# Supplementary Information 1 – Phylogenetic characters

The (1-270) characters utilised in this paper, are the characters complied and published in Benson and Druckenmiller (2014), with an addition of three new characters (271-273). For Characters (1-270), see the supplementary information for Benson and Druckenmiller (2014) available on Dryad for the character states and their history of use.

**271 Frontal, interfrontal vacuity (new character)**: frontals are loosely connected along the midline (0); frontals are partially separated along the midline by an interfrontal vacuity (1). Absent, frontals split entirely or partially by posterior process of the premaxilla or completely fused (?)

State (0) is present when the frontals are loosely sutured, but lack any emargination along the medial margin of the elements (e. g. *Muraenosaurus leedsii*; Figure S.11 A)

State (1) is only present in some cryptoclidid plesiosaurs (separate from the frontal foramen observed in some polycotylids) and *Brancasaurus brancai* (Sachs et al., 2016). When present, this state appears to be independent of ontogeny, as it has been confirmed in juvenile (e. g. NHMUK R2853) and adult specimens (e. g. *Tricleidus seeleyi*; Figure S.11 B).

Scored (0&1) in *Cryptoclidus eurymerus* and *Tatenectes laramiensis*, as a loosely sutured frontal is present, but the presence of a vacuity cannot be confirmed due to the preservation of the specimens.

**272 Dentary, mediolateral expansion of the dorsal surface (new character):**

No mediolateral expansion (0); a small lateral expansion present posteriorly; (1) mediolateral expansion, so the alveoli are laterally offset from the centre (2).

State (0) the dorsal surface of the dentary medial and lateral surfaces are uniform or convex and there is no or limited mediolateral expansion of the dentary in dorsal/ventral views (e. g. *Tricleidus seeleyi*; Figure S.12 A-B).

State (1): Some taxa show a lateral expansion of the dentary dorsal surface, although this is constrained to the posterior region of the dentary (e. g. *Cryptoclidus eurymerus*; Figure S.12 C).

State (2): some taxa show a mediolaterally extended dorsal surface of the dentary. This expansion is rapidly reduced on the medial and lateral surfaces, giving a triangular cross section at the midpoint of the dentary (e. g. PMO 224.248; Figure S.12 D-F).

**273 Morphology of the fibula (new character)**: Lunate, close to or as proximodistally long as wide (0); pentagonal anteroposteriorly wider than long, with equally sized distal facets for fibulare and astragalus (1)

Edited from character 92 in Smith (2007).

It should be noted that although the epipodials from the fore- and hind limbs in most plesiosaurs are similar in morphology, there are some differences in Cryptoclidid and Xenopsarian taxa.

State (0) is observed in most Early – Middle Jurassic plesiosaurians and pliosaurids (e. g. *Hauffiosaurus zanoi*; Figure S.13 A).

State (1) is observed in Cryptoclidid taxa (e. g. *Colymbosaurus svalbardensis*; Figure S.13 B)

**The impact of the new characters on the tree topology**

***Interfrontal vacuity***

Through examination of cryptoclidid specimens where the dorsal/ventral surface of the frontal is visible, an interfrontal vacuity along the frontal midline is clearly present in several taxa. In *Tricleidus seeleyi* (Fig. S.11B) and *Kimmerosaurus langhami* the medial margin of the frontal is slightly concave in dorsal view and has finished bone along the entire surface indicating the presence the interfrontal vacuity (AJR *pers. obs*.; NHMUK R3539; NHMUK R.8431). In *Cryptoclidus* *eurymerus*, the presence of this feature is ambiguous on the neotype (NHMUK R2860). In a referred specimen (PETMG R.283.412; Brown and Cruickshank, 1994), the elements are loosely sutured and a small vacuity is possibily present. Due to this *C. eurymerus* is scored for states 0 and 1 in the matrix. A similar situation is present in *Tatenectes laramiensis* (UW 24215 being poorly preserved, the medial surface of the frontal in a specimen of *Tatenectes laramiensis* (UW 24215) is smooth, indicating that a vacuity could be present (O’Keefe and Wahl, 2003a). This presence of this feature may not be limited to cryptoclidids; as a similar structure is observed in some xenopsarians, such as the Berriasian taxon *Brancasaurus brancai*, whichpreserves a small dorsomedian foramen along the frontal midline anterior to the pineal foramen (Sachs et al., 2016). Due to the uncertain occurrence in *T. laramiensis* and *Cryptoclidus*, and questionable homology in *Brancasaurus*, this character was not recovered as a synapomorphy for Cryptoclididae or any subclade. Additional cranial material in a broader sample of cryptoclidids is required to better understand the distribution of this character and its potential utility as a synapomorphy for this clade.

***Mediolateral expansion of the dentary***

A difference in the morphology of the dorsal (tooth bearing) surface of the dentary is observed between some cryptoclidid taxa and other members of Plesiosauria. In Early Jurassic taxa (with the possible exception of *Plesiopterys*), pliosauroids and xenopsarians, there is no mediolateral expansion of the dorsal dentary surface. Rather, the most common condition in plesiosaurians is that the lateral and medial surfaces are uniform and the alveoli are centred over the mandible. When present, a mediolateral expansion gives the mandible an inverted subtriangular shape in cross section, with the dorsal margin being widest. This feature is present in the majority of non-colymbosaurine cryptoclidids (with the exception of *Tricleidus seeleyi*), although in some taxa (*Cryptoclidus*), a partial lateral expansion of the dentary is only present posteriorly, or ambiguous between referred specimens possibly due to preservation (*Kimmerosaurus langhami*). The mediolateral expansion of the dentary unites *Spitrasaurus* spp. And *Ophthalmothule* on the strict consensus tree, however this character is poorly preserved in other taxa. This feature appears to have multiple states present in Cryptoclidids, with the ancestral state present in *Tricleidus seeleyi.*

***Fibula morphology***

In previous work, this character has been combined with the character describing radius morphology due to their morphological similarity (Smith, 2007, character 92). However, these are not homologous and should not be combined and differences between the ulna and fibula are evident in some cryptoclidid taxa (e.g. *Colymbosaurus svalbardensis*). In the resulting consensus tree, state (1) of this character was recovered as a synapomorphy for Cryptoclidia (Cryptoclididae + Xenopsaria).

**Data matrix**

The data matrix includes 76 OTUs and 273 characters. Missing data = “?”, dual character states = “()”. For the new characters (271-273): the character states for most OTUs were scored from the available literature, with the exception of the cryptoclidid taxa. These were scored from the literature in combination with personal observations on type and referred material (Supplementary Information 2).

**Time-calibration**

**Table S1.1:**

**Table over the first and last occurrences of taxa.**

Data from PBDB with some geological age mistakes corrected. Additional added occurrence for *Colymbosaurus svalbardensis* added from pers. obs (AJR) from MGUH collections.

|  |  |  |  |
| --- | --- | --- | --- |
|  | FAD | LAD | area |
| Plesiosaurus\_dolichodeirus | 201.3 | 183 | 1 |
| Eretmosaurus\_rugosus | 199.3 | 190.8 | 1 |
| Westphaliasaurus\_simonsensii | 190.8 | 182.7 | 1 |
| Seelyosaurus\_guilelmiimperatori | 183 | 182 | 1 |
| Microcleidus\_tournemirensis | 180.2 | 175.6 | 1 |
| Microcleidus\_brachypterygius | 183 | 182 | 1 |
| Microcleidus\_homalospondylus | 182 | 175.6 | 1 |
| Plesiopterys\_wildi | 183 | 182 | 1 |
| Cryptoclidus\_eurymerus | 166.1 | 163.5 | 1 |
| Kimmerosaurus\_langhami | 152.1 | 145 | 1 |
| Tatenectes\_laramiensis | 163.5 | 157.3 | 3 |
| Djupedalia\_engeri | 152.1 | 145 | 2 |
| Spitrasaurus\_spp | 152.1 | 145 | 2 |
| PMO\_224\_248 | 152.1 | 145 | 2 |
| Tricleidus\_seeleyi | 166.1 | 163.5 | 1 |
| Muraenosaurus\_leedsii | 166.1 | 163.5 | 1 |
| Picrocleidus\_beloclis | 166.1 | 163.5 | 1 |
| Pantosaurus\_striatus | 163.5 | 157.3 | 3 |
| Plesiosaurus\_mansellii | 152.1 | 145 | 1 |
| Abyssosaurus\_nataliae | 132.9 | 129.4 | 6 |
| Colymbosaurus\_megadeirus | 157.3 | 145 | 1 |
| Colymbosaurus\_svalbardensis | 152.1 | 145 | 2 |
| Umoonasaurus\_demoscyllus | 125 | 100.5 | 5 |
| Nichollssaura\_borealis | 113 | 100.5 | 3 |
| Leptocleidus\_capensis | 139.8 | 132.9 | 7 |
| Leptocleidus\_superstes | 129.4 | 125 | 1 |
| MIWG\_1997\_302 | 129.4 | 125 | 1 |
| Cimoliasaurus\_valdensis | 139.8 | 132.9 | 1 |
| Brancasaurus\_brancai | 145 | 139.8 | 1 |
| Edgarosaurus\_muddi | 113 | 100.5 | 3 |
| Plesiopleurodon\_wellesi | 100.5 | 93.9 | 3 |
| QM\_F51291\_2 | 113 | 100.5 | 5 |
| GWWU\_A3\_B2 | 145 | 139.8 | 1 |
| Speeton\_Clay\_plesiosaurian | 132.9 | 129.4 | 1 |
| Wapuskanectes\_betsynichollsae | 113 | 100.5 | 3 |
| Callawayasaurus\_colombiensis | 125 | 113 | 4 |
| Futabasaurus\_suzukii | 85.8 | 84.9 | 6 |
| Kaiwhekea\_katiki | 84.9 | 66 | 5 |
| Aristonectes\_parvidens | 72.1 | 66 | 4 |
| Libonectes\_morgani | 93.9 | 89.8 | 3 |
| Hydrotherosaurus\_alexandrae | 72.1 | 66 | 3 |

**Script used in R for time calibration**

**#** packages required *phytools*, *strap*, *paleotree*, *geiger*

#script for reading tree with singleton nodes. use read.newick instead

#nice feature to check that the range data and the tree data fit: check.names(tree, timedata) using geiger package

pt<-read.newick(file="filename.newick",)

pr<-read.csv("filename.csv", header=T, row.names = 1)

plio<-read.csv("filename.csv", header=T, row.names=1)

pt.ts <- DatePhylo(pt, pr, method="equal", rlen=5)

geoscalePhylo(tree=pt.ts, ages=pr, ranges=TRUE, cex.tip=1.5, cex.ts=2, cex.age=2, x.lim=c(40,210), quat.rm=TRUE, width=4, label.offset=1)

write.tree (pt.ts, file = "filename.newick")

**List of references for individual OTUs**

**Table A5.1:** List over references for the operational taxonomic units for adding the character states for new characters.

|  |  |
| --- | --- |
| **Operational taxonomic unit** | **References** |
| *Yunguisaurus liae* | Cheng et al., 2006; Sato et al. 2010; Shang et al., *in press*. |
| *Pistosaurus* postcranium | von Huene, 1948; Sues, 1987 |
| *Augustasaurus hagdorni* | Rieppel et al., 2002; Sander et al., 1997 |
| *Bobosaurus forojuliensis* | Dalla Vecchia, 2006; Fabbri et al., 2014 |
| *Anningsaura lymense* | Vincent and Benson, 2012 |
| *Stratesaurus taylori* | Benson et al., 2012, 2015 |
| *Avalonectes arturi* | Benson et al., 2012 |
| *Meyerasaurus victor* | Smith and Vincent, 2010 |
| *Maresaurus coccai* | Gasparini, 1997 |
| *Borealnectes russelli* | Sato and Wu, 2008 |
| *Rhomaleosaurus megacephalus* | Cruickshank, 1994; Smith, 2007, 2015 |
| *Archaeonectes* | NA |
| *Rhomaleosaurus cramptoni* | Smith, 2007; Smith and Dyke, 2008 |
| *Rhomaleosaurus zetlandicus* | Smith, 2007, 2013; Taylor, 1992a 1992b |
| *Rhomaleosaurus thortoni* | Smith and Benson, 2014 |
| *Thalassiodrracon hawkinsii* | Benson et al., 2011a; Storrs and Taylor, 1996 |
| *Hauffiosaurus longirostris* | Benson et al., 2011b |
| *Hauffiosaurus tomistomimus* | Benson et al., 2011b |
| *Hauffiosaurus zanoni* | Vincent, 2011 |
| *Marmornectes andrewi* | NA |
| *Peloneustes phiarchus* | Ketchum, 2008; Ketchum et al., 2011 |
| *Simolestes vorax* | NA |
| Pliosaurus BRSMGCs332 | NA |
| *Pliosaurus brachydeirus* | Knutsen, 2012 |
| *Gallardosaurus iturraldei* | Gasparini, 2009 |
| *Liopleurodon rossicus* | Halstead, 1971 |
| *Pliosaurus andrewsi* | Knutsen, 2012; Tarlo, 1960 |
| *Liopleurodon ferox* | Barrientos-Lara et al., 2015; Noè et al., 2003 |
| *Kronosaurus* | Cruickshank et al. 1999; Kear et al., 2006a |
| *Brachauchenius eulerti* | Schumacher et al., 2013 |
| *Brachauchenius lucasi* | Albright et al., 2011; Everhart, 2007; Hampe, 2005 |
| *Brachauchenius* MNA V9433 | NA |
| QM F51291 | Buchy et al., 2006 |
| *Attenborosaurus conybeari* | Wyse Jackson, 2004 |
| *Plesiosaurus dolichodeirus* | Vincent and Taquet, 2010 |
| *Eoplesiosaurus antiquior* | Benson et al., 2012 |
| *Eretmosaurus rugosus* | Brown, 1994 |
| *Westphaliasaurus simonsensii* | Schwermann and Sander, 2011 |
| *Seeleyosaurus guilelmiimperatoris* | Großmann, 2007 |
| *Microcleidus tournemirensis* | Bardet et al., 1999 |
| *Microcleidus brachypterygius* | Benson et al., 2012 |
| *Microcleidus homospondlyus* | Brown et al., 2013 |
| *Plesiopterys wildi* | O'Keefe, 2004 |
| *Cryptoclidus eurymerus* | Andrews, 1910; Brown, 1981; Brown et al., 1994 |
| *Muraenosaurus leedsii* | Andrews, 1910; Brown, 1981 |
| *Tricleidus seeleyi* | Andrews, 1910; Brown, 1981 |
| *Picrocleidus' beloclis* | Andrews, 1910; Brown, 1981 |
| *Tatenectes laramiensis* | O'Keefe et al., 2011; O'Keefe and Street, 2009 |
| *Pantosaurus striatus* | O'Keefe and Wahl, 2003b |
| *Plesiosaurus' mansellii* | Hulke, 1970 |
| *Spitrasaurus spp.* | Knutsen et al., 2012a |
| *Djupedalia engeri* | Knutsen et al., 2012b |
| *Colymbosaurus svalbardensis* | Knutsen et al., 2012c; Roberts et al., 2017 |
| *Colymbosaurus megadeirus* | Benson and Bowdler, 2014; Roberts et al., 2017 |
| *Abyssosaurus nataliae* | Berezin, 2011 |
| *Umoonasaurus demoscyllus* | Kear et al., 2006b |
| *Nichollssaura borealis* | Druckenmiller and Russel, 2008 |
| *Leptocleidus capensis* | NA |
| *Leptocleidus superstes* | Kear and Barrett, 2011 |
| *Cimoliasaurus valdensis* | Benson et al., 2013 |
| MIWG 1997 302 | NA |
| *Brancasaurus brancai* | Sachs et al., 2016 |
| GWWU As B2 | NA |
| Speeton Clay plesiosaurian | NA |
| *Wapuskanecttes betsynicholls* | Druckenmiller and Russell, 2006 |
| *Futabasaurus suzukii* | Sato et al., 2006 |
| *Callawaysaurus colombiensis* | Welles, 1962 |
| *Kaiwhekea katiki* | Cruickshank and Fordyce, 2002 |
| *Aristonectes paridens* | Gasparini et al., 2001, 2003 |
| *Libonectes morgani* | Sachs and Kear, 2017 |
| *Hydrotherosaurus alexandrae* | Welles, 1943 |
| *Edgarosaurus muddi* | Druckenmiller, 2002 |
| *Plesiopleurodon wellesi* | Carpenter, 1996 |
| QM F5191.2 | NA |

**Complete trees for Plesiosauria**

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