

Oligocene plotopterid skulls from western North America and their bearing on the
phylogenetic affinities of these penguin-like seabirds

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APPENDIX S1. Character descriptions.

- (1) Upper beak, praemaxilla with sharply hooked tip: no (0), yes (1).
- (2) Well-developed naso-frontal hinge: absent (0), present (1). In Ciconiidae, a naso-frontal hinge is present in *Leptoptilos*, but absent in other taxa.
- (3) Osseous narial openings: not as follows (0), reduced to a very small, caudally situated subround opening or completely absent (1), very long and slit-like (2).
- (4) Ramphotheca forming tubular external nostrils: no (0), yes (1).
- (5) Upper beak, marked furrow distal of nasal opening: absent (0), present (1).
- (6) Ventral surface of upper beak extensively ossified through fusion of ossa maxillaria and processus maxillares of ossa palatina: no (0), yes (1).
- (7) Os ectethmoidale vestigial or completely reduced: no (0), yes (1). This character is variable in Ardeidae; scoring further differs from Mayr (2005) concerning Spheniscidae.
- (8) Os lacrimale, ventral portion of processus orbitalis reduced in length, not reaching jugal bar: no (0), yes (1).
- (9) Os suprajugale: absent (0), present (1). This small ossicle is situated dorsal of the rostral end of the os jugale; it is separated from the latter in Phalacrocoracidae but fused with the os jugale in Sulidae and Anhingidae. Contrary to Livezey and Zusi (2006:character 720) and Smith (2010:character 28), we could not confirm its presence in Phaethontidae, Pelecanidae, and Fregatidae.
- (10) Os uncinatum: absent (0), present (1). In Threskiornithidae, an os uncinatum is present in *Plegadis*, but absent in the other taxa.
- (11) Ossa maxillaria, processus maxillopalatini greatly enlarged, inflated, and spongy: no (0), yes (1).
- (12) Os palatinum, pars choanalis very deep dorso-ventrally: no (0), yes (1).
- (13) Caudal portions of ossa palatina completely fused along their midline, suture obliterated: no (0), yes (1). Presence of fused ossa palatina in *Cochlearius* (Ardeidae) is here considered autapomorphic for this taxon. *Limnofregata* was scored after Smith (2010:fig. 7).
- (14) Ossa palatina forming an essentially flat plate with virtually no dorsoventral extension: no (0), yes (1).
- (15) Vomer: present, variably developed (0), absent (1).
- (16) Os pterygoideum very short, measuring as much or less than maximum width of processus mandibularis of quadratum: no (0), yes (1).
- (17) Functional processus basipterygoidei: present (0), absent (1).
- (18) Processus paroccipitales prominent and strongly protruding in caudal direction: no (0), yes (1). Plotopteridae were scored after Kawabe et al. (2014:fig. 1B).
- (19) Tubae auditivae completely open laterally: no (0), yes (1). The condition in Sulidae is uncertain and tubae auditivae seem to be absent.
- (20) Recessus tympanicus dorsalis: not as follows (0), greatly enlarged and situated rostrally to the articular facets of the quadrate (1), enlarged and situated laterally to the articular facets of the quadrate (2). Usually the recessus tympanicus is small and situated between the articular facets of the quadrate. *Limnofregata* was scored after Smith (2010:fig. 7).
- (21) Fossae temporales very marked and extending to midline of cranium: no (0), yes (1).
- (22) Marked depressions of fossae glandularum nasales on dorsal surface of cranium: no (0), yes (1).
- (23) Quadratum, condylus medialis with marked, rostrally or laterally projecting concave articular surface: no (0), yes (1). Scoring of this character differs from Mayr (2005) for Anhingidae and Phalacrocoracidae, which lack a marked articular surface.
- (24) Quadratum, processus orbitalis greatly reduced in size: no (0), yes (1).

- (25) Apparatus hyobranchialis, os basihyale greatly widened: no (0), yes (1). This character is coded unknown for Scopidae, of which no hyoid bones were available for study.
- (26) Apparatus hyobranchialis, os urohyale: present, rod-shaped (0), vestigial or absent (1). This character is coded unknown for Scopidae, of which no hyoid bones were available for study.
- (27) Mandible, ventral portion of rami mandibulae caudal of pars symphysialis medially inflected, so that mandible forms a deep trough: no (0), yes (1).
- (28) Mandible, distinct fossa along medial surface of distal section, caudal of symphysis: absent (0), present (1).
- (29) Mandible, intramam joint with internal ossification in and around Meckel's cartilage: absent (0), present (1); see Zusi and Warheit (1992). Contrary to the latter authors, Louchart et al. (2011) considered an intramam joint to be present in adult Pelecanidae, but we could not duplicate this observation in the specimens available to us.
- (30) Number of scleral ossicles: 14 or more (0), 12 or 13 (1); (after de Queiroz and Good, 1988; Warheit et al., 1989; and GM pers. obs.). The number of scleral ossicles varies in Sphenisciformes, and whereas, e.g., *Aptenodytes patagonicus* has 15, only 13 are present in *Eudyptes chrysocome*.
- (31) Number of praesacral vertebrae: 19 (0), 20 (1), 21 (2), 22 (3), 23 (4), 24 or more (5). For Pelecanidae the three caudalmost thoracic vertebrae, which are fused with the synsacrum, were included in the vertebral count. This character was coded as additive.
- (32) Atlas, incisura fossae: open (0), closed (1)
- (33) Third cervical vertebra, osseous bridge from processus transversus to processus articularis caudalis: present (0), absent (1).
- (34) 8th–11th cervical vertebrae: processus carotici ankylosed along midline, forming an osseous canal: no (0), yes (1). In Ciconiidae, the processus carotici are ankylosed in *Mycteria*, nearly so in *Ephippiorhynchus*, and separated in *Leptoptilos*, *Ciconia*, and *Anastomus*.
- (35) Caudalmost thoracic vertebrae: heterocoelous, i.e. articular surface saddle-shaped (0), platycoelous, i.e., articular surface flat (1), opisthocoelous, i.e., articular surface convex (2). The condition in Pelecanidae cannot be established as the caudalmost thoracic vertebrae are fused to a notarium. *Limnofregata* was scored after the descriptions and figures in Olson (1977). Plotopteridae were scored after *Hokkaidornis* (Sakurai et al., 2008).
- (36) Thoracic vertebrae pleurocoelous, i.e., lateral surfaces of corpus with deep depressions: no (0), yes (1). Plotopteridae were scored after *Hokkaidornis* (Sakurai et al., 2008).
- (37) Furcula, extremitas omalis with marked, laterally protruding facies articularis acrocoracoidea, which articulates with a distinct ovoid facies articularis clavicularis on the coracoid: no (0), yes (1). In Opisthocomidae and extant Fregatidae the extremitates omales of furcula and coracoid are fused, so that the status of this character cannot be evaluated. It is, however, absent in stem group Opisthocomiformes (Mayr et al., 2011), and was accordingly scored absent for this taxon. Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996).
- (38) Furcula, apophysis furculae: not as follows (0), abutting with an articular facet on the apex carinae of the sternum (1), fused with the apex carinae of the sternum (Balaenicipitidae and Fregatidae) (2), fused with the apex carinae of the sternum (Pelecanidae) (3). We consider fusion of the furcula with the apex carinae to be an autapomorphy of crown group Pelecanidae, because this feature is absent in the early Miocene *Pelecanus gracilis* (Milne-Edwards 1867-71:pl. 38). In Opisthocomidae the elongated apophysis furcula is fused with the apex carinae of the very low carina sterni, a condition that is considered non-homologous to that in Fregatidae, Pelecanidae, and Balaenicipitidae. Likewise, presence of a furcula/sternum articulation in *Ardea cinera*

- (Ardeidae) is here considered autapomorphic for this species. Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996).
- (39) Furcula, extremitas omalis with very long and pointed processus acromialis, which is directed perpendicular to main plane of bone; presence of omally directed process where extremitas omalis forms a kink: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996).
- (40) Coracoid, extremitas omalis very narrow in sterno-omal direction, forming a slender hook, which is strongly ventromedially protruding: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a coracoid referred to *Tonsala* by Dyke et al. (2011).
- (41) Coracoid, foramen nervi supracoracoidei: absent (0), present (1). In Opisthocomidae, there is a foramen, which does not perforate the shaft of the bone and represents a pneumatic opening. Following Mayr (2005), a foramen nervi supracoracoidei was scored absent in Sphenisciformes. Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a coracoid referred to *Tonsala* by Dyke et al. (2011).
- (42) Coracoid, extremitas sternalis, processus lateralis greatly elongated: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a coracoid referred to *Tonsala* by Dyke et al. (2011).
- (43) Scapula, acromion very long and markedly cranially projecting: no (0), yes (1). This character is absent in stem group Opisthocomiformes (Mayr et al., 2011), and its presence in the extant *Opisthocomus hoazin* is autapomorphic for the species.
- (44) Scapula forming a thin, sheet-like and greatly expanded blade: no (0), yes (1).
- (45) Sternum, sulci coracoidei: separated (0), crossing in midline of bone (1). Plotopteridae were scored after *Hokkaidornis* (Sakurai et al., 2008).
- (46) Sternum very short, with width exceeding length of bone: no (0), yes (1). Plotopteridae were scored after *Hokkaidornis* (Sakurai et al., 2008).
- (47) Sternum, apex carinae pointed and projecting much farther rostrally than sulci coracoidei: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996).
- (48) Sternum, caudal margin, trabeculae laterales reaching farther caudally than trabecula mediana: no (0), yes (1).
- (49) Humerus: not as follows (0), proximal end with deep, rounded head and ventrally directed caput humeri, distal end strongly flattened and ventrally protruding, sulci scapulotricipitalis et humerotricipitalis forming two deep furrows and shifted towards ventral margin of bone (1), as before but cranial trochlear ridge on distal end (formed by processus flexorius) projecting distal to the middle and caudal ridges (2). This character was coded as additive; scoring of the latter state is after Clarke et al. (2007:character 148). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a humerus referred to *Tonsala* by Dyke et al. (2011).
- (50) Humerus, intumescencia humeri: weakly convex or planar (0); inflated and bulbous (1) (Smith, 2010:character 204). This character was optimized as a synapomorphy of Plotopteridae, Phalacrocoracidae, and Anhingidae in the analysis of Smith (2010). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a humerus referred to *Tonsala* by Dyke et al. (2011).
- (51) Humerus, crista deltopectoralis: not as follows (0), very low (1), prominent and of triangular shape (2). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a humerus referred to *Tonsala* by Dyke et al. (2011).

- (52) Humerus, well-developed processus supracondylaris dorsalis: absent (0), present (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a humerus referred to *Tonsala* by Dyke et al. (2011).
- (53) Humerus, processus flexorius very short, distally abruptly ending, with flat distal surface, which forms a marked edge-like step: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a humerus referred to *Tonsala* by Dyke et al. (2011).
- (54) Ulna and radius greatly expanded and flattened: no (0), yes (1).
- (55) Carpometacarpus, os metacarpale alulare without well-developed processus extensorius and with essentially straight or slightly convex cranial margin: no (0), yes (1).
- (56) Carpometacarpus, cranial margin of os metacarpale majus distinctly bowed: no (0); yes (1). Scoring of this character is after Clarke et al. (2007:character 157).
- (57) Carpometacarpus, symphysis metacarpalis distalis incompletely fused: no (0), yes (1).
- (58) Os carpi ulnare flattened, with large caudal expansion: no (0), yes (1).
- (59) Phalanx proximalis digiti majoris, processus internus indicis (terminology after Stegmann, 1963): absent (0), present, variably developed (1).
- (60) Pelvis elongate and narrow, ratio width across antitrochanters: length of ilium less than 0.35: no (0), yes (1).
- (61) Pelvis, extreme lateral expansion of cranial end of alae praeacetabulares iliorum, coupled with reduction or ‘waisting’ in region just cranial to acetabulum: absent (0); present (1) (Smith, 2010:character 314). This character was optimized as a synapomorphy of Plotopteridae, Phalacrocoracidae, and Anhingidae in the analysis of Smith (2010). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996) and *Hokkaidornis* (Sakurai et al., 2008).
- (62) Pelvis, cristae iliaceae dorsales extensively fused with crista spinosa of synsacrum: no (0), yes (1).
- (63) Pelvis, cranialmost synsacral vertebrae with very long processus ventrales: no (0), yes (1).
- (64) Pelvis, number of ankylozed synsacral vertebrae less than 12: no (0), yes (1). In crown group Sphenisciformes the number of ankylozed synsacral vertebrae is variable, with 14 being present in *Aptenodytes* and 13 in *Spheniscus*. Plotopteridae were scored after *Hokkaidornis* (Sakurai et al., 2008).
- (65) Femur, pneumatic foramen on cranial surface of proximal end: absent (0), present (1).
- (66) Patella: not as follows (0), with marked sulcus/canal for tendon of musculus ambiens (1), as before and greatly enlarged (2). This character was coded as additive; scoring differs from Mayr (2005) in that a further state was added for the patella of Fregatidae.
- (67) Tibiotarsus, proximal end, cristae cnemiales strongly proximally protruding: no (0), yes (1).
- (68) Tibiotarsus, distal end bent medially, condylus medialis protruding farther distally than condylus lateralis: no (0), yes (1). Note that scoring of this character differs from Mayr (2005) concerning Pelecanidae, in which the character is present in, e.g., *Pelecanus onocrotalus* but absent in, e.g., *P. occidentalis*.
- (69) Tarsometatarsus: not as follows (0), very short and stocky, ratio distal width: length more than 0.3 (1), greatly elongated and slender (2). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a tarsometatarsus referred to *Tonsala* by Dyke et al. (2011).
- (70) Tarsometatarsus, hypotarsus with tendon of musculus flexor digitorum longus enclosed in bony canal: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a tarsometatarsus referred to *Tonsala* by Dyke et al. (2011).
- (71) Tarsometatarsus, hypotarsus with tendon of musculus flexor hallucis longus enclosed in

- bony canal: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a tarsometatarsus referred to *Tonsala* by Dyke et al. (2011).
- (72) Tarsometatarsus, trochlea metatarsi II distinctly longer than trochlea metatarsi IV, reaching as far distally as trochlea metatarsi III: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a tarsometatarsus referred to *Tonsala* by Dyke et al. (2011).
- (73) Tarsometatarsus, trochlea metatarsi IV markedly asymmetric in dorsal/plantar view, with lateral rim reaching much less far distally than medial rim: no (0), yes (1). Plotopteridae were scored after *Copepteryx* (Olson and Hasegawa, 1996), *Hokkaidornis* (Sakurai et al., 2008), and a tarsometatarsus referred to *Tonsala* by Dyke et al. (2011).
- (74) Limb bones pachyostotic, i.e. with greatly thickened bone walls: absent (0), present (1). See Hasegawa et al. (1979:pl. 16) concerning pachyostosis in Plotopteridae.
- (75) Musculus ambiens: present (0), vestigial or absent (1); (after George and Berger, 1966; McKittrick, 1991:character 29).
- (76) Musculus flexor cruris lateralis, pars accessoria ('Y' muscle in the formula of George and Berger, 1966: Tab. IX.1): present (0), absent (1); (after McKittrick, 1991:character 12).
- (77) Musculus caudofemoralis, pars pelvica ('B' muscle in the formula of George and Berger, 1966: Tab. IX.1): present (0), absent (1); (after McKittrick, 1991:character 16).
- (78) Musculus flexor hallucis longus and musculus flexor digitorum longus, type of arrangement; see George and Berger (1966: 447) for description of the different types (after McKittrick, 1991:character 52).
- (79) Gular pouch: absent (0), inconspicuous and feathered (1), large and naked (2).
- (80) Three anterior toes fully webbed: no (0), yes (1). In Fregatidae, webbing is restricted to the basal part of the toes.
- (81) Hallux greatly shortened and consisting of a single (ungual) phalanx only. no (0), yes (1).
- (82) Hallux included in webbed foot: no (0), yes (1). This character was considered an apomorphy of the 'Pelecaniformes', it was scored as unknown for Sphenisciformes and Procellariiformes whose hallux is greatly reduced.
- (83) Claw of third toe pectinate: no (0), yes (1). Note that scoring of this character by Mayr (2005) is incorrect for Anhingidae, in which the claw of the third toe is actually pectinate. In Threskiornithidae, a pectinate claw is present in *Plegadis*.
- (84) Glandula nasalis ('salt gland') single-lobed and with only a single efferent ductus: no (0), yes (1); after Technau (1936). Opisthocomidae and Balaenicipitidae lack a glandula nasalis.
- (85) Eggshell covered with layer of amorphous calcium carbonate: no (0), yes (1) (after Mikhailov, 1995 and own macroscopic examination of eggs).
- (86) Young at hatching: downy (0), naked (1) (after del Hoyo et al., 1992, 1996).
- (87) Young fed down gullet of adults (Cracraft, 1985): no (0), yes (1).
- (88) Eggs incubated beneath feet: no (0), yes (1) (after Cracraft, 1985; del Hoyo et al., 1992).
- (89) 'Sky-pointing'/'wing waving' display: absent (0), present (1); (after van Tets, 1965; Cracraft, 1985; del Hoyo et al., 1992).
- (90) Hop-display: absent (0), present (1); (after van Tets, 1965; Cracraft, 1985; del Hoyo et al., 1992).
- (91) 'Kink-throating' display: absent (0), present (1); (after van Tets, 1965; Cracraft, 1985; del Hoyo et al., 1992).
- (92) Neck in flight (underwater locomotion in penguins): stretched out (0), retracted and resting on back (1). In Ciconiidae, the neck is retracted in *Leptoptilos* and stretched out in the other taxa (after del Hoyo et al., 1992).
- (93) Syrinx, musculus tracheolateralis ('intrinsic muscles'): present (0), absent or reduced to a narrow ligament (in Balaenicipitidae) (1); after Beddard (1898).

- (94) Phallus: present (0), absent (1). Reduction of the phallus is an apomorphy of Neoaves, and occurred convergently in the galliform Phasianidae (Mayr, 2008).

APPENDIX S2. Character matrix of 94 morphological characters for the 22 taxa included in this study. Unknown character states are indicated by “?”, extinct taxa are marked by a dagger. Galliformes and Opisthocomidae were used for outgroup comparisons.

	Characters and character states																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Galliformes	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Opisthocomidae	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
Threskiornithidae	0	0	2	0	1	1	0	1	0	01	1	1	0	0	0	0	1	0	1	0	0	0	1	0
Ardeidae	0	0	0	0	1	1	01	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0
Ciconiidae	0	01	0	0	0	1	1	1	0	0	1	1	0	0	0	1	1	0	1	0	0	0	1	0
Gaviidae	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	1	1	1	0
Diomedidae	1	0	0	1	1	0	0	0	0	1	0	1	0	0	0	0	1	0	1	1	0	1	1	0
Oceanitinae	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0
Procellariidae	1	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	01	1	1	1	0
Scopidae	1	0	0	0	1	1	1	0	0	0	1	1	1	0	0	1	1	0	1	0	0	0	1	0
Balaenicipitidae	1	1	1	0	1	1	1	0	0	0	1	1	1	0	0	1	1	0	1	0	0	0	1	0
Phaethontidae	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0
† <i>Limnofregata</i>	0	0	2	?	?	?	0	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Fregatidae	1	0	1	0	1	1	1	0	0	1	0	0	1	0	0	0	1	0	1	1	0	0	0	0
Pelecanidae	1	1	1	0	1	1	1	0	0	0	1	1	1	0	1	1	1	0	1	2	0	0	0	0
†Plotopteridae	?	1	2	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
† <i>Waimanu</i>	?	0	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
† <i>Icadyptes</i>	?	0	2	?	1	1	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Spheniscidae	01	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0
Anhingidae	0	1	1	0	1	1	0	0	1	0	0	0	1	1	1	0	1	1	1	0	0	0	0	1
Phalacrocoracidae	1	1	1	0	1	1	0	0	1	0	0	0	01	1	1	0	1	1	1	1	1	0	0	1
Sulidae	0	1	1	0	1	1	1	0	1	0	0	0	1	1	1	0	1	1	?	1	1	0	1	1

	Characters and character states																							
	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Galliformes	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Opisthocomidae	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Threskiornithidae	1	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0
Ardeidae	0	0	0	0	0	0	4	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Ciconiidae	1	0	1	0	0	0	2	0	0	01	0	0	0	1	0	0	01	0	0	0	0	0	0	0
Gaviidae	1	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Diomedidae	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1
Oceanitinae	1	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0
Procellariidae	1	0	0	0	0	0	12	0	01	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0
Scopidae	?	?	1	0	0	0	2	0	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Balaenicipitidae	0	0	0	0	0	0	2	0	1	1	0	0	1	2	0	0	1	0	0	0	0	0	0	1
Phaethontidae	0	1	0	1	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0
† <i>Limnofregata</i>	?	?	0	?	?	?	0	0	0	?	1	?	0	1	?	0	0	0	0	0	?	1	0	1
Fregatidae	0	1	0	1	1	0	0	0	0	0	1	0	?	2	0	0	0	0	0	0	0	1	0	1
Pelecanidae	1	0	0	0	0	0	2	0	1	1	?	0	1	3	0	0	1	0	1	0	0	0	0	0
†Plotopteridae	?	?	0	1	1	?	?	?	?	?	2	1	1	1	0	0	0	0	1	1	0	0	1	?
† <i>Waimanu</i>	?	?	0	?	?	?	?	?	?	?	1	1	0	?	1	1	0	0	0	0	0	?	?	?
† <i>Icadyptes</i>	?	?	0	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Spheniscidae	1	0	0	0	0	01	2	0	1	0	2	0	0	0	1	1	0	0	0	1	0	0	0	1
Anhingidae	0	1	0	1	1	1	3	1	1	1	2	0	1	1	0	0	0	0	1	0	0	0	1	1
Phalacrocoracidae	0	1	0	1	1	1	4	1	1	0	2	0	1	1	0	0	0	0	1	0	0	0	1	1
Sulidae	0	1	0	0	1	1	2	1	1	1	1	0	1	1	0	0	0	0	1	0	0	0	1	1

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	Characters and character states																						
	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
Galliformes	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	01	0	0	0	0	1	0
Opisthocomidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
Threskiornithidae	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2	0	0
Ardeidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	1	0
Ciconiidae	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	2	0	0
Gaviidae	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0
Diomedidae	0	1	2	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0
Oceanitinae	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	2	1	1
Procellariidae	0	0	2	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	1	01
Scopidae	0	0	2	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2	1	1
Balaenicipitidae	0	1	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	2	1	1
Phaethontidae	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
† <i>Limnofregata</i>	0	0	2	0	?	0	0	0	0	0	1	0	0	?	0	0	?	?	0	0	1	0	0
Fregatidae	0	1	2	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	0
Pelecanidae	0	1	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	01	0	1	1
†Plotopteridae	1	0	1	0	0	1	1	0	0	1	?	1	1	0	0	0	0	2	0	1	1	0	0
† <i>Waimanu</i>	1	0	1	0	0	1	1	0	0	?	?	?	0	0	0	1	0	?	0	1	1	0	0
† <i>Icadyptes</i>	2	0	1	0	0	1	1	1	1	1	0	?	?	?	?	?	?	?	?	?	?	?	?
Spheniscidae	2	0	1	0	0	1	1	1	1	1	0	1	0	0	0	01	0	2	0	1	1	0	0
Anhingidae	0	0	1	0	1	0	0	0	0	0	1	1	1	1	1	0	0	2	0	1	1	1	1
Phalacrocoracidae	0	0	1	0	1	0	0	0	0	0	1	1	1	1	1	0	0	2	0	1	01	1	0
Sulidae	0	1	1	0	1	0	0	0	0	0	1	1	0	1	0	0	1	1	0	1	1	1	1

	Characters and character states																						
	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
Galliformes	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Opisthocomidae	0	0	0	0	0	0	1	0	0	0	0	0	?	0	0	0	0	0	0	0	0	0	1
Threskiornithidae	0	0	0	0	0	0	1	0	0	0	0	0	01	0	0	01	0	0	0	0	0	0	1
Ardeidae	1	0	0	1	0	1	1	0	0	0	0	1	0	01	1	0	0	0	0	0	1	0	1
Ciconiidae	0	0	0	01	0	1	1	0	0	0	0	0	1	0	01	0	0	0	0	0	01	1	1
Gaviidae	0	0	0	0	1	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Diomedidae	0	1	0	0	1	0	4	0	1	1	?	0	0	0	0	0	0	0	0	0	0	0	1
Oceanitinae	0	0	0	0	01	0	4	0	1	1	?	0	?	0	0	0	0	0	0	0	0	0	1
Procellariidae	0	1	0	0	1	0	4	0	1	1	?	0	0	0	0	0	0	0	0	0	0	0	1
Scopidae	0	0	0	1	0	1	?	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1
Balaenicipitidae	0	0	0	1	0	1	1	0	0	0	0	0	?	1	0	0	0	0	0	0	1	1	1
Phaethontidae	0	1	0	?	0	1	?	1	1	0	1	0	0	0	0	1	0	0	0	0	0	0	1
† <i>Limnofregata</i>	1	1	0	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Fregatidae	1	1	0	0	1	1	5	2	0	0	1	1	1	1	1	1	0	0	0	0	0	0	1
Pelecanidae	0	1	0	1	1	1	?	2	1	0	1	0	1	1	1	1	1	0	0	0	1	1	1
†Plotopteridae	1	1	1	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
† <i>Waimanu</i>	0	0	1	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
† <i>Icadyptes</i>	?	?	1	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Spheniscidae	0	0	1	0	1	0	2	0	1	0	?	0	1	1	0	1	0	0	0	0	0	0	1
Anhingidae	1	1	0	0	1	01	2	2	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1
Phalacrocoracidae	1	1	0	0	1	1	2	2	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1
Sulidae	1	1	0	0	1	1	1	2	1	0	1	1	1	1	1	1	1	1	1	0	0	0	1

APPENDIX S3. Newly added and revised characters of the Smith (2010) character matrix.

1. The following 38 characters were newly scored for *Tonsala*, based on the material described in the present study and information provided by Goedert and Cornish (2002) and Dyke et al. (2011; only concerning absence of the foramen nervi supracoracoidei in a coracoid referred to *T. buchanani* by these authors): 4:0 (“processus maxillaries of palatinum and processus maxillopalatini of maxillare not largely fused”); 5:0 (“ventral margin of maxilla not broader mediolaterally than the dorsal margin”); 8:0 (“osseous narial openings large”); 11:1 (“nasofrontal hinge present”); 17:0 (“pars choanalis very deep dorsoventrally”); 21:0 (“palatines fused along midline”); 22:0 (“dorsal surface of palatine not a nearly flat, horizontal plate”); 23:1 (vomer absent”); 38:1 (“intercondylar sulcus of mandibular process of quadrate a deep, parabolic channel”); 39:0 (“no pneumatic foramina associated with intercondylar sulcus of mandibular process of quadrate”); 40:0 (“sulcus for the nasal gland not marked and not situated on dorsal surface of supraorbital margin of frontal”); 42:0 (“convexity of dorsal surface of skull between lacrimals relatively flat to concave”); 76:1 (“fossae temporales marked and extending to midline of cranium”; see Kawabe et al., 2014:fig. 1); 105:1 (“caudalmost thoracic vertebrae opisthocelous”); 182:0 (“foramen nervi supracoracoidei absent”); 334:0 (“femur, orientation of femoral head with respect to proximodistal axis of femur: 90° or nearly so”); 337:0 (“femur without large, circular pneumatopore on craniomedial side of trochanter femoris”); 338:0 (“femur, lateral surface of trochanter femoris not deeply excavated”); 343:0 (“femur, cranial convexity of femoral shaft in lateral aspect straight, or very weakly convex”); 348:0 (“femur, trochlea fibularis on lateral condyle of distal femur well-defined”); 349:0 (“femur, mediolateral breadth of trochlea fibularis on lateral condyle of distal femur moderate, subequal to breadth of medial condyle”); 352:0 (“femur without large ovate accessory subfossa in sulcus patellaris”); 353:0 (“femur, medial and lateral edges of sulcus patellaris rounded, but robust, producing well-defined sulcus”); 354:0 (“femur without well-developed, proximodistally elongate crest/tubercle on the craniolateral edge of the distal femoral shaft, located slightly proximal to the proximal extent of the lateral edge of sulcus patellaris”); 362:0 (“tibiotarsus, cranial cnemial crest prominent and well-developed”); 369:1 (“tibiotarsus, well-developed triangular fossa on lateral face of base of crista cnemialis lateralis present”); 373:0 (“tibiotarsus, without pneumaticity associated with fossa flexoria on caudal surface of proximal portion”); 375:0 (“tibiotarsus, proximal half of craniomedial border of tibiotarsus not raised in a sharp medial ridge”); 377:0 (“tibiotarsus, distolateral attachment site for retinaculi mm. extensorum relatively indistinct scar or raised tuberculum”); 378:0 (“tibiotarsus, relative mediolateral position of distal portion of sulcus extensoris on cranial face of distal tibiotarsus: sulcus aligned in middle of cranial face”); 379:0 (“tibiotarsus, relative mediolateral position of distal portion of sulcus extensoris on cranial face of distal tibiotarsus: sulcus aligned in middle of cranial face”); 380:1 (“tibiotarsus, tuberculum retinaculi m. fibularis present as laterally prominent tuberculum or scarred ridge”); 381:1 (“tibiotarsus, distal end bent medially, and condylus medialis protruding slightly further distally than condylus lateralis”); 382:0 (“tibiotarsus, lateral rotation of distal tibiotarsus and condyles relative to proximal tibiotarsus absent”); 384:0 (“tibiotarsus, morphology of rim of medial condyle of tibiotarsus circular to suborbiculate”); 385:1 (“tibiotarsus, relative development of medial epicondylar depression: deep, well-defined sulcus, particularly caudodistal to medial epicondyle”); 386:0 (“tibiotarsus, without distinct notch in middle of distal rim of medial condyle”); 387:0 (“tibiotarsus, without weak, raised ridge extending across craniocaudal midline of incisura intercondylaris”).
2. Character 28 (presence/absence of os suprajugale) was revised for Balaenicipitidae, Phaethontidae, Fregatidae, and Pelecanidae, which lack an os suprajugale (contra Smith,

- 2010). Accordingly, this characters was scored “0” for *Balaeniceps*, *Phaethon* spp., *Fregata* spp., and *Pelecanus*; altogether, eight scorings were changed.
3. Character 204 (“anterior surface of crista bicipitalis (= “intumescencia”): inflated and bulbous”): scored absent (1) for all taxa except *Ciconia*, *Diomedea*, *Balaeniceps*, *Fregata*, and Sulidae. This character was erroneously scored present (0) for all taxa except *Diomedea*, Plotopteridae, Anhingidae, and Phalacrocoracidae by Smith (2010). Altogether, we changed 21 scorings for this character (concerning all taxa except *Ciconia*, *Fregata*, *Pelecanus*, Plotopteridae, Anhingidae, Sulidae, and Phalacrocoracidae).
 4. We consider the foramen in the coracoid of crown group Sphenisciformes to be non-homologous to a true foramen nervi supracoracoidei (see Mayr, 2005), and this foramen is also absent in stem group Sphenisciformes (e.g., Slack et al., 2006); accordingly a foramen nervi supracoracoidei was scored absent for *Eudyptula* and *Pygoscelis* (182:0).
 5. Four additional scorings were corrected for Spheniscidae, which were erroneously coded variable for these characters by Smith (2010): *Eudyptula* 139:1 (“craniocaudal breadth of extremitas omalis claviculae relative to ventral portion of clavicle: significantly broader”; as in *Pygoscelis*), *Eudyptula* 198:1 (“proximal end of humerus with a deep, rounded head and ventrally directed caput humeri”; as in *Pygoscelis*), *Pygoscelis* 218:1 (“fossa olecrani shape in distal aspect: shallow, triangular-shaped”, as in *Eudyptula*), *Pygoscelis* 439:0 (“relative development of sulcus on dorsal face of metatarsal II trochlea: extremely weak or absent”; as in *Eudyptula*).

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