**SUPPLEMENTARY MATERIAL**

**A lungfish survivor of the end-Devonian extinction and an Early Carboniferous dipnoan radiation**

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CHARACTER LIST

All characters are from Clack *et al.* (*in review*) which are derived from Qiao & Zhu (2015), Qiao & Zhu (2009), Schultze (2001), Ahlberg *et al*. (2006) and Friedman (2007) with modifications as- described below.

1. Pineal opening: 0. open; 1. closed. Schultze and Marshall (1993; char. 1), Schultze (2001; char. 1), Ahlberg *et al*., (2006; char. 55), Qiao and Zhu (2009; char. 1)

2. Pineal region marked by short eminence: 0. no; 1. yes.

3. Cosmine present on skull: 0. yes, full cover; 1. yes, but strongly reduced; 2. no. (Ordered)

4. Length of B bone: 0. short (less than 2 times its width); 1. long (equal or more than 2 times its width); 2. broad (wider than long).

5. Pit-lines on B bone: 0. absent; 1. anterior and middle pit-line present; 2. only anterior pit-line.

6. C-bone: 0. absent; 1. present.

7. D-bone: 0. many; 1. single; 2. absent.

8. Contact between E and C bones: 0. absent; 1. present.

9. Paired E bones: 0. mosaic; 1 present; 2. single E-bone; 3. Absent. The polarity of this character has been reversed from 0. absent; 1. present; 2. mosaic to reflect the occurrence of this character in the oldest (most basal) to more recent (derived) dipnoan taxa.

10. Length of E-bone(s): 0. less than twice their width; 1. more than twice their width.

11. I-bones meeting in midline: 0. yes; 1. no, separated by B bone. This character changed to just refer to I-bones rather than implying homology between the I-bones and postparietals.

12. Posterior process of I bone: 0. absent; 1. present.

13. J-bones meeting in midline: 0. yes; 1. no. This character changed to just refer to J-bones rather than implying homology between the J-bones and parietals.

14. L-bone: 0 = two present, 1 = one present, 2 = fused K+L, 3 = fused K+L+M, 4 = other bones included. Schultze and Marshall (1993; char. 25), Schultze and Chorn (1997; char. 10, 37, 38, 39, 40), Schultze (2001; char. 25), Schultze (2004; char. 18).

15. Length of L-bone: 0. similar to others in supraorbital canal series; 1. about twice as long as others in supraorbital canal series.

16. K-bone: 0 = single, 1 = space of K+X, 2 = neither single nor K+X (e.g. fused (i.e ‘space of’) K- + L-bones), 3 = K-bone absent. Schultze and Marshall (1993; char. 24), Schultze and Chorn (1997; char. 9,36), Schultze (2001; char. 24), Schultze (2004; char. 17).

17. K bone: 0. medial to X bone; 1. anterior to X bone; 2. in sequence.

18. M bone: 0. present; 1. absent.

19. N bone: 0. present; 1. absent.

20. Q bone: 0. absent; 1. present.

21. Z bone: 0. posterior to I bone; 1. lateral to I bone.

22. Maximum width of skull roof situated posterior to the level of the bone Y1: 0. yes; 1. No.

23. Sutures between median series of skull roofing bones: 0 = straight, 1 = interdigitate, 2 = open. Schultze and Marshall (1993; char. 3), Schultze (2001; char. 3), Schultze (2004; char. 1).

24. Elongated snout: 0. absent; 1. present.

25. Ossified upper lip in adult: 0. mosaic; 1. fused; 2. absent.

26. Snout/skull roof: 0. with diffuse posterior margin; 1. with sharp posterior margin. (Uncertain for *Eusthenopteron* but coded as ‘1’ given the clear demarcation between naso-parietal-frontal? and parietals).

27. Supraorbital and infraorbital canals: 0. separated; 1. connected.

28. Lateral line in bone 3: 0. absent; 1. present.

29. Cheek bones: 0. cheek bones 1­–11 present; 1. no 11; 2. no 10, 11.

30. Length of postorbital cheek: 0. substantially longer than diameter of orbit; 1. equal to or shorter than diameter of orbit.

31. Ratio length snout:cheek: 0. <1; 1. >=1. (Schultze & Marshal (1993) definition: Ratio snout/cheek: 0 = 1:1, 1 = 2 (>1.5):1, 2 = 3 (>2.5):1, 3 = >4:1. Schultze and Marshall (1993; char. 85), Schultze (2001; char. 85), Schultze (2004; char. 53).

32. Bone 6: 0. reaching ventral margin of cheek; 1. excluded from ventral margin of cheek by bone 10.

33. Bone 7: 0. approximately equilateral; 1. much longer than deep.

34. Size of bone 10 (quadratojugal): 0. large, as 5 or greater; 1. much smaller than 5, or absent.

35. Subopercular: 0. two; 1. one.

36. Buccohypophyseal opening (foramen): 0. present; 1. absent.

37. Palatal construction: 0. parasphenoid separates pterygoids; 1. pterygoids articulate with each other with suture; 2. pterygoids fused.

38. Parasphenoid: 0. fused into palate; 1. visible sutures; 2. overlapping (pterygoids).

39. Transverse curvature of palate: 0. flat; 1. arched.

40. Parasphenoid stalk: 0. no stalk; 1. simple stalk without sharp division into tapering proximal portion and parallel-sided distal portion; 2. stalk with sharp division into tapering proximal portion and parallel-sided distal portion. (Ordered)

41. Ratio of posterior length to anterior length of parasphenoid: 0. less than 1 or about 1; 1. greater than 1.

42. Furrow on ventral surface of parasphenoid stalk: 0. absent; 1. present.

43. Furrow on dorsal surface of parasphenoid stalk: 0. absent; 1. present.

44. Parasphenoid bearing denticle-lined ascending process: 0. no; 1. yes.

45. Dental material on parasphenoid: 0. present; 1. absent.

46. Parasphenoid reaching posterior margin of occiput: 0. no; 1. yes.

47. Shape of parasphenoid: 0 = anteriad elongated, 1 = plow-shaped, 2 = with lozenge, 3 = round anterior portion, 4 = angled anterior portion. Schultze and Marshall (1993; char. 49), Schultze and Chorn (1997; char. 18), Schultze (2001; char. 49), Schultze (2004; char. 34).

48. Position of parasphenoid: 0. below ethmosphenoid; 1. below otico-occipital; 2. below both.

49. Position of anterior end of parasphenoid: 0. in front of jaw articulation; 1. not in front.

50. Ratio of maximum width of parasphenoid to distance of articulation points of jaws: 0. less than 1/3; 1. between 1/3 and 2/3; 2. greater than 2/3.

51. Lateral angle of parasphenoid: 0 = no angle, 1 = angular, 2 = rounded, 3 = reflexed. Schultze and Marshall (1993; char. 48), Schultze (2001; char. 48), Schultze (2004; char. 33).

52. (Posterior) end of parasphenoid (stalk): 0. single point; 1. bifid; 2. trifid with lateral projections.

53. Margins of posterior stalk of parasphenoid: 0. converge to posterior angle; 1. subparallel.

54. “Vomer” *sensu* Miles (1977): 0. present; 1. absent.

55. “Dermopalatine 1” *sensu* Miles (1977): 0. median; 1. paired.

56. “Dermopalatine 1” *sensu* Miles (1977) / pterygoid: 0. fused to pterygoid; 1. present, not in contact; 2. isolated.

57. Series anterolateral to pterygoids: 0. present, with tusks; 1. present with denticles or dentine sheet; 2. present with tooth row. This is interpreted as meaning ‘dental’ series anterolateral to pterygoids.

58. Parasphenoid separating pterygoids along more than half of their length: 0. yes; 1. no.

59. Angle between midline and anterolateral margin of pterygoid: 0. less than 55 degrees; 1. more than 55 degrees. From Ahlberg et al (2006), character 24 and Qiao & Zhu (2009; 2015).

60. Anterior nostril: 0. located dorsal to oral margin; 1. marginal.

61. Posterior nostril: 0. located dorsal to oral margin; 1. marginal 2. palatal. (Ordered)

62. Internasal pits: 0. well developed; 1. reduced or absent.

63. Cosmine-like tissue within oral cavity: 0. no; 1. yes.

64. Premaxilla: 0. present; 1. absent.

65. Lateral lines in mandible: 0. parallel; 1. converging in one bone. *Diplocercides* only has one lateral line canal in the mandible (Forey *et al*., 2000).

66. Length of symphysis (ratio length of symphysis to length of jaw): 0. greater than 1/3; 1. between 1/5 and 1/3; 2. less than 1/5.

67. Adsymphysial plate: 0 = present, but fused, 1 = isolated, sutured bone, 2 = missing. Schultze and Marshall (1993; char. 66), Schultze (2001; char. 66), Schultze (2004; char. 45).

68. “Dentary”: 0. unpaired; 1. paired; 2. absent.

69. Dentary-prearticular relationship: 0. dentition-generating gap; 1. small midline hole only; 2. no gap.

70. Slot between dentary and prearticular: 0. broad; 1. narrow; 2. no slot.

71. Adductor fossa: 0. not overhung by prearticular; 1. overhung by prearticular.

72. Length of adductor fossa: 0. more than 20% of jaw length; 1. 5–20% of jaw length; 2. 0–5% of jaw length (ordered). For *Diplocercides*, see Friedman (2007, fig. 5c).

73. Morphology of adductor fossa: 0. open; 1. reduced to vestigial slit.

74. Coronoids: 0. present; 1. absent.

75. Lip fold: 0. absent; 1. present.

76. Meckelian bone: 0. wholly ossified; 1. only articular ossified, or not ossified at all.

77. Retroarticular process: 0. small and poorly developed; 1. robust, squarish.

78. Skin contact surface on infradentary bones: 0. reaching up to lip of adductor fossa; 1. widely separated from lip of adductor fossa. 1

79. Curvature of ventral mandibular margin: 0. strongly convex; 1. essentially flat.

80. Orientation of glenoid: 0. mostly dorsally; 1. posterodorsally.

81. Shape of glenoid fossa: 0. double structure; 1. single groove.

82. Angular and surangular: 0. separate; 1. fused into a single long bone.

83. Splenial and postsplenial: 0. separate; 1. fused. For *Diplocercides*, coded as ‘?’ due to uncertainty of homology and from fusion of infradentaries (see Friedman, 2007).

84. Teeth on upper lip: 0. shedding teeth; 1. statodont tooth row; 2. teeth absent.

85. Teeth on dentary: 0. shedding teeth present; 1. statodont tooth rows present; 2. teeth absent.

86. Number of tooth ridges *in adult specimens*: 0. <10; 1. >10. Kemp (1977) clearly demonstrated that the number of tooth ridges in growing *Neoceratodus forsteri* increases from larval stage to adult and that the number of tooth ridges differs between the lower and upper jaws. When coding for this character it is important to account for the complete growth series of the taxon and if this is not possible, justification must be given for coding for this character.

87. Tooth plates: 0. present; 1. absent. Not applicable in the context of outgroup otherwise absence would be considered a reversal.

88. Morphology of teeth on pterygoid and prearticular: 0. round/conical; 1., forming distinct proximodistal cutting ridge.

89. Addition of large dentine elements at regular intervals to lateral margin of pterygoid/ prearticular: 0. yes; 1. no.

90. Nature of large dentine elements: 0. teeth; 1. petrodentine cores; 2. thick irregular dentine; 3. ridges narrow regular dentine ridges.

91. Addition of marginal blisters to pterygoid/prearticular: 0. no; 1. yes.

92. Shape of marginal blisters: 0. bead-shaped; 1. elongated strips.

93. Addition of inter-row dentine along edge of pterygoid/ prearticular: 0. no; 1. yes.

94. Nature of inter-row dentine: 0. always fuses or wears down into sheet; 1. separate denticles persist between some tooth rows.

95. Pulp cavity: 0. tooth plates without pulp cavity; 1. with pulp cavity.

96. Diffuse dentine deposition on surface of palate/lower jaw: 0. yes, diffusely across whole palate; 1. no; 2. redeposition of denticles only within “footprint” (outer circumference) of resorbed tooth plate.

97. Relative areas of denticle field/thin dentine sheet on palate: 0. all or nearly all denticles; 1. both dentine sheet and denticles; 2. mostly dentine sheet; 3. denticles outside toothplate; 4 dentine sheet on resorption areas within toothplate.

98. Relative areas of denticle field and dentine sheet on lower jaw: 0. all or nearly all denticles; 1. both denticles and dentine sheet; 2. mostly dentine sheet.

99. Resorption of dentition on pterygoid/prearticular plate origin: 0. little or no resorption, origin left unmodified; 1. extensive resorption, removing mesial parts of plate; 2. resorption and deposition of dentine sheet within toothplate only, not crossing edges.

100. Distinct vertically growing “heel” on prearticular: 0. no; 1. yes.

101. Petrodentine: 0. absent; 1. present.

102. Sharp “additive” mesial and posterior edges on tooth plates: 0. absent; 1. present.

103. Behaviour of “additive edges” (if present): 0. quiescent; 1. active.

104.Braincase/skull table relationship: 0. broad contact; 1. supported by cristae.

105. Angle between quadrate and plane of parasphenoid: 0. 90–95 degrees; 1. 80–65 degrees; 2. 55–35 degrees.

106. Autostyly: 0. absent; 1. present.

107. Lateral commissure: 0. separate from palatoquadrate; 1. partly fused but distinguishable; 2. wholly fused to palatoquadrate. (ordered). The presence of a structure termed the lateral commissure in Dipnoi was rejected by Miles (1977).

108. Palatoquadrate: 0. fused into palate; 1. free.

109. Dorsolateral process on palatoquadrate: 0. absent; 1. present.

110. Metotic (lateral otic) fissure: 0. present; 1. absent.

111. Intracranial joint/ventral cranial fissure: 0. mobile joint; 1. ventral cranial fissure; 2. neither fissure nor joint.

112. Occiput inset from posterior margin of neurocranium: 0. no; 1. yes.

113. Notochordal canal occluded by ossified cranial centrum: 0. no; 1. yes.

114. Neural cavity and notochordal canal separated by an ossified shelf in the occipital region, posterior to the foramen for N. X: 0. yes; 1. no.

115. Ossification complete along ventral midline of notochordal canal posteriorly: 0. yes; 1. no.

116. Occipital region bears transverse processes flanking foramen magnum: 0. no; 1. yes.

117. Dorsal aorta: 0. divides at or anterior to occiput; 1. divides posterior to occiput. (Friedman 2007).

118. Lateral dorsal aortae: 0. run along ventral surface of neurocranium; 1. run in grooves on parasphenoid.

119. Occipital artery extramural: 0. no; 1. yes.

120. Neurocranium extends far posterior to hind margin of postparietals: 0. no; 1. yes.

121. Dorsolateral crista fenestrated: 0. no; 1. yes.

122. Median crista discontinuous: 0. no; 1. yes.

123. Little or no overlap between intersections of median and dorsolateral cristae with the dermal skull roof (median crista abbreviated): 0. no; 1. yes.

124. Lateral cristae fenestrated: 0. no; 1. yes.

125. Development of a pronounced ridge anterior to and continuous with the dorsolateral cristae: 0. no; 1. yes.

126. Articulation of first epibranchial posterior to the level of the foramen for N. IX: 0. no; 1. yes.

127. Notochord extending to or beyond level of N. V: 0. yes; 1. no.

128. Development of a deep “spiracular recess” *sensu* Thomson and Campbell (1971): 0. yes; 1. no.

129. Separate foramina for the internal carotid artery and efferent pseudobranchial artery: 0. no; 1. yes.

130. Jugular vein: 0. little or no groove; 1. travels through deep groove along length of otic region.

131. Foramina for the jugular vein and the ramus hyomandibularis N. VII on the posterior surface of the transverse wall of the otic region: 0. confluent; 1. separate.

132. Foramina for the jugular vein and the orbital artery on the posterior surface of the transverse wall of the otic region: 0. confluent; 1. separate.

133. Foramina for the ramus hyomandibularis N. VII and the orbital artery on the posterior surface of the transverse wall of the otic region: 0. confluent1; 1. separate.

134. Hyomandibular facet traverses fissure in transverse otic wall (hyomandibular facet extends on to palatoquadrate): 0. no; 1. yes.

135. Separate ossified canals for pineal and parapineal organs: 0. yes; 1. no.

136. Foramen for N. II above the level of foramen sphenoticum minus: 0. no; 1. yes.

137. Foramen for N. III above level of foramen sphenoticum minus: 0. no; 1. yes.

138. Ventral face of nasal capsule: 0. complete; 1. perforated by fenestration that opens posteroventrolaterally (fenestra ventralis); 2. solum nasi completely unossified. (ordered).

139. Nasal capsule set well posterior to snout margin or preoral eminence: 0. no; 1. yes.

140. Enlarged, knob-shaped protrusion on the posteroventral surface of the quadrate (hyosuspensory eminence of Miles, 1977): 0. absent; 1. present.

141. Overlap relationship between entopterygoids and parasphenoid: 0. parasphenoid overlaps entopterygoids dorsally; 1. entopterygoids overlap parasphenoid dorsally.

142. Cleithrum and clavicle: 0. with cosmine; 1. without cosmine.

143. Median fin morphologies: 0. all separate and short-based; 1. posterior dorsal fin long-based; 2. both dorsal fins long-based uninterrupted fin fringe.

144. Posterior dorsal fin support: 0. all radials carried by basal plate; 1. anterior radials on basal plate, posterior radials free; 2. no basal plate.

145. Anal fin support: 0. trapezoidal with no distinct shaft; 1. cylindrical proximal shaft and triangular distal plate.

146. Median fin radials: 0. cylindrical; 1. hourglass-shaped.

147. Vertebral column: 0. unconstricted notochord; 1. disc centra.

148. Neural arches and spines: 0. separate; 1. fused.

149. Scales: 0. rhombic; 1. round.

150. Cosmine on scales: 0. present; 1. absent.

151. Adlateral cristae (posterodorsal extensions of the lateral cristae that connect the otic region of the neurocranium to the visceral surface of the dermal skull roof) present: 0. yes; 1. no. (Character 15 in Friedman 2007)

152. Median callus on palate: 0. absent; 1. present. (Character 18 in Ahlberg *et al*. 2006)

153. B-bone: 0. absent; 1. present. (Character 8 in Schultze, 2001).

154. Foramen for the internal carotid anterior to that for the efferent pseudobranchial artery: 0. no; 1. yes. (Character 29 in Friedman 2007)

155. Ossification of neurocranium: 0 - completely ossified; 1 – poorly-ossified/cartilagenous.

156. C-bone(s): 0 – paired; 1 – single. Character state ‘1’ changed from ‘*single/absent*’ to differentiate between character 6: C-bone: 0. absent; 1. absent. (Character 11 of Lloyd *et al*. 2012).

157. Angle between first and last tooth ridge: 0. 50–100o; 1. less than 50o or greater than 100o.

158. Lower jaw: 0 = short mandible rami, 1 = elongated rami with short symphysis, 2 = elongated symphysis. Schultze and Marshall (1993; char. 61), Schultze (2001; char. 61). (Character 62 of Lloyd *et al*. 2012).

159. Kinesis between nasal region and braincase behind it: 0 = absent, 1 = present. Schultze and Marshall (1993; char. 4), Schultze (2001; char. 4), Schultze (2004; char. 2). (Character 4 of Lloyd *et al*. 2012).

160. A-bone: 0 = independent A-bone, 1 = not present as independent bone, 2 = incorporated into skull roof. Schultze and Marshall (1993; char. 5), Schultze (2001; char. 5), Schultze (2004; char. 3). (Character 5 of Lloyd *et al*. 2012).

161. Supraoccipital commissure: 0 = through Z-G-I-A-I-G-Z, 1 = through I-A-I, 2 = through I-B-I, 3 = through Z-B-Z, 4 = above bones. Schultze and 1Marshall (1993; char. 6), Schultze and Chorn (1997; char. 3), Schultze (2001; char. 6), Schultze (2004; char. 4). (Character 6 of Lloyd *et al*. 2012).

162. Adductor muscles: 0 = below skull roof, 1 = above skull roof. Schultze and Marshall (1993; char. 10), Schultze (2001; char. 10), Schultze (2004; char. 8). (Character 10 of Lloyd *et al*. 2012).

163. F-bone: 0 = not existing, 1 = present, 2 = place of F+E. Schultze and Marshall (1993; char. 15), Schultze (2001; char. 15), Schultze (2004; char. 12). (Character 15 of Lloyd *et al*. 2012).

164. Space taken by K+L or more bones (i.e. K- and L-bones missing if ‘0’): 0 = not, 1 = yes, 2 = in addition M, 3 = in addition M+N, 4 = in addition J+M, 5 = in addition X. Schultze and Marshall (1993; char. 16), Schultze (2001; char. 16), Schultze (2004; char. 13). (Character 16 of Lloyd *et al*. 2012).

165. G-bone: 0 = present, 1 = absent. Schultze and Marshall (1993; char. 18), Schultze (2001; char. 18). This character is logically possible for taxa outside the in group though in considering so the polarity is confused. Schultze and Marshall (1993) do not test the polarity of the character with the context of an outgroup and so we code it as ‘?’ for non-dipnoan taxa in this study. (Character 18 of Lloyd *et al*. 2012).

166. I-bone: 0 = present, 1 = space of I+J, 2 = space of I+J+L+M, 3 = space of I+Z, 4 = space of A+B+I+J, 5 = space of I+Y+Z. Schultze and Marshall (1993; char. 19), Schultze and Chorn (1997; char. 8), Schultze (2001; char. 19), Schultze (2004; char. 14). (Character 19 of Lloyd *et al*. 2012).

167. J-bone: 0 = present, 1 = space of J+K+L+M, 2 = space of I+J, 3 = space of J+L+M, 4 = space of A+B+I+J, 5 = space of J+C. Schultze and Marshall (1993; char. 22), Schultze and Chorn (1997; char. 2), Schultze (2001; char. 22), Schultze (2004; char. 16). (Character 22 of Lloyd *et al*. 2012).

168. Z-bone: 0 = behind skull roof, 1 = integrated into skull roof, 2 = space of Y+Z, 3 = lacking as isolated bone. Schultze and Marshall (1993; char. 29), Schultze and Chorn (1997; char. 12,34), Schultze (2001; char. 29), Schultze (2004; char. 22). (Character 29 of Lloyd *et al*. 2012).

169. Lateral line entering skull table through: 0 = bone Z, 1 = bone I, 2 = above bones. Schultze and Marshall (1993; char. 30), Schultze (2001; char. 30), Schultze (2004; char. 23). (Character 30 of Lloyd *et al*. 2012).

170. Y-bone: 0 = Y1- and Y2-bones present, 1 = only one Y-bone, 2 = space of X+Y, 3 = space of Y+Z. Schultze and Marshall (1993; char. 31), Schultze and Chorn (1997; char. 13,35), Schultze (2001; char. 31), Schultze (2004; char. 24). (Character 31 of Lloyd *et al*. 2012).

171. X-bone: 0 = isolated, 1 = space of X+K, 2 = space of X+Y, 3 = missing. Schultze and Marshall (1993; char. 32), Schultze and Chorn (1997; char. 14), Schultze (2001; char. 32), Schultze (2004; char. 25). (Character 32 of Lloyd *et al*. 2012).

172. T-bone: 0 = present, 1 = absent. Schultze and Marshall (1993; char. 34), Schultze (2001; char. 34). (Character 34 of Lloyd *et al*. 2012).

173. Bone 10: 0 = present, 1 = absent. Schultze and Marshall (1993; char. 36), Schultze (2001; char. 36), Schultze (2004; char. 28). (Character 36 of Lloyd *et al*. 2012).

174. Bone 11: 0 = present, 1 = absent. Schultze and Marshall (1993; char. 36), Schultze (2001; char. 36), Schultze (2004; char. 28). (Character 37 of Lloyd *et al*. 2012).

175. Space taken by L+M: 0 = not present, 1 = present, 2 = space of J+L+M, 3 = space of J+K+L+M (+ possible N), 4 = space of I+J+L+M, 5 = space of K+L+M. Schultze and Marshall (1993; char. 37), Schultze (2001; char. 37), Schultze (2004; char. 29). (Character 38 of Lloyd *et al*. 2012).

176. Maxilla and premaxilla: 0 = absent, 1 = present. Schultze and Marshall (1993; char. 38), Schultze (2001; char. 38). (Character 39 of Lloyd *et al*. 2012).

177. Ascending process on pterygoid: 0 = absent, 1 = short, 2 = long. Schultze and Marshall (1993; char. 56), Schultze and Chorn (1997; char. 20), Schultze (2001; char. 56), Schultze (2004; char. 40). State ‘2’ only found in post-Palaeozoic Dipnoi. (Character 57 of Lloyd *et al*. 2012).

178. Number of infradentaries: 0 = four, 1 = two, 2 = one, 3 = three. Schultze and Marshall (1993; char. 64), Schultze and Chorn (1997; char. 21), Schultze (2001; char. 64), Schultze (2004; char. 43). (Character 65 of Lloyd *et al*. 2012).

179. Ossified Meckelian bone: 0 = present, 1 = lacking. Schultze and Marshall (1993; char. 70), Schultze (2001; char. 70), Schultze (2004; char. 48). (Character 71 of Lloyd *et al*. 2012).

180. Dentition: 0 = dentine plates, 1 = tooth plates, 2 = toothed (shedding denticles). Schultze and Marshall (1993; char. 72), Schultze (2001; char. 72), Schultze (2004; char. 49). (Character 73 of Lloyd *et al*. 2012).

181. Form of marginal tooth ridge: 0 = absent, 1 = continuous, 2 = incomplete. Schultze and Marshall (1993; char. 73), Schultze (2001; char. 73). (Character 74 of Lloyd *et al*. 2012).

182. Tuberosities on palate: 0 = present and irregular, 1 = arranged radially, 2 = arranged in rows, 3 = absent. Schultze and Marshall (1993; char. 74), Schultze (2001; char. 74). (Character 75 of Lloyd *et al*. 2012).

183. Character 76 of Lloyd *et al*. (2012). 0 = no denticles, 1 = episodically shed denticles. Schultze and Marshall (1993; char. 75), Schultze (2001; char. 75), Schultze (2004; char. 50).

184. Tooth plates ridges: 0 = no tooth plates, 1 = without radial pattern, 2 = radial pattern with cusps, 3 = radial pattern without cusps, 4 = parallel ridges. Schultze and Marshall (1993; char. 76), Schultze and Chorn (1997; char. 23,32), Schultze (2001; char. 76). (Character 77 of Lloyd *et al*. 2012).

185. Ceratohyal: 0 = short and stout, 1 = long. Schultze and Marshall (1993; char. 79), Schultze and Chorn (1997; char. 26), Schultze (2001; char. 79), Schultze (2004; char. 51). (Character 80 of Lloyd *et al*. 2012).

186. Basihyal: 0 = short without denticles, 1 = long and denticulated, 2 = short and denticulated. Schultze and Marshall (1993; char. 80), Schultze (2001; char. 80), Schultze (2004; char. 52). (Character 81 of Lloyd *et al*. 2012).

**Notes on characters**

Character 5. Pit-lines on B bone: 0. absent; 1. anterior and middle pit-line present; 2. only anterior pit-line; 3. only posterior pit line. *Gnathorhiza* only possesses a posterior pit line which has not traditionally been coded. Here we add this as a fourth state unordered.

**Characters amended in the matrix of Kemp *et al.* (2017).**

Recoding of *Persephonichthys* is required for Character 21 when considering all lateral line canals. In the supraorbital series and the mandibular bones the lateral line canals are enclosed in bone in *Persephonichthys*.

*Uronemus*

Character 3 from 1 to 0. *Uronemus* possesses elaborate ornamentation on the surface of the calvarial bones as clearly seen in specimen NMS G 1976.19.3.

*Dipterus*

Character 3 from 0 to 1. There is no reference to surface ornamention on the calvarial bones of *Dipterus* in White (1965) for instance nor in the many specimens viewed by the authors.

*Sagenodus*

Character 3 from 0 to 1. There is no reference to surface ornamention on the calvarial bones of *Sagenodus* in the many specimens of the NMS and BMNH viewed by the authors.

*Chirodipterus*

Character 3 from 0 to 1. There is no reference to surface ornamention on the calvarial bones of *Chirodipterus* in Miles (1977) for instance nor in the specimens viewed by the authors in the BMNH.

Character 7. *Chirodipterus* is polymorphic for this character. An F-bone is present in *Chirodipterus* NHMUK PV P52563 (see Miles 1977, fig. 118 c).

*Ctenodus*

Character 2 from 0 to 1. The snout of *Ctenodus* is not mineralised.

Character 3 from 0 to 1. There is no reference to surface ornamention beyond that of the typical radiating ornamentation on the calvarial bones of *Ctenodus.* The ornamentation described in Sharp & Clack (2013) refers to the typical dipnoan radiating pattern and lateral line canal pores.

*Conchopoma*

Character 9 from 1 to 0. *Conchopoma* possesses a full complement of periorbital bones as figured by Marshall (1988, figs 2, 3).

*Persephonichthys*

Character 14 from 0 to 1. Pardo *et al.* (2014, p. 8) clearly state the periorbital bones are incomplete.

Character 65 from 1 to ?. There is no evidence of the structure of the fins in *Persephonichthys.*

Character 68 from 1 to ?

Character 72 from 1 to ?

Character 71 from 1 to ?

Character 70 from 1 to ?

**Changes made to matrix of Clack *et al*. (in press).**

*Ctenodus*

Character 2 from ‘?’ to ‘0’. There is no record of a pineal eminence in *Ctenodus*. See review of the genus by Sharp & Clack (2013).

Character 14 from ‘?’ to ‘2’. *Ctenodus* possesses a fused K+L bone. See review of the genus by Sharp & Clack (2013).

Character 16 from ‘0’ to ‘2’. *Ctenodus* possesses a fused K+L bone and so is coded as ‘2’. See review of the genus by Sharp & Clack (2013).

Character 19 from ‘?’ to ‘0’. Sharp & Clack (2013) note the presence of an N-bone in *Ctenodus*.

Character 20 from ‘0’ to ‘1’. A fused Q+N-bone is noted in *Ctenodus* by Westoll (1949).

Character 58 from ‘0’ to ‘1’. Figure 15 in Sharp & Clack (2013) appears to show that the parasphenoid separates the pterygoids for more than half their length but in this specimen the pterygoids are incomplete. Figure 15 shows a more complete specimen where the parasphenoid does note separate the pterygoids for more than half way.

*Chirodipterus onawayensis*

Character 74 from ‘0’ to ‘1’. *Chirodipterus onawayensis* does not possess coronoid bones. See Schultze (1982).

Characters 93–103 are coded from Ahlberg *et al.* (2006) and have not been recoded here.

*Conchopoma*

Character 2 from ‘?’ to ‘0’. The pineal eminence is a structure expressed as a slight protrusion on the dermal surface of the skull roof as exemplified by *Diabolepis*, not of the endocast, and as such this character can be coded as ‘0’ for *Conchopoma.*

Character 5 from ‘?’ to ‘0’. Heidtke (1986) and Marshall (1988) demonstrates that neither pit lines nor canals pass through the B-bone of *Conchopoma* and as such it can be coded as ‘0’.

Character 6 from ‘?’ to ‘1’. *Conchopoma* clearly has a single C-bone as figured by Heidtke (1986) and Marshall (1988).

Character 9 from ‘1’ to ‘1, 2’. Whereas Marshall (1988) describes *Conchopoma edesi* as possessing paired E-bones (state ‘1’), Heidtke (1986) demonstrates *Conchopoma gadiforme* as possessing a single bone described as a combined Q-, F-, E-bone. The implication is that the E-bone is present and fused with the Q- and F-bones rather than lost completely and whereas this may be questioned, here we take a pragmatic stance and adopt Heidtke’s (1986) interpretation for *Conchopoma gadiforme*.

Character 13 from ‘?’ to ‘1’. Both Heidtke (1986) and Marshall (1988) interpret and figure the J-bone in *Conchopoma* as being fused with the K- and L-bones and as such it can be regarded as being present and does not meet along the midline.

Character 19. *Conchopoma edesi* does not possess a N-bone whereas *Conchopoma* *gadiforme* does.

Character 28 from 1 to 0. Marshall (1988) shows that a lateral line is absent in bone 3 in *Conchopoma.*

Character 30 from ‘1’ to ‘2’. *Conchopoma* may not possess a complete circumorbital series. For this character, the only unequivocal coding is for the lack of bones 10 and 11 as these are absent. State ‘0’ may be inapplicable because bones 1 and 2 have not been confidently identified as being present (Marshall 1988).

Character 31 from ‘2’ to ‘?’. The snout of *Conchopoma* is unossified and so it is not possible to determine this character.

Character 32 from ‘1’ to ‘0’. Bone 6 does reach the ventral margin of the cheek in *Conchopoma*. See Marshall (1988).

Character 33 from ‘0’ to ‘1’. Bone 7 is longer than it is deep in *Gnathorhiza*. See Marshall (1988, fig. 7).

Character 34 from ‘1’ to ‘-’. *Conchopoma* does not possess bone 10 and so this character is coded as being inapplicable.

Character 35 from ‘1’ to ‘?’. The suboperculae are not known in *Conchopoma* and so this character is coded as unknown.

Character 39 from ‘?’ to ‘1’. The lateral margins of the parasphenoid of *Conchopoma edesi* curve ventrally forming an arch shape in transverse section. See Marshall (1988, fig. 8).

Character 40 from ‘?’ to ‘2’. *Conchopoma* possesses a posterior parasphenoid stalk. See Heidtke (1986) and Marshall (1988).

Character 45 from ‘1’ to ‘0’. Dental material is present on the parasphenoid of *Conchopoma*. See Heidtke (1986) and Marshall (1988).

Character 48 from ‘1’ to ‘?’. The otico-occipital is either poorly ossified or not ossified in *Conchopoma* and is not preserved. It is therefore not possible to determine where the parasphenoid lies in relation to the otico-occipital and so this character must be coded as ‘?’.

Character 50 from ‘0’ to ‘?’. To the best of the authors’ knowledge there are no specimens of *Conchopoma* that are preserved in such a way as to be able to determine the state of this character. It is therefore coded as ‘?’.

Character 51 from ‘3’ to ‘2’. The lateral angle of the parasphenoid of *Conchopoma* is rounded rather than reflexed. See Heidtke (1986) and Marshall (1988). A reflexed lateral angle of the parasphenoid is seen in *Neoceratodus.*

Character 52 from ‘?’ to ‘0, 1’. The posterior end of the parasphenoid stalk in *Conchopoma* may terminate in a single point as seen in *Conchopoma gadiforme (*Heidtke , 1986, fig. 3 D) or a single point as in *Conchopoma edesi* (Marshall, 1988, fig. 8).

Character 53 from ‘?’ to ‘1’. The margins of the posterior stalk of the parasphenoid of *Conchopoma* are parallel. See Heidtke (1986) and Marshall (1988).

Character 57 from ‘?’ to ‘1’. *Conchopoma* possesses denticales on the anterolateral margin of the pterygoid. See Marshall (1988).

Character 58 from ‘?’ to ‘0’. The parasphenoid of *Conchopoma gadiforme* separates the pterygoids completely. See Heidtke (1986).

Character 67 from ‘1’ to ‘2’. There is no evidence for an adysmphyseal plate in *Conchopoma*. The structures labelled as ‘da’ in Schultze (1975) and Heidtke (1986, fig. 3) are dentaries whereas those labelled as ‘ida’ are considered to be splenials (*cf.* Schultze, 2001).

Character 69 from ‘?’ to ‘1’. The dentary forms a narrow gap with the prearticular in *Conchopoma*. See Heidtke (1986, fig. 3).

Character 70 from ‘?’ to ‘1’. The dentary forms a narrow gap with the prearticular in *Conchopoma*. See Heidtke (1986, fig. 3).

Character 74 from ‘0’ to ‘1’. *Conchopoma* does not possess coronoid bones. See Heidtke (1986) and Marshall (1988).

Character 84 from ‘1’ to ‘?’. The ‘upper lip’ of *Conchopoma* is either poorly cartilagenous or unossified and does not preserve so this character is coded as ‘?’.

Character 85 from ‘?’ to ‘0’. Heidtke (1986) and Marshall (1988) both demonstrate that *Conchopoma* possesses denticles on the dentary and Marshall (1988) provides evidence that the denticles in *Conchopoma* are shed.

Character 86 from ‘?’ to ‘-’. *Conchopoma* does not possess tooth plates and so must be coded as inapplicable for this character.

Character 88 from ‘?’ to ‘-’. *Conchopoma* does not possess tooth plates and the denticles present are neither round nor conical and so this character must be coded as inapplicable.

Character 90 from ‘?’ to ‘-’. *Conchopoma* does not possess large dentine elements that can unequivocally be described as ‘teeth’ - it possesses denticles - and so this character must be coded as inapplicable.

Character 92 from ‘?’ to ‘-’. *Conchopoma* does not possess marginal nlister to the pterygoid/prearticular and so this character must be coded as inapplicable.

Character 104 from ‘0’ to ‘?’. The neurocranium of *Conchopoma* is not preserved so the coding state for this character is unknown.

Character 108 from ‘0’ to ‘?’. The palatoquadrate in *Conchopoma* was cartilagenous or poorly ossified and is not preserved so the coding state for this character is unknown.

Character 141 from ‘?’ to ‘1’. Heidtke (1986) interpret the entopterygoids of *Conchopoma* to overlap the parasphenoid dorsally. We adopt this interpretation for our coding.

Character 144 from ‘?’ to ‘2’. The posterior dorsal fin radials of *Conchopoma* are not supported by basal plates on the neural spines. See Schultze (1975).

Character 145 from ‘?’ to ‘-’. There is no distinct anal fin support in *Conchopoma*. The ventral median fin is a continuous fringe supported by haemal arches and radials. See Schultze (1975).

Character 146 from ‘?’ to ‘1’. The median fin radials in *Conchopoma* are hourglass-shaped. See Schultze (1975).

Character 147 from ‘?’ to ‘0’. The notochord in *Conchopoma* is unrestricted. See Schultze (1975) and Heidtke (1986).

Character 148 from ‘?’ to ‘0’. The neural arches and neural spines are separate in *Conchopoma*. See Schultze (1975) and Heidtke (1986).

Character 157 from ‘?’ to ‘-’. *Conchopoma* does not possess tooth plates and so this character is coded as inapplicable.

Character 159 from ‘0’ to ‘?’. The snout and nasal region and the braincase are not preserved in *Conchopoma* and so this character must be coded as ‘?’.

*Gnathorhiza*

Character 2 from ‘?’ to ‘0’. The pineal eminence is a structure expressed as a slight protrusion on the dermal surface of the skull roof as exemplified by *Diabolepis*, not of the endocast, and as such this character can be coded as ‘0’ for *Gnathorhiza.*

Character 5 from ‘?’ to ‘3’. *Gnathorhiza* only possesses a posterior pit line which has not traditionally been coded. Here we add this as a fourth state unordered.

Character 6 from ‘?’ to ‘1’. *Gnathorhiza* clearly has paired C-bones as figured by Carlson (1968) and Berman (1976).

Character 13 from ‘?’ to ‘1’. The J-bones of *Gnathorhiza* clearly do not meet in the middle as demonstrated by Carlson (1968) and Berman (1976).

Character 17 from ‘1’ to ‘-’. The X-bone is not present in *Gnathorhiza* and so this character is recoded as being inapplicable.

Character 18 from ‘1’ to ‘0’. Whereas a separate M-bone is not present in the lateral dermal skull series in *Gnathorhiza*, it is interpreted by Carlson (1968) and Berman (1976) to be present and fused with the K- and L-bones and so can be regarded as being present.

Character 22 from ‘?’ to ‘1’. Berman (1976; fig. 1 D) demonstrates that the maximum width of the skull is at the level with, if slightly anterior to, bone Y1.

Character 28 from ‘1’ to ‘-’. Berman (1976) shows that bone 3 is not present in *Gnathorhiza.* This character is therefore coded as being inapplicable.

Character 29 from ‘1’ to ‘2’. *Gnathorhiza* does not possess a complete circumorbital series. For this character, the only logical coding is for the lack of bones 10 and 11 as these are absent. State ‘0’ is inapplicable because bones 1-3 are also absent (Berman 1976).

Character 30 from ‘?’ to ‘1’. Berman (1976) illuatrates completely the cheek and orbit region in *Gnathorhiza* which shows that the postorbital cheek is approximately the same length as the orbit and can thus be coded as ‘1’.

Character 31 from ‘1’ to ‘?’. The snout of *Gnathorhiza* is unossified and so it is not possible to determine this character.

Character 32 from ‘?’ to ‘0’. Bone 6 does reach the ventral margin of the cheek in *Gnathorhiza*. See Berman (1976).

Character 33 from ‘?’ to ‘1’. Bone 7 is longer than it is deep in *Gnathorhiza*. See Berman (1976, fig. 1).

Character 34 from ‘?’ to ‘-’. *Gnathorhiza* does not possess bone 10 and so this character is coded as being inapplicable.

Character 37 from ‘0’ to ‘1’. The pterygoids of *Gnathorhiza* are separated by the parasphenoid posteriorly but are interpreted to articulate with each other along the antero-lateral margin. See Berman (1976).

Character 40 from ‘?’ to ‘2’. *Gnathorhiza* possesses a posterior parasphenoid stalk. See Carlson (1968) and Berman (1976).

Character 41 from ‘1’ to ‘0’. The parasphenoid of *Gnathorhiza* figured by Berman (1976) shows an unclear distinction between the anterior corpus and the posterior stalk. However, if the stalk is considered to begin either at the thinnest point of the parasphenoid or more anteriorly, the ratio of the posterior portion to the anterior portion is still less than 1 and so this character can be coded as ‘0’.

Character 45 from ‘0’ to ‘1’. Dental material is not present on the parasphenoid of *Gnathorhiza*. See Berman (1976).

Character 48 from ‘1’ to ‘?’. The otico-occipital is either poorly ossified or not ossified in *Gnathorhiza* and is not preserved. It is therefore not possible to determine where the parasphenoid lies in relation to the otico-occipital and so this character must be coded as ‘?’.

Character 50 from ‘0’ to ‘?’. To the best of the authors’ knowledge there are no specimens of *Gnathorhiza* that are preserved in such a way as to be able to determine the state of this character. It is therefore coded as ‘?’.

Character 52 from ‘?’ to ‘3’. The posterior end of the parasphenoid stalk in *Gnathorhiza* is trifid with lateral projections. See Berman (1976, fig. 4 B, J).

Character 53 from ‘?’ to ‘1’. At the narrowest point, the margins of the stalk of the parasphenoid are subparallel (see Berman 1976). Towards the posterior the margins actually diverge into the lateral projections.

Character 57 from ‘?’ to ‘2’. *Gnathorhiza* possesses tooth plates anterolateral to the pterygoids. See Berman (1976, fig. 4).

Character 59 from ‘?’ to ‘0’. From Carlson (1968) the angle between midline and anterolateral margin of the pterygoid can be measured as 43o and thus coded as ‘0’.

Character 69 from ‘?’ to ‘-’. The absence of dentary bones in *Gnathorhiza* means that this character must be coded as ‘-’.

Character 70 from ‘?’ to ‘-’. The absence of dentary bones in *Gnathorhiza* means that this character must be coded as ‘-’.

Character 72 from ‘?’ to ‘1’. From the description and figures in Berman (1976, fig. 5) the adductor fossa can be measured as being between 5–20% the total jaw length in *Gnathorhiza*.

Charater 74 from ‘?’ to ‘1’. No coronoids are present in *Gnathiorhiza.*

Character 79 from ‘?’ to ‘1’. Specimens figured in Berman (1976, fig. 5) demonstrate that the curvature of the ventral margin is flat in *Gnathorhiza.*

Character 80 from ‘?’ to ‘1’. The glenoid figured in Berman (1976, fig. 7) shows that the glenoid in *Gnathorhiza* is oriented posterodorsally.

Character 82 from ‘?’ to ‘1’. Specimens figured in Berman (1976, fig. 5) demonstrate that the angular and surangular are fused in *Gnathorhiza.*

Character 83 from ‘?’ to ‘1’. The description and specimens figured in Berman (1976, fig. 5) demonstrate that the splenial and postsplenial are fused in *Gnathorhiza*.

Character 84 from ‘2’ to ‘?’. The ‘upper lip’ of *Gnathorhiza* is either poorly cartilagenous or unossified and does not preserve so this character is coded as ‘?’.

Character 85 from ‘?’ to ‘-’. The absence of dentary bones in *Gnathorhiza* means that this character must be coded as ‘-’.

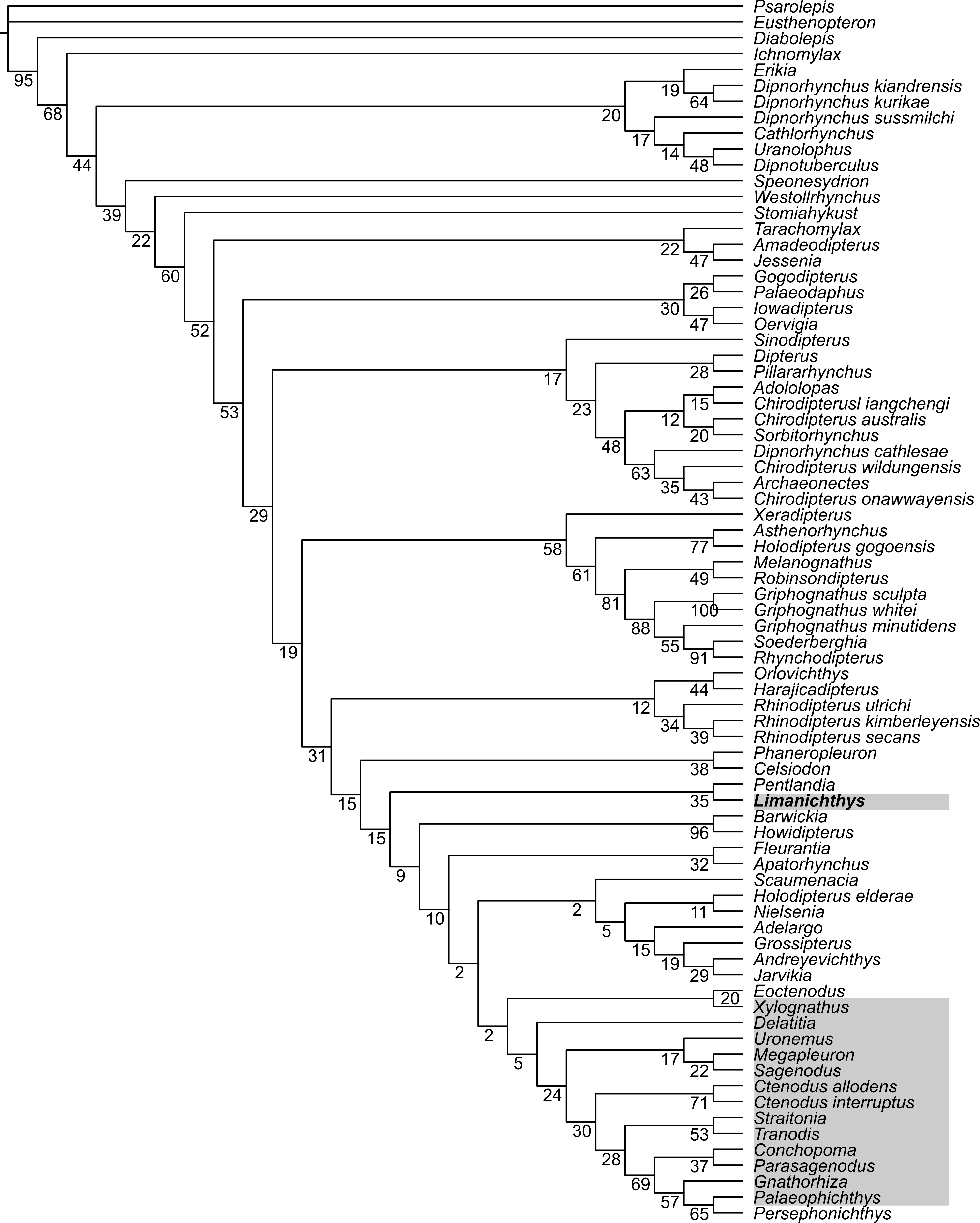
Character 92 from ‘?’ to ‘-’. *Gnathorhiza* does not possess marginal nlister to the pterygoid/prearticular and so this character must be coded as inapplicable.

Character 108 from ‘0’ to ‘?’. The palatoquadrate in *Gnathorhiza* was cartilagenous or poorly ossified and is not preserved so the coding state for this character is unknown.

Character 141 from ‘?’ to ‘1’. Carlson (1968) and Berman (1976) interpret the entopterygoids of *Gnathorhiza* to overlap the parasphenoid dorsally. We adopt this interpretation for our coding.

Character 159 from ‘0’ to ‘?’. The snout and nasal region and the braincase are not preserved in *Gnathorhiza* and so this character must be coded as ‘?’.

S**upplementary figure 1**. 50% majority rule tree for Bayesian analysis showing nodes with posterior probability <50%.



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