**Supplemental Tables**

**Breaking the mold: telescoping drives the evolution of more integrated and heterogeneous skulls in cetaceans**

Mónica Romina Buono & Evangelos Vlachos

**Table S1**: List of the specimens used for the construction of the anatomical networks of the skulls and the sources. Physical maturity of the specimens was taken from the literature or determined following the criteria of closure of the cranial sutures suggested by Perrin (1975) and Walsh & Berta (2011) unless indicated.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **TAXA** | **Family** | **Taxon** | **Collection number** | **Physical maturity** | **Reference** |
| **STEM CETACEA**  | Pakicetidae | *Pakicetus attocki**Pakicetus inachus*  | H-GSP 1846718470, 96231, 96623GSP-UM084 | --adultjuvenileadult1 | Nummela et al., 2006 Gingerich & Russell, 1981; Gingerich & Russel 1990 (Fig. 8);  |
| “Protocetidae” | *Aegyptocetus**Georgiacetus*Protocetidae indet.*Artiocetus clavis* | MSNTUP I-15459GSM350CMM-V-4536GSP-UM3458 | adult adult-- | Bianucci & Gingerich, 2011Hulbert et al., 1998Godfrey et al., 2013Gingerich et al., 2001 |
| Basilosauridae | *Dorudon atrox* | UM 100139  UM 93220 UM 101222UM 97512UM 97506 | juvenilejuvenileadultadultadult | Uhen, 2004; Marx et al 2016 (fig. 3.8) |
| **MYSTICETI** | Aetiocetidae | *Aetiocetus cotylalveus**Aetiocetus* *weltoni* | USNM 25210 UCMP12290  |  adult subadult | Emlong, 1966Demeré & Berta, 2008Marx et al 2016 (Fig. 4.10) |
|  | Eomysticetidae | *Yamatocetus* | KMNH VP 000,017 |  subadult2 | Okazaki 2012 (p:4); Marx et al. 2016 fig. 4.12 |
|  | Balaenidae | *Eubalaena australis* | CNP-MAMM748MLP 1508MoNZ 2239USNM 267612 | neonatesubadultjuvenile?3adult | Marx et al., 2016Tsai et al., 2014MB personal observations |
|  | Balaenopteridae | *Balaenoptera acutorostrata**B.borealis**B. physalus**B. musculus**B. edeni**B.omurai**B.brydei**B. ricei* | CNP-MAMM 100750USNM 61715USNM 504244USNM 236680USNM 550467USNM 16039USNM 124326GRM223NSMT-M32505RMNH 78N33USNM 594665 | juvenilesubadultsubadultsubadultsubdultadultadultadultadultadultadult | Marx et al., 2016 (fig. 4.17)Muller, 1954; Ichishima, 2016Tsai et al., 2014Wada et al., 2003 (fig.1)Yamada et al 2006Tsai et al., 2014Rosel et al., 2021 |
|  | Cetotheriidae  | *Caperea* | NMNZ MM 2235 NMNZ MM 2254 | adult5subadult5 | Marx et al., 2016Tsai et al., 2014 |
|  |  | *Piscobalaena nana* | MNHN SAS 1617MNHN SAS 1618MNHN SAS 1623 |  adult adultadult | Bouetel et al., 2006 |
| **ODONTOCETI** | Xenorophidae | *Albertocetus meffordorum* | CCNHM 303CCNHM 218USNM 525001 | subadultadultsubadult | Boessenecker et al., 2017; Uhen, 2008 |
|  | Platanistoidea | *Waipatia* | OU 22095 | subadult/adult | Fordyce, 1994 |
|  | Platanistoidea | *Notocetus vanbenedeni* | MLP 5-5, 5-10 | adultadult | Viglino, 2019 personal communications from M.Viglino (August, 2021) |
|  | Physeteridae | *Physeter* | USNM 35315 MACN-Ma 29768  | subadultadult | Flower,18684personal observations from F. Paolucci, (June 2021) |
|  | Delphinidae | *Tursiops truncatus* | USNM 550403CNP-MAM 100-644CNP-MAM 100953CNP-MAM 100952CNP-MAM 100954CNP-MAM 100957 | adultadultsubadultadultadultadult | Mead & Fordyce (2009) |

1 Based on a byzigomatic width of 145mm (Gingerich & Russel, 1981), higher than the adult specimen H-GSP 96231 of *Pakicetus attocki.* There is not evidence in the dental morphology (e.g. deciduous dentition) or cranial futures suggesting a juvenile condition.

2 Based on the degree of cranial close suture and fusion of vertebral and forelimb epiphysis

3 Specimen with basioccipital-basisphenoid suture completely closed; however, most of the basicranial sutures (e.g. squamosal-alisphenoid; pterygoid-basioccipital; pterygoid/palatine) are not fused which might indicate a juvenile condition. Besides, cancellous bones surface of squamosal/pterygoid also indicates an immature condition.

4 This work includes an adult specimen and comparison with a juvenile.

5 Based on information available in Buchholtz (2011)

**Institutional abbreviations**: **CCNHM**, Mace Brown Museum of Natural History, Charleston, South Carolina, USA; **CMM-V**, Calvert Marine Museum fossil Vertebrate collection, Solomons, Maryland, USA; **CNP-MAMM**, Laboratorio de Mamíferos Marinos, Centro Nacional Patagónico, Puerto Madryn, Argentina; **GSP-UM**, Geological Survey of Pakistan, University of Michigan; Michigan, USA; **GRM**, Indian Museum, Kolkata, Indian; **GSM**, Georgia Southern Museum, Statesboro, Georgia, USA; **H-GSP**, Geological Survey of Pakistan, Howard University, Washington, D.C., USA; **KMNH**, Kitakyushu Museum of Natural History and Human History, Kitakyushu, Japan; **MLP**, Museo de La Plata, La Plata, Argentina; **MNHN**, Museum National d`Histoire Naturelle, Paris, France; **NMNZ**, Museum of New Zealand Te Papa Tongarewa, Wellington, New Zealand, **NSMT-M,** National Science Museum, Tokyo, Japan; **OU**, Geology Museum, University of Otago, Dunedin, New Zealand; **RMNH,** National Museum of Natural History, Leiden; **UCMP**, University of California Museum of Paleontology, Berkeley, USA; **UM**, University of Michigan Museum of Paleontology, Ann Arbor, Michigan; **USNM**, National Museum of Natural History, Washington, D.C., USA;

**Table S2.** PERMANOVA analysis considering the taxonomic classification of the tetrapods groups. Statistically significant p < 0.05 marked with bold.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| p/F | Ichthyostegalia | Seymouriamorpha | Amphibia | Procolophonomorpha | Testudinata | Sauropsida | Crocodilia | Dinosauria | Aves | Lepidosauria | Squamata | Synapsida | Mammalia | Cetacea |
| Ichthyostegalia |   | 1 | 0.4967 | 1 | 0.1092 | 1 | 1 | 0.7994 | 1 | 1 | 0.5162 | 0.8085 | 0.1267 | **0.0441** |
| Seymouriamorpha | 12.39 |   | 0.2498 | 1 | 0.104 | 1 | 1 | 0.7921 | 1 | 1 | 0.5063 | 0.1989 | 0.1263 | **0.0452** |
| Amphibia | 2.37 | 2.86 |   | 0.5026 | 0.0824 | 0.1008 | 0.7564 | **0.0324** | 0.7533 | 0.5013 | **0.0333** | **0.0327** | 0.2638 | 0.087 |
| Procolophonomorpha | 2.86 | 2.86 | 0.9135 |   | 0.1037 | 0.2461 | 1 | **0.5917** | 1 | 1 | 0.7559 | 0.605 | 0.1216 | **0.0442** |
| Testudinata | 17.74 | 23.12 | 3.179 | 3.691 |   | **0.0049** | 0.3976 | 0.0034 | 0.1018 | 0.1015 | **0.0039** | **0.0013** | **0.0002** | **0.0001** |
| Sauropsida | 0.05763 | 0.106 | 8.539 | 1.781 | 35.18 |   | 0.2506 | 0.3193 | 0.243 | 1 | 0.2077 | 0.1721 | **0.0092** | **0.0004** |
| Crocodilia | 35.18 | 35.18 | 0.7009 | 0.7009 | 1.865 | 2.736 |   | 0.5975 | 1 | 1 | 0.6226 | 0.206 | 0.1203 | **0.045** |
| Dinosauria | 0.2654 | 0.5267 | 6.728 | 0.5874 | 16.93 | 1.203 | 0.8705 |   | 0.1979 | 0.8 | 0.4592 | 0.4014 | **0.004** | **0.0002** |
| Aves | 0.8705 | 0.8705 | 0.2868 | 0.2868 | 12.66 | 13.38 | 13.38 | 8.477 |   | 1 | 0.1258 | 0.203 | 0.3738 | **0.0428** |
| Lepidosauria | 8.477 | 8.477 | 1.954 | 1.954 | 13.05 | 0.5914 | 0.5914 | 0.1744 | 0.1744 |   | 0.6271 | 0.8031 | 0.1291 | **0.0476** |
| Squamata | 0.4184 | 0.8273 | 5.813 | 0.09684 | 8.598 | 1.726 | 0.3968 | 0.6537 | 4.653 | 0.2977 |   | 0.8426 | **0.0009** | **0.0001** |
| Synapsida | 0.8627 | 2.086 | 7.563 | 0.8387 | 24.96 | 2.051 | 2.329 | 0.9133 | 19.41 | 0.8431 | 0.1547 |   | 0.0034 | **0.0002** |
| Mammalia | 18.15 | 20.94 | 1.496 | 9.211 | 34.23 | 48.01 | 7.649 | 38.97 | 1.492 | 15.58 | 32.49 | 47.27 |   | **0.0001** |
| Cetacea | 29.04 | 37.17 | 3.224 | 8.692 | 16.73 | 73.35 | 7.935 | 50.47 | 6.701 | 22.76 | 29.96 | 53.08 | 41.55 |   |

**References**

Bianucci, G, & Gingerich, PD. (2011). *Aegyptocetus tarfa*, n. gen. et sp. (Mammalia, Cetacea), from the middle Eocene of Egypt: clinorhynchy, olfaction, and hearing in a protocetid whale. *Journal of Vertebrate Paleontology*, 31: 1173-1188.

Boessenecker, RW, Ahmed, E, & Geisler, JH. (2017). New records of the dolphin *Albertocetus meffordorum* (Odontoceti: Xenorophidae) from the lower Oligocene of South Carolina: encephalization, sensory anatomy, postcranial morphology, and ontogeny of early odontocetes. *PLoS One*, 12: e0186476.

Bouetel, V, & de Muizon, C. (2006). The anatomy and relationships of *Piscobalaena nana* (Cetacea, Mysticeti), a Cetotheriidae ss from the early Pliocene of Peru. *Geodiversitas*, 28: 319-395.

Buchholtz, EA. (2011). Vertebral and rib anatomy in *Caperea marginata*: implications for evolutionary patterning of the mammalian vertebral column. *Marine Mammal Science*, 27: 382-397.

Deméré, TA, & Berta, A. (2008). Cranial anatomy of the toothed mysticete *Aetiocetus weltoni* and its implications for aetiocetid phylogeny. *Zoological Journal of the Linnean Society*, 154: 308-352.

Emlong, DR. (1966). A new archaic cetacean from the Oligocene of northwest Oregon. *Bulletin of the Museum of Natural History*, University of Oregon 3: 1-51.

Flower, WH. (1868). On the osteology of the cachalot or sperm-whale *(Physeter macrocephalus). Transactions of the Zoological Society of London* 6: 309-372.

Fordyce, RE, & Barnes, LG. (1994). The evolutionary history of whales and dolphins. *Annual Review of Earth and Planetary Sciences*, 22: 419-455.

Gingerich, PD, & Russell, DE. (1981). *Pakicetus inachus*, a new archaeocete (Mammalia, Cetacea) from the early-middle Eocene Kuldana Formation of Kohat (Pakistan). *Contributions from the Museum of Paleontology the University of Michigan*, 25: 235-246.

Gingerich, PD, & Russell, DE. (1990). Dentition of early Eocene *Pakicetus* (Mammalia, Cetacea). *Contributions from the Museum of Paleontology the University of Michigan*, 28:1-20.

Gingerich, PD, ul Haq, M., Zalmout, IS, Khan, IH, & Malkani, MS. (2001). Origin of whales from early artiodactyls: hands and feet of Eocene Protocetidae from Pakistan. *Science*, 293: 2239-2242.

Godfrey, SJ, Geisler, J, & Fitzgerald, EM. (2013). On the olfactory anatomy in an archaic whale (Protocetidae, Cetacea) and the minke whale *Balaenoptera acutorostrata* (Balaenopteridae, Cetacea). *The Anatomical Record*, 296: 257-272.

Hulbert, RC, Petkewich, RM, Bishop, GA, Bukry, D, & Aleshire, DP. (1998). A new middle Eocene protocetid whale (Mammalia: Cetacea: Archaeoceti) and associated biota from Georgia. *Journal of Paleontology*, 72: 907-927.

Ichishima, H. (2016). The ethmoid and presphenoid of cetaceans. *Journal of Morphology*, 277: 1661-1674.

Marx, FG, Lambert, O, & Uhen, MD. (2016). Cetacean paleobiology. West Sussex: John Wiley & Sons.

Mead JG, Fordyce RE. 2009. The therian skull: a lexicon with emphasis on the odontocetes. *Smithsonian Contributions to Zoology,* 627:1-261.

Muller, J. (1954). Observations on the orbital region of the skull of the Mystacoceti. *Zoologische Mededelingen*, 32: 279-290.

Nummela, S, Hussain, ST, & Thewissen, JGM. (2006). Cranial anatomy of Pakicetidae (Cetacea, Mammalia). *Journal of Vertebrate Paleontology*, 26: 746-759.

Okazaki, Y. (2012). A new mysticete from the upper Oligocene Ashiya Group, Kyushu, Japan and its significance to mysticete evolution. *Bulletin of the Kitakyushu Museum of Natural History and Human History,* Series A (Natural History), 10: 129-152.

Rosel, PE, Wilcox, LA, Yamada, TK, & Mullin, KD. (2021). A new species of baleen whale (Balaenoptera) from the Gulf of Mexico, with a review of its geographic distribution. *Marine Mammal Science*, 37: 577-610.

Tsai, CH, Fordyce, RE, Chang, CH, & Lin, LK. (2014). Quaternary fossil gray whales from Taiwan. Paleontological Research, 18: 82-93.

Uhen, MD. (2004). Form, function, and anatomy of *Dorudon atrox* (Mammalia, Cetacea): an archaeocete from the middle to late Eocene of Egypt. *University of Michigan Papers on Paleontology* 34:1-222.

Uhen, MD. (2008). A new *Xenorophus*-like odontocete cetacean from the Oligocene of North Carolina and a discussion of the basal odontocete radiation. *Journal of Systematic Palaeontology*, 6: 433-452.

Viglino, M. (2019). Sistemática, filogenia y paleoecología de *Notocetus* *vanbenedeni* del Mioceno temprano de Patagonia y la evolución de los Platanistoidea (Mammalia, Cetacea, Odontoceti). Ph.D. thesis (unpublished). Universidad de Buenos Aires, Ciudad Autónoma de Buenos Aires.

Viglino M, Gaetán CM, Cuitiño JI, & Buono MR. 2021. First toothless platanistoid from the early Miocene of Patagonia: the golden age of diversification of the Odontoceti. *Journal of Mammalian Evolution* *28*: 337-358 DOI 10.1007/s10914-020-09505-w.

Wada, S, Oishi, M, & Yamada, TK. (2003). A newly discovered species of living baleen whale. *Nature*, 426: 278-281.

Yamada, TK, Chou, LS, Chantrapornsyl, S, Adulyanukosol, K, Chakravarti, SK, Oishi, M, ... &

Kurihara, N. (2006). Middle-sized balaenopterid whale specimens (Cetacea: Balaenopteridae) preserved at several institutions in Taiwan, Thailand, and India. *Memoirs of the National Science Museum, Tokyo,* 44: 1-10.