

The taxonomic utility of forefin morphology in Lower Jurassic ichthyosaurs: *Protoichthyosaurus*  
and *Ichthyosaurus*

DEAN R. LOMAX\*,<sup>1</sup> JUDY A. MASSARE,<sup>2</sup> and RASHMIBEN T. MISTRY<sup>3</sup>

<sup>1</sup>School of Earth, Atmospheric and Environmental Sciences, The University of Manchester,  
Oxford Road, Manchester, M13 9PL, U.K. dean.lomax@manchester.ac.uk

<sup>2</sup>Department of Earth Sciences, SUNY College at Brockport, Brockport, NY, 14420, U.S.A.  
jmassare@brockport.edu

<sup>3</sup>School of Biological Sciences, University of Reading, Whiteknights, Reading, RG6 6AH, U.K.  
rashmi.mistry@outlook.com

\* Corresponding author

## DETAILS OF PHYLOGENETIC ANALYSIS

The phylogenetic analysis is largely based on the character list and coding developed by Fischer et al. (2013), with a few modifications that are enumerated below.

1. We have omitted taxa that were younger than Lower Jurassic and were less than 40% complete on the Fischer et al. (2013) matrix. This included *Arthropterygius* (33% complete), *Maiaspondylus* (36% complete), *Athabascasaurus* (35% complete), *Chacaicosaurus* (26% complete) and *Mollesaurus* (18% complete). We retained *Malawania* (27% complete), however, because it was recovered as a sister taxon to *Ichthyosaurus* by Fischer et al. (2013).

2. We omitted *Ophthalmosaurus natans* and *Platypterygius hercynicus* because the genus was represented by a better known species, *O. icenicus* and *P. australis*, respectively. As with the previously mentioned genera, these are more derived forms.

3. We used the character list and coding of Fischer et al. (2013), but modified seven characters:  
Character 2 (Fischer et al. 2013, character 7). Extent of nasals relative to anterior process of maxilla, lateral view: maxilla extends anteriorly as far as nasals or further anteriorly (0); nasals extend farther anteriorly than the maxilla (1)  
Character 11 (Fischer et al. 2013, character 16). Squamosal shape: square or rectangular (0); triangular (1); squamosal absent (2)  
Character 39 (Fischer et al. 2013, character 48). Radius with anterior notch: present (0); absent (1).  
Character 40 (Fischer et al. 2013, character 49). Postaxial accessory digits on forefin: absent (0); present (1).  
Character 44 (Fischer et al. 2013, character 54). Digital bifurcation: absent (0); present (1).  
Character 46 (Fischer et al. 2013, character 55). Manual digit V: absent (0); present (1).  
Character 55 (Fischer et al. 2013, character 65). Tibia with anterior notch: present (0); absent (1).

These changes required recoding our characters 39, 40, 46 and 55 for all taxa.

4. We removed the following characters from Fischer et al. (2013): 1, 2, 6, 31, 32, 51 and 52 for reasons stated in Ji et al. (2016). We also eliminated character 3 because it does not specify where the cross section is taken and character 4 as it depends on preservation and how much of the root is exposed. Also, both characters are not always exposed in laterally compressed specimens of Lower Jurassic ichthyosaurs. Both 44 and 45 were removed because they were unclear and character 56 because it depends on how complete the fore and hind fins are.

5. We added two new characters to the matrix to capture differences in forefin morphology: 42 and 45.

6. We recoded *Ichthyosaurus communis* based on our own observations.

7. This is the first time that *Protoichthyosaurus* has been included in a phylogenetic analysis. The coding is based on our own observations.

## CHARACTER LIST

The character list and coding was based largely on Fischer et al. (2013). Characters are polarized using *Mikadocephalus gracilirostris* as the outgroup. All characters are unordered. Characters that are not referenced were developed as part of this study.

1. Overbite: absent or slight (0); clearly present (1) (Motani 1999: character 33, Fischer et al. 2013: character 5).

2. Extent of nasals relative to anterior process of maxilla, lateral view: maxilla extends anteriorly as far as nasals or further anteriorly (0); nasals extend farther anteriorly than the maxilla (1) (rephrased from Fischer et al. 2013: character 7).

3. Descending process of the nasal on the dorsal border of the nares: absent (0); present (1) (Fernández 2007: character 2, Fischer et al. 2013: character 8).

4. Processus narialis of the maxilla in lateral view: present (0); absent (1) (Fischer et al. 2011: character 9, inverted coding, Fischer et al. 2013: character 9).

5. Processus supranarialis of the premaxilla: present (0); absent (1) (Maisch and Matzke 2000: character 10, Fischer et al. 2013: character 10).

6. Processus narialis of prefrontal: absent (0); present (1) (Fischer et al. 2011: character 11, Fischer et al. 2013: character 11).

7. Anterior margin of the jugal: tapering, running between lacrimal and maxilla (0); broad and fan-like, covering large area of maxilla ventrolaterally (1) (Druckenmiller and Maxwell 2010: character 6, Fischer et al. 2013: character 12).

8. Sagittal eminence: present (0); absent (1) (Fernández 2007: character 5, inverted coding Fischer et al. 2011: character 13, Fischer et al. 2013: character 13).

9. Processus temporalis of the frontal: absent (0); present (1) (Fischer et al. 2011: character 14, Fischer et al. 2013: character 14).

10. Supratemporal-postorbital contact: absent (0); present (1) (Sander 2000: character 27, inverted coding Fischer et al. 2011: character 15, Fischer et al. 2013: character 15).

11. Squamosal shape: square or rectangular (0); triangular (1); squamosal absent (2) (Modified from Fischer et al. 2013: char. 16).

12. Quadratojugal exposure: extensive (0); small, largely covered by squamosal and postorbital (1) (Maisch and Matzke 2000: character 30, modified Fischer et al. 2011: character 17, Fischer et al. 2013: character 17).

13. Lower temporal arch between jugal and quadratojugal: present (0); absent (1) (Sander 2000: character 25, modified, Fischer et al. 2013: character 18).
14. Basipterygoid processes: short, giving basisphenoid a square outline in dorsal view (0); markedly expanded laterally, being wing-like, giving basisphenoid a marked pentagonal shape in dorsal view (1) (Fischer et al. 2011: character 18, Fischer et al. 2013: character 19).
15. Extracondylar area of basioccipital: wide (0); reduced but still present ventrally and laterally (1); extremely reduced, being nonexistent at least ventrally (2) (Fernández 2007: character 10, modified Fischer et al. 2011: character 19, Fischer et al. 2013: character 20).
16. Basioccipital peg: present (0); absent (1) (Motani 1999: character 29, modified Fischer et al. 2011: character 20, Fischer et al. 2013: character 21).
17. Ventral notch in the extracondylar area of the basioccipital: present (0); absent (1) (Fischer et al. 2012: character 19, Fischer et al. 2013: character 22).
18. Shape of the paroccipital process of the opisthotic: short and robust (0); elongated and slender (1) (Fischer et al. 2012: character 20, Fischer et al. 2013: character 23).
19. Stapes proximal head: slender, much smaller than opisthotic proximal head (0); massive, as large or larger than opisthotic (1) (Sander 2000: character 34, modified Fischer et al. 2011: character 21, Fischer et al. 2013: character 24).
20. Angular lateral exposure: much smaller than surangular exposure (0); extensive (1) (Motani 1999: character 32, inverted coding Fischer et al. 2011: character 22, Fischer et al. 2013: character 25).
21. Posterior dorsal/anterior caudal centra: 3.5 times or less as high as long (0); four times or more as high as long (1) (Maxwell 2010: character 15, inverted coding Fischer et al. 2011: character 24, Fischer et al. 2013: character 26).
22. Tail fluke centra: strongly laterally compressed (0); as wide as high (1) (rephrased from Maxwell 2010: character 16, Fischer et al. 2013: character 27).
23. Neural spines of atlas-axis: completely overlapping, may be fused (0); functionally separate, never fused (1) (Druckenmiller and Maxwell 2010: character 26, Fischer et al. 2013: character 28).
24. Chevrons in apical region: present (0); lost (1) (Sander 2000: character 72, modified, Fischer et al. 2013: character 29).
25. Rib articulation in thoracic region: predominantly unicipital (0); exclusively bicipital (1) (Maisch and Matzke 2000: character 53).

26. Tail as long or longer than the rest of the body (0); distinctly shorter (1) (Maisch and Matzke 2000: character 65, Fischer et al. 2013: character 33).
27. No lunate tailfin (0); well-developed lunate tailfin (1) (Maisch and Matzke 2000: character 66, Fischer et al. 2013: character 34).
28. Glenoid contribution of the scapula: extensive, being at least as large as the coracoid facet (0); reduced, being markedly smaller than the coracoid facet (1) (Fischer et al. 2012: character 27, Fischer et al. 2013: character 35)
29. Prominent acromion process of scapula: absent (0); present (1) (Fischer et al. 2011: character 28, Fischer et al. 2013: character 36).
30. Anteromedial process of coracoid and anterior notch: present (0); absent (1) (Fischer et al. 2011: character 29, modified, Fischer et al. 2013: character 37).
31. Plate-like dorsal ridge on humerus: absent (0); present (1) (Motani 1999: character 56, Fischer et al. 2013: character 38).
32. Protruding triangular deltopectoral crest on humerus: absent (0); present (1); present and very large, matching in height the trochanter dorsalis, and bordered by concave areas (2) (Fischer et al. 2011: character 31, modified, Fischer et al. 2013: character 39).
33. Humerus distal and proximal ends in dorsal view (thus regardless of the size of the dorsal and ventral processes): distal end wider than proximal end (0); nearly equal or proximal end slightly wider (1) (Fischer et al. 2013, character 40)
34. Humerus anterodistal facet for accessory zeugopodial element anterior to radius: absent (0); present (1) (Godefroit 1993: character 10, modified, Fischer et al. 2011: character 33, Fischer et al. 2013: character 41).
35. Humerus with posterodistally deflected ulnar facet and distally facing radial facet: absent (0); present (1) (Fischer et al. 2011: character 34, modified, Fischer et al. 2013: character 42).
36. Humerus/intermedium contact: absent (0); present (1) (Fernández 2007: character 16, Fischer et al. 2013: character 43).
37. Radio-ulnar foramen: present (0); absent (1) (Maisch and Matzke 2000: character 84, modified, Fischer et al. 2013: character 46).
38. Manual pisiform: absent (0); present (1) (Motani 1999: character 67, inverted coding Fischer et al. 2011: character 36, Fischer et al. 2013: character 47).
39. Radius with anterior notch: present (0); absent (1) (modified and recoded from Fischer et al. 2013: character 48).

40. Postaxial accessory digits on forefin: absent (0); present (1) (modified and recoded from Fischer et al. 2013: character 49).
41. Preaxial accessory digits on forefin: absent (0); present (1) (Maisch and Matzke 2000: character 91, modified, Fischer et al. 2013: character 50).
42. Primary elements, excluding accessory digits or pisiform, in third (distal carpal) row of forefin: three (0); four or more (1).
43. Tightly packed rectangular phalanges: absent, phalanges are mostly rounded (0); present (1) (Maisch and Matzke 2000: character 102, modified, Fischer et al. 2011: character 42, Fischer et al. 2013: character 53).
44. Digital bifurcation: absent (0); present (1) (Fischer et al. 2011: character 43 modified, Fischer et al. 2013: character 54).
45. Distal carpal 3 contacts the ulnare in forefin: absent (0); present (1).
46. Manual digit V (recognized by presence of metacarpal 5): absent (0); present (1) (modified and recoded from Motani 1999: character 73).
47. Ischium-pubis fusion in adults: absent or present only proximally (0); present with an obturator foramen (1); present with no obturator foramen (2) (Mazin 1982: character 13, modified Fischer et al. 2011: character 44, Fischer et al. 2013: character 57).
48. Ischium or ischiopubis shape: plate-like, flattened (0); rod-like (1) (Motani 1999: character 87, modified Fischer et al. 2011: character 45, Fischer et al. 2013: character 58).
49. Iliac antero-medial prominence: present (0); absent (1) (Motani 1999: character 81, Fischer et al. 2013: character 59).
50. Prominent, ridge-like dorsal and ventral processes demarcated from the head of the femur and extending up to mid-shaft: absent (0); present (1) (Fischer et al. 2011: character 46, Fischer et al. 2013: character 60).
51. Wide distal femur blade (distal end): present (0); absent, the proximal and distal extremity of the femur being sub-equal in dorsal view (1) (Fischer et al. 2013, character 61).
52. Astragalus/femoral contact: absent (0); present (1) (Maxwell 2010: character 33, Fischer et al. 2013: character 62).
53. Femur anterodistal facet for accessory zeugopodial element anterior to tibia: absent (0); present (1) (Fischer et al. 2011: character 48, Fischer et al. 2013: character 63).
54. Spatium interosseum between tibia and fibula: present (0); absent (1) (Maisch and Matzke 2000: character 114, modified, Fischer et al. 2013: character 64).

55. Tibia with anterior notch: present (0); absent (1) (modified and recoded from Fischer et al. 2013: character 65).

56. Postaxial accessory digit: absent (0); present (1) (Fischer et al. 2011: character 50, Fischer et al. 2013: character 66).

TABLE 1S: Coding of all taxa in the matrix that was used for the phylogenetic analysis. Polymorphic states are denoted by A [01]; Missing data denoted by dashes.

	10	20	30
Mikadocephalus graciliros.	0000000--0	000-----0	-----000
Hudsonelpidia brevirostris	0-----	-----	-----
Macgowania janicep	0100-----	100-----0	-----
Leptonectes tenuirostris	0-00-00000	111-0-----	0---000000
Excalibosaurus costini	1-0-----	----00----	---0-00010
Eurhinosaurus longirostris	1100000000	111-0--000	0-10000000
Temnodontosaurus spp	0000000001	1010000000	0000000000
Suevoleviathan disinteger	0100000-00	101-----0	-----01-00
Hauffiopteryx typicus	0100---000	111-00--10	0---1110-0
Stenopterygius quadrissicus	0101000001	1110000010	1111111110
Ophthalmosaurus icenicus	0111101101	111A1A0111	1011111010
Acamptonectes densus	--1----1--	---1111111	00-1---010
Brachypterygius extremus	00110-1---	--11211--1	-----10
Caypullisaurus bonpartei	000100---0	001-----1	0-----111
Aegirosaurus leptospondylus	0111111-11	111-----1	-----11---
Platypterygius australensis	0000001011	2011211011	0111-1-011
Sveltonectes insolitus	011111111-	--10211-11	00-1---110
Malawania anachronus	-----	-----	-----00-
Ichthyosaurus communis	0101000000	010-000--0	0000111100
Protoichthyosaurus prostax.	0001000--0	010-----0	000-111100
Protoichthyosaurus applebyi	-101000---	-----	0-0-1--10-

TABLE 1S (cont.)

	40	50	
Mikadocephalus	0000000-0-	-----0000	0000--
Hudsonelpidia	0000000-10	010-010010	000000
Macgowania	--00000-00	010001----	-----
<i>L. tenuirostris</i>	0000000000	0100010000	000000
Excalibosaurus	0000001000	0000000000	000000
Eurhinosaurus	0-000011A0	0A000A0000	000000
Temnodontosaurus	0000001000	0000000000	000000
Suevoleviathan	0-00001-10	0001010010	000100
Hauffiopteryx	0-00001000	01000100-0	000100
<i>S. quadrissicus</i>	010000110A	01A101100-	100100
<i>O. icenicus</i>	1211101111	1100011001	100110
Acamptonectes	11111011--	1-0-----	-----
Brachypterygius	1-10011111	110001----	-----
Capullisaurus	1211001111	1110-121-1	10-111
Aegirosaurus	1-10011111	11100121--	100111
<i>P. australensis</i>	1211001111	11100120-1	101111
Sveltonectes	1210001-11	11100121-1	101111
Malawania	-110001-10	010001----	-----
<i>I. communis</i>	0110001011	A111010110	100101
<i>P. prostaxalis</i>	0110001011	001110--10	A0011-
<i>P. applebyi</i>	0-10001011	001110--0-	-----

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