021?10??1200?0????11??2  
00131221?????????????1?010??1??1??1????00?201??1100?1????112011121?????????????????  
????????1?????1?????????1?????????????1?????????????1?????011001111110020?????????????????  
?????????????????0?1203001?????????00200111?2111?????????????????????????????????21210101  
0132?0000?0100012111211???21210101  
112222???

***Bistahieversor sealeyi***

0012111111221001100211001001211000001102102110??1012100110221111212101?220101001?11112  
001312212302201012030110100010?2111?01122110112110111001312110112011121111221010?01102100  
01111112100111110110211??111101010?111?11020000100?111010011111100200?0110111112  
02222220101111211132110002203001?????????0020011132111?????????10011200001011?  
??1320100????100???21210101  
1?122?220111121121112101102011111212011111010

***Lythronax argestes***

001212??21?????0?????0000012111000021102102110??10121001?????????????????????112  
101312212?????????21?????1?????????????2211111211011100?????112011121?????????????????  
?????????????????1??1????????201?11111?????????111?10011101111111020?????1111122  
02222220102011?????0?2203002?????????????????????????????????020213110121?????????????????  
?????????????????111112111?221?1?????02?11111212011111?????

***Tyrannosaurus rex***

0012112111221001100211000001213111021102102110??10101101122111222111220101101?121112  
101312302202201012131110110010121112022111112110111101312112112011101111221011101102100  
011111110011011101102111121111011201111111211111101111110011101111111020110111111112  
022222201021111211132110002203002111110101112002001113211121100110112111000112000010111  
001320100000010001211121112211110112001211101210201111111111102021411012101011121112121010  
1112222111112111221111210110221111121201111120

***Tarbosaurus bataar***

0012112111221001100211000001213111021102112110??10101101122111222110122011101?121112  
10131230220220101213111011001012111212022111112110111101312112112011101111221011101102100  
011111110011111101202111121111011201111111211111101111110011101111111020110111111112  
022221201020111211132110001203002111110101112002001113211121100110112111000112000010111  
001320100000010001211121112211110112001111101210201111111111102021411012101011121112121010  
1112222111112111221111210110221111121201111120

***Zhuchengtyrannus magnus***

?????????1?????1?????000001213?111021102112???  
?????????????????????????1???  
?????????????????1?????????????????????????????????????1111100111011111111020?????????????????  
?????????????????0?1203002???  
???

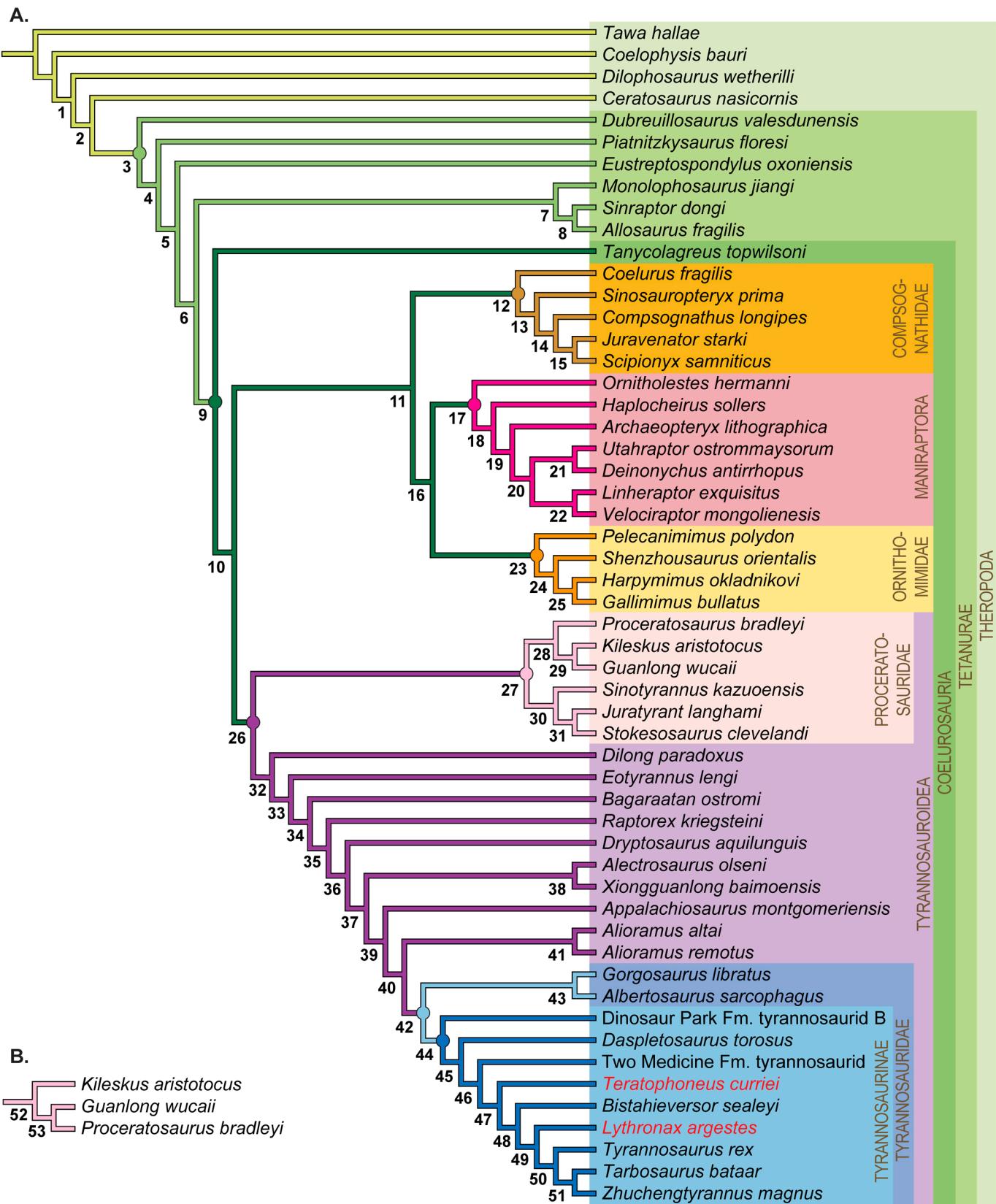


Figure S1. Numbered nodes for the synapomorphy list (Supporting Information Table S4). Nodes are labeled for reference to the synapomorphy list for Tree 1 (A) and the only different typology recovered in Tree 2 (B).

## TABLE S4: SYNAPOMORPHY LIST

Character state changes were optimized and synapomorphies for clades included below (character number and state change indicated):

- Node 1:** all taxa excluding *Tawa* and *Coelophysoides*: Char. 4: 0→2, Char. 5: 0→1, Char. 7: 1→0, Char. 8: 1→0, Char. 41: 0→1, Char. 43: 0→1, Char. 110: 0→1, Char. 245: 0→1, Char. 316: 0→1, Char. 322: 0→1, Char. 352: 0→1, Char. 387: 0→1, Char. 398: 0→1, Char. 401: 0→1, Char. 408: 0→1, Char. 423: 0→1, Char. 447: 0→1, Char. 451: 0→1, Char. 452: 0→1, Char. 458: 0→1, Char. 459: 0→1, Char. 470: 0→1.
- Node 2:** all taxa excluding *Tawa*, *Coelophysoides*, and *Dilophosaurus*: Char. 25: 1→0, Char. 26: 1→0, Char. 33: 0→2, Char. 70: 0→1, Char. 129: 1→2, Char. 161: 0→1, Char. 163: 0→1, Char. 174: 0→1, Char. 258: 0→1, Char. 330: 0→1, Char. 360: 0→1, Char. 454: 0→1, Char. 457: 0→1, Char. 463: 0→1, Char. 475: 0→1, Char. 476: 0→1, Char. 477: 0→1, Char. 479: 0→.
- Node 3:** all taxa excluding *Tawa*, *Coelophysoides*, *Dilophosaurus*, and *Ceratosaurus*: Char. 19: 0→1, Char. 42: 0→1, Char. 83: 0→1, Char. 140: 1→0, Char. 150: 0→1, Char. 178: 0→1, Char. 196: 0→1, Char. 240: 1→0, Char. 263: 0→1, Char. 337: 0→1, Char. 353: 0→1, Char. 468: 0→.
- Node 4:** all taxa excluding *Tawa*, *Coelophysoides*, *Dilophosaurus*, *Ceratosaurus*, and *Dubreuillosaurus*: Char. 345: 0→1.
- Node 5:** all taxa excluding *Tawa*, *Coelophysoides*, *Dilophosaurus*, *Ceratosaurus*, *Dubreuillosaurus* and *Piatnitzkysaurus*: Char. 304: 0→1, Char. 316: 1→0, Char. 363: 0→1, Char. 366: 0→1, Char. 418: 0→1, Char. 445: 0→1, Char. 456: 0→1, Char. 465: 0→1.
- Node 6:** all taxa excluding *Tawa*, *Coelophysoides*, *Dilophosaurus*, *Ceratosaurus*, *Dubreuillosaurus*, *Piatnitzkysaurus*, and *Eustreptospondylus*: Char. 7: 0→1, Char. 27: 0→1, Char. 43: 1→0, Char. 151: 0→1, Char. 338: 0→1, Char. 356: 0→1, Char. 364: 0→1, Char. 420: 0→1, Char. 453: 0→1.
- Node 7:** Allosauroidae: Char. 15: 0→1, Char. 67: 0→1, Char. 89: 0→1, Char. 90: 0→1, Char. 131: 0→1, Char. 191: 0→1, Char. 210: 0→1, Char. 323: 0→1, Char. 335: 0→1.
- Node 8:** *Allosaurus* + *Sinraptor*: Char. 3: 0→1, Char. 42: 1→0, Char. 61: 0→1, Char. 103: 0→1, Char. 141: 0→1, Char. 153: 0→1, Char. 165: 0→1, Char. 173: 0→1, Char. 177: 0→1, Char. 190: 0→1, Char. 271: 0→1, Char. 298: 2→1, Char. 326: 0→1, Char. 334: 0→1, Char. 350: 0→1, Char. 406: 0→1.
- Node 9:** Coelurosauria: Char. 8: 0→1, Char. 64: 1→0, Char. 66: 0→1, Char. 286: 0→2, Char. 330: 1→0, Char. 349: 1→0, Char. 353: 1→0, Char. 451: 1→0, Char. 459: 1→0, Char. 470: 1→2, Char. 471: 0→1, Char. 475: 1→2.
- Node 10:** Coelurosauria excluding *Tanycolagreus*: Char. 4: 2→0, Char. 5: 1→0, Char. 468: 1→0, Char. 477: 1→0, Char. 482: 0→2.
- Node 11:** Coelurosauria excluding *Tanycolagreus* and Tyrannosauroidea: Char. 75: 1→0, Char. 101: 0→1, Char. 106: 0→1, Char. 115: 1→0, Char. 120: 0→1, Char. 124: 1→0, Char. 151: 1→0, Char. 241: 1→0, Char. 245: 1→0, Char. 258: 1→0, Char. 259: 1→0, Char. 302: 0→1, Char. 322: 1→0, Char. 359: 0→1, Char. 465: 1→0.
- Node 12:** Compsognathidae: Char. 250: 0→1, Char. 475: 2→1.
- Node 13:** Compsognathidae excluding *Coelurus*: Char. 336: 0→1, Char. 354: 0→1, Char. 363: 1→0, Char. 458: 1→0.
- Node 14:** Compsognathidae excluding *Coelurus* and *Sinosauroptryx*: Char. 290: 1→0, Char. 358: 1→0, Char. 425: 1→0, Char. 442: 0→1.
- Node 15:** *Scipionyx* + *Juravenator*: Char. 12: 0→1, Char. 20: 0→1, Char. 81: 1→0, Char. 140: 0→1, Char. 322: 0→1, Char. 330: 0→1, Char. 340: 0→1, Char. 379: 0→2, Char. 384: 0→1, Char. 385: 0→1, Char. 411: 0→1.
- Node 16:** Ornithomimidae and Maniraptora: Char. 42: 1→0, Char. 61: 0→1, Char. 104: 1→0, Char. 255: 0→1, Char. 297: 0→2, Char. 320: 0→1, Char. 324: 0→1, Char. 373: 0→1, Char. 406: 0→1, Char. 425: 1→0, Char. 448: 0→1, Char. 478: 01→2.
- Node 17:** Maniraptora: Char. 3: 0→1, Char. 214: 0→1, Char. 354: 0→1, Char. 411: 0→2, Char. 420: 1→2, Char. 424: 0→1, Char. 453: 1→0.
- Node 18:** Maniraptora excluding *Ornitholestes*: Char. 6: 0→1, Char. 54: 0→1, Char. 81: 1→0, Char. 82: 0→1, Char. 129: 2→3, Char. 269: 1→0, Char. 429: 1→2, Char. 434: 0→1, Char. 439: 0→1.
- Node 19:** Dromaeosauridae + *Archaeopteryx*: Char. 7: 1→0, Char. 34: 1→0, Char. 60: 1→0, Char. 61: 1→0, Char. 99: 1→0, Char. 212: 0→1, Char. 280: 0→1, Char. 345: 1→0, Char. 347: 0→1, Char. 357: 0→1, Char. 361: 0→1, Char. 364: 1→0, Char. 368: 0→1, Char. 375: 0→1, Char. 376: 0→1, Char. 389: 0→1, Char. 422: 0→1, Char. 430: 0→1.
- Node 20:** Dromaeosauridae: Char. 2: 1→0, Char. 8: 1→0, Char. 57: 2→0, Char. 122: 0→1, Char. 128: 0→1, Char. 153: 0→1, Char. 207: 0→1, Char. 215: 0→1, Char. 246: 0→1, Char. 300: 3→2, Char. 322: 0→1, Char. 329: 0→12, Char. 330: 0→1, Char. 400: 0→2, Char. 441: 0→3, Char. 442: 0→1, Char. 447: 1→2, Char. 499: 0→1.
- Node 21:** *Utahraptor* + *Deinonychus*: Char. 16: 0→1, Char. 17: 0→1, Char. 325: 0→1, Char. 326: 0→1, Char. 328: 0→1, Char. 332: 0→1, Char. 335: 0→1.
- Node 22:** *Linheraptor* + *Velociraptor*: Char. 15: 0→1, Char. 58: 0→1, Char. 107: 0→1, Char. 245: 0→1, Char. 272: 0→1, Char. 277: 0→1.

- Node 23:** Ornithomimidae: Char. 2: 1→0, Char. 13: 0→1, Char. 16: 0→1, Char. 20: 0→1, Char. 27: 1→0, Char. 62: 2→0, Char. 68: 0→2, Char. 86: 0→2, Char. 131: 0→2, Char. 163: 1→0, Char. 174: 1→0, Char. 175: 0→1, Char. 187: 0→1, Char. 209: 0→1, Char. 213: 0→1, Char. 239: 0→1, Char. 247: 0→1, Char. 253: 0→1, Char. 263: 1→0, Char. 278: 0→1, Char. 289: 1→3, Char. 303: 0→3, Char. 337: 1→0, Char. 362: 0→1, Char. 371: 0→2, Char. 379: 0→2, Char. 390: 0→2, Char. 394: 0→2, Char. 396: 0→2.
- Node 24:** Ornithomimidae excluding *Pelacanrimimus*: Char. 54: 0→1, Char. 299: 0→1.
- Node 25:** *Harpymimus* + *Gallimimus*: Char. 128: 0→1, Char. 240: 0→1, Char. 330: 0→1, Char. 411: 0→1.
- Node 26:** Tyrannosauroidae: Char. 13: 0→1, Char. 14: 0→1, Char. 15: 0→1, Char. 56: 0→1, Char. 57: 2→0, Char. 128: 0→1, Char. 131: 0→2, Char. 140: 0→2, Char. 147: 0→1, Char. 168: 0→2, Char. 187: 0→1, Char. 188: 0→1, Char. 197: 0→1, Char. 202: 0→1, Char. 204: 0→1, Char. 254: 0→1, Char. 264: 0→1, Char. 268: 0→1, Char. 288: 0→1, Char. 290: 1→2, Char. 291: 0→1, Char. 318: 2→0, Char. 366: 1→0, Char. 392: 0→1, Char. 405: 0→1, Char. 439: 0→1.
- Node 27:** Proceratosauridae: Char. 2: 1→2, Char. 20: 0→1, Char. 29: 0→1, Char. 432: 0→1, Char. 436: 0→1.
- Node 28:** *Kileskus* + Node 29 (*Guanlong* + *Proceratosaurus*): Char. 1: 1→2, Char. 244: 0→1.
- Node 29:** *Guanlong* + *Proceratosaurus*: Char. 29: 1→2, Char. 33: 1→2.
- Node 30:** *Sinotyrannus* + Node 31 (*Stokesosaurus clevelandi* + *Juratyrant langhami*): Char. 408: 0→1.
- Node 31:** *Stokesosaurus clevelandi* + *Juratyrant langhami*: Char. 409: 2→1.
- Node 32:** *Dilong*, *Eotyannus*, *Bagaraatan*, *Raptorex*, *Dryptosaurus*, *Alectrosaurus*, *Xiongguanlong*, *Appalachiosaurus*, *Alioramus*, and Tyrannosauridae: Char. 125: 0→1, Char. 155: 1→2, Char. 159: 0→1, Char. 171: 1→0, Char. 235: 2→1, Char. 236: 0→1, Char. 287: 0→1, Char. 292: 0→1, Char. 297: 0→2, Char. 314: 0→1, Char. 367: 0→1, Char. 391: 0→1, Char. 411: 0→1.
- Node 33:** *Eotyannus*, *Bagaraatan*, *Raptorex*, *Dryptosaurus*, *Alectrosaurus*, *Xiongguanlong*, *Appalachiosaurus*, *Alioramus*, and Tyrannosauridae: Char. 81: 1→0, Char. 290: 2→3, Char. 291: 1→2, Char. 365: 0→1, Char. 379: 0→1, Char. 383: 0→1.
- Node 34:** *Bagaraatan*, *Raptorex*, *Dryptosaurus*, *Alectrosaurus*, *Xiongguanlong*, *Appalachiosaurus*, *Alioramus*, and Tyrannosauridae: Char. 249: 0→1, Char. 250: 0→1, Char. 395: 0→1, Char. 396: 0→2.
- Node 35:** *Raptorex*, *Dryptosaurus*, *Alectrosaurus*, *Xiongguanlong*, *Appalachiosaurus*, *Alioramus*, and Tyrannosauridae: Char. 246: 0→1, Char. 277: 0→1, Char. 316: 0→1, Char. 464: 0→1, Char. 466: 0→1, Char. 469: 0→2.
- Node 36:** *Dryptosaurus*, *Alectrosaurus*, *Xiongguanlong*, *Appalachiosaurus*, *Alioramus*, and Tyrannosauridae: Char. 296: 0→1, Char. 455: 0→1, Char. 467: 0→1, Char. 471: 1→2.
- Node 37:** *Alectrosaurus*, *Xiongguanlong*, *Appalachiosaurus*, *Alioramus*, and Tyrannosauridae: Char. 488: 0→1, Char. 489: 1→2, Char. 493: 0→1, Char. 494: 0→1, Char. 497: 0→1.
- Node 38:** *Alectrosaurus* + *Xiongguanlong*: Char. 460: 1→0, Char. 463: 1→0, Char. 464: 1→0.
- Node 39:** *Appalachiosaurus*, *Alioramus*, and Tyrannosauridae: Char. 54: 0→1, Char. 65: 0→1, Char. 148: 0→1, Char. 451: 0→1, Char. 454: 1→2, Char. 468: 0→1, Char. 486: 0→1, Char. 491: 1→2, Char. 500: 0→1.
- Node 40:** Tyrannosauridae + Node 41 (*Alioramus remotus* + *Alioramus altai*): Char. 52: 0→1, Char. 64: 0→1, Char. 66: 1→2, Char. 69: 0→1, Char. 74: 0→1, Char. 147: 2→3, Char. 152: 0→1, Char. 210: 0→1, Char. 219: 0→1, Char. 220: 0→1, Char. 227: 0→1, Char. 229: 0→1, Char. 231: 0→1, Char. 455: 1→2.
- Node 41:** *Alioramus remotus* + *Alioramus altai*: Char. 53: 0→1, Char. 67: 0→1, Char. 73: 0→1, Char. 121: 0→1, Char. 124: 1→0, Char. 128: 1→2, Char. 186: 0→1, Char. 201: 0→1, Char. 300: 2→1.
- Node 42:** Tyrannosauridae: Char. 3: 0→1, Char. 9: 0→1, Char. 31: 0→1, Char. 42: 1→0, Char. 43: 1→2, Char. 46: 1→2, Char. 77: 1→0, Char. 89: 0→1, Char. 95: 0→1, Char. 104: 1→0, Char. 105: 0→1, Char. 107: 0→1, Char. 108: 0→1, Char. 110: 1→2, Char. 113: 0→1, Char. 122: 1→2, Char. 123: 0→1, Char. 137: 1→2, Char. 140: 1→0, Char. 213: 0→1, Char. 222: 0→1, Char. 247: 0→1, Char. 251: 0→1, Char. 272: 1→2, Char. 279: 0→1, Char. 313: 0→1, Char. 315: 1→2, Char. 316: 1→0, Char. 318: 1→2, Char. 321: 0→1, Char. 324: 0→2, Char. 327: 0→1, Char. 335: 0→1, Char. 399: 0→1, Char. 441: 0→1, Char. 442: 1→2, Char. 481: 1→2, Char. 490: 0→1.
- Node 43:** Albertosauridae: Char. 72: 1→0, Char. 108: 1→2, Char. 114: 0→1, Char. 194: 0→1, Char. 197: 1→0.
- Node 44:** Tyrannosaurinae: Char. 4: 1→2, Char. 13: 1→2, Char. 14: 1→2, Char. 24: 0→1, Char. 47: 0→1, Char. 55: 0→2, Char. 61: 0→1, Char. 90: 1→2, Char. 97: 1→2, Char. 100: 1→2, Char. 102: 1→2, Char. 110: 2→3, Char. 133: 0→1, Char. 149: 1→2, Char. 152: 1→2, Char. 154: 0→1, Char. 177: 1→2, Char. 180: 0→1, Char. 181: 0→1, Char. 182: 0→1, Char. 185: 0→1, Char. 188: 1→2, Char. 203: 0→1, Char. 221: 0→1, Char. 226: 0→1, Char. 261: 0→1, Char. 293: 0→1, Char. 297: 2→1.
- Node 45:** Tyrannosaurinae excluding Dinosaur Park new tyrannosaurid taxon: Char. 40: 0→1, Char. 59: 0→1, Char. 80: 0→1, Char. 146: 0→1, Char. 162: 0→1, Char. 165: 0→1, Char. 189: 0→1, Char. 242: 0→1, Char. 296: 1→0.
- Node 46:** Tyrannosaurinae excluding *Daspletosaurus torosus*: Char. 34: 0→1, Char. 62: 1→2, Char. 72: 1→0, Char. 209: 0→1, Char. 230: 0→1.

- Node 47:** Tyrannosaurinae excluding *Daspletosaurus torosus* and the Upper Two Medicine Formation tyrannosaurid): Char. 6: 0→1, Char. 11: 0→1, Char. 33: 2→1, Char. 73: 0→1, Char. 76: 1→2, Char. 88: 0→1, Char. 93: 0→1, Char. 94: 2→3, Char. 96: 1→2, Char. 108: 1→2, Char. 121: 0→1, Char. 127: 1→0, Char. 160: 1→2, Char. 180: 1→0, Char. 186: 0→1, Char. 193: 0→1, Char. 253: 1→0, Char. 254: 1→2, Char. 269: 1→2, Char. 270: 1→2, Char. 275: 1→2, Char. 276: 1→2, Char. 277: 1→2, Char. 298: 1→2, Char. 300: 2→3, Char. 364: 2→3.
- Node 48:** Tyrannosaurinae excluding *Daspletosaurus torosus*, the Upper Two Medicine Formation tyrannosaurid and *Teratophoneus*: Char. 10: 0→1, Char. 31: 1→2, Char. 67: 0→1, Char. 117: 1→0, Char. 138: 0→1, Char. 181: 1→0, Char. 297: 1→2, Char. 351: 1→2.
- Node 49:** *Lythronax* + Node 50 (*Tyrannosaurus* + Node 51 (*Tarbosaurus* + *Zhuchengtyrannus*)): Char. 6: 1→2, Char. 9: 1→2, Char. 27: 1→0, Char. 39: 1→2, Char. 91: 0→1, Char. 134: 0→1, Char. 252: 0→1, Char. 281: 1→2, Char. 303: 1→2.
- Node 50:** *Tyrannosaurus* + Node 51 (*Tarbosaurus* + *Zhuchengtyrannus*): Char. 33: 1→3, Char. 35: 0→1, Char. 36: 0→1, Char. 37: 0→1, Char. 55: 2→0, Char. 57: 0→1, Char. 97: 2→3, Char. 98: 1→0, Char. 144: 0→1, Char. 160: 2→0, Char. 207: 1→2, Char. 427: 3→4.
- Node 51:** *Tarbosaurus* + *Zhuchengtyrannus*: Char. 45: 0→1, Char. 297: 2→1, Char. 4: 0→2, Char. 5: 0→1, Char. 7: 1→0, Char. 8: 1→0, Char. 41: 0→1, Char. 43: 0→1, Char. 110: 0→1, Char. 245: 0→1, Char. 316: 0→1, Char. 322: 0→1, Char. 352: 0→1, Char. 387: 0→1, Char. 398: 0→1, Char. 401: 0→1, Char. 408: 0→1, Char. 423: 0→1, Char. 447: 0→1, Char. 451: 0→1, Char. 452: 0→1, Char. 458: 0→1, Char. 459: 0→1, Char. 470: 0→1.

Differential support for the alternative positions of *Kileskus*, *Guanlong* and *Proceratosaurus* in the second MPT.

- Node 52:** *Kileskus* + Node 53 (*Guanlong* and *Proceratosaurus*): Char. 1: 1→2.
- Node 53:** *Guanlong* and *Proceratosaurus*: Char. 35: 1→0, Char. 272: 1→0.

**TABLE S5: STRATIGRAPHIC POSITION OF SELECT TAXA**

Sources of age ranges for taxa included in the biogeographic analysis updated where possible to Walker et al. (2012).

<b>Taxon</b>	<b>Formation</b>	<b>Landmass</b>	<b>Stage</b>	<b>Published Age</b>	<b>Citations for age</b>
<i>Dilong</i>	Yixian	Asia	Barremian	139-126	Xu et al., 2004
<i>Eotyrannus</i>	Wessex	Europe	Barremian	130-125	Hutt et al., 2001
<i>Bagaraatan</i>	Nemegt	Asia	Campanian-Maastrichtian	70.6-68	Carpenter et al., 2011
<i>Raptorex</i>	Lujiautun Beds Jehol Group	Asia	Hauterivian-Barremian	130	Sereno et al., 2009
<i>Dryptosaurus</i>	New Egypt	Appalachia	Maastrichtian	66.5-66	Brusatte et al., 2011; Landman et al., 2004; Gradstein et al., 2012
<i>Xiongguanlong</i>	Xinminpu Group	Asia	Aptian-Albian	120-125	Li et al., 2009
<i>Alectrosaurus</i>	Iren Dabasu	Asia	Campanian	76.5-70	Carpenter et al., 2011
<i>Appalachiosaurus</i>	Demopolis	Appalachia	Campanian	78-77.5	Carr et al., 2005
<i>Alioramus</i>	Nemegt	Asia	Campanian-Maastrichtian	70.6-68	Brusatte et al., 2012; Carpenter et al., 2011
<i>Gorgosaurus</i>	Dinosaur Park	Laramidia	Campanian	77-75.5	Roberts et al., 2005; Roberts et al., 2013
<i>Albertosaurus</i>	Horseshoe Canyon	Laramidia	Campanian	72-68.3	Eberth and Braman, 2012
<i>Daspletosaurus torosus</i>	Oldman	Laramidia	Campanian	78-77	Roberts et al., 2005; Roberts et al., 2013
<b>Two Medicine Fm. tyrannosaurid LSB</b>	Upper Two Medicine	Laramidia	Campanian	74.5-74	Roberts et al., 2005; Roberts et al., 2013
<i>Teratophoneus</i>	Kaiparowits	Laramidia	Campanian	76-75.5	Roberts et al., 2005; Roberts et al., 2013
<i>Bistahieversor</i>	Kirtland-Fruitland	Laramidia	Campanian	74.2-73	Carr and Williamson, 2010; Roberts et al., 2005; Roberts et al., 2013
<i>Lythronax</i>	Wahweap	Laramidia	Campanian	80.6-79.9	Jinnah et al., 2009
<i>Tyrannosaurus</i>	Hell Creek	Laramidia	Maastrichtian	67.5-66	Brochu, 2003; Gradstein et al., 2012
<i>Tarbosaurus</i>	Nemegt	Asia	Campanian-Maastrichtian	70.6-68	Carpenter et al., 2011
<i>Zhuchengtyrannus</i>	Xingezhuang	Asia	Campanian	120-73.5	Hone et al. 2011

**TABLE S6. RESULTS OF THE BIOGEOGRAPHIC ANALYSIS**

**Node 32: *Dilong + Tyrannosaurus***

Analysis:	Ancestral Range Reconstructions:		Log	Likeli-hood	Relative Probability
	Dilong Branch	Tyrannosaurus Branch			
Smoothed Temporal Calibration	Asia	Asia + Europe	-40.50	0.94130	
No Weighting	Asia	Asia	-43.47	0.04850	
Smoothed Temporal Calibration	Asia	Asia + Europe	-40.79	0.96850	
Weighted					
Strict Temporal Calibration	Asia	Asia + Europe	-42.11	0.64340	
No Weighting	Asia	Asia	-42.87	0.30120	
	Asia	Europe	-44.67	0.04997	
Strict Temporal Calibration	Asia	Asia + Europe	-42.71	0.77890	
Weighted	Asia	Asia	-44.14	0.18580	

**Node 33: *Eotyrannus + Tyrannosaurus***

Analysis:	Ancestral Range Reconstructions:		Log	Likeli-hood	Relative Probability
	Eotyrannus Branch	Tyrannosaurus Branch			
Smoothed Temporal Calibration	Europe	Asia	-40.59	0.86250	
No Weighting	Europe	Europe + Asia	-42.81	0.09404	
Smoothed Temporal Calibration	Europe	Asia	-40.89	0.87380	
Weighted	Europe	Europe + Asia	-43.17	0.08961	
Strict Temporal Calibration	Europe	Asia	-42.01	0.71540	
No Weighting	Europe	Europe + Asia	-43.21	0.21590	
	Europe + Asia	Asia	-44.95	0.03767	
Strict Temporal Calibration	Europe	Asia	-42.74	0.75450	
Weighted	Europe	Europe + Asia	-44.13	0.18810	
	Europe + Asia	Asia	-45.74	0.03751	

**Node 34: *Bagaraatan + Tyrannosaurus***

Analysis:	Ancestral Range Reconstructions:		Log	Likeli-hood	Relative Probability
	Bagaraatan Branch	Tyrannosaurus Branch			
Smoothed Temporal Calibration	Asia	Asia	-40.54	0.90590	
No Weighting	Asia + Europe	Europe	-43.08	0.07129	
Smoothed Temporal Calibration	Asia	Asia	-40.85	0.91230	
Weighted	Asia + Europe	Asia	-43.39	0.07174	
Strict Temporal Calibration	Asia	Asia	-41.92	0.77970	
No Weighting	Asia + Europe	Asia	-43.70	0.13230	
	Europe	Asia	-44.38	0.06661	
Strict Temporal Calibration	Asia	Asia	-42.67	0.80880	
Weighted	Asia + Europe	Asia	-44.52	0.12760	
	Europe	Asia	-45.54	0.04609	
	Asia	Asia + Europe	-45.60	0.03695	

### Node 35: *Raptorex* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	Dryptosaurus Branch	Tyrannosaurus Branch		
Smoothed Temporal Calibration No Weighting	Asia	Asia	-40.46	0.98480
Smoothed Temporal Calibration Weighted	Asia	Asia	-40.77	0.98790
Strict Temporal Calibration No Weighting	Asia	Asia	-41.69	0.97960
Strict Temporal Calibration Weighted	Asia	Asia	-42.48	0.98380

### Node 36: *Dryptosaurus* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	Raptorex Branch	Tyrannosaurus Branch		
Smoothed Temporal Calibration No Weighting	Asia	Asia	-40.58	0.86890
	Appalachia	Asia	-43.66	0.04017
	Appalachia	Appalachia + Asia	-43.68	0.03920
	Appalachia + Asia	Asia	-44.32	0.02059
Smoothed Temporal Calibration Weighted	Asia	Asia	-40.87	0.89170
	Appalachia	Asia	-44.02	0.03819
	Appalachia	Appalachia + Asia	-44.43	0.02549
Strict Temporal Calibration No Weighting	Asia	Asia	-42.11	0.64840
	Appalachia	Appalachia + Asia	-44.60	0.05338
	Asia + Appalachia	Asia	-44.64	0.05145
	Appalachia	Asia	-44.69	0.04917
	Europe	Asia	-45.08	0.03320
	N. Laramidia	N. Laramidia + Asia	-45.14	0.03107
	Asia	Asia + N. Laramidia	-45.14	0.03107
	Asia	Asia + Appalachia	-45.36	0.02512
	Asia + Europe	Asia	-45.44	0.02322
	N. Laramidia	Asia	-45.44	0.02313
Strict Temporal Calibration Weighted	Asia	Asia	-42.87	0.66610
	Asia + Appalachia	Asia	-45.21	0.06388
	Appalachia	Asia	-45.29	0.05884
	Appalachia	Appalachia + Asia	-45.44	0.05077
	Asia	Asia + Appalachia	-45.91	0.03171
	Asia	Asia + N. Laramidia	-45.94	0.03085
	N. Laramidia	N. Laramidia + Asia	-46.14	0.02524
	N. Laramidia	Asia	-46.37	0.01999
	Europe	Asia	-46.56	0.01661

### Node 37: *Xiongguanlong* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Xiongguanlong</i> + <i>Alectrosaurus</i> Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	Asia	Asia	-40.55	0.89340
	Asia	Asia + Appalachia	-43.43	0.05017
	Asia	Asia + N. Laramidia	-43.85	0.03301
Smoothed Temporal Calibration Weighted	Asia	Asia	-40.85	0.91270
	Asia	Asia + Appalachia	-44.03	0.03794
Strict Temporal Calibration No Weighting	Asia	Asia	-41.85	0.84070
	Asia	Appalachia	-44.78	0.04495
	Asia	N. Laramidia	-44.99	0.03621
	Asia	Asia + Appalachia	-45.44	0.02304
	Asia	Asia + N. Laramidia	-45.66	0.01848
Strict Temporal Calibration Weighted	Asia	Asia	-42.62	0.84930
	Asia	Appalachia	-45.54	0.04610
	Asia	N. Laramidia	-45.88	0.03279
	Asia	Asia + Appalachia	-46.19	0.02408

### Node 38: *Xiongguanlong* + *Alectrosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Xiongguanlong</i> Branch	<i>Alectrosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	Asia	Asia	-40.44	0.99710
Smoothed Temporal Calibration Weighted	Asia	Asia	-40.76	0.99720
Strict Temporal Calibration No Weighting	Asia	Asia	-41.70	0.97100
Strict Temporal Calibration Weighted	Asia	Asia	-42.49	0.97120

### Node 39: *Appalachiosaurus* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Appalachiosaurus</i> Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	Asia	Asia	-40.95	0.60360
	Appalachia	Asia	-42.61	0.11420
	N. Laramidia	N. Laramidia + Asia	-42.76	0.09827
	Asia	Asia + N. Laramidia	-42.76	0.09827
	Appalachia + Asia	Asia	-43.74	0.03688
Smoothed Temporal Calibration Weighted	Asia	Asia	-41.21	0.64000
	Asia	Asia + N. Laramidia	-43.02	0.10420
	Appalachia	Asia	-43.03	0.10360
	N. Laramidia	N. Laramidia + Asia	-43.39	0.07236
	Appalachia + Asia	Asia	-44.08	0.03615
Strict Temporal Calibration No Weighting	Appalachia	N. Laramidia	-42.11	0.64390
	Appalachia	Appalachia + N. Laramidia	-43.79	0.12100
	N. Laramidia	N. Laramidia + Asia	-44.61	0.05304
	Asia	Asia + N. Laramidia	-44.61	0.05304
	Appalachia	Asia	-44.64	0.05161
	Appalachia + N. Laramidia	N. Laramidia	-44.78	0.04474
Strict Temporal Calibration Weighted	Appalachia	N. Laramidia	-42.96	0.60750
	Appalachia	Appalachia + N. Laramidia	-44.35	0.15070
	Asia	Asia + N. Laramidia	-45.24	0.06233
	Appalachia	Asia	-45.24	0.06204
	N. Laramidia	N. Laramidia + Asia	-45.63	0.04215
	Appalachia + N. Laramidia	N. Laramidia	-45.64	0.04151

### Node 40: *Alioramus* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Alioramus</i> Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	Asia	N. Laramidia	-40.92	0.61900
	Asia	Asia	-42.24	0.16540
	Asia + N. Laramidia	N. Laramidia	-42.46	0.13350
	Asia	Asia + N. Laramidia	-43.49	0.04736
Smoothed Temporal Calibration Weighted	Asia	N. Laramidia	-41.25	0.61510
	Asia	Asia	-42.55	0.16760
	Asia + N. Laramidia	N. Laramidia	-42.75	0.13600
	Asia	Asia + N. Laramidia	-43.82	0.04676
Strict Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-42.03	0.70190
	Asia	N. Laramidia	-43.73	0.12790
	Appalachia	N. Laramidia	-43.97	0.10070
	Asia + N. Laramidia	N. Laramidia	-45.02	0.03531
Strict Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-42.87	0.66270
	Asia	N. Laramidia	-44.46	0.13490
	Appalachia	N. Laramidia	-44.50	0.12990
	Asia + N. Laramidia	N. Laramidia	-45.78	0.03622

### **Node 41: *A. altai* + *A. remotus***

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>A. altai</i> Branch	<i>A. remotus</i> Branch		
Smoothed Temporal Calibration No Weighting	Asia	Asia	-40.52	0.92790
Smoothed Temporal Calibration Weighted	Asia + N. Laramidia	Asia	-44.07	0.02649
Strict Temporal Calibration No Weighting	Asia	Asia	-40.84	0.92540
Strict Temporal Calibration Weighted	Asia + N. Laramidia	Asia	-44.37	0.02689
Strict Temporal Calibration No Weighting	Asia	Asia	-41.68	0.99430
Strict Temporal Calibration Weighted	Asia	Asia	-42.47	0.99430

### **Node 42: *Gorgosaurus* + *Tyrannosaurus***

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Gorgosaurus</i> Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-40.62	0.83410
Smoothed Temporal Calibration Weighted	N. Laramidia + Asia	N. Laramidia	-42.73	0.10190
Smoothed Temporal Calibration Weighted	N. Laramidia	N. Laramidia + Asia	-43.55	0.04460
Strict Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-40.94	0.83460
Strict Temporal Calibration Weighted	N. Laramidia + Asia	N. Laramidia	-43.05	0.10150
Strict Temporal Calibration Weighted	N. Laramidia	N. Laramidia + Asia	-43.86	0.04484
Strict Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-41.69	0.98140
Strict Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-42.48	0.98090

### **Node 43: *Gorgosaurus* + *Albertosaurus***

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Gorgosaurus</i> Branch	<i>Albertosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-40.49	0.95650
Smoothed Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-40.80	0.95940
Strict Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-41.69	0.98760
Strict Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-42.47	0.98960

#### Node 44: Dinosaur Park Fm taxon + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	Dinosaur Park taxon Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-40.49	0.95240
Smoothed Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-40.80	0.95530
Strict Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-41.69	0.98650
Strict Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-42.47	0.98920

#### Node 45: *Daspletosaurus* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Daspletosaurus</i> Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-40.53	0.93230
	N. Laramidia	N. + S. Laramidia	-43.09	0.07094
Smoothed Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-40.83	0.92850
	N. Laramidia	N. + S. Laramidia	-43.53	0.06278
Strict Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-41.74	0.93440
	N. Laramidia	N. + S. Laramidia	-44.45	0.06244
Strict Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-42.51	0.95030

#### Node 46: Two Medicine Fm taxon + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	Two Medicine taxon Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-40.98	0.58280
	N. Laramidia	S. Laramidia	-41.82	0.25120
	N. Laramidia	N. + S. Laramidia	-42.52	0.12540
Smoothed Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-41.23	0.62710
	N. Laramidia	S. Laramidia	-42.33	0.20750
	N. Laramidia	N. + S. Laramidia	-42.78	0.13280
Strict Temporal Calibration No Weighting	N. Laramidia	N. Laramidia	-42.14	0.62600
	N. Laramidia	S. Laramidia	-43.20	0.21770
	N. Laramidia	N. + S. Laramidia	-43.77	0.12260
Strict Temporal Calibration Weighted	N. Laramidia	N. Laramidia	-42.80	0.71060
	N. Laramidia	N. + S. Laramidia	-44.42	0.14110
	N. Laramidia	S. Laramidia	-44.50	0.13020

### Node 47: *Teratophoneus* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Teratophoneus</i> Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	S. Laramidia	S. + N. Laramidia	-40.89	0.63650
	S. Laramidia	S. Laramidia	-41.61	0.31010
	S. + N. Laramidia	S. Laramidia	-44.26	0.02202
Smoothed Temporal Calibration Weighted	S. Laramidia	S. + N. Laramidia	-41.11	0.70690
	S. Laramidia	S. Laramidia	-42.12	0.25650
Strict Temporal Calibration No Weighting	S. Laramidia	S. + N. Laramidia	-42.02	0.70350
	S. Laramidia	S. Laramidia	-43.06	0.25080
Strict Temporal Calibration Weighted	S. Laramidia	S. + N. Laramidia	-42.65	0.82690
	S. Laramidia	S. Laramidia	-44.37	0.14800

### Node 48: *Bistahieversor* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Bistahieversor</i> Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	S. Laramidia	S. + N. Laramidia	-40.86	0.65890
	S. Laramidia	S. Laramidia	-41.59	0.31780
	S. Laramidia	S. + N. Laramidia	-42.08	0.26810
Strict Temporal Calibration No Weighting	S. Laramidia	S. + N. Laramidia	-42.01	0.71360
	S. Laramidia	S. Laramidia	-42.98	0.27030
Strict Temporal Calibration Weighted	S. Laramidia	S. + N. Laramidia	-42.64	0.83300
	S. Laramidia	S. Laramidia	-44.30	0.15840

### Node 49: *Lythronax* + *Tyrannosaurus*

Analysis:	Ancestral Range Reconstructions:		Log Likeli-hood	Relative Probability
	<i>Lythronax</i> Branch	<i>Tyrannosaurus</i> Branch		
Smoothed Temporal Calibration No Weighting	S. Laramidia	N. Laramidia	-40.85	0.66620
	S. Laramidia	S. Laramidia	-42.10	0.19120
	S. Laramidia	S. + N. Laramidia	-42.40	0.14090
Smoothed Temporal Calibration Weighted	S. Laramidia	N. Laramidia	-41.30	0.58260
	S. Laramidia	S. + N. Laramidia	-42.26	0.22220
	S. Laramidia	S. Laramidia	-42.40	0.19290
Strict Temporal Calibration No Weighting	S. Laramidia	N. Laramidia	-42.08	0.66440
	S. Laramidia	S. Laramidia	-43.01	0.26280
	S. Laramidia	S. + N. Laramidia	-44.31	0.07131
Strict Temporal Calibration Weighted	S. Laramidia	N. Laramidia	-42.73	0.76710
	S. Laramidia	S. Laramidia	-44.34	0.15340
	S. Laramidia	S. + N. Laramidia	-45.02	0.07772

### Node 50: *Tarbosaurus* + *Tyrannosaurus*

Ancestral Range Reconstructions:

Analysis:	<i>Tarbosaurus</i> Branch	<i>Tyrannosaurus</i> Branch	Log Likeli-hood	Relative Probability
Smoothed Temporal Calibration No Weighting	Asia	N. Laramidia	-40.91	0.62740
	N. Laramidia	N. + S. Laramidia	-41.66	0.29570
	Asia	Asia + N. Laramidia	-44.04	0.02734
Smoothed Temporal Calibration Weighted	Asia	N. Laramidia	-41.37	0.54550
	N. Laramidia	N. + S. Laramidia	-41.72	0.38300
	N. Laramidia	N. Laramidia	-44.48	0.02430
Strict Temporal Calibration No Weighting	Asia	N. Laramidia	-41.71	0.96700
Strict Temporal Calibration Weighted	Asia	N. Laramidia	-42.49	0.96790

## ADDITIONAL REFERENCES.

- Allain, R. Discovery of a megalosaur (Dinosauria, Theropoda) in the middle Bathonian of Normandy (France) and its implications for the phylogeny of basal Tetanurae. *Journal of Vertebrate Paleontology* **22**, 548-563 (2002).
- Allain, R. Redescription de *Streptospondylus altdorfensis*, le dinosaure théropode de Cuvier, du Jurassique de Normandie. *Geodiversitas* **23**, 349-367 (2001).
- Allain, R. The postcranial anatomy of the megalosaur *Dubreuillosaurus valesdunensis* (Dinosauria, Theropoda) from the middle Jurassic of Normandy, France. *Journal of Vertebrate Paleontology* **25**, 850-858 (2005).
- Averianov, A.O., Krasnolutskii, S.A. & Ivantsov, S.V. A new basal coelurosaur (Dinosauria: Theropoda) from the Middle Jurassic of Siberia. *Proceedings of the Zoological Institute RAS* **314**, 42-57 (2010).
- Bakker, R.T., Williams, M., and Currie, P.J. *Nanotyrannus*, a new genus of pygmy tyrannosaur, from the latest Cretaceous of Montana. *Hunteria* **1**(5), 1-30 (1988).
- Barsbold, R., Osmólska, H. The skull of *Velociraptor* (Theropoda) from the Late Cretaceous of Mongolia. *Acta Palaeontologica Polonica* **44**, 189-219 (1999).
- Benson, R.B.J. New information on *Stokesosaurus*, a tyrannosauroid (Dinosauria: Theropoda) from North America and the United Kingdom. *Journal of Vertebrate Paleontology* **28**, 732-750 (2008).
- Bonaparte, J.F. Les Dinaures (Carnosaures, Allosauridés, Sauropodes, Cétiosauridés) du Jurassique moyen de Cerro Cóndor (Chubut, Argentine). *Annales de Paléontologie* **72**, 247-289 (1986).
- Brochu, C.A. Osteology of *Tyrannosaurus rex*: insights from a nearly complete skeleton and high-resolution computed tomographic analysis of the skull. *Journal of Vertebrate Paleontology Memoir* **7**, 1-138 (2003).
- Brusatte, S.L. *et al.* Tyrannosaur Paleobiology: new research on ancient exemplar organisms. *Science* **329**, 1481-1485 (2010).
- Brusatte, S.L., Benson, R.B.J., Currie, P.J. & Zhao, X.-J. The skull of *Monolophosaurus jiangi* (Dinosauria: Theropoda) and its implications for early theropod phylogeny and evolution. *Zoological Journal of the Linnean Society* **158**, 573-607 (2010).
- Brusatte S.L., Benson, R.B.J., Norell, M.A. The anatomy of *Dryptosaurus aquilunguis* (Dinosauria: Theropoda) and a review of its tyrannosauroid affinities American Museum Novitates 3717:1-53 (2011).
- Brusatte, S.L., Carr, T.D. & Norell, M.A. The osteology of *Alioramus*, a gracile and long-snouted tyrannosaurid (Dinosauria: Theropoda) from the Late Cretaceous of Mongolia. *Bulletin of the American Museum of Natural History*, **366**, 1-197 (2012).
- Brusatte, S.L., Carr, T.D., Erickson, G.M., Bever, G.S. & Norell, M.A. A long snouted, multi-horned tyrannosaurid from the Late Cretaceous of Mongolia. *Proceedings of the National Academy of Science (USA)* **106**, 17261-17266 (2009).
- Calvo, J.O., Porfiri, J.D. & Kellner, A.W.A. On a new maniraptoran dinosaur (Theropoda) from the Upper Cretaceous of Neuquén, Patagonia, Argentina. *Arquivos do Museu Nacional* **62**, 549-566 (2004).
- Carpenter, K., Hayashi, S., Kobayashi, Y., Maryańska, T., Barsbold, R., Sato, K. and Obata, I. *Saichania Chulsanensis* (sic) (Ornithischia, Ankylosauridae) from the Upper Cretaceous of Mongolia. *Palaeontographica, Abt. A: Palaeozoology – Stratigraphy* **294**(1–3), 1-61 (2011).
- Carr, T.D. & Williamson, T.E. *Bistahievors sealeyi*, gen. et sp. nov., a new tyrannosauroid from New Mexico and the origin of deep snouts in Tyrannosauroidea. *J. Vertebr. Paleontol.* **30**, 1-16 (2010).
- Carr T.D., Williamson, T.E., Schwimmer, D.R. A new genus and species of tyrannosauroid from the Late Cretaceous (Middle Campanian) Demopolis Formation of Alabama. *J. Vertebr. Paleontol.* **25**: 119–143 (2005).
- Carr, T.D. Craniofacial ontogeny in Tyrannosauridae (Dinosauria: Theropoda). *Journal of Vertebrate Paleontology* **19**, 497-520 (1999).
- Carr, T.D., Williamson, T.E., Britt, B.B. & Stadtman, K. Evidence for high taxonomic and morphologic tyrannosauroid diversity in the Late Cretaceous (Late Campanian) of the American Southwest and a new short-skulled tyrannosaurid from the Kaiparowits formation of Utah. *Naturwissenschaften* **98**, 241-247 (2011).
- Carrano, M.T., & Hutchinson, J.R. The pelvic and hind limb musculature of *Tyrannosaurus rex* (Dinosauria: Theropoda). *Journal of Morphology* **253**, 207-228 (2002).
- Carrano, M.T., Hutchinson, J.R., & Sampson, S.D. New information on *Segisaurus halli*, a small theropod dinosaur from the early Jurassic of Arizona. *Journal of Vertebrate Paleontology* **25**, 835-849 (2005).
- Carrano, M.T., Sampson, S.D. & Forster, C.A. The osteology of *Masiakasaurus knopfleri*, a small abelisauroid (Dinosauria: Theropoda) from the Late Cretaceous of Madagascar. *Journal of Vertebrate Paleontology* **22**, 510-534 (2002).
- Chiappe, L.M., Norell, M.A. & Clark, J.M. The skull of a new relative of the stem-group bird *Mononykus*. *Nature* **392**, 275-278 (1998).
- Chiappe, L.M., Göhlich, U.B. Anatomy of *Juravenator starki* (Theropoda, Coelurosauria) from the Late Jurassic of Germany. *Neues Jahrbuch für Geologie und Paläontologie - Abhandlungen* **258**, 257-296 (2010).
- Coria, R.A., & Currie, P.J. A new carcharodontosaurid (Dinosauria, Theropoda) from the Upper Cretaceous of Argentina. *Geodiversitas* **28**, 71-118 (2006).
- Currie, P.J. & Chen, P.-J. Anatomy of *Sinosauropelta prima* from Liaoning, northeastern China. *Canadian Journal of Earth Sciences* **38**, 1705-1727 (2001).

- Currie, P.J. & Varriacchio, D.J. A new dromaeosaurid from the Horseshoe Canyon Formation (Upper Cretaceous) of Alberta, Canada; pp. 112-132 in P.J. Currie, E. B. Koppelhus, M. A. Shugar, and J. L. Wright (eds.), *Feathered Dragons*. Indiana University Press, Indianapolis (2004).
- Currie, P.J. and Zhao, X-J. A new carnosaur (Dinosauria: Theropoda) from the Jurassic of Xinjiang, People's Republic of China. *Canadian Journal of Earth Sciences* **30**, 2037-2081 (1993).
- Currie, P.J. Cranial anatomy of tyrannosaurid dinosaurs from the Late Cretaceous of Alberta, Canada. *Acta Palaeontologica Polonica* **48**, 191-226 (2003).
- Currie, P.J. New information on the anatomy and relationships of *Dromaeosaurus albertensis* (Dinosauria, Saurischia). *Journal of Vertebrate Paleontology* **15**, 576-591 (1995).
- Currie, P.J., Hurum, J.H. & Sabath, K. Skull structure and evolution in tyrannosaurid dinosaurs. *Acta Palaeontologica Polonica* **48**, 227-234 (2003).
- Dal Sasso, C. & Maganuco, S. Scipionyx samniticus (Theropoda: Compsognathidae) from the Lower Cretaceous of Italy: Osteology, ontogenetic assessment, phylogeny, soft tissue anatomy, taphonomy and palaeobiology, *Memorie della Società Italiano di Scienze Naturali e del Museo Civico di Storia Naturale di Milano* **37**, 1-281 (2011).
- Dashzeveg, D., Dingus, L., Loope, D.B., Swisher, C.C., Dulam, T. and Sweeney, M.R. New stratigraphic subdivision, depositional environment, and age estimate for the Upper Cretaceous Djadokhta Formation, southern Ulan Nur Basin, Mongolia. *American Museum Novitates* **3498**, 1-31 (2005).
- Eberth, D.A. and Braman, D.R. A revised stratigraphy and depositional history for the Horseshoe Canyon Formation (Upper Cretaceous), southern Alberta plains. *Canadian Journal of Earth Sciences* **49**, 1053-1086 (2012).
- Elzanowski A. & Wellnhofer, P. Cranial morphology of Archaeopteryx: evidence from the seventh skeleton. *Journal of Vertebrate Paleontology* **16**, 81-94 (1996).
- Gauthier, J. Saurischian monophyly and the origin of birds. *Memoirs of the California Academy of Sciences* **8**, 1-55 (1986).
- Gradstein, F.M., Ogg, J.G., Schmitz, M. & Ogg, G. The Geologic Time Scale 2012. Elsevier 793-853 (2012).
- Harris, J.D. Reanalysis of *Acrocanthosaurus atokensis*, its phylogenetic status, and implications, based on a new specimen. *New Mexico Museum of Natural History and Science Bulletin* **13**, 1-75 (1998).
- Hicks, J.F., Fastovsky, D., Nichols, D.J.U. and Watabe, M. Magnetostratigraphic correlation of Late Cretaceous dinosaur-bearing localities in the Nemegt and Ulan Nuur Basins, Gobi Desert, Mongolia. *Geological Society of America Program Abstracts A*, 323 (2001).
- Holtz, T.R. Jr. Arctometatarsalia revisited: The problem of homoplasy in reconstructing theropod phylogeny; pp. 97-121 in Gauthier, J. & Gall, L.F. (eds.), *New perspectives on the Origin and Early Evolution of Birds: Proceedings of the International Symposium in Honor of John H. Ostrom*. Peabody Museum of Natural History, New Haven (2001).
- Holtz, T.R. Jr. Tyrannosauroidea. In D. B. Weishampel, P. Dodson and H. Osmólska (eds.) *The Dinosauria. Second Edition*. University of California Press. 111-136 (2004).
- Holtz, T.R.J. The phylogenetic position of the Tyrannosauridae: implications for theropod systematics. *Journal of Paleontology* **68**, 1100-1117 (1994).
- Hone, D.W., Wang, K., Sullivan, C., Zhai, X., Chen, S., Li, D., Ji, S., Ji, Q. and Xu, X. A new, large tyrannosaurine theropod from the Upper Cretaceous of China. *Cretaceous Research* **32**: 495-505 (2011).
- Hutchinson, J.R. The evolution of femoral osteology and soft tissues on the line to extant birds (Neornithes). *Zoological Journal of the Linnean Society* **131**, 169-197 (2001b).
- Hutt, S., Naish, D., Martill, D.M., Barker M.J. and Newberry, P. A preliminary account of a new tyrannosauroid theropod from the Wessex Formation (Early Cretaceous) of southern England. *Cretaceous Research* **22**, 227-242 (2001).
- Hwang, S.H., Norell, M.A., Quiang, J. & Keqin, G. A large compsognathid from the Early Cretaceous Yixian Formation of China. *Journal of Systematic Paleontology* **2**, 13-30 (2004).
- Ji, Q., Ji, S-A. & Zhang, L-J. First large tyrannosauroid theropod from the Early Cretaceous Jehol Biota in northeastern China. *Geological Bulletin of China* **28**, 1369-1372 (2009).
- Jinnah Z.A., Roberts E.M., Deino A.L., Larson J.S., Link, P.K., and Fanning, C.M. New  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  and detrital zircon U-Pb ages for the Upper Cretaceous Wahweap and Kaiparowits formations on the Kaiparowits Plateau, Utah: implications for regional correlation, provenance, and biostratigraphy. *Cretaceous Research* **30**:287-299 (2009).
- Kobayashi, Y. & Barsbold, R. Reexamination of a primitive ornithomimosaur, *Garudimimus brevipes* Barsbold, 1981 (Dinosauria: Theropoda), from the Late Cretaceous of Mongolia. *Canadian Journal of Earth Sciences* **42**, 1501-1521 (2005).
- Kurzanov S.M. A new Late Cretaceous carnosaur from Nogon-Tsav Mongolia. *Sovmestnaá Sovetsko-Mongolskáá Paleontologiceskáá Ekspediciá, Trudy* **3**, 93-104 (in Russian) (1976).
- Landman, N.H., Johnson, R.O. and Edwards, L.E. Cephalopods from the Cretaceous/Tertiary boundary interval on the Atlantic coastal Plain, with a description of the highest ammonite zones in North America. Part 2. Northesatern Monmouth County, New Jersey. *American Museum of Natural History Bulletin* **287**, 1-107 (2004).
- Li, D., Norell, M.A., Gao, K., Smith, N.D. & Makovicky, P.J. A longirostrine tyrannosauroid from the Early Cretaceous of China. *Proceedings of the Royal Society of London Biology* **277**, 183-190 (2009).

- Makovicky, P. J. and H. D. Sues. Anatomy and phylogenetic relationships of the theropod dinosaur *Microvenator celer* from the Lower Cretaceous of Montana. *American Museum Novitates* **3240**, 1-27 (1998).
- Makovicky, P.J., Pesteguia, S. & Agnolin, F.L. The earliest dromaeosaurid theropod from South America. *Nature* **437**, 1007-1011 (2005).
- Mayer, G.B., Pohl, B., Hartman, S. & Peters, D.S. The tenth skeletal specimen of *Archaeopteryx*. *Zoological Journal of the Linnean Society* **149**, 97-116 (2007).
- Molnar, R.E. The cranial morphology of *Tyrannosaurus rex*. *Palaeontographica Abteilung A* **217**, 137-176 (1990).
- Nesbitt, S.J., Smith, N.D., Irmis, R.B., Turner, A.H., Downs, A. & Norell, M.A. A complete skeleton of a Late Triassic Saurischian and the early evolution of dinosaurs. *Science* **326**, 1530-1533 (2009).
- Norell, M.A., & Makovicky, P.J. Important features of the dromaeosaurid skeleton II: information from newly collected specimens of *Velociraptor mongoliensis*. *American Museum Novitates* **3282**, 1-45 (1999).
- Norell, M.A., and P.J. Makovicky. Important features of the dromaeosaurid skeleton: information from a new specimen. *American Museum Novitates* **3215**, 1-28 (1997).
- Novas, F.E. & Pol, D. New evidence on deinonychosaurian dinosaurs from the Late Cretaceous of Patagonia. *Nature* **433**, 858-861 (2005).
- Osmólska, H. An unusual theropod dinosaur from the Late Cretaceous Nemegt Formation of Mongolia. *Acta Palaeontologica Polonica* **41**, 1-38, (1996).
- Ostrom, J.H. Osteology of *Deinonychus antirrhopus*, and unusual theropod from the lower Cretaceous of Montana. *Bulletin Peabody Museum of Natural History* **30**, 1-165 (1969).
- Paul, G.S. The segnosaurian dinosaurs: relics of the Prosauropod—Ornithischian transition? *Journal of Vertebrate Paleontology* **4**, 507-515 (1984).
- Pérez-Moreno, B.P., Sanz, J.L., Sudre, J. & Sigé, B. A theropod dinosaur from the Lower Cretaceous of southern France. *Revue de Paléobiologie* **7**, 173-188 (1993).
- Peyer, K.A. Reconsideration of *Compsognathus* from the upper Tithonian of Canjuers, Southeastern France. *Journal of Vertebrate Paleontology* **26**, 879-896 (2006).
- Rauhut, O.W.M. Braincase structure of the Middle Jurassic theropod dinosaur *Piatnitzkysaurus*. *Canadian Journal of Earth Sciences* **41**, 1109-1122 (2004).
- Rauhut, O.W.M. The interrelationships and evolution of basal theropod dinosaurs. *Special Papers in Palaeontology* **69**, 1-214 (2003).
- Rauhut, O.W.M. The interrelationships and evolution of basal theropod dinosaurs. *Special Papers in Palaeontology* **69**, 1-214 (2003).
- Rauhut, O.W.M., Milner, A.C., & Moore-Fay, S. Cranial osteology and phylogenetic position of the theropod dinosaur *Proceratosaurus bradleyi* (Woodward, 1910) from the Middle Jurassic of England. *Zoological Journal of the Linnean Society* **158**, 155-195 (2010).
- Rowe, T. & Gauthier, J. Ceratosauria; pp. 151-168 in D. B. Weishampel, P. Dodson, and H. Osmólska (eds.), *The Dinosauria*. University of California Press, Berkeley (1990).
- Russell, D.A. & Dong, Z. -M. The affinities of a new theropod from the Alxa Desert, Inner Mongolia, People's Republic of China. *Canadian Journal of Earth Sciences* **30**, 2107-2127 (1993).
- Russell, D.A. Tyrannosaurs from the Late Cretaceous of Western Canada. *National Museum of Natural Science Publications in Paleontology No. 1* (1970).
- Sadleir, R.W., Barrett, P.M. & Powell, H.P. The anatomy and systematics of *Eustreptospondylus oxoniensis*, a theropod dinosaur from the Middle Jurassic of Oxfordshire, England. *Monograph of the Palaeontographical Society* **627**, 1-82 (2008).
- Sampson, S.D., Witmer, L.M., Forster, C.A., Krause, D.W., O'Connor, P.M., Dodson, P., Ravoayy, F. Predatory Dinosaur Remains from Madagascar: Implications for the Cretaceous Biogeography of Gondwana. *Science* **280**, 1048-1051 (1998).
- Sereno, P.C., Wilson, J.A., Larsson, H.C.E., Dutheil, D.B., & Sues, H.-D. Early Cretaceous Dinosaurs from the Sahara. *Science* **266**, 267-271 (1994).
- Sereno, P. C., S. McAllister and S. L. Brusatte. TaxonSearch: a relational database for documenting taxa and their phylogenetic definitions. *Phyloinformatics* **8**, 1-21 (2005).
- Sereno, P. C., D. B. Dutheil, M. Iarochene, H. C. E. Larsson, G. H. Lyon, P. M. Magwene, C. A. Sidor, D. J. Varrichio and J. A. Wilson. Predatory dinosaurs from the Sahara and Late Cretaceous faunal differentiation. *Science* **272**, 986-991 (1996).
- Sereno, P.C. A rationale for phylogenetic definitions, with application to the higher-level taxonomy of Dinosauria. *Neues Jahrbuch für Geologie und Paläontologie Abhandlungen* **210**, 41-83 (1998).
- Sereno, P.C., & Brusatte, S.L. Comparative assessment of tyrannosauroid interrelationships. *Journal of Systematic Paleontology* **7**, 455-470 (2009).
- Sereno, P.C., Tan, L., Brusatte, S.L., Keig斯坦, H.J., Zhao, X. & Cloward, K. Tyrannosaurid skeleton design first evolved at small body size. *Science* **326**, 418-422 (2009).

- Shuvalov, V.F. The Cretaceous stratigraphy and palaeobiogeography of Mongolia. In Benton, M.J., Shishkin, M.A., Unwin, D.M. and Kurochkin, E.N. eds. The age of dinosaurs in Russia and Mongolia. Cambridge Univ. Press: 256–278; Cambridge, UK. 2000.
- Smith, N.D., Makovicky, P.J., Hammer, W.R., & Currie, P. J. Osteology of *Cryolophosaurus ellioti* (Dinosauria: Theropoda) from the Early Jurassic of Antarctica and implications for early theropod evolution. *Zoological Journal of the Linnean Society* **151**, 377-421 (2007).
- Tykoski, R.S. Anatomy, ontogeny, and phylogeny of coelophysoid theropods. *Ph.D. dissertation, University of Texas, Austin*, 553p. (2005).
- Walker, A.D. Triassic reptiles from the Elgin area, *ornithosuchus* and the origin of carnosaurs. *Philosophical transactions of the Royal Society of London B* 248, 53-134 (1964).
- Welles, S.P. & Long, R.A. The tarsus of theropod dinosaurs. *Annals of the South African Museum* **64**, 91-218 (1974).
- Wellnhofer, P. A new specimen of *Archaeopteryx* from the Solnhofen limestone. *Los Angeles County Museum of Natural History, Science Series* **36**, 3-23 (1992).
- Wellnhofer, P. Das fünfte Skelettexemplar von *Archaeopteryx*. *Palaeontographica* **147**, 169-216 (in German) (1974).
- Xu, X., Clark, J.M., Forster, C.A., Norell, M.A., Erickson, G.M., Eberth, D.A., Jia, C. & Zhao, Q. A basal tyrannosauroid dinosaur from the Late Jurassic of China. *Nature* **439**, 715-718 (2006).
- Xu, X., Norell, M.A., Kuang, X., Wang, X., Zhao, Q. & Jia, C. Basal tyrannosauroids from China and evidence for protofeathers in tyrannosauroids. *Nature* **431**, 680-684 (2004).
- Zanno, L.E. A taxonomic and phylogenetic reevaluation of Therizinosauria (Dinosauria: Theropoda): implications for the evolution of Maniraptora. *Ph.D. dissertation, University of Utah, Salt Lake City*, 329p. (2008).
- Zhao X-J. & Currie, P.J. A large crested theropod from the Jurassic of Xinjiang, People's Republic of China. *Canadian Journal of Earth Sciences* **30**, 2027-2036 (1993).
- Zhao, X-J., Benson, R.B.J., Brusatte, S. L. & Currie, P.J. The postcranial skeleton of *Monolophosaurus jiangi* (Dinosauria: Theropoda) from the Middle Jurassic of Xinjiang, China, and a review of Middle Jurassic Chinese theropods. *Geological Magazine* **147**, 13-7 (2010).