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Systematic revision of a Miocene sperm whale from Patagonia, Argentina, and the phylogenetic signal of tympano-periotic bones in Physeteroidea

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Supplementary Online Material

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Character matrix

1- Rostrum length (ordered): (0) rostrum elongated, ratio between rostrum length and skull width > 1.2; (1) ratio ≤ 1.2 and ≥ 0.95; (2) short rostrum, ratio < 0.95. **The scoring of *'Aulophyseter'* was changed from ? to 1.**

2- Maxilla, premaxilla and vomer, all reaching the tip of the rostrum which is not formed only by the premaxillae: (0) absent; (1) present.

3- Supracranial basin of the skull (ordered): (0) absent; (1) present; (2) extended onto the whole dorsal surface of the rostrum.

4- Dorsal exposure of the maxilla on the rostrum (ordered): (0) exposure limited to less than half the rostrum length; (1) maxilla exposed on more than half the length of the rostrum, narrower than the premaxilla at some levels; (2) wider than the premaxilla all along.

5- Constriction of premaxilla anterior to antorbital notch followed by anterior expansion: (0) absent, suture maxilla-premaxilla on the rostrum roughly anteriorly directed; (1) present, suture maxilla-premaxilla distinctly anterolaterally directed.

6- Mesorostral groove: (0) open; (1) partially open at the level of antorbital notch; (2) closed to the level of the antorbital notch and with the premaxilla angled downward into the midline, creating a trough down the middle of the rostrum; (3) close along all the length (modified from Boersma and Pyenson, 2015)

7- Upper tooth row: (0) deep alveoli with interalveolar septa well developed; (1) deep alveoli with rudimentary septa (2) shallow alveolar groove without septa.

The scoring of the following taxa was changed : *'Aulophyseter'* from 0 to 1; *Eudelphis* from 0 to 1; *Zygophyseter* from 0 to 1; *A. deinodon* and *A. robustus* from 0 to 1; *Physeterula* from 0 to ?; *Orycerocetus* from 1 to 0; *Aulophyseter, Physeter, Nanokogia, Kogia* spp. from 1 to 2.

8- Premaxillary teeth: (0) present; (1) absent. This character cannot be coded for taxa lacking

distinct upper alveoli.

9- Maximum width of skull (postorbital or bizygomatic width) (ordered): (0) < 40 cm; (1) ≥ 40 and < 60 cm; (2) ≥ 60 and < 100 cm; (3) ≥ 100 cm.

10- Antorbital notch (ordered): (0) absent; (1) present; (2) transformed into a very narrow slit.

11- Right antorbital notch: (0) outside the supracranial basin; (1) inside the supracranial basin.

12- Number and size of **right** dorsal infraorbital foramina, in the area of the antorbital notch and posteriorly (ordered): (0) small to moderate size foramina, at least three-four; (1) three large foramina; (2) two large foramina; (3) one large foramen (maxillary incisure).

13- Right premaxilla: (0) posteriorly extended as the left premaxilla; (1) more posteriorly extended than the left premaxilla.

14- Widening of right premaxilla: (0) not widened posteriorly; (1) posterior extremity of the right premaxilla laterally widened, occupying at least one third of the width of the supracranial basin, mostly on the right side; (2) right premaxilla more laterally expanded such that supracranial basin overhangs the right orbit.

15- Sagittal crest: (0) absent; (1) present as a shelf covered by the pointed right premaxilla.

16- Left premaxillary foramen: (0) present; (1) reduced or absent (modified from Lambert *et al.* 2016).

17- Increase in size of the right premaxillary foramen: (0) absent, ratio between width of foramen and width of premaxilla at that level ≤ 0.20; (1) present, ratio > 0.20.

18- Anteroposterior level of right premaxillary foramen (ordered): (0) distinctly anterior to antorbital notch; (1) slightly anterior to antorbital notch; (2) same level or posterior to antorbital notch.

19- Asymmetry of the bony nares: (0) absent or reduced; (1) strong, left bony nares significantly larger than right naris.

20- Nasals (ordered): (0) both nasals present; (1) one nasal absent; (2) both nasals absent.

21- Right maxilla reaching the sagittal plane of the skull on the posterior wall of the supracranial basin: (0) absent; (1) present.

22- Fusion of lacrimal and jugal: (0) absent; (1) present.

23- Projection of the lacrimal-jugal between frontal and maxilla: (0) short or absent; (1) long.

24- Dorsoventral level of the preorbital process of the frontal: (0) higher than the lateral margin of rostrum base; (1) at approximately the same level; (2) considerably lower.

25- Frontal-maxilla suture, with skull in lateral view (ordered): (0) forming an angle < 15° with the longitudinal axis of the rostrum; (1) 15°-35°; (2) > 35°.

26- Temporal fossa (ordered): (0) anteroposteriorly longer than distance between antorbital process of the maxilla and anterior wall of temporal fossa(width/height>1); (1) approximately same length (width/height=1); (2) distinctly shorter (with/height<1).

27- Zygomatic process of squamosal in lateral view: (0) 'L'-shaped with dorsal margin ventrally bending in its posterior portion; **(1) equilateral triangle shaped, with dorsal margin dorsally bending in its posterior portion (length no more than two times higher than height at mid-length); (2) isosceles triangle shaped, with dorsal margin dorsally bending in its posterior portion (elongated, length more than two times higher than height at mid-length). The scoring of the following taxa was changed as: *Zygophyseter, Acrophyseter robustus, Diaphorocetus* and *'Aulophyseter'* from 1 to 2.**

28-Postglenoid process of the squamosal (with skull in lateral view): (0) significantly ventrally longer than posttympanic process; (1) roughly same ventral extent as post-tympanic process.

29- In lateral view of the skull, wide notch posterior to the postglenoid process of the squamosal for the enlarged posterior process of the tympanic: (0) absent; (1) present but

partially developed, paraoccipital concavity moderately excavated; (2) present and well developed, paraoccipital concavity transformed in a wide and deep notch.

30- Long axis of the skull: (0) roughly parallel to the long axis of the body (perpendicular to the surface of the occipital condyles); (1) projected ventrally; (2) projected dorsally (modified from Lambert *et al.* 2010).

31- Occipital shield (ordered): (0) convex and forming an angle of about 40° with the longitudinal axis of the rostrum; (1) as state 0 with an angle of about 60°; (2) flat or concave forming an angle of about 90°; (3) flat or concave forming an angle distinctly greater than 90°.

32- Falciform process of the squamosal (ordered): (0) contacting the corresponding pterygoid; (1) forming a thin plate not contacting the pterygoid; (2) reduced to a simple peg or absent.

33- Anterior bullar facet of the periotic (ordered): (0) very anteroposteriorly elongated; (1) reduced; (2) absent or very small.

We coded MLP 76-IX-5-1 as 2

34- In lateral view posterior extension of the posterior process of the periotic: (0) ventrally oriented; (1) parallel to the horizontal plane of the bone and not ventrally orientated.

We coded MLP 76-IX-5-1 as 0

35- Accessory ossicle of the tympanic bulla (ordered): (0) absent or small; (1) enlarged and partially fused with the anterior process of the periotic, (2) present and partially fused with the anterior process.

We coded MLP 76-IX-5-1 as 1

36- Involucrum of the tympanic bulla with an evident central concavity, visible in ventral and medial views, due to the marked pachyostosis of its anterior and posterior portion: (0) absent;

(1) present.

We coded MLP 76-IX-5-1 as 1

37- Size of teeth (greatest transverse diameter of root expressed as percentage of the maximum width of skull): (0) < 5%; (1) > 5%. Considering the strong heterodonty in *Cynthiacetus* and *Zygorhiza* this character is restricted to single-rooted teeth.

38- Dental enamel: (0) present; (1) absent

We coded MLP 76-IX-5-1 as 0

39- Number of mandibular teeth (ordered): (0) 11; (1) 12-14; (2) > 14.

40- Transverse compression of the posterior lower teeth (portion out of the alveolus): (0) strong; (1) weak or absent.

41- Mandibular condyle with: (0) well developed angular process; (1) ventral position and an angular process low or absent.

42- Anteroposterior level of last upper alveolus or posterior end of vestigial alveolar groove: (0) posterior to antorbital process; (1) at level of antorbital notch or slightly anterior; (2) distinctly anterior to the notch.

43- Lateral margin of the supraorbital process of the maxilla: (0) dorsoventrally thin; (1) significantly dorsoventrally thickened, making a subvertical wall.

44- Postorbital process of the frontal: (0) moderately posteroventrally extended; (1) much ventrally extended (vertical length of process equal or greater than horizontal length of orbit), with a correspondingly low position of the zygomatic process of the squamosal.

45- Height of temporal fossa: (0) dorsal margin at top of skull or somewhat lower; (1) much lower, temporal fossa making less than half the skull height.

46- Contact between jugal and zygomatic process of squamosal: (0) anteroposteriorly long contact; (1) proportionally short, more rounded contact; (2) no contact. In specimens with no jugal preserved, the contact surface can sometimes be observed on the zygomatic process (e.

g. *Orycterocetus crocodilinus* USNM 22926).

47- Length of the zygomatic process of the squamosal (horizontal length from anterior tip to posterior margin of squamosal): (0) ratio between length of the process and bizygomatic width of skull > 0.35; (1) ratio < 0.35.

48- Medial to tympanosquamosal recess, deep and rectilinear narrow groove in ventral surface of squamosal, from spiny process area to temporal fossa: (0) absent or shallow and poorly delineated; (1) present.

49- Superior process of the periotic: (0) dorsally extended and anteroposteriorly long; (1) anteroposteriorly shorter, but dorsally extended beyond the medial margin of the internal acoustic meatus; (2) dorsally short.

We coded MLP 76-IX-5-1 as 1.

50- Posteromedial outline of the pars cochlearis in dorsal view: (0) angular; (1) flattened, barely convex, and roughly continuous with posterior margin of superior process.

We coded MLP 76-IX-5-1 as 1.

51- Curvature of the mandible in lateral view: (0) absent or reduced, ventral margin roughly rectilinear or rising moderately anterodorsally; (1) conspicuous, ventral margin distinctly convex rising both posterodorsally and anterodorsally; (2) present, ventral margin concave.

52- Symphyseal angle on the mandibles: (0) < 35°; (1) 35°-55°; (2) > 55°.

53- Lateral margin of atlas: (0) roughly rectilinear or laterally concave; (1) convex, with laterally pointed transverse process at mid-height of the bone. Not applicable to *Kogia* (single block of cervical vertebrae).

54- Notch in the anterior margin of the basihyal: (0) wide and shallow notch; (1) narrow and deep notch; (2) no notch, rectilinear or convex anterior margin.

55- In lateral view of the skull, shape of lateral margin of maxilla anterior to antorbital notch or at the level of maxillary flange: (0) distinctly convex; (1) straight; (2) concave.

Phylogenetic Analyses

The phylogenetic analyses under equal weights with unordered characters resulted in 297 Most Parsimonious Trees (MPTs) of 186 steps (CI=0.473; RI=0.690). The strict consensus tree (Fig S1A) does not recover Physeteroidea as a clade, and the topology shows a major polytomy including four groups: 1) *Acrophyseter* spp.; 2) *Aprixokogia*, *Scaphokogia*, *Koristerocetus*, *Pliokogia*, *Nanokogia*, *Praekogia*, *Kogia sima* and *Kogia breviceps*; 3) *Zygophyseter* and *Brygmophyseter*; 4) *Physeter* and *Aulophyseter*. The taxa MLP-76-IX-5-1, *Squalodon, Agorophius*, *Kogia pusilla*, *Thalassocetus*, *Idiophyseter*, *Placoziphius*, *Diaphorocetus*, *Idiorophus*, *Physeterula*, *Orycterocetus crocodilinus*, "*Aulophyseter" rionegrensis*, *Livyatan*, *Albicetus*, and *Eudelphis* are also within the polytomy. Under equal weights with ordered characters (Fig. S1B), we recovered 805 MPTs of 196 steps. The strict consensus shows a completely unresolved tree.

Under implied weights (k=3, 10 and 20) with unordered characters (Fig. S1C), we recovered 21 MPTs each time (fit= 16.18095; 7.39799; 4.20200, respectively; CI=0.473; RI=0.690). The strict consensus tree in each case does not recover a monophyletic Physeteroidea, and instead shows a basal polytomy including: MLP-76-IX-5-1, *Squalodon*, *Placoziphius*, *Diaphorocetus*, *Eudelphis*, *Agorophius,* and two clades, one comprising the macroraptorial forms (*Brygmophyseter*, *Zygophyseter*, *Livyatan*, *Albicetus*, and *Acrophyseter* spp.), and the other clade includes two subclades: the first subclade comprises *Idiorophus*, *"Aulophyseter" rionegrensis*, *Physeterula*, *Idiophyseter*, *Physeter* and *Aulophyseter*; and the second subclades includes *Orycterocetus crocodilinus*, *Thalassocetus*, *K. pusilla*, *Aprixokogia*, *Scaphokogia*, *Koristerocetus*, *Pliokogia*, *Nanokogia*, *Praekogia*, *K. sima*, and *K. breviceps*.

Under implied weights using k= 3 and with ordered characters, we recovered 9 MPTs (fit: 19.04524; CI= 0.440, RI= 0.677). The strict consensus tree (Fig. S1D) also does not recover Physeteroidea as a clade. There is a big polytomy comprising: MLP-76-IX-5-1,

Kogia pusilla, *Diaphorocetus, Albicetus, Brygmophyseter, Zygophyseter, Eudelphis*, and four clades: (i) *Squalodon* and *Agorophius*; (ii) *Acrophyseter* spp. (iii) *Idiorophus*, "*Aulophyseter" rionegrensis*, *Idiophyseter*, *Physeter*, *Aulophyseter*, *Placoziphius*, *Orycterocetus crocodilinus*, and *Physeterula*; (iv) *Livyatan, Thalassocetus*, *Aprixokogia*, *Scaphokogia*, *Koristerocetus*, *Pliokogia*, *Nanokogia*, *Praekogia*, *K. sima* and *K. breviceps*.

With k=10 and k=20, we recovered 7 MPTs each time (fit: 8.41833 and 4.71753, respectively; CI= 0.449, RI=0.689). Unlike the previous analysis, the strict consensus (Fig. S1E) recovered Physeteroidea as a clade in each case. The internal phylogenetic relationships between MLP 76-IX-5-1, *Placoziphius*, *Diaphorocetus*, *Brygmophyseter*, *Zygophyseter*, *Eudelphis* are unresolved. Then, within physeteroids we recovered two clades: one including *Livyatan*, *Albicetus*, and *Acrophyseter* spp.; and the other one composed by two subclades, one comprising genera *Idiorophus*, "*Aulophyseter" rionegrensis*, *Idiophyseter*, *Physeter*, *Aulophyseter*, *Physeterula*; and the secon subclade including *Orycterocetus crocodilinus*, *Thalassocetus*, *Kogia pusilla*, *Aprixokogia*, *Scaphokogia*, *Koristerocetus*, *Pliokogia*, *Nanokogia*, *Praekogia*, *Kogia sima* and *K.breviceps*.

Finally, the IterPCR analysis detected MLP 76-IX-5-l as unstable taxa, except in the analyses under implied weights using k=3 and with ordered characters.

Figure S1: Strict consensus trees obtained under: equal weights and unordered characters (A); equal weights and ordered characters (B); Implied weights with k=3 and unordered characters

(C, same topology for k=10 and k=20); Implied weights with k=3 and ordered characters (D); and Implied weights with k=10 and ordered characters (E, same topology for k=20). Numbers associated with branches are Bremer decay values.

Phylogenetic signal analysis

Ordered characters and Implied weights:

	K	PIC.variance.obs	PIC.variance.rnd.mean	PIC.variance.P	PIC.variance.Z
character 33: Anterior bullar facet of the periotic	0.04392541	2.081921	1.535004	0.8851149	1.248029
character 34: In lateral view Posterior extension of the posterior process of the periotic	0.07605343	0.4097128	0.358819	0.6963037	0.3922663
character 35: Accessory ossicle of the tympanic bulla	0.03989646	1.265934	0.8997169	0.8971029	1.359524
character 36: Involucrum of the tympanic bulla with an evident central concavity, visible in ventral and medial views, due to the marked pachyostosis of its anterior and posterior portion	0.05959255	0.6728112	0.6425696	0.5724276	0.1544846
character 49: Superior process of the periotic	0.05142492	1.154564	1.02364	0.6533467	0.3892065
character 50: Posteromedial outline of the pars cochlearis in dorsal view	0.04441788	0.8655682	0.5603644	0.9360639	1.699196

Ordered characters and Equal weights

	K	PIC.variance.obs	PIC.variance.rnd.mean	PIC.variance.P	PIC.variance.Z
character 33: Anterior bullar facet of the periotic	0.0442203	2.067917	1.621868	0.8261738	1.002917
character 34: In lateral view Posterior extension of the posterior process of the periotic	0.06995446	0.4454228	0.3693566	0.7532468	0.5876802
character 35: Accessory ossicle of the tympanic bulla	0.04927237	1.025024	0.9239688	0.6653347	0.3590392
character 36: Involucrum of the tympanic bulla with an evident central concavity, visible in ventral and medial views, due to the marked pachyostosis of its anterior and posterior portion	0.07048461	0.5688418	0.6510699	0.3696304	-0.4121555
character 49: Superior process of the periotic	0.06221888	0.9543191			
character 50: Posteromedial outline of the pars cochlearis in dorsal view	0.06447826	0.5962454	0.5760399	0.5554446	0.1096439

Unordered characters and Implied weight

	K	PIC.variance.obs	PIC.variance.rnd.mean	PIC.variance.P	PIC.variance.Z
character 33: Anterior bullar facet of the periotic	0.0391288	2.338901	1.568013	0.959041	1.113176
character 34: In lateral view Posterior extension of the posterior process of the periotic	0.06605984	0.4721964	0.3592286	0.8111888	0.8873444
character 35: Accessory ossicle of the tympanic bulla	0.04368061	1.156552	0.943804	0.7872128	0.7643282
character 36: Involucrum of the tympanic bulla with an evident central concavity, visible in ventral and medial views, due to the marked pachyostosis of its anterior and posterior portion	0.04879639	0.8224997	0.6467762	0.7972028	0.9019881
character 49: Superior process of the periotic	0.05137075	1.155233	1.049713	0.6393606	0.2948296
character 50: Posteromedial outline of the pars cochlearis in dorsal view	0.05012601	0.7680702	0.5668818	0.8481518	1.113176

Unordered characters and Equal weights

	K	PIC.variance.obs	PIC.variance.rnd.mean	PIC.variance.P	PIC.variance.Z
character 33: Anterior bullar facet of the periotic	0.0442203	2.067917	1.581307	0.8511489	1.063243
character 34: In lateral view Posterior extension of the posterior process of the periotic	0.06995446	0.4454228	0.3620549	0.7682318	0.652079
character 35: Accessory ossicle of the tympanic bulla	0.04927237	1.025024	0.9362823	0.6423576	0.3095887
character 36: Involucrum of the tympanic bulla with an evident central concavity, visible in ventral and medial views, due to the marked pachyostosis of its anterior and posterior portion	0.07048461	0.5688418	0.6666513	0.3386613	-0.4889836
character 49: Superior process of the periotic	0.06221888	0.9543191	1.060289	0.4245754	-0.3002856
character 50: Posteromedial outline of the pars cochlearis in dorsal view	0.06221888	0.9543191	1.079383	0.3866134	-0.3520159

Biochron ranges for the taxa included

Taxon	FAD	LAD
Zygorhiza	37.2	33.9
Cynthiacetus	37.2	33.9
Agorophius	33.9	23.03
Squalodon	23.03	13.82
Eudelphis	15.97	11.68
Zygophyseter	10.5	8.14
Brygmophyseter	16	15
Diaphorocetus	20.44	19
Placoziphius	23.03	13.82
Physeteroidea indet. MLP 76-IX-5-1 (*"Preaulophyseter"*)	9.61	7.24
Acrophyseter sp.	6.9	6.7
Acrophyseter deinodon	8.7	6.5
Acrophyseter robustus	13	11
Albicetus	16	14
Livyatan	11.62	7.24
"Aulophyseter" rionegrensis	9.61	7.24
Idiorophus	20.44	19
Idiophyseter	15.97	13.82
Physeter macrocephalus	3.6	0.0
Physeterula	11.62	7.24
Aulophyseter morricei	15.97	13.8
Orycterocetus crocodilinus	20.4	11.6
Thalassocetus	20.04	11.6
Kogia pusilla	3.6	2.58
Aprixokogia	5.332	3.6
Scaphokogia	11.62	7.24
Koristocetus	11.62	7.24
Pliokogia	5.33	3.6
Nanokogia	11.62	7.24
Praekogia	7.246	5.332
Kogia sima	3.6	0.0
Kogia breviceps	3.6	0.0