**Appendix 1: Morphological characters used in phylogenetic analysis**

**Skull**

1. Temporal lines (Wang et al, 2005: character 1)

0=converge to form a sagittal crest,

1=parallel, do not form a sagittal crest.

The derived character state, in which the temporal crests never communicate with each other, appears to have arisen independently at least three times in arctoids: in phocids, in *Plesictis*, and in the leptarctines. The leptarctines and *Plesictis* display widely separated temporal lines.

2. Frontal, anterior root of sagittal crest (Boessenecker and Churchill, 2015; character 34)

0=crest emerges from one point of supraorbital process, either from one point or slightly bifid

1=anterior emergence of crest bifid, and preceded by prominent divergent crests that originate on the posterior portion of the supraorbital process

3. Postorbital constriction (modified from Wolsan, 1993: character 1; Wang et al, 2005: character 34).

0= short

1=intermediately long

2=long

Postorbital constriction is considered long when it is longer than its greatest width. Post-orbital constriction refers to the constriction of the skull in ventral view immediately posterior to the orbits. Here, the distance is measured from the supraorbital processes to the postorbital constriction itself (that is where this region is most narrow), prior to the posterior expansion of the skull caused by the braincase. Post-orbital constriction is likely a synapomorphy of pinnipedimorphs, but also occurs in the early-diverging Amphicyonid, *Temnocyon.*

4. Palatine, anterior palatine foramina {1} <15> (Berta, 1991: character 5; Bryant et al.,1993: character 1)

 0=located at maxilla/palatine suture

1=anterior to the suture

The plesiomorphic condition, anterior palatine foramina located at the maxillary-palatine suture, occurs in canids, ursids, Amphicyonids, ailurids, Phocines, and non-aquatic mustelids. Anteriorly-located foramina arise appear to arise independently in pinnipedimorphs, mephitis, and aquatic mustelids, excepting the aberrant mid-Miocene *Mionictis*.

5. Palatine, posterior limit (Wang et al., 2005; character 2)

 0=located near the posterior limit of the toothrow,

1=expanded, posterior to toothrow

In Amphicyonids, canids, and some early-diverging musteloids, the palatine does not extend significantly beyond the toothrow. In *Puijila*, *Potamotherium* and many derived musteloids the posterior choana opens near the level of the glenoid fossa.

6. Palatine, width of posterior margin (modified from Wyss and Flynn, 1993; Wozencraft, 1989)

0=nearly equal to intercanine width

1=somewhat wider than width between canines; >1.1x wider

2=significantly wider than width between canines >1.5x wider

monachine seals display a highly divergent tooth row, with the width at the posterior margin over three times as wide as the width at the canines. Divergent tooth rows (>1.5x wider than width at canines) are also observed in canids, phocids, and desmatophocines, among other taxa. Wyss and Flynn (1993) suggested this likely represents a phocoid (Phocidae + Desmatophocidae) synapomorphy. However early-diverging odobenids, including *Proneotherium* and *Prototaria,* display tooth rows that are no less divergent than those of *Desmatophoca.*

7. Palatal midline ridge (Rybczynski et al., 2009; character 4)

0=absent

1=present.

The appearance of the palatal midline ridge is highly variable, with the most common condition consisting of a mediolaterally-thick anterior ridge fading into a thinner posterior ridge, as observed in *Puijila, Potamotherium, Kolponomos, Allocyon, Amphicticeps* and *Desmatophoca brachycephalus.* This trait is likely a synapomorphy of pinnipedimorphs and their ancestors. This configuration is best exemplified by *Puijila* and *Amphicticeps*. The ridge, when present in highly variable in form. A less sharply-defined ridge is present in *Pteronarctos, Imagotaria,* and *Allodesmus.*

8. Palate, arching (Deméré and Berta, 2001: Character 6)

 0=relatively flat

 1=transversely arched (palatal arch averages >30)

A transversely arched palate has been identified as an odobenid synapomorphy (Kohno, 2006; Boessenecker and Churchill, 2013), but also appears in a number of aberrant pinnipedimorphs. Deméré and Berta (2002) polarized this trait by developing a ‘Palatal-arch ratio’ to quantify the character. As many of the fossils studied preserve this area poorly, we do not follow their convention of computing an average palatal arch-ratio, but instead take the relevant measurements (ratio of palatal midline depth to chord length of transverse arch) at the transverse plane of the lingual border of the P4.

9. Palatine, incisive foramina (modified from Valenciano et al., 2016: character 3)

 0=located at the level of C

 1=located at the level of C-I3 diastema

 2=elongated; continue well posteriorly to C

 3=absent

In many arctoids, the incisive foramina (their ventral opening) are aligned with the canine (state 0), or located slightly anteriorly to it, occasionally due to an extended C-I3 diastema (state 1). In state 2, observed in some phocids and some early pinnipeds, the incisive foramina are located well posteriorly of the canine. Most specimens of *Odobenus* completely lack incisive foramina.

10. Maxilla, palatine process (=pterygoid process) (modified from Berta, 1991: character 1)

0=absent

1=posterolaterally-directed point

2=thin and broad shelf

Our coding of this process reflects the description of Berta (1991). In the plesiomorphic condition, the palate, posterior to the molars, narrows quickly after the tooth row, becoming as narrow as the pteryoids. In this condition, the lateral margin of the posterior most portion of the palate is straight or concave. In ursids and some pinnipedimorphs, the posterior portion of the palate is laterally expanded, and a spur of bone projects posteriorly. No mustelids display development of this process, but specimens of *Mydaus* and *Conepatus* display incipient development of this process. phocids may atavistically retain this process, as it is present in some specimen of *Lobodon*, and is present in *Erignathus*. In some other pinnipedimorphs, the lateral margin may be expanded as a thin broad shelf, that comes to a cornered edge posterolaterally

11. Embrasure pit between P4/ M1 (Berta, 1991: character 34)

0=present and deep

 1=shallow or absent

12. Maxilla, nasolabialis fossa (modified from Berta, 1991; character 2)

 0=absent or very weakly developed

1=present

The nasolabialis fossa is a variably-deep depression located immediately anteromedially to the anterior orbital rim, which serves to house the levator (=quadrator) labii superioris muscle, which is involved with retraction of the upper lip. The nasolabialis fossa is absent in canids, but its presence may be plesiomorphic for arctoids, appearing in Cephalogale, Allocyon and Amphicticeps, three taxa near the base of Arctoidea. It is also absent in derived ursids, mephitids, procyonids, and crown pinnipeds.

13. Maxilla, fossa muscularis (Berta, 1991 : character 32)

 0=absent

1=present

The fossa musularis is located within the anterior orbital margin, dorsomedial to the infraorbital foramen, and serves as the origin for the interior oblique muscle of the eye (Davies, 1964). A somewhat deeper pit, nearly resembling a foramen is present in ursids and some derived mustelids. A shallow depression that does not pierce the lacrimal bone is observed in stem pinnipeds and cephalogale.

14. Maxilla, contribution to orbital wall (modified from Berta and Wyss, 1994: character 9)

0=no contribution

1=small contribution; just a sliver of maxilla squeezes onto orbit

2=contributes heavily to anteromedial wall of orbit

3=contributes heavily to anteroventral wall of orbit, and slightly wraps over the orbital rim

15. Infraorbital foramen, in anterior view (modified from Berta and Wyss, 1994: character 11)

 0=slit-like with long canal

1=rounded with long canal

2=rounded with short canal (canal does not extend past foramen)

3=rounded and large (mediolaterally wider than max length of incisive foramina in ventral view)

A slit-like infraorbital opening leading to a long canal is the plesiomorphic conditions for caniformes, and is observed in canids, Amphicyonids, and some ursids. A round infraorbital foramen appears in all other arctoids, though its size and the length of the canal vary considerably. Some mustelids have longer canals, but most have short canals, and moderately-sized foramina. pinnipeds and their ancestors, and other aquatic arctoids (including otters and *Mionictis*) display a large, round infraorbital foramen with a short canal.

16. Caninus fossa (=infraorbital fossa) (Bininda-Emonds and Russell, 1996; character 19)

0=absent; portion of maxilla lateral to tooth row is convex

1=present; portion of maxilla lateral to tooth row is concave

If present, the caninus fossa appears anteriorly on the alveolar margin of the maxilla. It is unknown if the phocid caninus fossa accommodates the nasolabialis muscle or the caninus muscle ((de Muizon, 1982), or whether the two muscles are even distinct from each other or synonymous (Bininda-Emonds and Russell, 1996). The caninus fossa was used as a synapormorphy of Phocines by de muizon (1982a), but appears more broadly throughout pinnipedimorphs. However, it does appear more prominent in many phocids (excepting *Erignathus*) than in non-phocids.

17. Orbital Vacuities (modified from Kohno, 2006: character 20)

 0=absent

1=present, anteriorly positioned

2=present, posteriorly positioned

3=present, anteriorly positioned with dorsal portion eclipsing frontal or orbitosphenoid

The orbital vacuity (=sphenopalatine vacuity) is enlarged in all pinnipeds compared to terrestrial carnivorans. However, the make-up of this vacuity differs between the three families. In otariids the vacuity is greater and eclipses the bone dorsad of it (state 3). This condition is approached by monachines, but the eclipse of the bone dorsad to it (either the frontal or the orbitosphenoid) is not observed to the same extent. In Phocines, the vacuity is smaller and does not contact the frontal or orbitosphenoid

18. Nasals, in dorsal view

0=most posterior point occurs at midline; taper posteriorly

1=posterior margin is rounded; taper posteriorly

2=posterior margin forms an “M” shape; lateral margin straight and parasagittal or anterior portion tapers posteriorly, and posterior portion is straight or appears somewhat divergent

3=straight, transverse posterior margin; lateral margin straight and parasagittal

In state 2, exhibited by otariids, the anterior portion of the nasals may taper strongly posteriorly, as in *Arctocephalus*, and the posterior portion may appear slightly divergent, rather than parasagittally straight. Nevertheless, the key distinction is the shape of the posterior margin.

19. Anterior Narial opening (Kohno, 2006: character 2)

0=large, thin margin, and rounded

1=large thick margin and dorsoventrally elliptical

2=large thick margin with prenarial shelf

20.Premaxilla-nasal contact, in dorsal view (modified from Wyss and Flynn, 1993; character 5)

 0=40-60% of length of nasal, no contact with frontal

 1=less than 40% length of nasal, no contact with frontal

 2=more than 60% length of nasal, no contact with frontal

 3=more than 60% length of nasal, contacts frontal

The length of the contact between the premaxilla and nasal is substantial in many caniforms. A short nasal process of the premaxilla has been reported as a possible synapomorphy of phocoids (Wyss and Flynn, 1993; Berta and Wyss, 1994). However, a shortened contact between the premaxilla and nasal bones occurs in a variety of fossil taxa, including *Potamotherium*, which displays shortened nasalsand *Amphicticeps,* which displays elongated nasals. Additionally, adult male specimens of *Arctocephalus* display a premaxilla-nasal contact that is no less shortened than that examined in several genera of phocids (e.g., *Phoca, Halichoerus*).

21. Antorbital process (modified from Deméré, 1994b**)**

 0=absent or small

1=present on maxilla/frontal suture

2=present on maxilla

3=present on frontal

The plesiomorphic condition is a small antorbital process, represented by either a small bump or a vertically-elongated and slightly-protruding extension of the frontal and/or the maxilla. odobenids and otariids display larger antorbital processes, though the placement of these processes slightly differs. Some other arctoids, like *Potamotherium*, and *Enhydra,* occasionally display small, but conspicuous antorbital processes that project well into the orbit.

22. Lacrimal

 0=present, contact maxilla only,

1=present, contacts maxilla and jugal

2=absent

3=foramen present, but sutures in adult are fused

The lacrimal is large in most arctoids, but is lost in pinnipeds. It is difficult to code this character for many pinnipedimorphs, and some other musteloids, as the lacrimal become well-fused to the surrounding bones throughout ontogeny, obscuring the extent of the lacrimal and even its presence. In otariids, the lacrimal is present at an early age, but fuses to the maxilla and frontal (not the jugal) (King, 1971; Berta and Wyss, 1994). Wozencraft (1989) noted the presence of a vestigial lacrimal foramen in otariids, and Bininda-Emonds and Russell (1996) observed a similar vestigial foramen in *Odobenus.*

23. Zygomatic arch

0=horizontally flat,

1=slightly dorsally arched

2=strongly dorsally arched, steeply inclined from the glenoid.

The zygomatic arch is plesiomorphically only slightly dorsally arched. In some pinnipeds, it becomes horizontally flat or ventrally arched anteriorly. Measurements are taken from the most dorsal point of the glenoid to the most dorsal point of the zygomatic arch, not including the jugal process. Skull height is taken from the most dorsal point of the glenoid to a point along the dorsal edge of the skull that is aligned to the coronal plane.

24. Posterior portion of zygoma in dorsal view (Churchill and Boessenecker, 2014: character 38)

0=straight or somewhat medially bowed

1=deflected laterally

25. Zygomatic arch, jugal-maxillary contact in ventral view

 0=interlocking

 1=overlapping.

In state 1 (overlapping), the maxilla is medial to the jugal. In state 0, the most posterior process of the maxilla occupies a portion between the upper and lower processes of the jugal, appearing arrow-like.

26. Zygomatic arch, jugal-squamosal contact in lateral view (modified from Kohno, 2006: character 19)

 0=overlapping, anterior end of squamosal immediately posterior to postorbital process of the jugal

1=interlocking

2=overlapping, with anterior end of squamosal located well posterior to the postorbital process of the jugal.

3=thin and shortened

For state 1 (interlocking) the jugal-squamosal contact forms a V-shape that points anteriorly, exemplified by *Allodesmus* or *Desmatophoca*. For state 2, the anterior end of the squamosal, where it overlies the jugal, is thinner than the jugal. For state 3, the jugal and squamosal are only weakly fused, even in adult odobenines, representing a synapomorphy for the clade.

27. Frontal, supraorbital process (modified from Berta 1991: character 7))

 0=small, not projecting

1=absent

2=large, forming a shelf-like, quadrate, lateral projection

3= extensive; temporal crests continue into laterally projecting process that comes to a point

Situated at the dorsal-most portion of the interior margin of the orbit, the supraorbital processes are plesiomorphically thin and laterally-projecting in canids (state 3), but become reduced and do not project laterally in stem arctoids (state 0). odobenids and phocids display a complete lack of supraorbital processes, while otariids display large, anteroposteriorly widened supraorbital processes that also project significantly laterally. This trait may be correlated with size of the frontal sinuses, which often are housed by or incompletely protrude into the supraorbital processes.

28. Optic Foramina, visibility through skull in lateral view (modified from Furbish, 2015: character, 20)

0=do not pierce skull, or produce a slight opening not immediately visible in lateral view

1=pierce skull in the form of a large, immediately visible opening

State 0 is typical for carnivorans, in which optical foramina are present on the lateral surface of the postorbital region, opening into obliquely angled optic canals. In some arctoids, the optic foramina may be just barely visible on the other side of the skull if the skull is oriented in a very specific manner. We do not code this condition as derived. Alternatively, in state 1, characterizing later diverging otariids, the optical foramina contact each other, and this confluence produces a common fissure visible on both sides of the skull.

29. Alisphenoid canal, foramen rotundum

0=located within alisphenoid canal, separated from orbital fissure

1=located within alisphenoid canal; alisphenoid shares common opening with orbital fissure

2=separate individual opening; separated from alisphenoid canal (if present) and orbital fissure/anterior lacerate foramen

3=shares a common opening with orbital fissure

30. Alisphenoid canal, caudal (alar) opening (modified from Wolsan, 1993: character 4)

 0= present

1= absent

In many mammals the alisphenoid canal (alar canal) opens posteriorly forming the caudal alar opening located near the foramen ovale. The alisphenoid canal is independently lost in mustelids (not including paleo-mustelids/oligobunines) and phocids, with possible independent losses occurring in *Potamotherium*, and possibly *Mionictis.* Other pinnipeds typically display a shortened alisphenoid canal. One specimen of *Callorhinus ursinus* (ROM 94.1.8.3 (Mam. 31E.1.2)) lacks an alisphenoid canal on its left side, leaving behind only a shallow groove (there is no sign of breakage on this specimen.

31. Alisphenoid, pteryoid strut bracing posterior part of palate against braincase (Kohno 2006: character 13)

0=slender

1=dorsoventrally thin and laterally projected

2=dorsoventrally thick and laterally broad

3=laterally thin and rolled

32. Parietal-squamosal contact (Furbish, 2015: character 13)

0=straight

1=parabolic

33. Squamosal, postglenoid foramen (Wyss and Flynn, 1993)

 0=present and large

1=vestigial or absent

The post-glenoid foramen connects the external jugular vein and the superior venous sinus (Wyss and Flynn, 1993). Most arctoids have a large postglenoid foramen, posteriorly appressing the glenoid fossa. The post-glenoid foramen is completely absent in pinnipeds, and reduced in their fossil relatives, including *Enaliarctos* and *Puijila.* Tedford (1994) suggests the loss of the post-glenoid foramen may be an adaptation for internal jugular drainage, and thus may be convergent in these taxa.

34. Glenoid fossa (Kohno 2006: character 26)

 0=deep

 1=shallow and anteroposteriorly broad

 2=laterally-shortened

35. Anteroventrolateral corner of braincase (modified from Mitchell and Tedford, 1973; Churchill and Boessenecker, 2014: character 49)

0=smoothly rounded

1=square; nearly forms a right angle

36. Squamosal, pseudosylvian sulcus on braincase (Berta, 1991: character 17)

 0=weakly present or absent

1=prominent

The pseudosylvian fissure is formed in the anterior half of the brain and is oriented vertically, or slightly caudally. In some taxa the fissure is very deep and results in the formation of a corresponding groove that can be seen on the outside of the braincase. Many fossil pinnipeds, including *Potamotherium,* the Enaliarctines and the DesmatoPhocines, display a prominent pseudosylvian sulcus, while many later-diverging pinnipeds lack this feature, or exhibit a reduced condition, including *Acrophoca* and *Imagotaria.* To our knowledge, a prominent pseudosylvian sulcus has not been reported in fully mature specimens of any extant pinnipeds. However, all adult male specimens of *Arctocephalus* possess a prominent indentation in the position of the pseudosylvian sulcus. Furthermore, juvenile individuals of other crown otariid genera (e.g., *Callorhinus*)may also display a prominent pseudosylvian sulcus. Some other musteloids, including *Ailruus* and *Sthenictis* display a very weakly defined pseudosylvian sulcus.

37. Postlateral sulcus aka entolateral sulcus (Wolsan, 1993; character 11)

 0=absent

 1=present

38. Cruciate sulcus (Radinsky, 1971)

0=large or unreduced

1=absent or very reduced

39. Postsylvian sulcus (Bryant et al., 1993: character 37)

0=long; vertically oriented

1=short; no ventral extension

40. Coronal Gyrus

0=narrow

1=expanded; wide

The coronal gyrus, enclosed anteriorly by the coronal sulcus and posteriorly by the suprasylvian sulcus, roughly corresponds to the primary somatosensory cortex (Radinsky, 1968; Sawyer et al., 2016) and is anteroposteriorly broadened (state 1) in some semi-aquatic taxa (excepting *Enhydra*). Some pinnipedimorphs display an intense broadening of this area. Extant pinnipeds typically display a coronal gyrus that is less obliquely-oriented, and less broadened than that of pinnipedimorphs but still large relative to that of terrestrial carnivorans (personal obs.). The somatosensory cortex in pinnipeds is not as strictly circumscribed by the coronal sulcus, explaining the partial reduction in coronal gyrus size. In state 0, the coronal gyrus is not particularly enlarged compared to the other gyrii of the brain.

41. Squamosal, mastoid process (modified from Berta and Wyss (1994): characters 23 and 24)

0=not prominent

1=laterally projecting with a curving ventral extension; anteroposteriorly constricted

2=laterally projecting, anteroposteriorly constricted with a concave posterior face

3=laterally projecting and dorsoventrally constricted/bulbous

4=pachyostotic

The extent of the mastoid process may not be completely independent of the extent of the mastoid sinus. Thus, our character states for the mastoid depend on the extension beyond the endocranial swellings. In state 2, the posterior surface of the mastoid process may be strongly concave (as in *Puijila*), or weakly concave (as in *Enaliarctos emlongi*).

42. Squamosal, Paroccipital process

0=small with no discernable shape

1= enlarged and exacavated

2= enlarged and unexcavated

3=rod-like; much longer than wide

4=flattened and wider than long

5= mediolaterally compressed; comes to a point ventrally enlarged and exacavated

The paroccipital process serves as the origin of the digastric muscle, which is the sole muscle used to open the jaw (Ewer, 1973). A discrepant distribution of the various states across caniformes suggests the size and shape of the paroccipital process are highly homoplastic. The relationship between the paroccipital and the mastoid appears to have phylogenetic significance in arctoids (Berta and Wyss, 1994).

43. Relationship between paroccipital and mastoid processes (modified from Berta and Wyss (1994): character 24)

 0=not closely associated or connected by a low (dorsally high) ridge

 1=connected by a high crest

44. Squamosal, suprameatal fossa (Wang et al, 2005: character 5)

0=absent or a mere depression,

1=small dorsal excavation

2=dorsally deep

3=partially covered anteriorly

The suprameatal fossa is a concavity formed on the cranial surface of the external auditory meatus. A small suprameatal fossa arises independently multiple times, becoming enlarged in some musteloids (Wang, et al., 2005), and appearing partially closed by posterior wall of meatus, as seen in some musteloids including mustelines (weasels) and lutrines (otters) among others (Wolsan, 1993).

45. Squamosal, epitympanic recess and epitympanic sinus (modified from Wolsan, 1993: character 9 Decker and Wozencraft, 1993; Bryant et al., 1993: character 34; Ahrens, 2012: characters 23 and 24)

 0=absent

 1=present but unexpanded

 2=expansion into mastoid and squamosal areas to produce a large accessory chamber

 3=very deep (dorsally excavated) epitympanic recess, reaching above promontory, and mediolaterally wider than carotid canal

 4=epitympanic recess not expanded, but middle ear cavity invades mastoid region via posterior expansion

The epitympanic sinus is an accessory cavity of the tympanic cavity located lateral and somewhat dorsal to the epitympanic recess, to which it opens into. Possession of an epitympanic sinus (state 1) was previously considered a synapomorphy of Procyonidae, but inspection of XRHCT data has challenged this interpretation (Ahrens, 2012). Ahrens defined the epitympanic sinus as a dorsal expansion of the epitympanic recess. We prefer Segall’s (1943) and Whitmore’s (1953) definition, though we agree with Ahrens (2012) that possession of the epitympanic sinus is more broadly distributed than previously believed. Neverthless, the Procyonidae may display a unique state, in which the the epitympanic sinus continues posteriorly as a canal that does not open into the tympanic cavity. *Canis* and *Melogale* display a similar condition, but their ‘canal’ abruptly ends nearly as soon as it becomes ventrally encompassed by temporal bone, while the canals of *Procyon* and *Potos* are further elongated, and are at least incipiently separated from the epitympanic recess. State 2, an extreme expansion of the epitympanic recess into the mastoid and squamosal, is a synapomorphy of mephitids (Wang et al., 2005), with at least one mephitid ancestor displaying a dorsally excavated epitympanic recess that does not penetrate the tympanic bone, possibly a transitional stage toward a completely formed mastoid sinus. Some mustelids display a mastoid sinus which is similar in appearance to the mastoid sinus of mephitids, but has no connection with the epitympanic recess, and is thus unlikely to be homologous (Geraads and Spassov, 2016). A deeply excavated and significantly broadened epitympanic recess (State 3) occurs in phocids (excluding monachus) and desmatophocids.

NOTE: The suprameatal fossa of mustelids, which extends ventrally and is closed anteriorly by the wall of the meatus, appears in a similar area to the epitympanic sinus, but ostensibly shares a similarity in form to the suprameatal fossa, and is thus, hypothesised be homologous with the suprameatal fossa rather than the epitympanic sinus.

46. Basioccipital (modified from Berta and Wyss, 1994: Character 42)

0=not broadened

1=broad between bullae

2=short; wide and broader posteriorly

In most carnivorans the basioccipital is long and narrow. In many arctoids this element is broadened in ventral view, whereas in pinnipeds such as odobenids and phocids, the basioccipital is broader still, and also widens posteriorly. For measurements compare width of BO anteriorly with width of BO posteriorly near carotid foramen

47**.** Caudal portion of Basioccipital, in ventral view

0=no keel/crest; no excavation or minor excavation restricted to lateral portions

1=median keel present; no or little excavation

2=median keel prominent and diverges anteriorly to produce a Y-shaped crest; no or little excavation

3=Y-shaped crest prominent and encases deep triangular excavations on either side of median keel

A flat basioccipital is observed in many mustelids and phocids. Excavation of the lateral portions of the basioccipital is present in many taxa, to accommodate the rectus capitis ventralus muscles. This excavation is variable in its depth, and may or may not be paired with a median keel, which may or may not diverge anteriorly into two oblique crests.

48. Basisphenoid, in ventral view (modified from Berta and Wyss, 1994: character 44)

 0=concave

1=convex

49. Basioccipital, inferior petrosal sinus (modified from Tomiya and Tseng, 2016)

0=indistinct embayment on lateral wall of basioccipital

1=shallow embayment; sinus with well-defined medial margin, but not particularly large

2=deep basioccipital embayment; sinus is deep with both medial and lateral edges sharp and well defined

This character refers to the portion of the petrosal sinus that is medial to the petrosal.

This character is most reliably identified in coronal slices of the basioccipital from CT data, but can also be visible if an unobscured dorsal view of the basioccipital region is possible. In the Amphicyonid condition, the lateral border of the basioccipital is strongly excavated, in the region running alongside the petrosal and carotid canal, resulting in a deep embayment enclosed by strong dorsal and ventral arms. In most other caniformes, including mustelids, only a minor dorsolateral excavation is present, and the shallow embayment lacks prominent arms. In some caniformes, no excavation is present whatsoever.

50.Basioccipital, posterior lacerate foramen

 0= small

1=large and round

2=large, transversely oval

3=anteroposteriorly enlongate fissure

The posterior lacerate foramen allows for the passage of the glossopharyngeal, vagus, and spinal accessory nerves. In caniformes, this opening also accommodates the internal jugular vein, except in some mustelids, who display a separated jugular foramen.

51. Auditory bulla, carotid canal, posterior opening (Wang, 2005: character 4)

0=adjacent to posterior lacerate foramen

1=considerably anterior to posterior lacerate foramen

State 1 arises independently in phocids and many musteloids. *Monachus* displays state 0, indicating that state 1 arose independently in phocids and desmatophocids.

52. Auditory bulla, carotid canal, anterior opening

 0=vertical

1=horizontal, visible only from bullar chamber

In an intact skull the carotid canal opens so that it is visible on the ventral surface of the skull (character state 1). In character state 2, the carotid artery reaches the braincase from within the bulla, and does not show any external opening.

53. Auditory bulla, tubular external auditory meatus (Wolsan, 1993; character 8)

0=no differentiation of meatal trough of ectotympanic

1=meatal trough less than 1/3rd length of bulla

2=meatal trough more than 1/3rd length of bulla

54. Auditory bulla, ectotympanic, pseudoseptae (Wang, 2005: character 37)

0=absent

1=present

55. Crista tympani

0=small diameter; strongly produced into tympanic cavity

1=large diameter; not strongly produced into tympanic cavity

The tympanic crest (=crista tympani; =crista tympanica) is a medial projection of the lateral portion of the tympanic bone into the tympanic cavity, ventral to the external auditory meatus. In state 0, the tympanic crest is dorsoventrally thin and flange-like, and extends significantly into the tympanic cavity. In state 1, the tympanic crest is large both anteroposteriorly and dorsoventrally, but does not project as a flange significantly into the tympanic cavity. Tedford (1976) used this trait to ally *Enaliarctos* with otarioids and *Potamotherium* with phocids.

56. Cerebellar (=subarcuate=floccular) fossa

0=broad and deep

1=filled in by bone

Anteriorly, the subarcuate fossa, or cerebellar fossa, which houses the paraflocculus, begins as a medial excavation of the dorsal portion of the petrosal. In state 0, the subarcuate fossa expands posteriorly and eventually becomes enclosed by the petrosal. This fossa is large in canids and Carnivoran ancestors (*Miacis*), and experiences a great deal of variability in arctoids. In state 1, the fossa is filled in by bone and is not readily discernible. The polarity of this trait was formery used to support a closer relationship between otariids and odobenids, but was seemingly discarded in the pinniped literature after Wyss (1987) comprehensively mapped the polarity of this feature in arctoids, determining both states were widespread among arctoids and the trait was not phylogenetically informative.

57. Carotid canal in ventral view (modified from Churchill and Boessenecker, 2013; 43; Bininda-Emonds and Russell, 1996; character 82)

 0=obscured by medially-inflated caudal entotympanic; smoothly integrated into bulla

 1=caudal entotympanic not medially-inflated; carotid canal well visible in ventral view and not smoothly integrated into bulla

 2=caudal entotympanic projects medially and overhangs carotid canal

58. Auditory bulla

0=flattened

1=inflated and rounded

2=greatly inflated

3=very small, covering only a sliver of the tympanic cavity; not well-ankylosed to rest of skull

In character state 2 the caudal entotympanic portion of the bulla is inflated to such a degree that in ventral view it overhangs the posterior lacerate foramen. In some cases the posterior lacerate foramen may be obscured. State 3 is displayed by *Temnocyon*, fossil of which rarely preserve an entotympanic (Hunt, 2011).

59. Auditory Bulla, Posterior projection

 0=absent

 1=present

The tympanic bulla displays a posterior projection that may also overhang the posterior lacerate foramen, however, this obscurity is not caused by great inflation of the caudal entotympanic. (Churchill and Boessenecker, 2014)

60. Auditory bulla, caudal entotympanic (Hunt, 1974)

 0= Type B; entotympanic contributes significantly more than ectotympanic

 1= Type A; entotympanic and ectotympanic contribute similarly to bulla

61. Tympanohyal depression (modified from Bininda-Emonds and Russell, 1996: character 111)

0=closely associated with stylomastoid foramen,

1=separated and located posterior and/or medial to stylomastoid foramen

2=separated and located anterolateral to stylomastoid foramen

The tympanohyal depression provides a surface of attachment for the tympanohyal cartilage that is the most proximal element of the hyoid apparatus. This depression varies in size and depth across arctoids but is typically positioned posterior and/or medial to the stylomastoid foramen, and posterolateral to the auditory bulla, and may share a common fossa with the stylomastoid foramen, which permits the facial canal an exit from the skull. In many musteloids, it is very closely associated with the stylomastoid foramen (state 0), whereas in others, it is separated by a bony flange or a process (state 1). In phocids, the tympanohyal depression is widely separated from the stylomastoid foramen, and uniquely located antero-lateral to it (state 2).

62. Petrosal in ventral view, visibility in posterior lacerate foramen (Berta and Wyss (1994), character 34)

 0=not visible

1= visible

In most arctoids the petrosal in the intact skull is not visible on the ventral surface of the skull (state 0). In character state 1 the petrosal is readily visible, and forms the anterior rim of the posterior lacerate opening.

63. Petrosal, connection to surrounding elements (Wozencraft, 1989; Bininda-Emonds and Russell, 1996)

0=well-fused ventromedially with basioccipital and laterally with temporal bone

1=loosely attached to surrounding bones; sits atop basioccipital, rather than firmly affixed to it

Repenning (1972) noted the petrosal isolation of the petrosal in phocids. HRµCT allows for this feature to be clearly distinguishable. In pinnipeds, the petrosal, or at least its anterior portion, never fully fuses to the basioccipital, or the temporal bone. In ‘fissipeds’, these bones appear fully fused.

64. Tentorium (Wozencraft, 1988: character 43;: character 14; Kohno, 2006: character 29)

 0=far from petrosal

 1=appressed to petrosal

 2= reduced

3=absent

In state 0, the tentorium is large, and while it does not directly appress the petrosal, it may originate just lateral to it. In state 1, the tentorium begins as a thickened, medially projecting process located just anterior and dorsal to the lateral half of the petrosal’s dorsal surface, so that it appears this portion of the tentorium is perched upon the petrosal. In state 2, the tentorium is reduced, and its ventral-most portions contact the basicranial region well posteriorly of the tympanic bullae, or in the case of *Canis*, contact the temporal bones laterally. In state 3, the tentorium is completely absent, as observed in mephitids.

65. Bony Falx (Nojima, 1990)

0=absent

1=present, vertical; arises at junction with tentorium or anterior to it

2=present, only posteriorly as skull narrows

66. Petrosal, internal auditory meatus (Wyss and Flynn, 1993)

 0= single rounded opening,

1= two openings, conjoined

2= two foramina

The internal auditory meatus transmits cranial nerves VII, and VIII. In state 0, these nerves share a common opening, or are only incipiently separated internally (the separation is not readily visible) (Sanfelice and Drehmer, 2013). In state 1, the nerves display a bilobed opening, readily apparent on the surface of the petrosal. In state 2, observed in phocids, distinctly separate openings exist for each nerve. State 1 has previously been proposed as an odobenid synapomorphy. However, a similar degree of separation is occasionally observed in *Potamotherium, Enaliarctos*, and some crown otariids. It is unclear if this condition departs significantly from the plesiomorphic condition.

67. Petrosal, fossa for tensor tympani muscle (modified from Berta and Wyss, 1994: character 30)

 0=present as a dorsomedially excavated pit

1=absent

2=shallow groove restricted to lateral portion of promontory

Plesiomorphically for arctoids, the tensor tympani inserts on a depression on the lateral promontory wall, just anterior to the oval window. The fossa for the tensor tympani is typically very dorsally deep, although it becomes shallow in some pinnipedimorphs. In later-diverging pinnipeds, the tensor tympani inserts on the wall of the Eustachian Canal. *Pteronarctos* displays a unique condition, in which a groove on the lateral promontory wall is present, but it is not accompanied by any dorsal excavation.

68. Petrosal, Posterior promontorium process(Wang et al, 2005: character 27)

0=absent

1=present.

69. Petrosal, fenestra cochleae (= round window) (Wozencraft, 1988: character 42; Berta and Wyss, 1994: character 33)

 0=opens into middle ear

1=opens externally (External Cochlear Foramen of Burns and Fay, 1970; de Muizon 1982a)

70.Petrosal, fenestra cochleae (=round window) (Wozencraft, 1988: character 43; Wyss and Flynn, 1993: character 24)

 0=approximately equal in size to oval window

1=larger than oval window

In pinnipeds, a cochlear fossula is present, which is a distinct recess in the auditory capsule housing the round window (variably present in *Potamotherium* according to Flynn, 1988). (see Wyss, 1987 for alternative view on state definitions and coding of *Potamotherium)*

71. Petrosal, basal whorl of cochlea (Wozencraft, 1988: character 44; Wyss and Flynn, 1993: character 28)

 0=posterolateral orientation

1=transverse to skull

72. Petrosal, canal for cochlear aqueduct (Berta and Wyss, 1994: character 32)

0=pierces the petrosal

1=merged with the round window

73. Basal whorl of scala tympani (Berta and Wyss, 1994: character 27)

0=small

1=enlarged

The basal whorl of the scala tympani is enlarged in pinnipedimorphs, including *Enaliarctos*.

74. Petrosal, shape in dorsal view (Berta and Wyss, 1994: character 29)

 0= flattened with pointed apex

1= inflated, rounded with apex not pointed

2= greatly expanded with rounded apex blunter in outline

The apex refers to the anterior portion of the petrosal. In dorsal view, the petrosal is typically flattened, with a sharply pointed apex anteriorly. In most pinnipeds, the petrosal becomes somewhat dorsally inflated, and loses the sharpness of its apex, though retaining the general triangular shape of terrestrial carnivorans. In most phocids, the petrosal is further expanded dorsally, covering the entirety of the ventral portion of the petrosal in dorsal view, and the apex becomes blunt and amorphous, losing its triangular shape.

75. Incus (=epitympanic recess) (Berta and Wyss, 1994: character 46)

 0=small

1=moderately large

2= large

3=very large

A greatly enlarged incus occurs in desmatophocines and phocids. This trait appears independent of the presence of an epitympanic recess. Enlarged ossicular mass is likely an adaptation for underwater hearing (Nummela, 2008)

76. Malleus, muscular process (Berta and Wyss, 1994: character 47; Flynn et al., 1988: characters 21, 22)

 0=present, large process

1=present, small bump

2= absent

The muscular process is large in most fissipeds. Its apex serves as the insertion for the fossa for the tensor tympani (Miller, 1979). However, a reduction of the muscular process is observed in ursids (Wyss, 1987), though the fossa for the tensor tympani still inserts in a similar location on the malleus (Ruf and Maier, 2010). Thus this character is likely independent of character \_\_.

77. Malleus, processus gracilis and anterior lamina (Wyss 1987; Wyss and Flynn, 1993)

 0=well developed

1=small or vestigial

Reduction of the processus gracilis and anterior lamina characterizes pinnipeds. Some codings from Segall (1943)

**Mandible**

78. Flange below mandibular angle (Berta and Wyss, 1994: character 52)

 0=absent

1=present

This flange provides attachment for the digastric muscle. In arctoids, the ventral margin of the mandible is typically smoothly curving in a dorsal direction towards the angular process. However, in some pinnipeds, including many phocids, desmatophocids, and *Otaria,* the ventral margin of the mandible drops slightly ventrally posterior to the molars, and then curves rather abruptly dorsally beneath the mandibular angle. This area serves as the insertion site for the digastric muscle (Mori, 1958; Ewer, 1973)

79. Ascending ramus **(**modified from Wang et al., 2005: character 25)

 0=projected dorsally

1=inclined posteriorly

2= inclined anteriorly

80. Genial Tuberosity (Boessenecker and Churchill 2013: character 37)

 0=Weakly-developed; Deepest point of mandible positioned centrally/posteriorly

 1=Strongly developed; Deepest point of mandible positioned anteriorly

The genial tuberosity is a ventral expansion of the mandibular symphysis, typically observed in lateral view, and best exemplified by *Kolponomos* and the desmatophocids.

81. Angular process in ventral view

0=aligned with rest of ventral margin of mandible

1=deflected laterally

2=deflected medially and/or canted mediolaterally; not significantly expanded

3=deflected medially; significantly expanded process

82. Mandible, anterior portion of symphyseal region (Boessenecker and Churchill 2015, character 38)

 0=Smooth compact bone

 1=Rugose, vascular bone

**Dentition**

83. Shape of Upper Incisor Row (Welsey-Hunt and Flynn, 2005)

 0=straight

 1=parabolic

84. I1 (Wozencraft, 1988)

 0=present

1=absent

85. I1 and I2, crown, transverse grooves (Wozencraft, 1988: character 58)

 0=absent

1=present

In state 1, the transverse grooves are remarkably distinct, abruptly penetrating the posterior face (occlusal surface) of the incisor roughly midway up the crown.

86. I3, lingual cingulum ((Berta and Wyss, 1994: character 59)

 0=present

 1=absent

87. Canine, lateral groove

 0=absent

 1=present

This groove travels along the length of the lateral surface of the canine, gently curving to follow the long axis of the canine. They appear in ailurids and potosine procyonids (Wang, 1997; Wallace and Wang, 2004; supplementary)

88. P1 (Wyss and Flynn, 1993: character 33)

 0=present

1=absent

The P1 is plesimorphically present in arctoids. The P1 is lost independently in neomustelids, *ailurus,* and in some hypercarnivorous arctoids, like the canid *Enhydrocyon* and the ailurid *Simocyon.*

89. P1- P2 lingual cingula (Kohno, 2006: character 45)

0=distinct but small

1=well-developed with cuspules

2=weak and bulbous

90. P2, pseudoprotocone (Wyss and Flynn, 1993 : character 34)

 0=small, fissiped-like, or absent

1=large, molarized with cingula

State 1 refers to a mesial-bucally expanded P2 that resembles the molars in size and complexity. This arises independently in *Ailrurus* and *Kolponomos.*

91. P3 protocone shelf expanded lingually

 0= absent

 1= present

State 1 refers to molarization seen in the P3 of some pinnipeds. In these cases the tooth roots may also be expanded in size. In some early arctoids, the P3 is somewhat lingually expanded, with partially bilobed posterior roots. However, these early arctoids lack development of the lingual portion of the crown, and are thus coded as possessing the plesiomorphic state.

92. P4, parastyle (4) Wyss and Flynn, 1993: character 35)

 0=absent or vestigial

1=present

The parastyle of the P4 is lost in later-diverging mustelids, but is present in paleomustelids, neomustelids, procyonids and their ancestors, *Puijila* and *Mustelavus*. The basal condition for Arctoidea appears to be the absence of a well-developed parastyle. The parastyle appears to have arisen early within Mustelida, before being lost again in mustelids. The presence of this trait in *Puijila* may represent a retention of the basal condition or an independent acquisition.

93. P4, carnassial notch (Wozencraft, 1988: character 67)

 0=present

1=absent

2=vestigial

A well-developed carnassial notch is the basal condition for arctoids, and caniformes more broadly. The carnassial notch is lost independently in crown pinnipeds and neomustelids.

94. P4, protocone (modified from Wang et al., 2005: characters 10 and 11)

0 = conical and anteriorly positioned relative to the paracone

1= conical and centrally or posteriorly positioned relative to the paracone

2= shelf like and posteriorly positioned, no hypoconal basin

3= shelf like and with hypoconal basin

4=absent

5=conical and with hypocone

6=shelf-like and centrally positioned relative to protocone

In some carnivorans, including ursids and basal pinnipeds the protocone is undifferentiated, forming a shelf (= “crescentic protocone” of Wolsan, 1993). In derived pinnipeds, including *Thalassoleon*, the protocone is completely absent (see also Berta and Wyss, 1994: character 63). (modified from Wang et al, 2005: character 33). Character states 0 and 1 are associated with the presence of a cingulum.

95. Premolar/Molar relative size (Wozencraft, 1988: character 76)

 0=approximately equal in size

1=M considerably reduced

2=M enlarged

The basal condition is ostensibly premolars and molars of equal size. The extreme reduction of molars characterizes pinnipeds and their fossil ancestors, but is also observed convergently in *Enhydrocyon.* Molar enlargement occurs in ursoids, and in littoral taxa that use their molars to crush sea-shells (*Mionictis,* possibly *Kolponomos*). Molar reduction is thought to be associated with hypercarnivory in some carnivorans, including the clade containing felids and hyaenids (Wyss and Flynn, 1993). A reduction of the M1 also characterizes several arctoids which are known to be or thought to have been hypercarnivorous, including *Gulo, Megalictis,* and the earliest-diverging pinnipedimorphs.

96. P4, rooting (Boessenecker and Churchill, 2015: character 71)

0=3-rooted

1=3-rooted but posterior root bilobed

2=2-rooted

3=1-rooted

97. P4, Metastyle length (modified from Berta 1991: character 7; Berta 1994: characters 22 and 26)

 0=long; comparable in length to parastyle, or longer

 1=short and thin

 2=short and broad, with accessory cusps

 3=suppressed

98. M1, hypocone (Wozencraft,1988: character 74)

 0=lingual cingulum well developed, but no cusp

1=absent

2=present

The presence of a distinct cusp (the hypocone) on the lingual border of the M1 appears to be the plesiomorphic condition in arctoids, with the cusp being replaced by prominent cingulum in ursids, mustelids, procyonoids, and ailurids, and the cusp being completely lost in pinnipeds, early neomustelids (*Plesiogale/Paragale)*, and possibly Amphicynodontinae (*Kolponomos/Allocyon)*

99. M1, metaconule (Flynn et al., 1988: character 27)

 0=present, small

1=present, large

2=absent

A small metaconule (=cuspule between metacone and protocone) is the plesiomorpic condition for arctoids. A distinctly large metaconule characteries crown ursids (and *Kolponomos)* and ailurids. The metaconule is absent in early-diverging Amphicyonids, early-diverging ursoids, paleomustelids and their descendents, and pinnipeds.

100. M1, paraconule (Tedford et al., 1994 : character 8)

 0=absent or small

1=present and large

The paraconule is a small cuspule located between the paracone and the protocone, typically along the path of the preprotocrista.

101. M1, metacone vs paracone (Wesley-Hunt and Flynn, 2005: character 48)

 0=paracone>metacone

1=paracone < or equal to metacone

Coding was applied only to unworn or little worn cusps. Height was observed in lateral view.

102. M1, protocone and metaconule, longitudinal crest (modified from Flynn et al., 1988: character 28)

0=present and oriented laterally,(45 degrees or more)

1=present and oriented posteriorly

2=absent

Also referred to as the postprotocrista(Wang et al, 2005: characters 23 and 29. A prominent postprotocrista is the basal condition for arctoids, and characterizes Ursidae, Amphicynodontinae, and Amphicyonidae. A reduction of the postprotocrista occurs in mustelids. The postprotocrista was independently lost in pinnipeds and mustelids. *Leptarctus* has a vestigial postprotocrista, as does *Puijila.*

103. M1, preprotocrista (modified from Finarelli, 2008: character 47))

0=present

1=absent

104.M1, parastyle (Tedford et al., 1994: character 7)

 0=present

1=present, large

2=absent

Absence of a parastyle may be the basal arctoid condition, and reappears several times within Arctoidea. A small parastyle characterizes musteloids, some canids and some Amphicyonids, and may alternatively represent the plesiomorphic condition. The derived condition is a bulkier parastylar wing that protrudes mesiobuccally and rises well above the level of the paracone or metacone. This condition may have arisen early within Arctoidea (*Mustelavus)* and retained in early-diverging mustelids (paleomustelids and leptarctines) and early-diverging pinnipeds.

105. M1, constriction between paracone + metacone and protocone (Wozencraft, 1988: character 75; Wolsan, 1993: character 17)

 0=absent

1=present

State 1 refers to the internal constriction or ‘pinching’ observed in some arctoids, namely the oligobunines (Wolsan character 17:c-d)

106. M1, lingual vs buccal half (Wolsan, 1993; character 17)

 0=buccal half longer

 1=equal

 2=lingual half longer

107. M1, rooting (Kohno, 2006: character 49)

0=3-rooted

1=2-rooted

2=1-rooted

3=M1 absent

In state 1, the posterior roots of the M1 may be bilobed.

108. M2, size (Flynn et al., 1988: character 25)

 0=present, nearly equal in size to M1 (more than 0.5x M1 size)

1=reduced (less than 0.5x M1 size)

2=absent

3=present, large (as large or larger than M1)

“Reduced” molars (state 1) are smaller in size than M1, and have one or two roots.

109. M2 position (Tedford et al., 1994: character 24)

 0=posterior or posterolateral to M1

1=posterolingual to M1

The M2 is considered posterolingual to the M1 when its buccal border is aligned with or located lingual to the linguo-buccal centre of the M1.

110. M2, metaconule (Tedford et al., 1994: character 6)

 0=small or not developed

1=developed

2=absent

111. M2, Postprotocrista

0=Present

 1=Absent

112. M2, Hypocone(Finarelli, 2008: character 56)

 0=absent

 1=cingulum

The M2 hypocone is not strongly developed in any arctoid taxa examined, appearing as an elevated ridge of lingual cingulum, much like that observed on the M1 in many arctoid taxa. An M2 hypocone is retained in canids, ailurids, and ursids, and is likely plesiomorphic for musteloids. Independent losses may have occurred in mustelids and procyonids, as a probablefossil mustelid (*Brachypsalis*)and probable fossil procyonid (*Stromeriella*) retain a hypocone.

113. M3 (Wozencraft, 1988: character 79)

 0=present

1=absent

114. I1, presence (Wozencraft, 1988: character 5)

 0=present

1=absent

All known pinnipeds, including early-diverging stem forms, like *Puijila* and *Enaliarctos*, display only two lower incisors. It is assumed the first incisor is lost, as nearly all arctoids display an I1 that is smaller than the other incisors. However, the homology of this feature is difficult to establish without ontogenetic insights. *Kolponomos* lacks an I1 alveolus, and has been coded as possessing the derived condition, a notion corroborated by CT data (Tseng et al., 2016).

115. c, posterior crista (Boessenecker and Churchill, 2013: character 57)

 0=absent

 1=present

116. Lower postcanines, roots

 0=Double

 1=Single

117. P1 (Wyss and Flynn, 1992: character 40)

 0=present

1=absent

118. Premolars, size

 0=increasing posteriorly

 1= P3= P4

State 1 refers to the condition observed in otarioids and phocids, in which the P3 and the P4 are the same size. In nearly all other arctoids, the P4 is at least somewhat larger than the P3.

119. P3, accessory cusps

0=no accessory cusps present

1=paraconid, metaconid and hypoconid present

2=paraconid and hypoconid present; metaconid absent

3=metaconid and hypoconid present; paraconid absent

4=paraconid and metaconid present; hypoconid absent

5=paraconid present; hypoconid and metaconid absent

The protoconid, the primary cusp of the premolars, may be flanked mesially by the paraconid, and distally by the closely appressed metaconid and a hypoconid situated along the distal border. These cusps are completely lacking in extant mustelids, otariids, and ursids, but appear prominently in other arctoids. Several early pinnipedimorphs display all three cusps.

120. P4, accessory cusps

0=no metaconid, distal wall of protoconid convex or flat

1=all

2=metaconid present, but lacking paraconid

3=metaconid absent; distal wall of protoconid concave

Similar to their P3 accessory cusps, mustelids have reduced the prominence of the accessory cusps of their P4, while many canids, pinnipeds, and procyonids display the full suite of accessory cusps.

121. M1, Metaconid on ml (Wang et al, 2005: character 17).

0=equal or higher than paraconid

1=lower than paraconid

2=absent.

122. M1, metaconid mesiodistal position

 0=aligned with protoconid; well-defined wall

 1=posteriorly displaced beyond protoconid; no wall

 2=posteriorly displaced beyond protoconid, so metaconid is visible in lateral view, and share a well-defined wall

In state 0, the metaconid and protoconid share an erect cliff-like wall overlooking the trigonid that is nearly perpendicular to the long axis of the tooth. In state 1, the metaconid has been posteriorly displaced compared to the protoconid, so that they do not appear to share a well-defined wall. This migration may or may not be caused by a reduction of the metaconid, which can be observed convergently in several hypercarnivorous taxa (*Enhydrocyon, Megalictis, Simocyon*) and in pinnipeds.

123. M1, hypoconid (Berta, 1991: character 21)

 0=large or unreduced

1=vestigial or absent

124. M1,talonid (Wolsan, character 22)

0=trigonid 1.5-2.5x longer than talonid

1=trigonid >2.5x longer than talonid

2=trigonid <1.5x longer than talonid

This character was quantified as the maximum length of the trigonid compared to the maximum length of the talonid. Trigonid length was measured from the anterior (mesial) most tip of the trigonid to the posterior most tip of the metaconid-protoconid wall. Talonid length was measured from the anterior-most tip of the metaconid-protoconid wall to the posterior (distal)-most tip of the talonid. Thus, in taxa with an open trigonid, there will be some overlap between the measured areas.

125. M1, Entoconid (Wang et al, 2005: character 18)

0=poorly developed or absent

1= presence of a lingual notch

2=cuspidate

Ancestrally within caniformes, the entoconid of M1 is reduced or absent. mustelids are derived in possession of a conspicuous lingual notch anterior to the entoconid, and some arctoids are derived in possessing a cuspidate entoconid.

126. M2, size (Wang et al, 2005: character 19)

0= similar in size to M1 (>0.5 length of M1 and similar width)

1= significantly smaller than M1 (<0.5 length of M1)

2 = absent

3= larger than M1

127. M2, hypoconulid (Flynn et al., 1988: characters 31, 32)

 0=small

1=absent

2=elongated

128. M2, metaconid

 0=aligned with protoconid

 1=posteriorly

129. M2, metaconid

 0=higher than protoconid

 1=lower than protoconid

 2=subequal

130. M2, entoconid (Valenciano 2016: character 72)

 0=present

 1=absent

131. M2, talonid size (Wolsan, 1993: character 27)

 0=talonid basin distinctly longer than trigonid basin

 1=talonid/trigonid basins subequal in length

 2=trigonid larger

 3=No distinction between basins

132. M3 (Wang et al, 2005: character 22).

 0=similar in size to M2

1=smaller than M2

2= absent

The M3 is lost in musteloids and pinnipeds (Berta and Wyss, 1994).

**Postcranial**

133. Atlas, cervicospinal branch

 0=present and large; well ventrally- and anteriorly-placed

 1=absent or reduced

The foramina of the cervicospinal branch, visible within the posterior transverse foramina and travelling through the vertebral body to open medially on the vertebral canal, are distinctively large in pinnipedimorphs and some early arctoids, but are reduced in many musteloids, or even absent altogether.

134. Atlas, posterior transverse foramina (Spaulding and Flynn, 2012: character 206)

 0=dorsal to transverse processes

 1=In-line with or ventral to transverse processes

In state 0 the posterior transverse foramina (or vertartebral foramina) do not pass through a significant portion of the transverse processes, but rather are anteroposteriorly reduced and run through a flange dorsal to the transverse processes, as observed in canids and pinnipedimorphs. In state 1, the canal for the posterior transverse foramina is anteroposteriorly elongated and runs through the transverse process itself.

135. Axis, Cranial Articular Processes

 0=confluent with dens

1=well-separated from dens by a ridge

136. Cervical vertebrae, size (modified from Berta and Wyss, 1994: character 77)

0=centrum of cervical roughly same size as lumbar

1=centrum of cervical <1.0 size of lumbar

2=centrum of cervical half the volume of that of lumbar

3=centrum of cervical larger than that of lumbar with reduced spinal canal half the size diameter of centrum

Size corresponds to breadth of centrum, anteroposteriorly and mediolaterally

137. Vertebrae, Neural Foramen

 0=unexpanded

 1=expanded

138. 71. Lumbar vertebrae, number (e.g., Howell, 1929)

 0=7 or 6

 1=5

139. Lumbar vertebrae, transverse processes (Berta and Wyss, 1994: character 80)

0=short; about as long as wide

1=long; 2-3times longer than wide

In coding this character, we selected the more posterior lumbar vertebrae with longest transverse processes.

140. Sacrum, number of fused vertebrae

 0=three

 1=four

 2=five

 3=two

141. Tail (Wozencraft, 1988: character 86)

 0=long

 1=vestigial

pinnipeds and some of their ancestors (*Enaliarctos*), and derived ursids display a very short tail composed of only a few caudal vertebrae (typically under 10. Other arctoids usually have many more caudal vertebrae and a longer tail.

142. Scapula, teres major process (e.g., Tedford, 1976)

 0=small or absent

 1=large

A scapula with an expanded posterodorsal region for teres musculature is found in many swimming and digging specialized mammals. Notably, because the scapula is a fragile element, and often not preserved in the fossil record, this character is unknown for most taxa.in this analysis. An expanded scapula is seen in *Puijila* + *Enaliarctos* +*Potamotherium*, but whether this character is an autapomorphy of the pinniped clade is uncertain.

143. Scapula, post-scapular fossa (Tedford, 1976; Wozencraft, 1988, Wyss and Flynn, 1993)

0=absent

1=present, prominent

2=present, modified

The postscapular fossa is located on the axillary border of the scapula, caudad of the infraspinous fossa, and is associated with the origin of the sub-scapula muscle. The post-scapular fossa is extremely excavated in derived ursids, and present, but to a lesser extent, in many procyonids and ailurids. All other arctoids lack this fossa.

144. Scapula, metacromion process (e.g., Tedford, 1976; modified from Spaulding and Flynn, 2012: character 105)

 0=small

 1=large, flange-like

The metacromion process diverges from the acromion and extends posteriorly. The metacromion is very small or absent in arctoids, except for early pinnipedimorphs and mustelids.

145. Scapula, Supraspinous Fossa

 0=similar size to or smaller than infraspinous fossa

 1=significantly larger than infraspinous fossa

146. Scapula, spine (Berta and Wyss, 1994: modified from character 84)

 0=unreduced

 1=knob-like, travelling only a short distance along the scapula

147. Scapula, secondary spine (=anterior scapular ridge) of supraspinous fossa (Berta and Wyss, 1994, character 86; Furbish, 2015, character 54)

 0=Absent

 1=present as a spine or ridge

 2=present as a scapular undulation

A well-developed secondary spine arises on the supraspinous fossa in otariids, running a similar orientation as the scapular spine, dividing the supraspinous fossa into two nearly equally-sized halves (English, 1977). This is not to be confused with the secondary spine of the infraspinous fossa of Riggs (1945) or Tedford (1976), which appears more variably in phocids, early-diverging pinnipedimorphs, and many other arctoids groups.

148. Humerus, shaft (Berta et al., 1990) (Berta & Wyss, 1994: characters 88, 90)

0=long slender, with deltopectoral ridge not strongly developed

1=short and robust with deltopectoral ridge elevated and not significantly overhanging both sides of ridge

2=short and robust with deltopectoral ridge elevated and hanging over both sides of ridge

The development of the deltopectoral ridge is best-viewed in lateral or medial aspect. In state 0, the shaft may be somewhat flattened, but lacks the strong anterior bow (the v-shape).

149. Humerus, entepicondylar foramen (Wyss, 1988)

 0=present

 1=absent

150. Humerus, supinator ridge (Wyss, 1988)

 0=present

 1=absent or poorly developed

The supinator ridge is a plate-like extension of the lateral portion of the distal end of the humerus that serves as an attachment for forearm supinator muscles. When present, this ridge may either be sharp and crest-like (state 1) or may be little more than a rounded eminence (state 1).

151. Humerus, greater tubercle

 0=rises above head

 1=ventral to or in line with head

To code this character, the humerus should be held in an upright position.

152. Humerus, lesser tuberosity (Spaulding and Flynn, 2012; character 115)

0=no crest/ridge down shaft

 1=with a crest/ridge leading down shaft

In state 1, the shaftward portion of the lesser tuberosity is cylindrical and projects considerably from the shaft. In state 0, this portion of the lesser tuberosity does not project significantly from the shaft, and may be represented by a thin, but sharp crest.

153. Humerus, Olecranon Fossa (Spaulding and Flynn 2012; character 107)

0=unperforated and deep

1=perforated

2=unperforated and shallow

154. Humerus, medial flexor muscle attachment

 0=hangs lower than distal-most portion of trochlea

 1=in line with or dorsal to distal-most portion of trochlea

155. Humerus, Diameter of distal trochlea (Kohno, 2006: character54)

 0=medial lip same diameter as distal capitulum

 1=medial lip diameter greater than distal distal capitulum

156. Radius, distal end (Wyss, 1988)

 0=not expanded anteroposteriorly

 1=anteroposteriorly flattened and expanded strongly anteroposteriorly with a small radial process

 2=anteroposteriorly flattened and expanded strongly anteroposteriorly with a large radial process

157. Radius, Pronator teres process (Berta and Wyss, 1994: character 96; Boessenecker and Churchill, 2013)

 0=absent

 1=present, on proximal 40% of radius

 2=present, distal 60% of radius

158. Ulna, Mediolateral diameter of coronoid process + lesser sigmoid notch

 0=>2x smallest GSM width

 1=<2x smallest GSM width

 2=<1x smallest GSM width

159. Ulna, olecranon process

 0=not posteriorly expanded

 1=posteriorly expanded

A posteriorly expanded olecranon is observed in crown pinnipeds.

160. Digits, length (e.g., Wyss, 1988)

 0=digit III manus and pes elongated

 1=digit I manus and V manus and pes elongated

161. Metapodials/phalanx (e.g., Wyss, 1988)

 0=keeled heads

 1=flattened heads

162. Metacarpals/Phalanges (Spaulding and Flynn, 2012: character 152)

 0=much longer than sum of phalangeal lengths

 1=phalanges are longer than metacarpals

163. Metacarpal I, insertion of pollicle extensor

0=smooth

1=pit

2=round

164. Manus, fifth intermediate phalanx (e.g., Wyss, 1988)

 0=not reduced

 1=strongly reduced

165. Manus/pes, cartilaginous extension (e.g., Wyss, 1987)

 0=absent

 1=present

166. Pes, digit length

 0=central digits elongated

 1=digits I and v emphasized

167. Innominate, ilium (e.g., Howell, 1929)

 0=long, (ilium>obturator foramen)

 1=intermediately short (ilium roughly equal in length to or slightly longer than obturator foramen

 2=short (length of obturator foramen significantly greater than length of ilium)

168. Ilium, separate foramen for obturator nerve (Berta and Wyss, 1994: character 113)

 0=absent

 1=present

169. Ilium, Ischiatic Spine

 0=not prominent

 1=dorsally and/or medially expanded

170. Pubic symphysis (Berta and Wyss, 1994: character 109)

0=unfused

1=fused

171. Insertion for Iliopsoas muscle (Berta and Wyss, 1994: character 112)

0=on femur

1=on ilium

172. Femur, shaft (e.g., Berta et al., 1989)

 0=long, round in cross section

 1=short, mediolaterally expanded

In many arctoids the femoral shaft is roughly round in cross section along the length of the shaft, but in some taxa, such as *Ailurus*, the femoral shaft distally appears mediolaterally expanded. The appearance of a femoral shaft that is expanded mediolaterally, and appears “flattened” along its length is a pinniped characteristic.

173. Femur, second trochanter (e.g., Howell, 1929; (Berta and Wyss, 1994: character 116)

 0=present, long

 1=(short) vestigial

 2=absent

Ancestrally, the second trochanter is longer than wide (nearly rod-like) and strongly medially-projecting. While some taxa display a simple bony knob (state 1), other taxa, namely phocids, lose the second trochanter completely, leaving no trace of it.

174. Femur, Ligamentum Teres Femoris (Berta and Wyss, 1994: character 115)

 0=Present

 1=Absent

175. Femur, greater trochanter height (Spaulding and Flynn, 2012: character 161)

 0=greater trochanter lower than head

1=greater trochanter higher or sub-equal than head when femur is held erect along its long axis (possibly off its condylar angle)

 2=greater trochanter higher or sub-equal than head when femur is positioned with distal condyles flat (possibly off long axis);

All pinnipedimorphs display an elongated greater trochanter that is extended upwards. However, phocids display an extreme state in which the greater trochanter is still level at or higher than the femoral head even when the femur is positioned so that the condyles are flat. The greater trochanter of the phocid femur is also flattened and obliquely-oriented. Such flattening and expansion was previously considered a pinniped synapomorphy, but we consider the otariids to display a different condition. The greater trochanter of the otariid is somewhat expanded, but does not depart significantly from the condition observed in other arctoids. It is difficult to discern the continuity of the greater trochanter with the lateral border of the femur, so we excluded that aspect from our character states.

176. Femur, trochanteric fossa (Berta and Wyss, 1994: character 119)

 0=present and unreduced (concavity is readily visible

 1=absent or very reduced (shallowly concave)

177. Femur, entepicondyloid ridge

 0=absent,

 1=present

The entepicondyloid ridge, or medial epicondylar ridge, projects significantly from the medial epicondyle as a plate-like extension, similar to the supinator ridge of the humerus. De Muizon (1982a) reported of partial development of this feature in Semantorids, in the form of a convexity dorsal to the medial epicondyle. However, this minor degree of convexity is also observed in otariids and other musteloids, and does not depart significantly from the plesiomorphic condition, and twas thus coded as 0.

178. Femur, fossa antero-proximal to trochlea

 1=present

 0=absent

This fossa serves as the insertion for the articularis genus muscle, and is located on the anterior side of the distal portion of the shaft, just dorsal to the trochlea.

179. Femur, distal termination of trochlea

 0=confluent with condyles

1=does not contact medial condyle

2=does not contact lateral condyle

3=does not contact either condyle

In most carnivorans, the trochlea is continous with the lateral and medial femoral condyles on the distal surface of the femur, producing a smooth and continuous articular surface. However, in some pinnipeds, non-articular cortical bone interrupts this surface. This discontinuity can sever the connection between the trochlea and a single condyle, or disconnect both condyles from the trochlea. While it would stand to reason that variability may be explained ontogeny, this does not appear to be the case, as fully ossified adult specimens of *Eumetopias* variably display both conditions.

180. Femur, condylar angle (Berta and Wyss, 1994: character 118)

 0=aligned with long axis

 1=>10% off long axis

181. Patella (Berta and Wyss, 1994: character 120)

 0=flat

 1=conical

182. Tibia, grooves for attachment of tibialis posterior and flexor digitorum longus (see savage, 1957; Repenning and Tedford, 1977)

 0=confluent, single groove

 1=multiple grooves, separated

In nearly all arctoids, the tibialis posterior and flexor digitorum longus share a groove on the distal portion of the tibia. Savage (1957) observed that these grooves are not confluent in *Potamotherium*, but are rather separated by a low crest. This condition is also observed in *Puijila.* In *Enaliarctos mealsi*, these two grooves are separated by a bump, rather than a distinctive keel or ridge.

183. Tibia, Fibula-Tibia Fusion (Berta and Wyss, 1994: character 122)

0=unfused

1=fused

184. Fibula, processus lateralis

 0=unreduced, splitting peroneal tendons

 1=reduced; peroneal tendons not well-separated

The processes lateralus is a keel or knob-like eminence projecting laterally from the lateral malleolus. This process, when developed, separates the long peroneal tendon from tendons of the brevis and tertius (Berta and Ray, 1990).

185. Astragalus, posterior process (e.g., King, 1983; Wozencraft, 1988: character 78)

 0=absent,

 1=intermediately developed

 2=strongly developed

This process prevents the hindflipper from being brought plantigrade (polly). In state 2, the posterior process is remarkably elongated, paralleling the calcaneal tuber. In state 1, the posterior process is somewhat developed, but is not nearly as long as the calcaneal tuber.

186. Astragalus, Confluence of navicular and sustentacular facets

 0=confluent

 1=well-separated

In state 0, a portion of the sustentacular facet extends up the neck to connect with the navicular facet. In state 1, the sustentacular and navicular facets do not contact eachother.

187. Astragalus, trochlear groove

 0=deep (>10% of dv breadth)

1=shallow (<10% of dorsoventral breadth of trochlea)

2=No groove

188. Astragalus, trochlea

 0=internal condyle higher than external

 1=equal or external condyle somewhat higher

189. Astragalus, Sustentacular facet, proximal termination

 0=confluent with proximal end of astragalus

 1=distinctively separated from proximal end of astragalus by a groove

In condition 1, the sustentacular facet does not extend far proximally into the trochlea, and is separated from the proximal end of the astragalus by a prominent groove. In condition 0, the sustentacular facet, or at least the lateral portion of it, extends to contact the proximal end of the astragalus (trochlea). The separation in otariids is not as significant as that observed in phocids or odobenids, but a groove is still present. See Wyss, 1988 for discussion of pinniped condition.

190. Astragalus, length of neck

 0=not short

1=short

State 0 refers to the lack of a projecting neck in *Ursus* and some other arctoids, so that the head barely rises above the trochlea.

191. Calcaneum, medial projection of tuber (Kohno 2006; character 59)

0=absent

1=present

192. Calcaneum, secondary shelf of the sustentaculum (e.g., Berta and Deméré, 1986)

 0=absent

 1=present

193. Calcaneum, peroneal tubercle – groove for tendon of peroneus longus

 0=absent or very reduced

 1=present

194. Calcanum, groove for gastrocnemius upon volar surface of calcaneal head

 0=strongly developed; head of calcaneal tuber concave

 1=weakly developed; head of calcaneal tuber convex

In terrestrial arctoids, the groove for the gastrocnemius is well-excavated into the volar surface of the calcaneal head, whereas in pinnipeds, the volar surface of the calcaneal head is convex. The gastrocnemius in pinnipeds likely inserts parallel to the long-shaft of the bone (Howell, 1929; Polly, 2009)

195. Calcaneum, shape of head in proximal view

 0=sub-rectangular

1=triangular

phocids lack the lateral tubercles of the calcaneal head for attachment of the superficial digital flexor (Polly), and thus, the head appears diamond- or triangle-shaped.

196. Cuboid, distal concave facet

 0=surface is uniform

 1=surface is divided by a prominent ridge, separating medial and lateral halves for IV and V metatarsal respectively

197. Cuboid, development of distal ectocuneiform facet

 0=not well-developed or absent

1=present, small and square-like

 2=present and anteroposteriorly elongated

All arctoids have a proximal ectocuneiform facet, but many lack the development of an antero-distal facet. This facet is entirely absent in most musteloids (though some musteloids display a vestigial facet – *Teruelictis)*, and reduced in phocids. The position of the facet along the distal border varies across taxa.

198. Entocuneiform/Mesocuneiform articulation (Kohno, 2006: character 60)

 0=abutting

 1=overlapping

199. Palmar process of cuneiform (Bininda-Emonds and Russell, 2006: character 162)

0=present

1=absent

200. Scapholunar, head of sesamoid process

 0=confluent with radial facet

1=on dorsal surface, head of sesamoid process separated from radial facet by a roughened/grooved area

201. Scapholunar, pit for magnum (Demere 1994: character 50)

 0=absent

1=present

202. Scapholunar, sesamoid process orientation and robusticity

 0=laterally directed and robust

 1=anteriorly directed and robust

 2=anterolaterally directed and reduced

 3=laterally directed and reduced

203. Baculum, abruptly curving distal end (Barysnikov et al., 2003: character 1)

0=absent

1=present

204. Bacula, urethral groove on ventral surface (Barysnikov et al., 2003: character 4)

0= prominent

1=shallow or absent

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| **Genus** | **Reference(s)** |
| *Acrophoca* |  |
| *Allocyon* | Merriam, 1930 |
| *Allodesmus* | Kohno, 1996; Boessenecker and Churchill, 2018 |
| *Amphicticeps* | Schmidt-Kittler, 1981; Wang et al., 2005 |
| *Amphictis* | Riggs, 1898 |
| *Arctodus* |  |
| *Brachypsalis* | Peterson, 1910 |
| *Broiliana* | Wolsan, 1993 |
| *Desmatophoca* | Deméré and Berta, 2002 |
| *Devinophoca* | Koretsky and Holec, 2002; Koretsky and Rahmat, 2015; Rahmat and Koretsky, 2016; Koretsky et al., 2016 |
| *Enaliarctos* | Mitchell and Tedford, 1973; Tedford, 1976; Berta and Ray, 1990; Berta, 1991; Berta and Wyss, 1994 |
| *Hadrokirus* | Amson and Muizon, 2014 |
| *Hemicyon* | Colbert, 1941; Ginsburg and Morales, 1998 |
| *Hesperocyon* | Wang, 1994 |
| *Imagotaria* | Kohno, 2006; Boessenecker and Churchill, 2013 |
| *Kolponomos* | Stirton, 1960; Tedford et al., 1994; Tseng et al., 2016 |
| *Megalictis* | Peterson, 1910; Baskin, 1998; Valenciano et al., 2016 |
| *Mionictis* |  |
| *Mustelavus* | Wang et al., 2005; Tomiya and Tseng, 2016 |
| *Neotherium* | Kohno et al., 1995; Kohno, 2006; Boessenecker and Churchill, 2013 |
| *Oligobunis* | Baskin, 1998 |
| *Paragale* | Radinsky, 1971; Schmidt-Kittler, 1981; Wolsan, 1993; Wang et al., 2005 |
| *Phoberogale* | Radinsky, 1971; Ginsburg and Morales, 1995; De Bonis 2013 |
| *Pinnarctidion* | Berta, 1994b |
| *Piscophoca* |  |
| *Plesiogale* | Schmidt-Kittler, 1981; Wolsan, 1991Wang et al., 2005 |
| *Pontolis* | Boessenecker and Churchill, 2013 |
| *Potamotherium* | Savage, 1957; Radinsky, 1968; 1971 |
| *Promartes* | Radinsky, 1971; Schmidt-Kittler, 1981 |
| *Promephitis* | Geraads and Spassov, 2016 |
| *Proneotherium* | Kohno et al., 1995; Demere et al., 2001 |
| *Prototaria* | Kohno, 1994; Kohno et al., 1995 |
| *Pseudobassaris* | Wolsan and Lange-Badré 1996; Wang et al., 2005 |
| *Pteronarctos* | Berta, 1994a |
| *Semantor* | Orlov, 1933 |
| *Simocyon* | Wolsan, 1993; Wang, 1997; Salesa et al., 2008 |
| *Sthenictis* | Tseng et al., 2009 |
| *Stromeriella* |  |
| *Temnocyon* | Hunt, 2011 |
| *Thalassoleon* | Deméré and Berta, 2005; Churchill and Boessenecker, 2014 |
| *Zodiolestes* | Hough, 1944; Schmidt-Kittler, 1981 |