

Supplementary Information for:

Hyoliths with pedicles constrain the origin of the
brachiopod body plan

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Supplementary Text

This document contains supplementary material to Sun et al. (2018). It is best viewed in HTML format at ms609.github.io/hyoliths.

It opens with a detailed discussion of analyses of the morphological dataset constructed to accompany Sun et al. (2018), and their results.

The results presented in the main paper employ the algorithm described by Brazeau et al. (2018) for correct handling of inapplicable data in a parsimony setting. This document depicts how each character is most parsimoniously reconstructed on an optimal tree.

For completeness, we also document the results of standard Fitch parsimony analysis, and the results of Bayesian analysis, neither of which treat inapplicable data in a logically consistent fashion.

Supplementary figures and tables appear after the text.

Chapter 1

Phylogenetic dataset

Analysis was performed on a new matrix of 47 early brachiozoan taxa, including hyoliths, tommotiids and mickwitzziids, which were coded for 220 morphological characters (132 neomorphic, 88 transformational).

Namacalathus was incorporated as a 48th taxon, but preliminary results did not uphold the homology of its potentially brachiozoan-like features. As such, we excluded it from our analysis due to its morphological distance from ingroup taxa, a likely source of long branch error. *Daliyatia* was instead selected as an outgroup as camenellans have been interpreted as the earliest diverging members of the Brachiozoa (Skovsted et al., 2015; Zhao et al., 2017).

Characters are coded following the recommendations of Brazeau et al. (2018):

- We have employed reductive coding, using a distinct state to mark character inapplicability. Character specifications follow the structural syntax of Sereno (2007) in order to highlight ontological dependence between characters and emphasize the structure of the dataset.
- We have distinguished between neomorphic and transformational characters (sensu Sereno, 2007) by reserving the token 0 to refer to the absence of a neomorphic (i.e. presence/absence) character. The states of transformational characters (i.e. characters that describe a property of a feature) are represented by the tokens 1, 2, 3, ...
- We code the absence of neomorphic ontologically dependent characters (sensu Vogt, 2017) as absence, rather than inapplicability.

The complete dataset comprises 10560 character codings, of which 912 are inapplicable and 4355 were neither ambiguous nor inapplicable. The amount and quality of data that *is* coded is more instructive than a measure of how many cells are ambiguous (Wiens, 1998, 2003). Of the 220 characters, the number that were coded with an applicable token for each taxon is:

<u>_Namacalathus_</u>	53 ;	<u>_Halkieria evangelista_</u>	58 ;	<u>_Heliomedusa orienta_</u>
<u>_Haplophrentis carinatus_</u>	72 ;	<u>_Dailyatia_</u>	50 ;	<u>_Kutorgina chengjiangensis_</u>
<u>_Pedunculotheca diania_</u>	64 ;	<u>_Acanthotretella spinosa_</u>	65 ;	<u>_Lingulosacculus_</u>
<u>_Cotyledion tylodes_</u>	61 ;	<u>_Alisina_</u>	80 ;	<u>_Lingulellotreta malongensis_</u>
<u>_Loxosomella_</u>	161 ;	<u>_Askepasma toddense_</u>	70 ;	<u>_Longtancunella chengjiangensis_</u>
<u>_Flustra_</u>	165 ;	<u>_Antigonambonites planus_</u>	78 ;	<u>_Micrina_</u>
<u>_Amathia_</u>	152 ;	<u>_Botsfordia_</u>	68 ;	<u>_Micromitra_</u>
<u>_Pelagodiscus atlanticus_</u>	155 ;	<u>_Clupeafumosus socialis_</u>	70 ;	<u>_Mickwitzia muralensis_</u>
<u>_Terebratulina_</u>	176 ;	<u>_Coolinia pecten_</u>	73 ;	<u>_Mummpikia nuda_</u>
<u>_Lingula_</u>	195 ;	<u>_Novocrania_</u>	181 ;	<u>_Nisusia sulcata_</u>
<u>_Phoronis_</u>	166 ;	<u>_Craniops_</u>	60 ;	<u>_Orthis_</u>
<u>_Sipunculus_</u>	164 ;	<u>_Gasconsia_</u>	64 ;	<u>_Paterimitra_</u>
<u>_Serpula_</u>	166 ;	<u>_Ussunia_</u>	51 ;	<u>_Salanygolina_</u>
<u>_Tonicella_</u>	181 ;	<u>_Eccentrotheca_</u>	49 ;	<u>_Siphonobolus priscus_</u>
<u>_Dentalium_</u>	164 ;	<u>_Eoobolus_</u>	74 ;	<u>_Tomteluva perturbata_</u>
<u>_Wiwaxia corrugata_</u>	70 ;	<u>_Glyptoria_</u>	69 ;	<u>_Yuganotheca elegans_</u>

The matrix can be viewed interactively and downloaded at Morphobank (project 2800). [This link will become live on publication of the paper. Referees should follow the pre-publication link to the dataset that has been provided in the main manuscript.]

A static version of the NEXUS file used to generate this supplementary information can be downloaded directly from https://raw.githubusercontent.com/ms609/hyoliths/master/mbank_X24932_6-7-2018_1143.nex.

Chapter 2

Parsimony analysis

The phylogenetic dataset contains a considerable proportion of inapplicable codings ($912/10560 = 8.6\%$ of tokens), which are known to introduce error and bias to phylogenetic reconstruction when the Fitch algorithm is employed (Maddison, 1993; Brazeau et al., 2018). As such, we employed a new tree-scoring algorithm that correctly handles inapplicable data (Brazeau et al., 2018), implemented in the *MorphyLib* C library (Brazeau et al., 2017). We employed the R package *TreeSearch* v0.1.2 (Smith, 2018) to conduct phylogenetic tree search with this algorithm.

As this is a new method, we also employed the traditional, Fitch algorithm, even though this approach is known to generate erroneous trees. The results of this analysis can be viewed in a later section.

2.1 Search parameters

Heuristic searches were conducted using the parsimony ratchet (Nixon, 1999) under equal and implied weights (Goloboff, 1997). The consensus tree presented in the main manuscript represents a strict consensus of all trees that are most parsimonious under one or more of the concavity constants (k) 2, 3, 4.5, 7, 10.5, 16 and 24, an approach that has been shown to produce higher accuracy (i.e. more nodes and quartets resolved correctly) than equal weights at any given level of precision (Smith, 2017).

2.2 Analysis

The R commands used to conduct the analysis are reproduced below. The results can most readily be replicated using the R markdown files (.Rmd) used to generate these pages.

2.2.1 Initialize and load data

```
# Load data from locally downloaded copy of MorphoBank matrix
my_data <- ReadAsPhyDat(filename)
my_data[ignored_taxa] <- NULL
iw_data <- PrepareDataIW(my_data)
```

2.2.2 Generate starting tree

Start by quickly rearranging a neighbour-joining tree, rooted on the outgroup.

```

nj.tree <- NJTree(my_data)
rooted.tree <- EnforceOutgroup(nj.tree, outgroup)
start.tree <- TreeSearch(tree=rooted.tree, dataset=my_data, maxIter=3000,
                        EdgeSwapper=RootedNNISwap, verbosity=0)

```

2.2.3 Implied weights analysis

The position of the root does not affect tree score, so we keep it fixed (using RootedXXXSwap functions) to avoid unnecessary swaps.

```

for (k in kValues) {
  iw.tree <- IWRatchet(start.tree, iw_data, concavity=k,
                      ratchHits = 60, searchHits=55,
                      swappers=list(RootedTBRSwap, RootedSPRSwap, RootedNNISwap),
                      verbosity=0L)
  score <- IWScore(iw.tree, iw_data, concavity=k)
  # Write a single best tree
  write.nexus(iw.tree,
              file=paste0("TreeSearch/hy_iw_k", k, "_",
                          signif(score, 5), ".nex", collapse=''))

  iw.consensus <- IWRatchetConsensus(iw.tree, iw_data, concavity=k,
                                     swappers=list(RootedTBRSwap, RootedNNISwap),
                                     searchHits=55,
                                     nSearch=150, verbosity=0L)
  write.nexus(iw.consensus,
              file=paste0("TreeSearch/hy_iw_k", k, "_",
                          signif(IWScore(iw.tree, iw_data, concavity=k), 5),
                          ".all.nex", collapse=''))
}

```

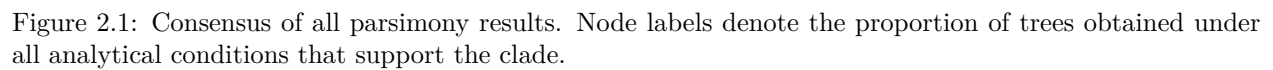
2.2.4 Equal weights analysis

```

ew.tree <- Ratchet(start.tree, my_data, verbosity=0L,
                  ratchHits = 25, searchHits=55, # ratchHits = 10 not enough
                  swappers=list(RootedTBRSwap, RootedSPRSwap, RootedNNISwap))
ew.consensus <- RatchetConsensus(ew.tree, my_data, nSearch=250, searchHits = 55,
                                swappers=list(RootedTBRSwap, RootedNNISwap),
                                verbosity=0L)
write.nexus(ew.consensus, file=paste0(collapse='', "TreeSearch/hy_ew_",
                                     Fitch(ew.tree, my_data), ".nex"))

```

2.3 Results



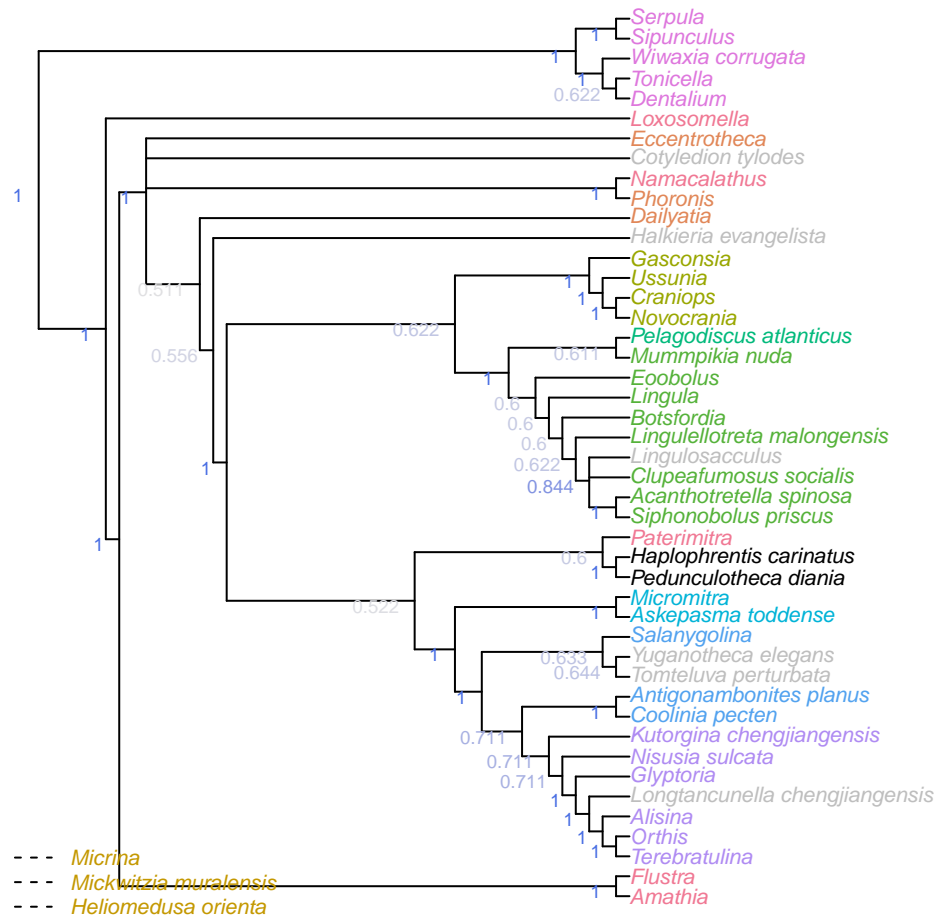


Figure 2.2: Consensus of all parsimony results, with taxa omitted to show underlying clade support. Node labels denote the proportion of trees obtained under all analytical conditions that support the clade.

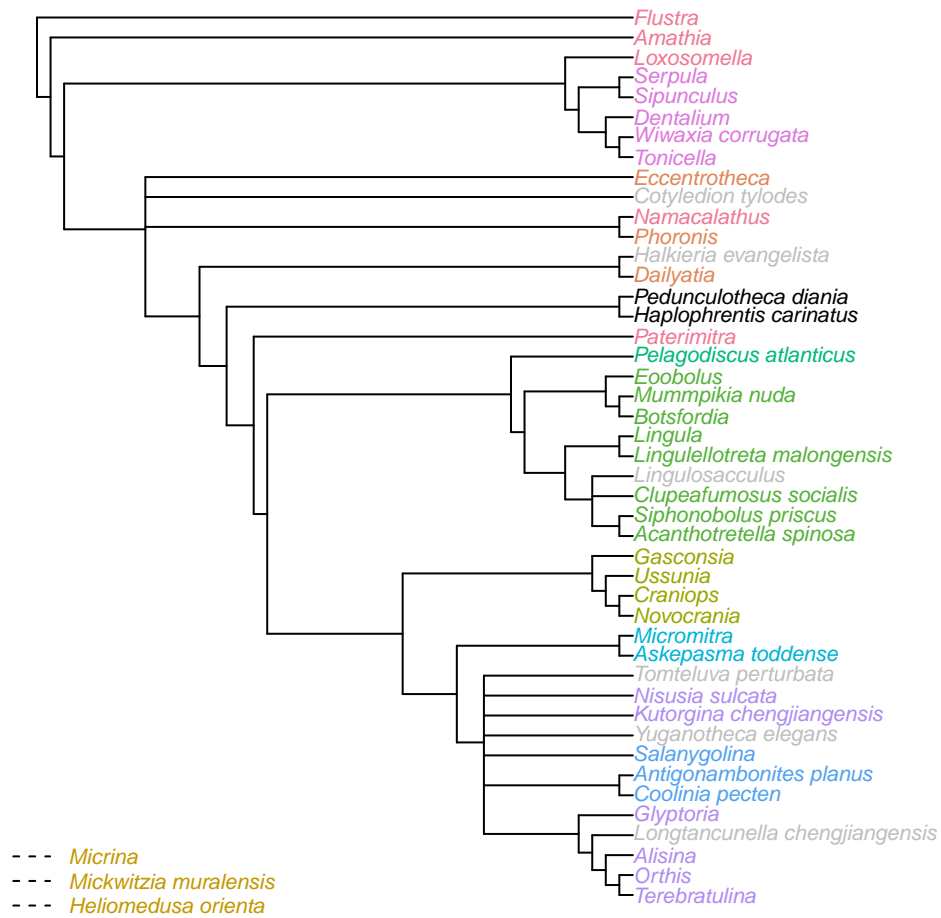


Figure 2.3: Strict consensus of implied weights analyses at all values of k . Wildcard taxa have been excluded from the consensus tree shown above to improve resolution.

```
##
```

```
## > Results not available for panel 3
```

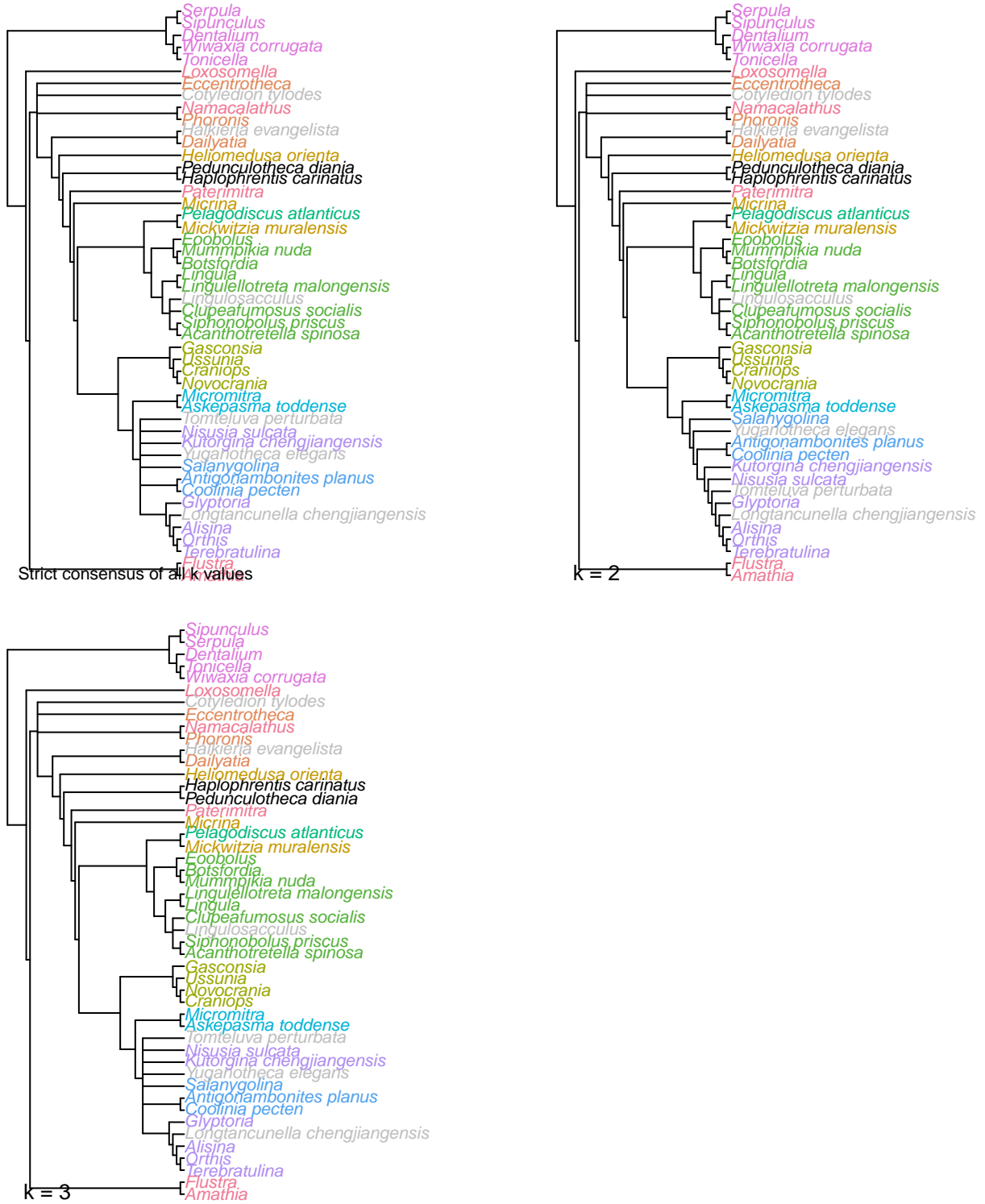


Figure 2.4: Consensus trees of implied weights analyses at all values of k , and at the individual values $k = 2, 3$ and 4.5 .

```
##  
## > Results not available for panel 4  
##  
## > Results not available for panel 5  
##  
## > Results not available for panel 6  
##  
## > Results not available for panel 7
```

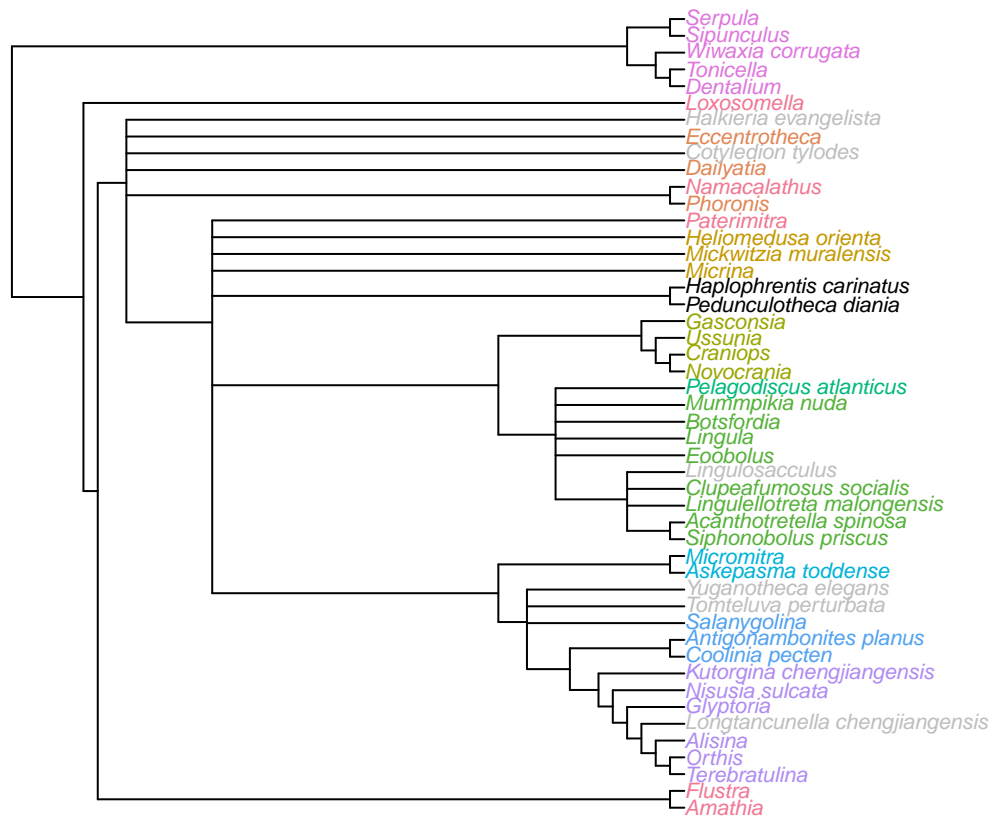


Figure 2.5: Strict consensus of most parsimonious trees under equally weighted parsimony

Chapter 3

Character reconstructions

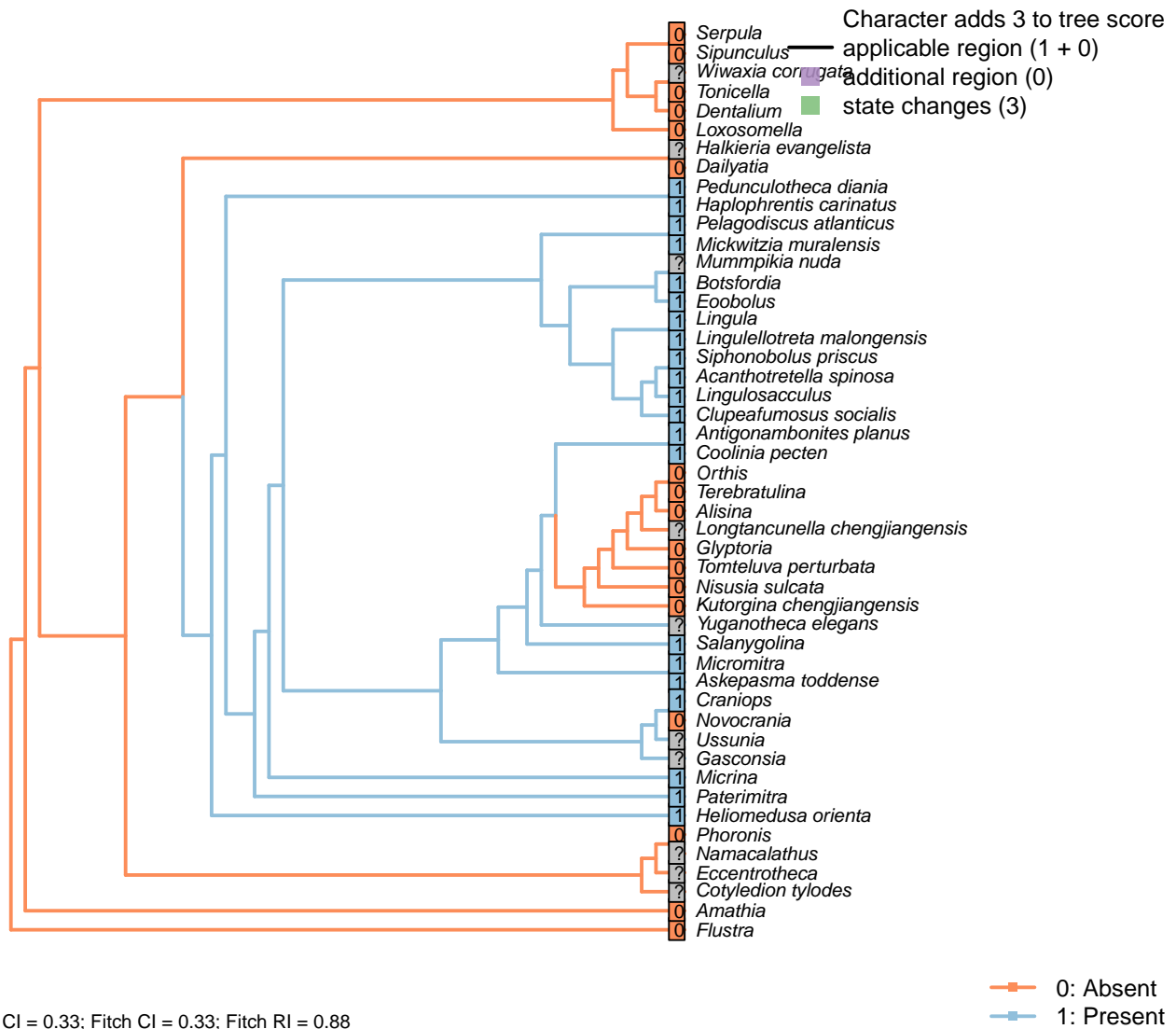
This page provides definitions for each of the characters in our matrix, and justifies codings in particular taxa where relevant. Further citations for codings that are not discussed in the text can be viewed by browsing the morphological dataset on MorphoBank (project 2800). This link will become live on publication of the paper. Referees should follow the pre-publication link to the dataset that has been provided in the main manuscript.

Alongside its definition, each character has been mapped onto a tree. Here, we have arbitrarily selected one most parsimonious tree obtained under implied weighting, $k = 4.5$. Other trees can be viewed in the HTML version of this document at ms609.github.io/hyoliths. Each tip is labelled according to its coding in the matrix. These states have been used to reconstruct the condition of each internal node, using the parsimony method of Brazeau et al. (2018) as implemented in the *Inapp R* package.

We emphasize that different trees will give different reconstructions. The character mappings are not intended to definitively establish how each character evolved, but to help the reader quickly establish how each character has been coded, and to visualize at a glance how each character fits onto a given tree.

3.1 Brephic shell

[1] Embryonic shell



The embryonic shell or protegulum is secreted by the embryo immediately before hatching.

Acanthotretella spinosa: On hatching, the polyplacophoran larva lacks a shell field.

Shell fields develop during the trochophore larva stage. The larva of the chiton *Mopalia* has two distinct shell fields: that anterior to the prototroch will develop into the first shell plate; the one posterior to the prototroch becomes the subsequent plates (Wanninger and Haszprunar, 2002a).

This disc-shaped posterior plate, whose position corresponds to the conchiferan shell field, bears a polygonal ornament and is subdivided by a series of grooves that prefigure the adult shell plates (Wanninger and

Haszprunar, 2002a).

Alisina: The shell does not form until the trochophore larval stage, which has been exquisitely described in *Antalis* (Wanninger and Haszprunar, 2001).

This shell field is initially disc-like, subsequently expanding to fuse ventrally and produce the cylindrical protoconch. The prototroch is clearly delineated from the telotroch in post-metamorphic juveniles (Wanninger and Haszprunar, 2001).

Eoobolus: Shell not secreted until after metamorphosis (Popov et al., 2010).

Heliomedusa orientalis: The earliest shell is not described by Hanken and Harper (1985) or Watkins (2002).

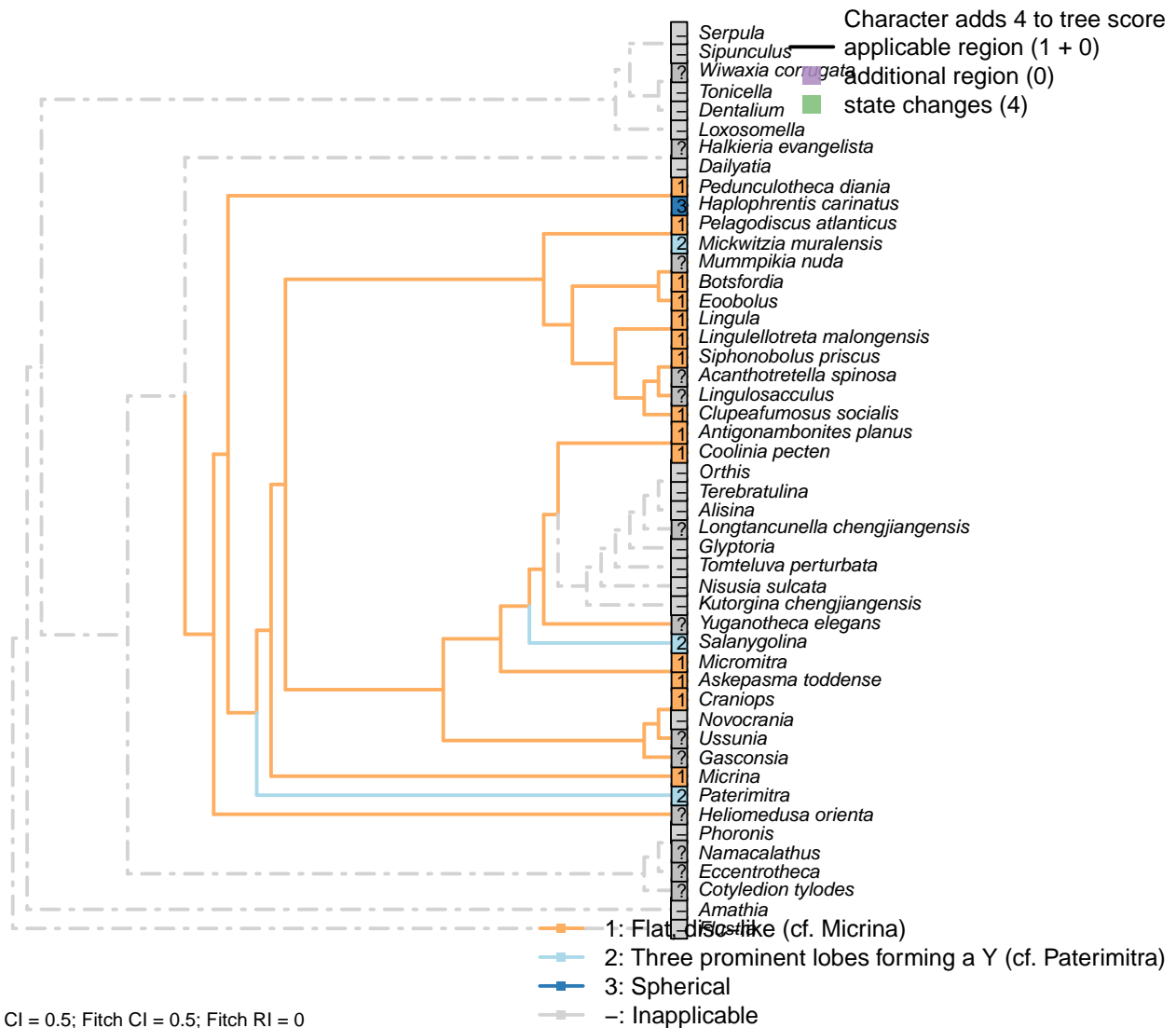
Lingula: Absent, with no possible equivalent (Nielsen, 1966).

Namacalathus: Inapplicable insofar as reproduction occurs by budding; there is no evidence for a free-living larval stage. Nevertheless, the presence of a sexual reproductive phase in addition to asexual reproduction cannot be discounted.

Sipunculus: Reed and Cloney (1982).

Ussunia: Described by Topper et al. (2013a).

[2] Morphology

**Character 2: Brephic shell: Morphology**

- 1: Flat, disc-like (cf. *Micrina*)
 - 2: Three prominent lobes forming a Y (cf. *Paterimitra*)
 - 3: Spherical
- Transformational character.

The brephic shell is the shell possessed by the young organism (see Ushatinskaya and Korovnikov, 2016, and references therein for discussion of terminology).

Micrina resembles linguliforms (Holmer et al., 2011): in both, the brephic mitral shell has one pair of setal sacs enclosed by lateral lobes, whereas the brephic ventral shell has two lateral setal tubes.

Paterimitra and *Salanygolina* have “identical” ventral brephic shells (Holmer et al., 2011), resembling the shape of a ship’s propeller.

Haplophrentis is coded following typical hyoliths, which have a spherical brephic shell; *Pedunculotheca*’s, in

contrast, is seemingly cap-shaped.

Acanthotretella spinosa: Disc-like, subdivided by transverse grooves (Wanninger and Haszprunar, 2002a).

Dentalium: See fig. 159 in Williams et al. (1997).

Eccentrotheca: See fig. 3 in Bassett and Popov (2017).

Glyptoria: The embryonic shell is more or less circular in outline – see Freeman and Lundelius (1999), fig. 6A.

Mummpikia nuda: Disc-like (Li and Holmer, 2004).

Novocrania: Renoid – see fig. 4B3 in Topper et al. (2013b).

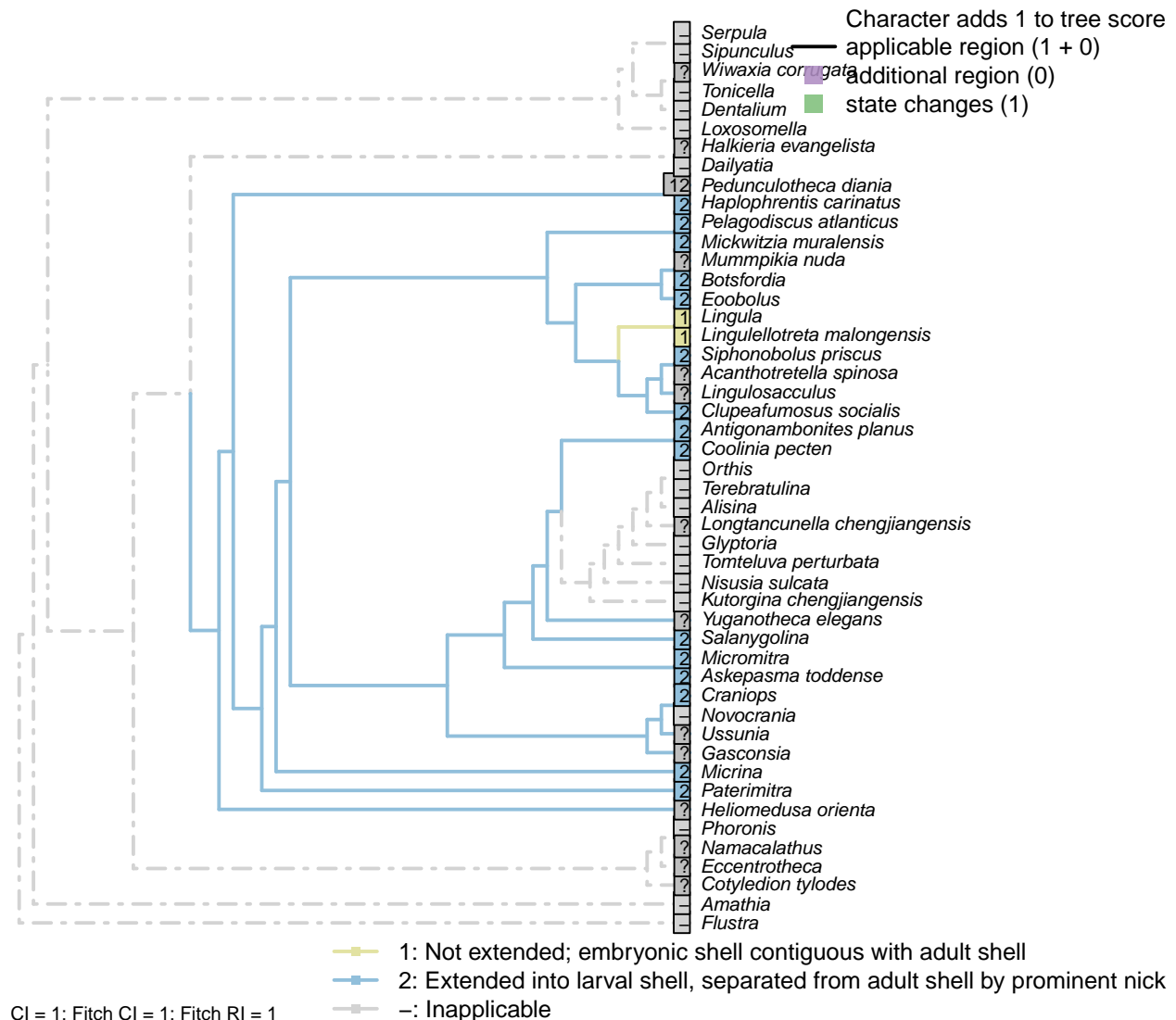
Paterimitra: Subtriangular – essentially round.

Salanygolina: Trifoliate appearance results from prominent attachment rudiment and bunching of setal sacs (Balthasar, 2009).

Serpula: See e.g. fig 169 in Williams et al. (1997).

Ussunia: The flat larval shell of *Clupeafumosus* resembles that of *Micrina* in outline (Topper et al., 2013a; cf. Holmer et al., 2011).

[3] Embryonic shell extended in larvae

**Character 3: Brephic shell: Embryonic shell extended in larvae**

- 1: Not extended; embryonic shell contiguous with adult shell
 - 2: Extended into larval shell, separated from adult shell by prominent nick
- Transformational character.

Many taxa add to their embryonic shell (the protegulum possessed by the embryo upon hatching) during the larval phase of their life cycle. The shell that exists at metamorphosis, marked by a halo or nick point, is variously termed the “first formed shell”, “metamorphic shell” or “larval shell” (Bassett and Popov, 2017).

Acanthotretella spinosa: Wanninger and Haszprunar (2002a).

Glyptoria: Prominent nick; see Freeman and Lundelius (1999), fig. 6A.

Lingulellotreta malongensis: Nick point indicated by arrows in fig. 1 of Balthasar (2009).

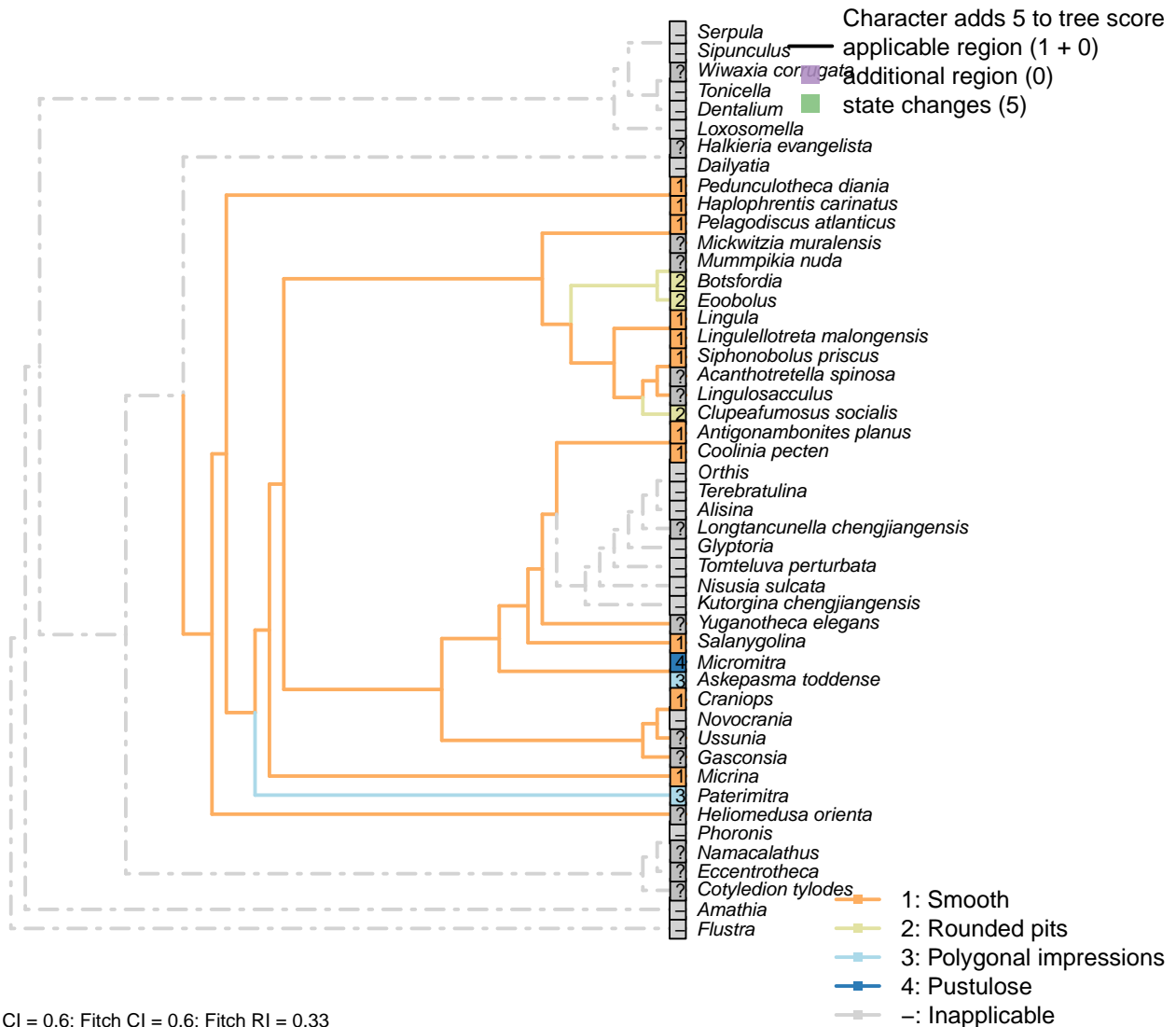
Mummpikia nuda: No prominent nick point (Holmer et al., 1997; Li and Holmer, 2004).

Pelagodiscus atlanticus: The flattened region at the umbo of the ventral valve in smaller specimens conceivably represents an embryonic shell, though it may alternatively represent a cicatrix or colleplax-like

structure.

Ussunia: Described by Topper *et al.* (2013a).

[4] Surface ornament



Pitting of the larval shell characterises acrotretids and their relatives. Pustules occur on Paterinidae. See

Character 3 in Williams *et al.* (2000) tables 5–6.

Dentalium, Serpula: Smooth, following family-level codings of Williams *et al.* (2000), table 6.

Lingulellotreta malongensis: Pitted (Williams *et al.*, 2000, table 8).

Mummpikia nuda: Smooth (Holmer *et al.*, 1997; Li and Holmer, 2004).

Novocrania: Indented with hexagonal pits (Williams *et al.*, 1998, appendix 2).

Orthis: Smooth (Holmer *et al.*, 2011).

Paterimitra: Pustolose in Paterinidae (Williams *et al.*, 2000, table 6).

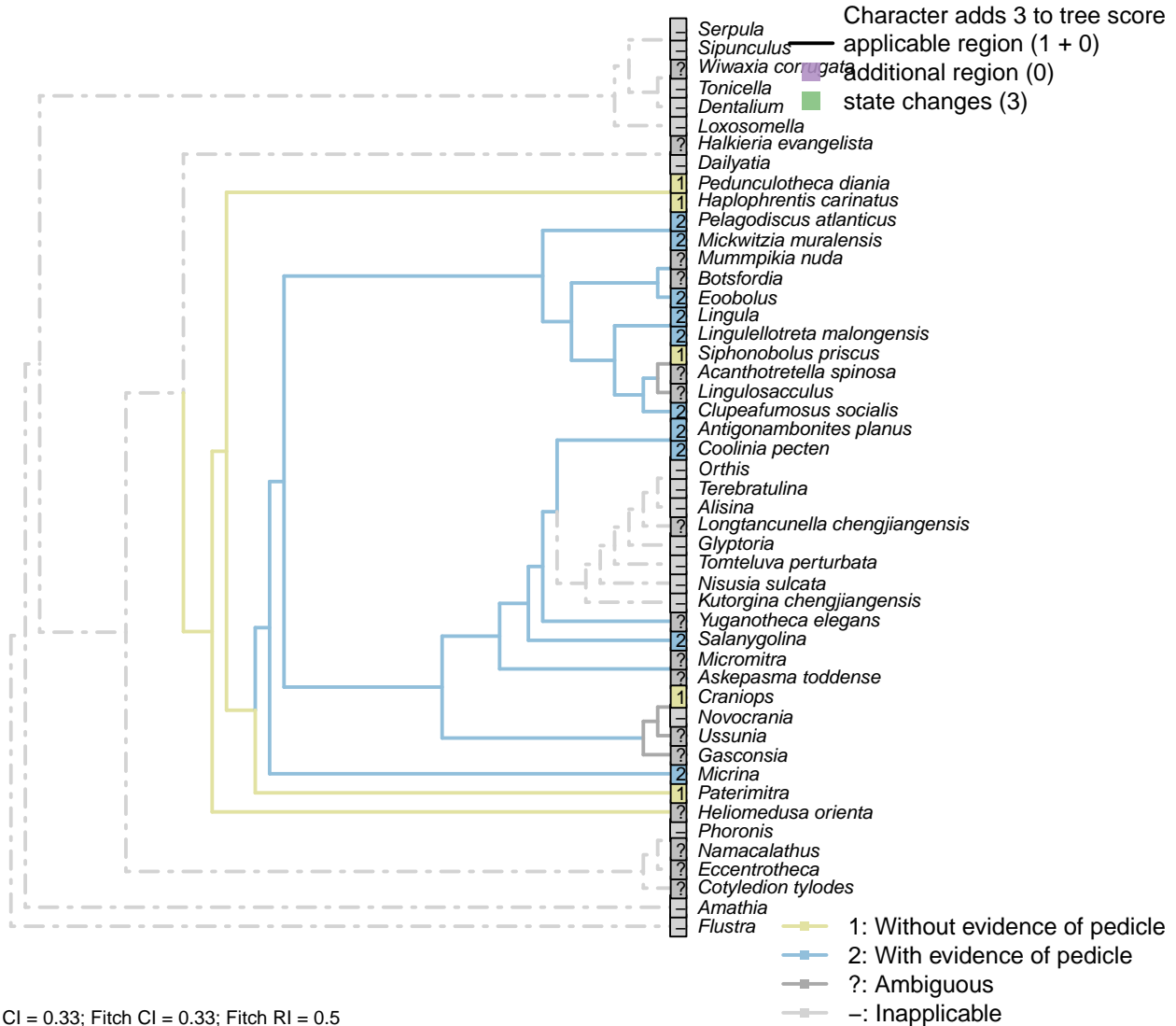
Ussunia: “Larval shells on both valves [...] are covered by fine, shallow pits” – Topper *et al.* (2013a).

NA: Polygonal texture present (Holmer *et al.*, 2011), as in the adult shell.

NA: Smooth (Holmer *et al.*, 2009).

NA: “Smooth brephic shell” – Popov *et al.* (2009).

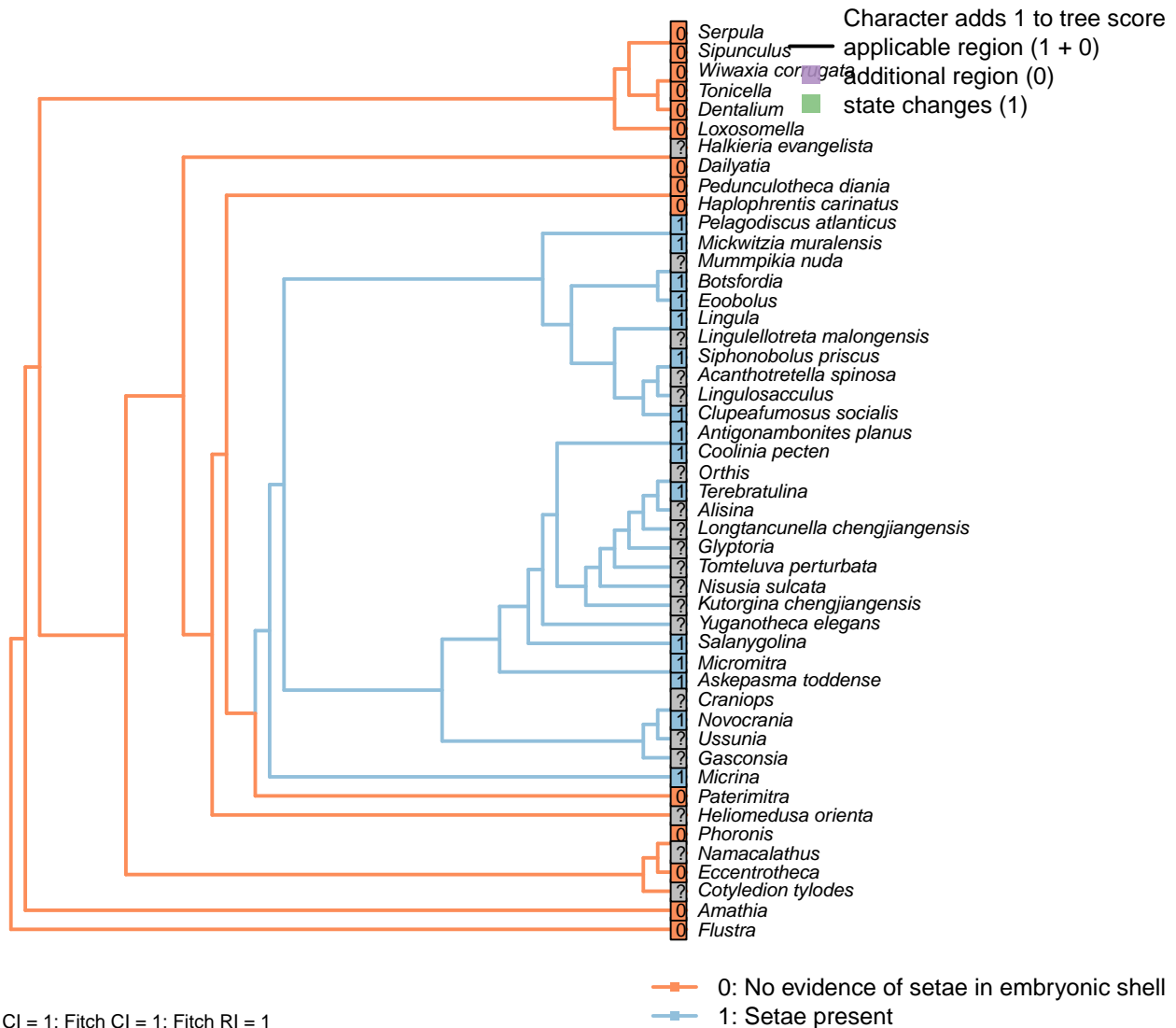
[5] Larval attachment structure



et al. (2013a).

NA: Interpreted as having planktotrophic (and thus non-attached) larvae (Popov *et al.*, 2009).

[6] Setulose



Character 6: Brephic shell: Setulose

0: No evidence of setae in embryonic shell

1: Setae present

Neomorphic character.

The protegulum of *Micrina* is penetrated with canals that were originally associated with setae, a character that it has in common with linguliforms (Holmer *et al.*, 2011).

Gasconsia: “One specimen shows fine capillae running laterally from the posterior tubercles on the dorsal valve (Pl. 3, fig. 5b). This is possibly the imprints of setae.” – Ushatinskaya and Korovnikov (2016).

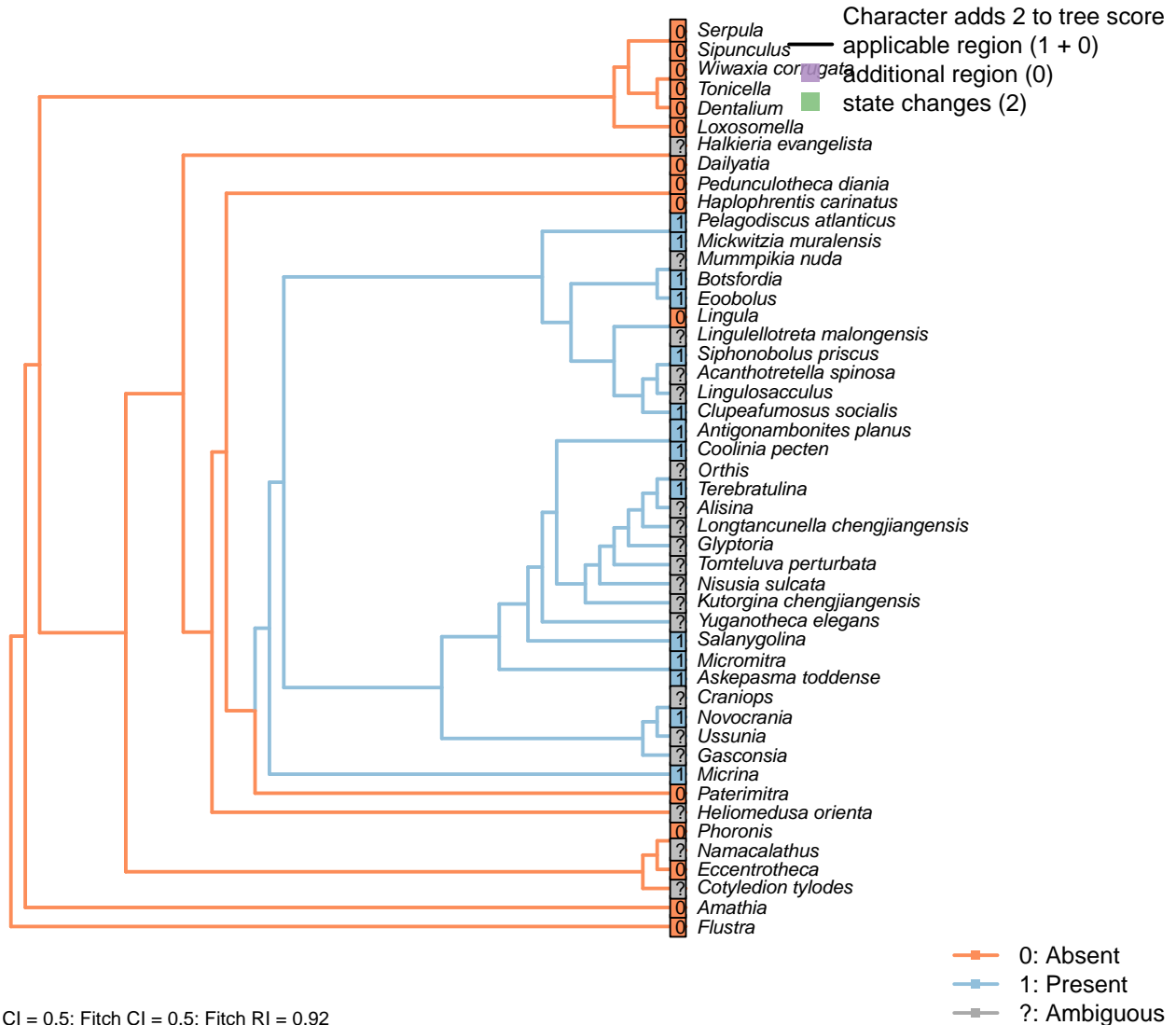
Mummpikia nuda: Possible suggestion of setal sacs present on brephic shell (Holmer *et al.*, 1997; Li and

Holmer, 2004), but outline inadequately preserved to code with confidence; treated as ambiguous.

Salanygolina: Four setal sacs.

Ussunia: Setal bundles interpreted as present in acrotretids by Ushatinskaya (2016).

3.2 Brephic shell: Setal sacs [7]



Character 7: Brephic shell: Setal sacs

0: Absent

1: Present

Neomorphic character.

Setal sacs are recognizable as raised lumps on the juvenile shell (see Bassett and Popov, 2017).

Micrina and linguliforms have setal sacs on their mitral/dorsal embryonic shell, whereas these are absent in

Paterimitra (Holmer et al., 2011).

Dentalium: Lingulids' larval setae are not arranged in bundles (Carlson, 1995).

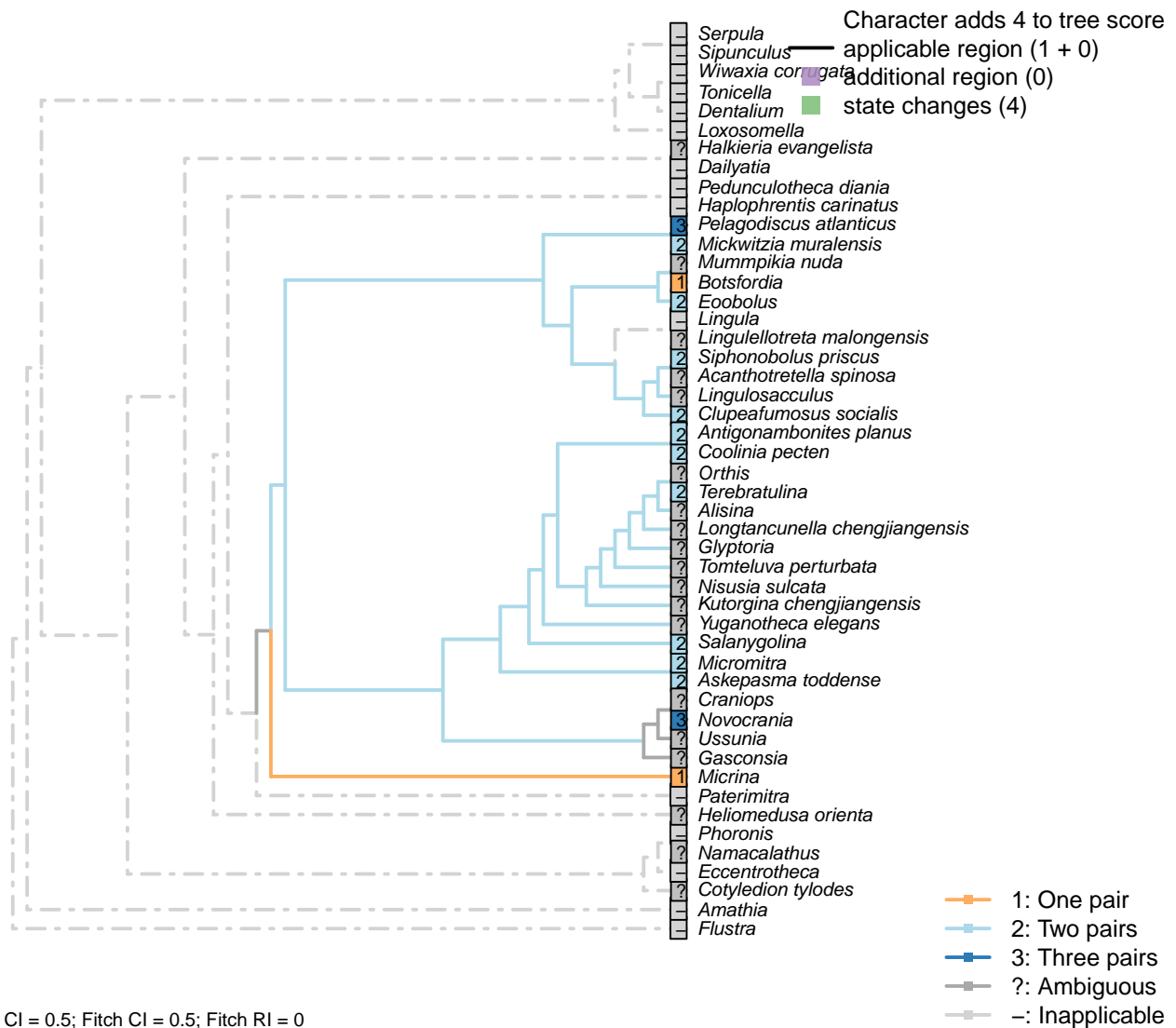
Eoobolus, *Serpula*: Three pairs (Carlson, 1995).

Gasconsia: A single pair of low tubercles are (Ushatinskaya and Korovnikov, 2016, state "may be") located in the middle region of the dorsal and the ventral brephic valve; these are interpreted as a single pair of setal sacs, with the identity of the (dorsally unpaired) tubercles uncertain.

Mummpikia nuda: Possible suggestion of setal sacs present on brephic shell (Holmer et al., 1997; Li and Holmer, 2004), but outline inadequately preserved to code with confidence; treated as ambiguous.

Ussunia: Setal bundles interpreted as present in acrotretids by Ushatinskaya (2016).

[8] Number



3: Three pairs

Transformational character.

Two pairs on e.g. *Coolina*; one on e.g. *Micrina*.

Eoobolus, *Serpula*: Three pairs (Carlson, 1995).

Gasconsia: “larval shell with one to three apical tubercles in ventral valve and two in dorsal valve” (Williams et al., 2000) – if these correspond to setal sacs, then we interpret this as equivalent to one pair.

In *B. minuta*, the ventral valve bears a single medial tubercle (which in figured material seems to have two bilaterally symmetrical fields), whereas the dorsal valve bears two apical tubercles (Li and Holmer, 2004) – supporting the interpretation of a single pair of setal sacs.

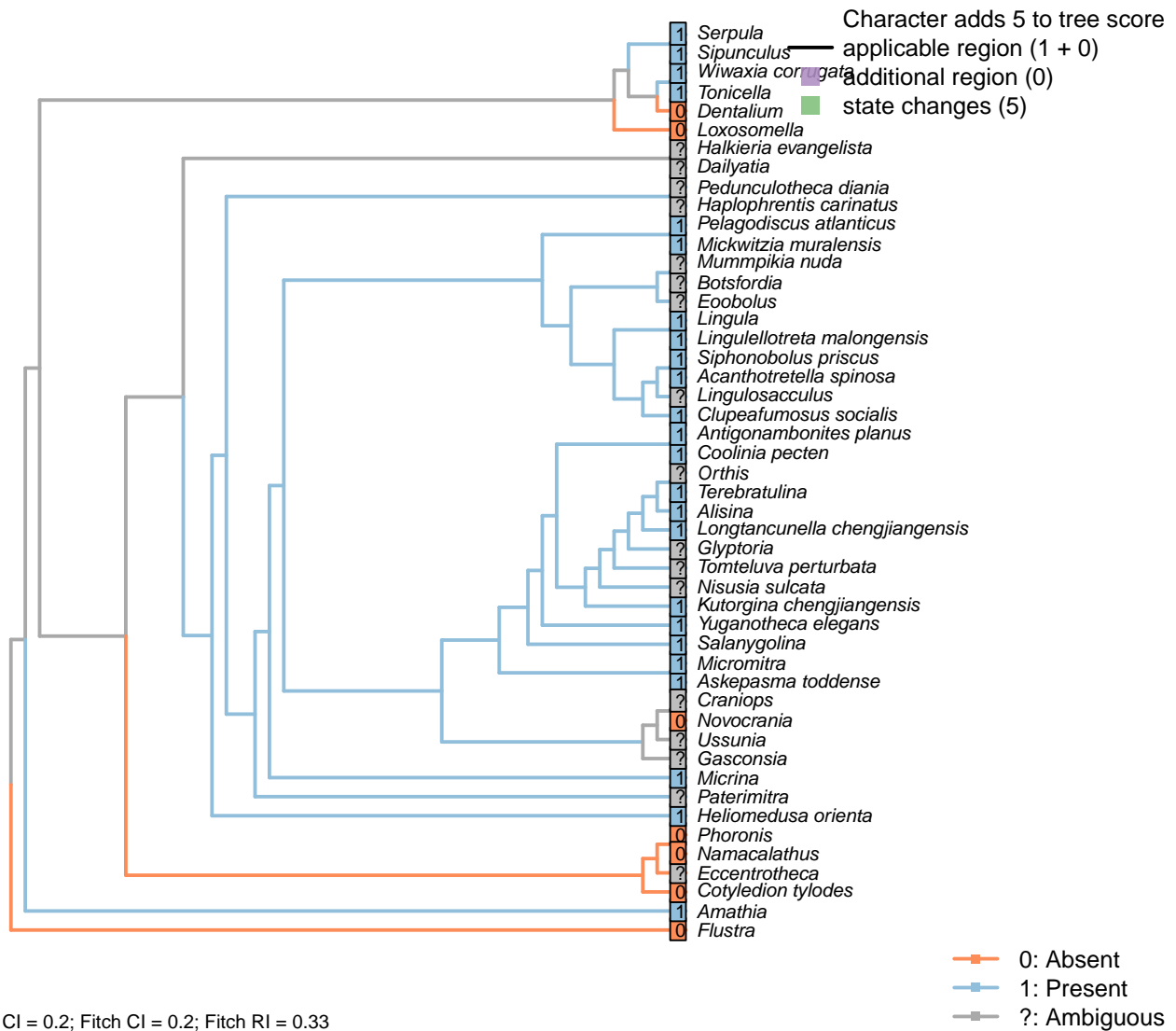
Salanygolina: See fig. 2 in Balthasar (2009).

Ussunia: Two pairs identified in acrotretids by Ushatinskaya (2016).

NA: Two pairs of setal sacs (Popov et al., 2009).

3.3 Setae

[9] Present in adults



Character 9: Setae: Present in adults

0: Absent

1: Present

Neomorphic character.

Although preservation of setae (in adults) is exceptional, their presence can be inferred from shelly material (see Holmer and Caron, 2006).

Acanthotretella spinosa: The girdle elements of certain polyplacophorans are chitinous and secreted by microvilli (Fischer et al., 1980; Leise and Cloney, 1982; Leise, 1988); it is therefore likely that they are homologous with the setae of other lophotrochozoans.

Askepasma toddense: Sclerites likely correspond with lophotrochozoan setae (Butterfield, 1990; Smith, 2014;

Zhang et al., 2015).

Clupeafumosus socialis: Note that the setae do not obviously emerge from tubes, leading Holmer and Caron to question their homology with the setae of other taxa (*Heliomedusa*, *Mickwitzia*).

Both valves of *Acanthotretella* were covered by long spine-like and shell penetrating setae. The setae of *A. decaius* are usually preserved along anterior and anterolateral margins (Hu et al., 2010).

Eoobolus: “Adult craniids are without setae (a feature shared with the thecideides, the shells of which are also cemented).” – Williams et al. (2007).

Halkieria evangelista: The absence of chitin or microvillar lineations in sipunculan hooks argues against their interpretation as setae, but they are coded as conceivable homologues, with these characteristics treated separately.

Mummpikia nuda: “Setae appear short, delicate, and are closely fringed with the entire mantle margin, hardly extending beyond the edge of shell” – Zhang et al. (2005).

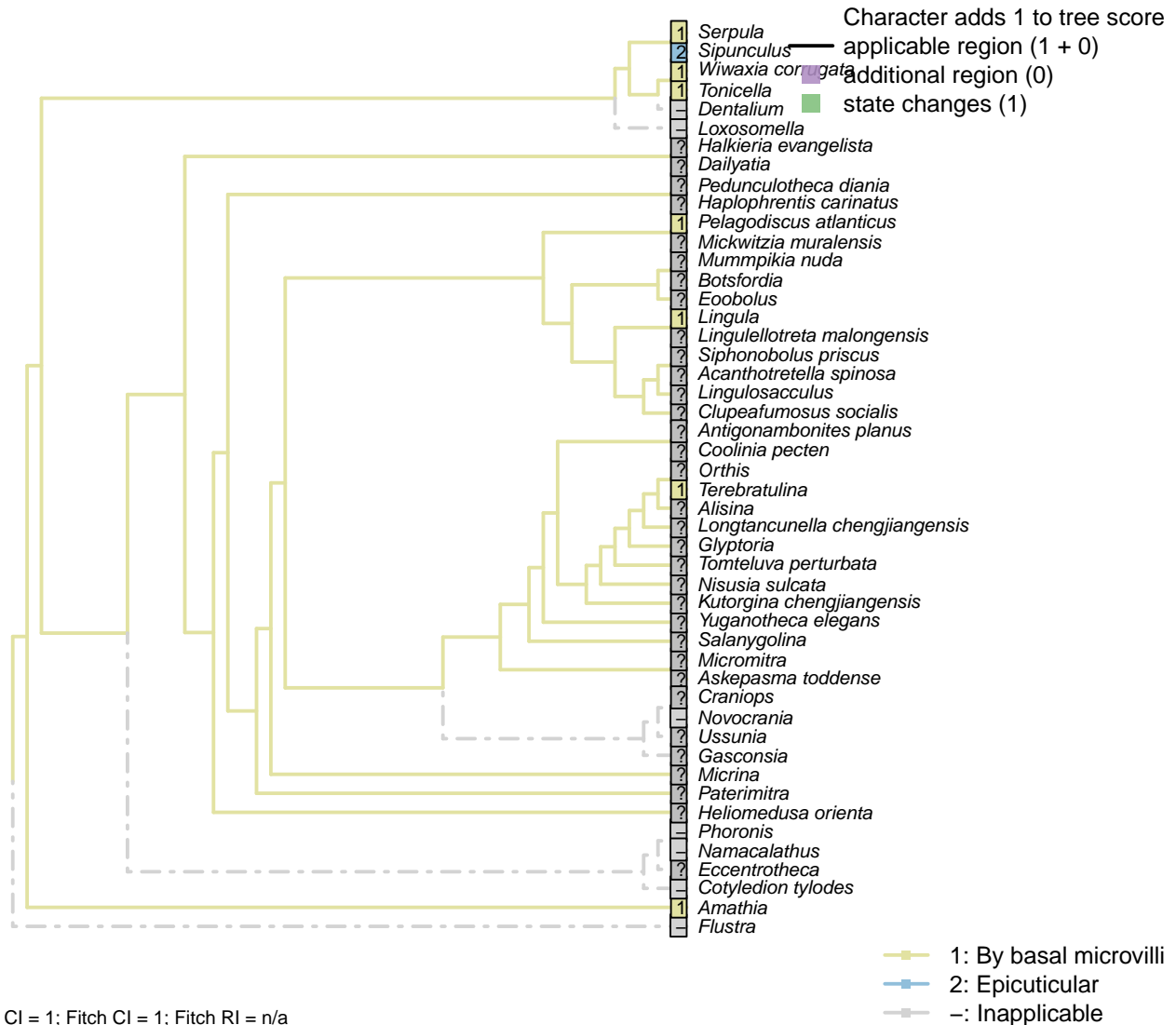
Phoronis: A gizzard is not present in all bryozoans, and has not been reported in *Flustra*.

Sipunculus: The teeth of the Bryozoan gizzard have been homologized with annelid setae (Gordon, 1975).

Ussunia: Setal bundles interpreted as present in acrotretids by Ushatinskaya (2016).

NA: Phosphatised setae emerge from hollow spines (Popov et al., 2009).

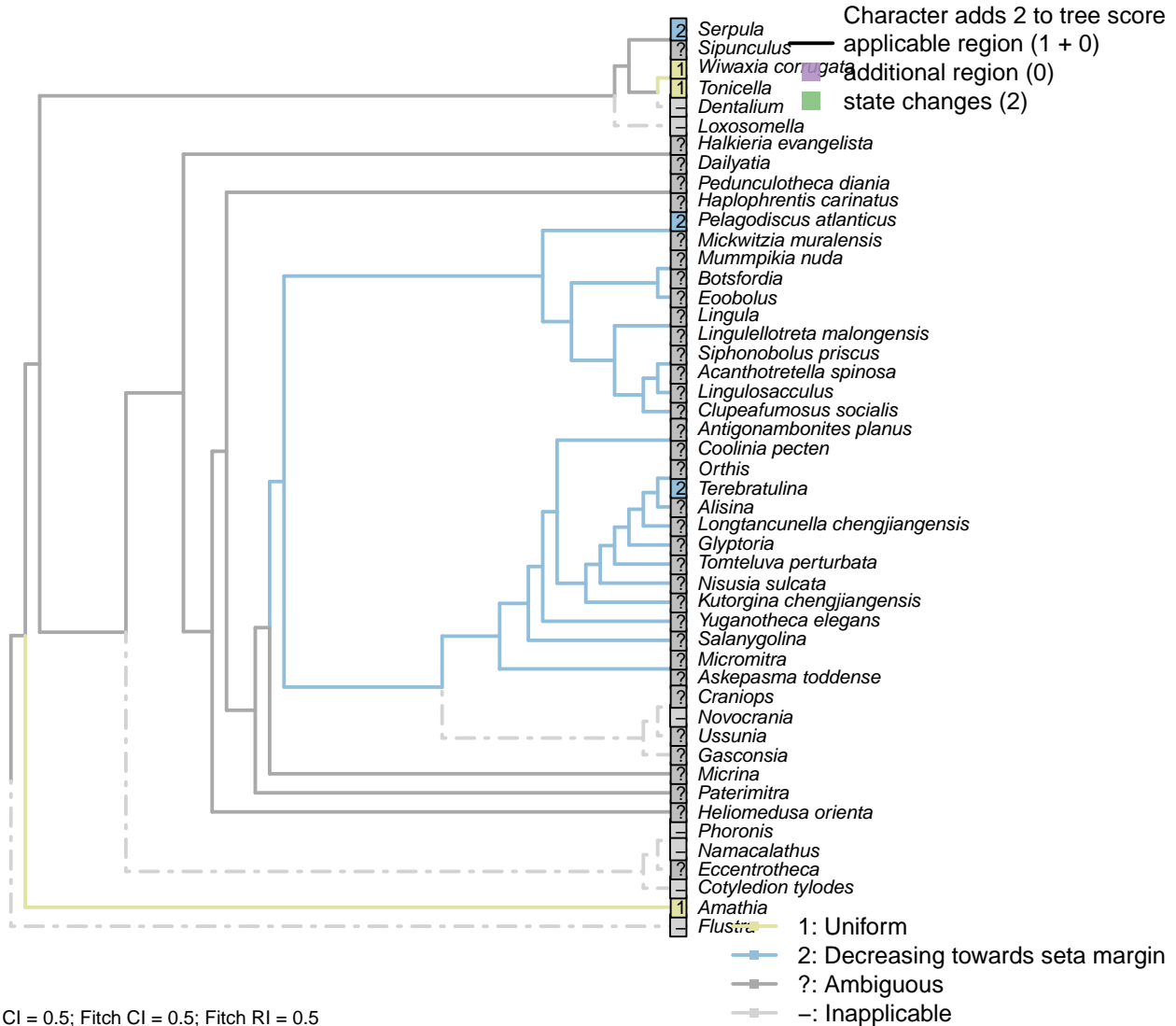
3.4 Setae: Secretion [10]



The majority of lophotrochozoan sclerites bear a characteristic striated texture that denotes their secretion by basal microvilli (Butterfield, 1990). The seta-like hooks of sipunculans lack this texture, suggesting that they may not be homologous with other setae.

Halkieria evangelista: No evidence of microvillar secretion (e.g. Schulze et al., 2005).

[11] Microvillar diameter

**Character 11: Setae: Secretion: Microvillar diameter**

1: Uniform

2: Decreasing towards seta margin

Transformational character.

The diameter of secretory microvilli may vary across the diameter of a seta (Smith, 2014).

Acanthotretella spinosa: Uniform (Fischer et al., 1980; Leise and Cloney, 1982).

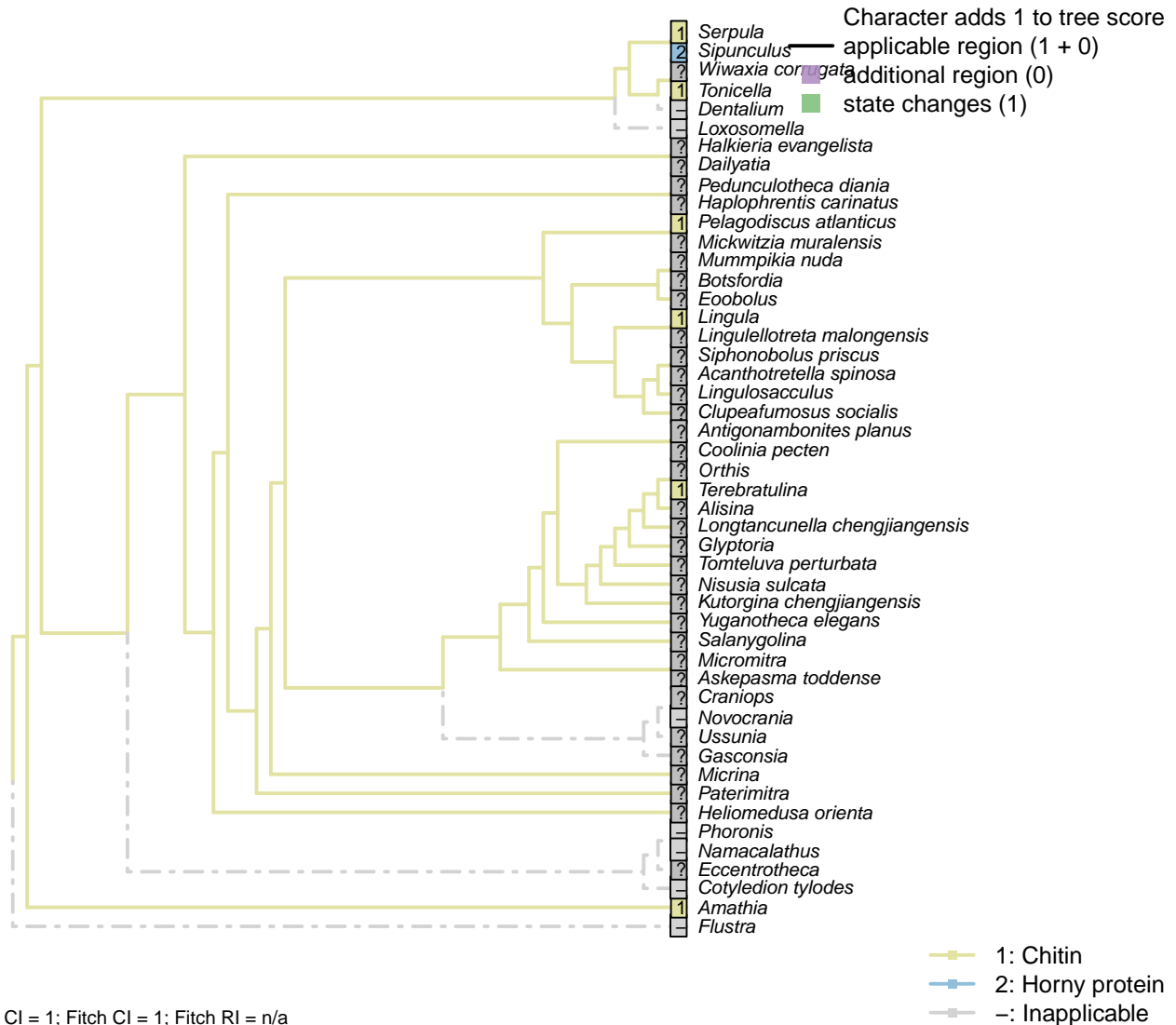
Dailyatia: Following *Scolecopsis* (Hausen, 2005); *Diasoma* (Orrhage, 1971).

Serpula: Slight decrease towards margin in *Discinisca* (Lüter, 2003).

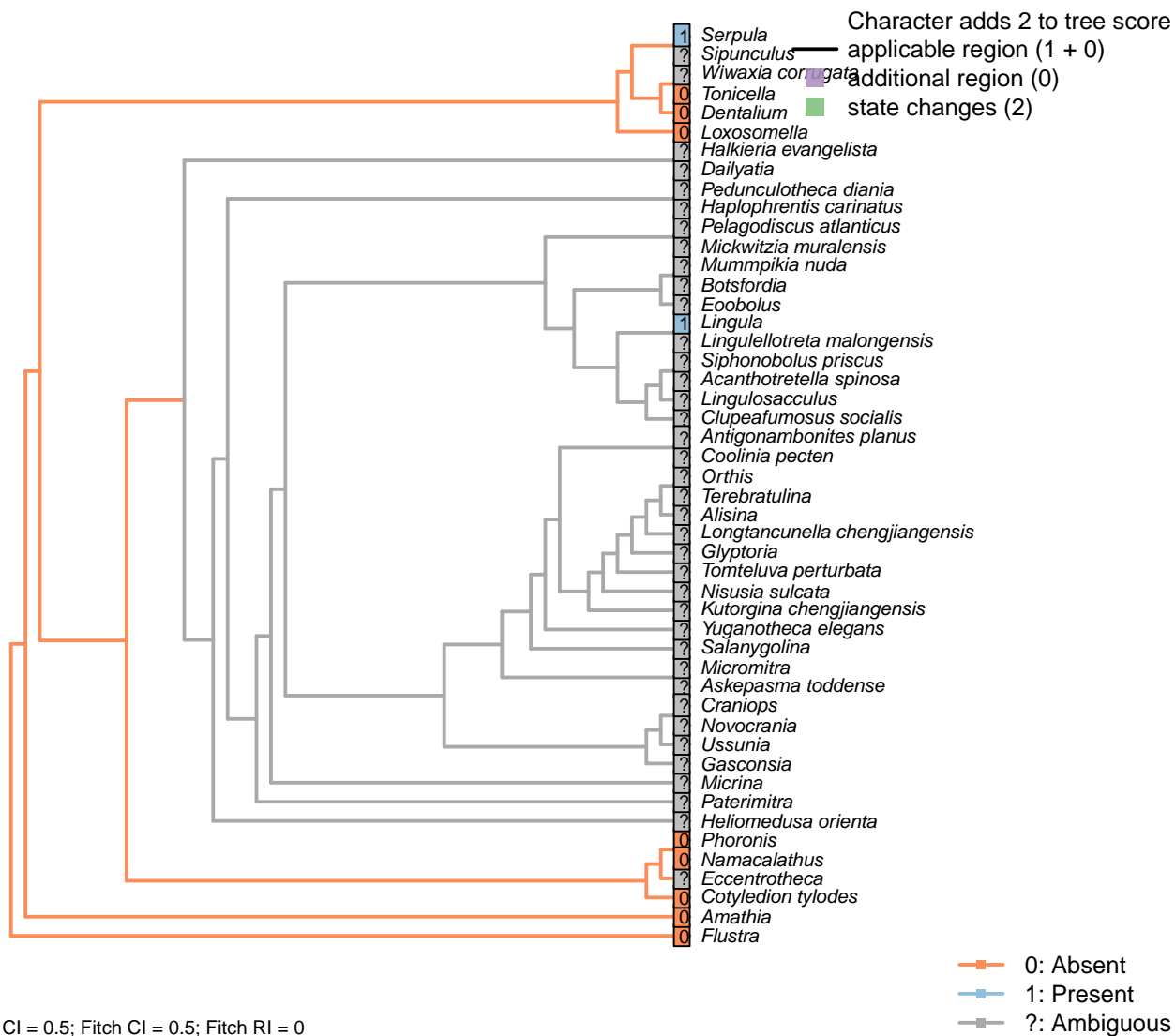
Sipunculus: No trend in microvillar size (Gordon, 1975).

Tonicella: Decreases towards margin in *Terebratalia* larvae (Gustus and Cloney, 1972).

3.5 Setae: Composition [12]



[13] Enamel

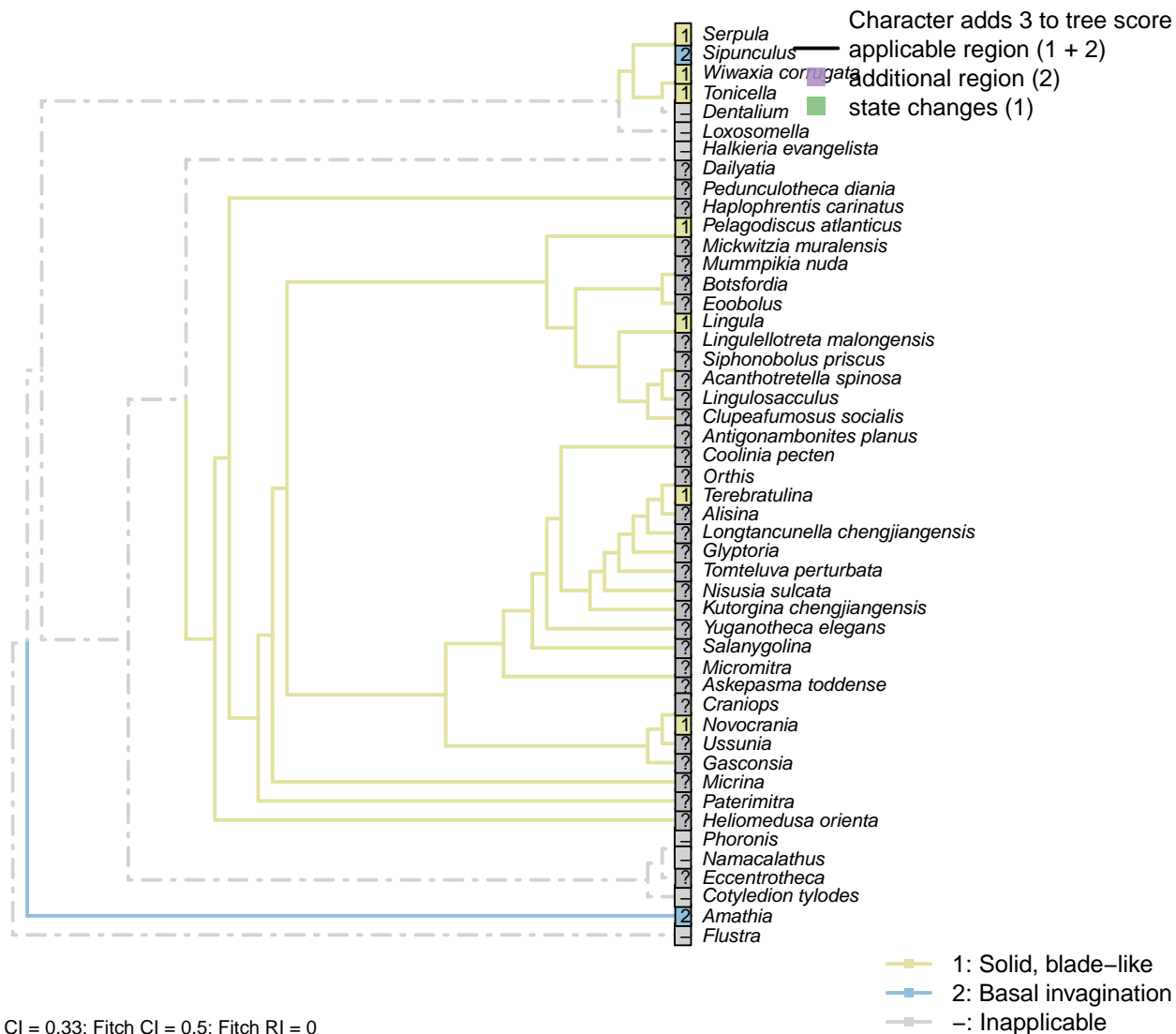


Micrina: Throughout the shell – see Williams et al. (2007) – causing the pustulose appearance remarked

upon by Chen et al. (2007).

Mummpikia nuda: At margin of shell (Zhang et al., 2005).

[15] Constitution



Character 15: Setae: Constitution

1: Solid, blade-like

2: Basal invagination

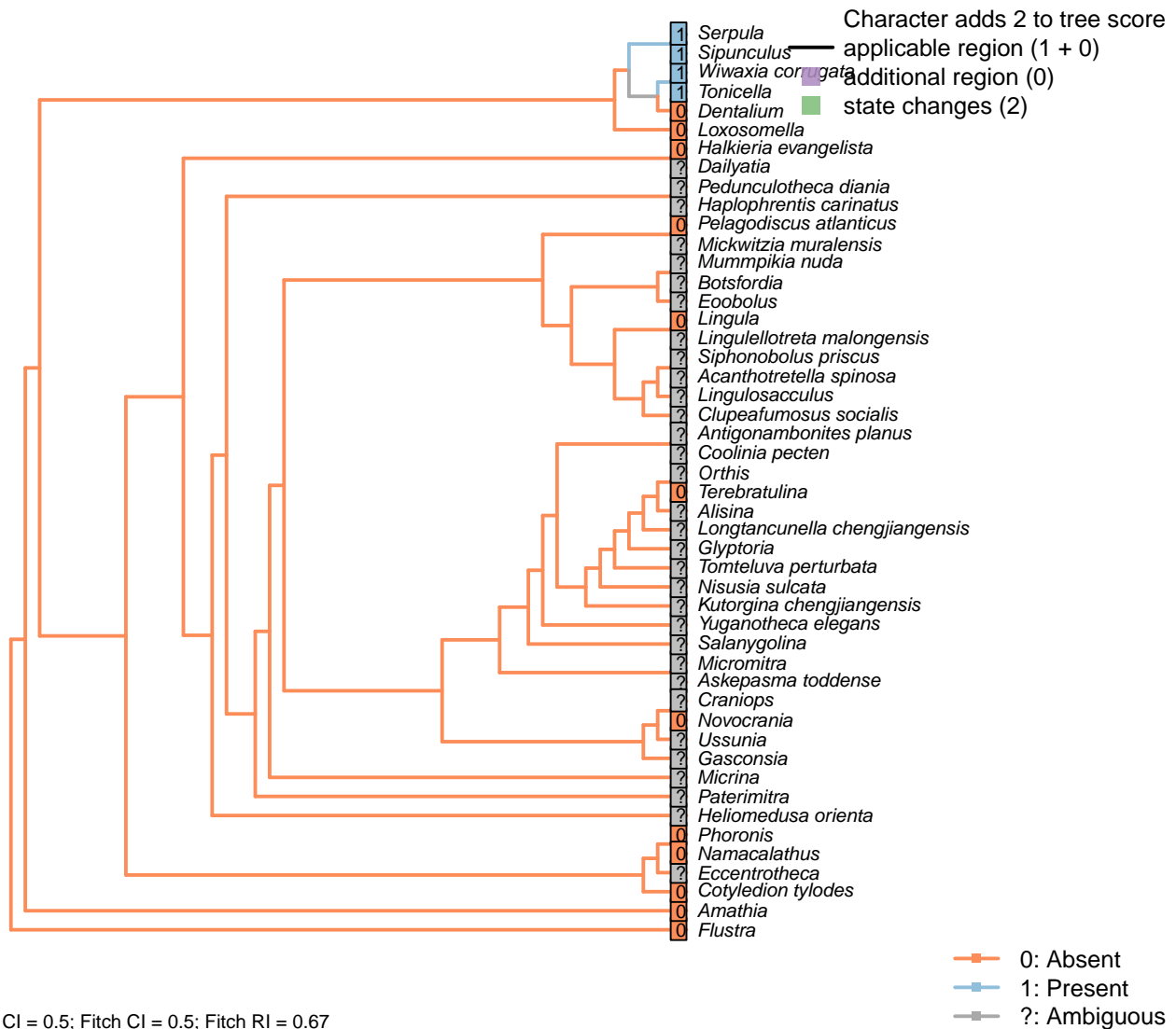
Transformational character.

Sipunculan “setae” are basally invaginated, suggesting that they may not be homologous with annelid chaetae.

Sipunculus: Cytoplasmic intrusion into a central cavity (Gordon, 1975).

3.6 Body organization

[16] Serial repetition



Character 16: Body organization: Serial repetition

0: Absent

1: Present

Neomorphic character.

Serial repetition in adult, whether expressed in valves, soft tissues or exoskeletal elements. See character 13 in Rouse (1999); 19 in Vinther et al. (2008); 38 in Haszprunar (1996); 40–41 in Sutton and Sigwart (2012); Wanninger (2009).

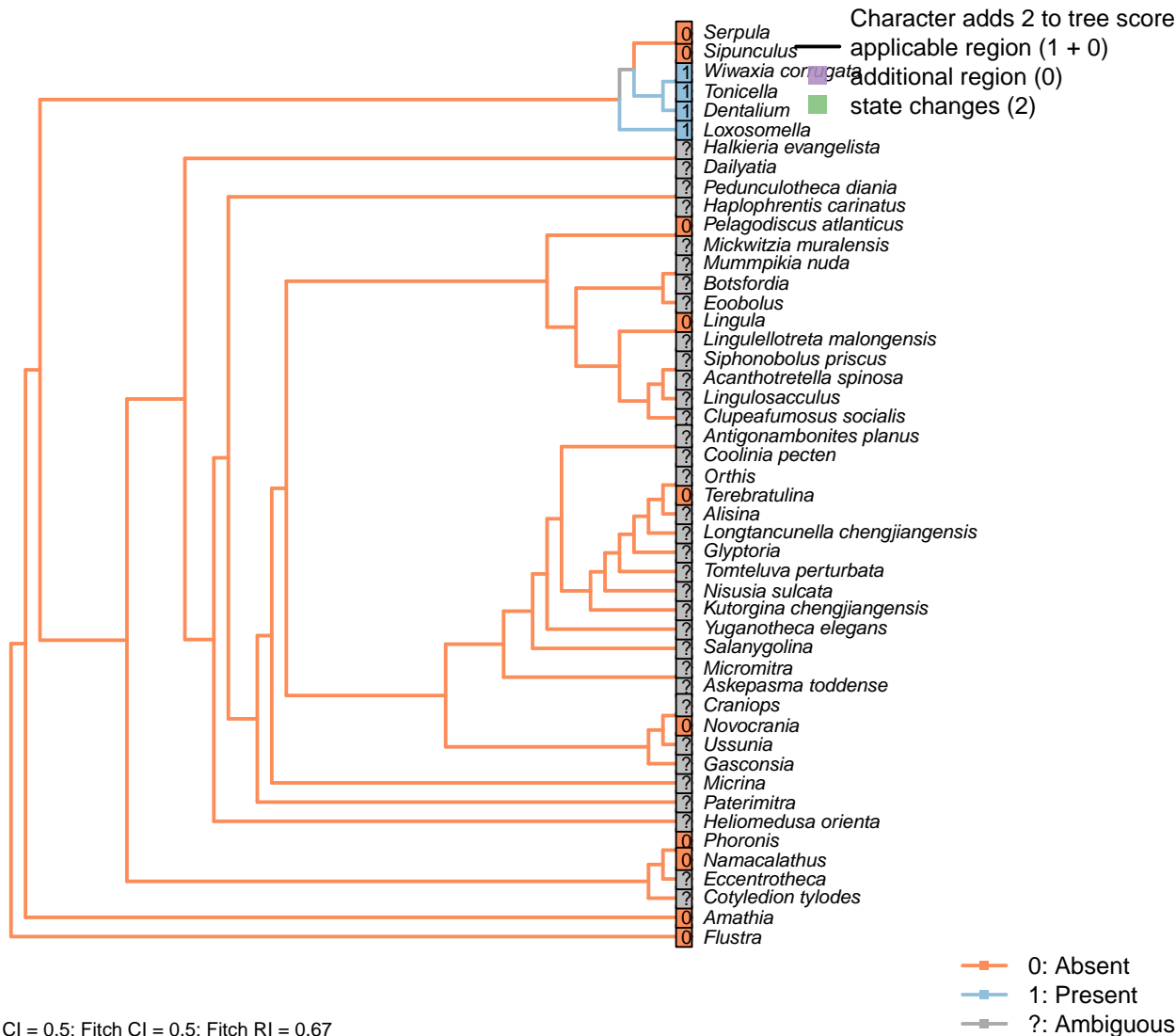
Antigonambonites planus: Elements of the *Halkieria* scleritome adhere to a quincunx arrangement, with different spacing of elements in each zone; there is no evidence of a metameric arrangement.

Botsfordia: Unknown whether sclerites are serially repeated, or whether metameres were present in underly-

ing soft anatomy.

Namacalathus: Not evident.

[17] Foot



Character 17: Body organization: Foot

0: Absent

1: Present

Neomorphic character.

See characters 8 in Haszprunar (1996); 4 in Vinther et al. (2008); 137 in Rouse (1999); 21 in Buckland-Nicks (2008); 37 in Sutton and Sigwart (2012); 1, 3 and 4 in Haszprunar and Wanninger (2008).

It is assumed that the adult foot is homologous with (and thus contingent on) the larval foot.

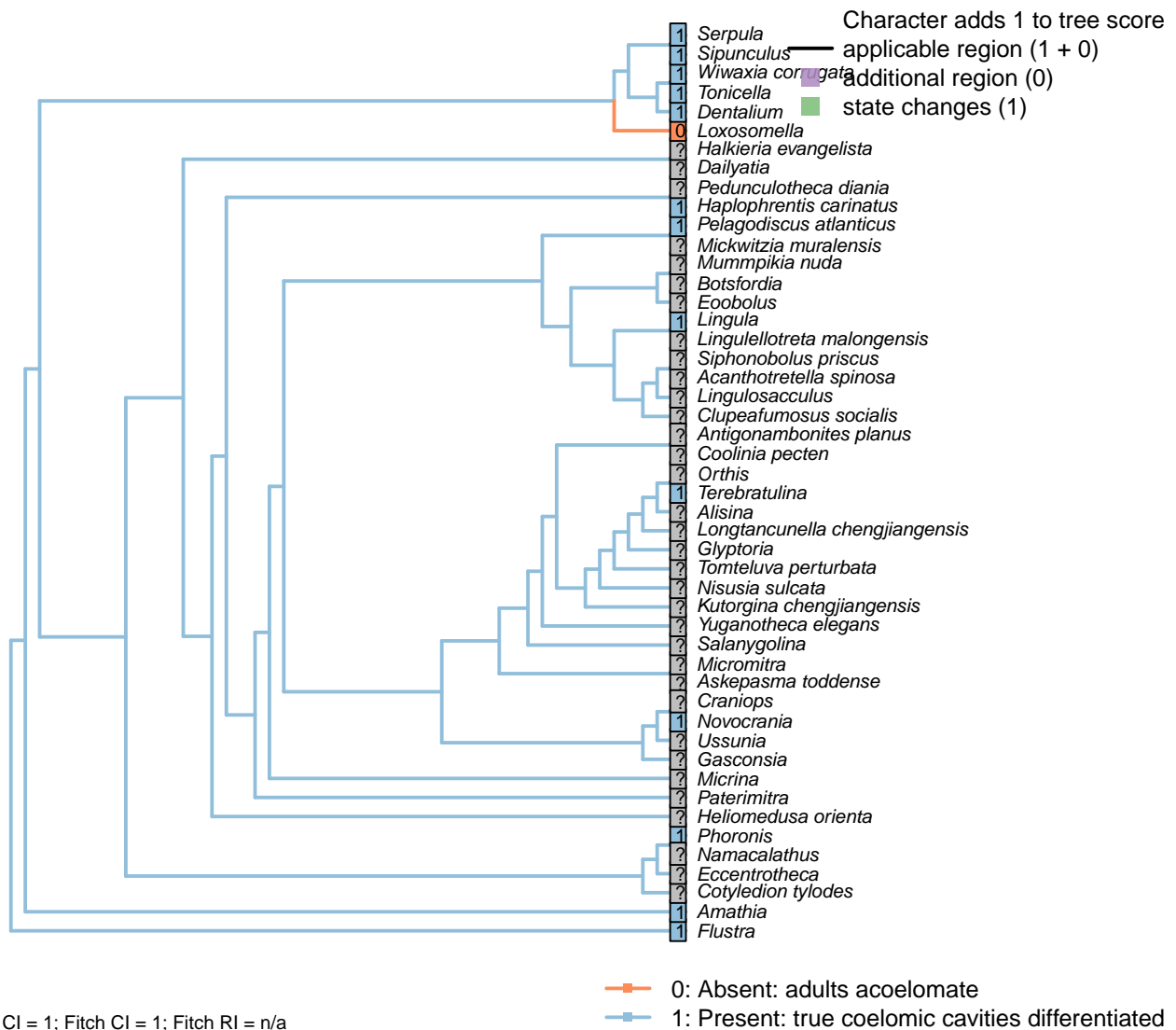
Antigonambonites planus: The ventral surface of *Halkieria* is unarmoured, but its soft anatomy is unknown.

Halkieria evangelista: LISTED AS PRESENT IN Smith (2012a): WHY?.

Lingula: See Haszprunar and Wanninger (2008).

Terebratulina: The stalk may conceivably be homologous with the entoproct foot, but the evidence for homology is weak.

[18] Coelom



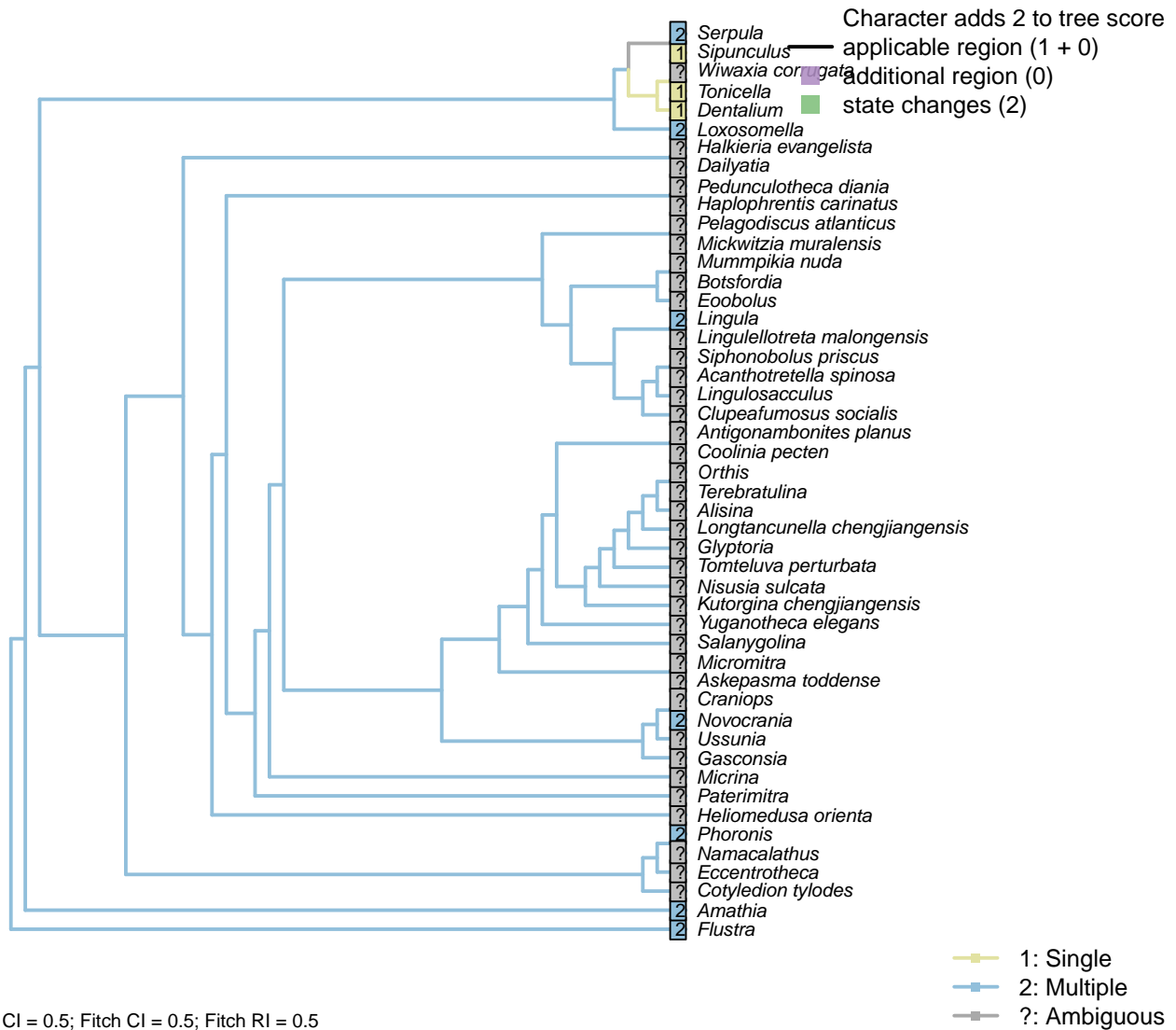
Amathia: Internal cavities indicated by differentiation of internal organs (see Moysiuk et al., 2017).

Lingula: “Adult entoprocts are acoelomate” – Fuchs and Wanninger (2008).

Phoronis: “Adult ectoprocts differentiate true coelomic cavities” – Fuchs and Wanninger (2008).

Wiwaxia corrugata: Temereva (2017).

[19] Number



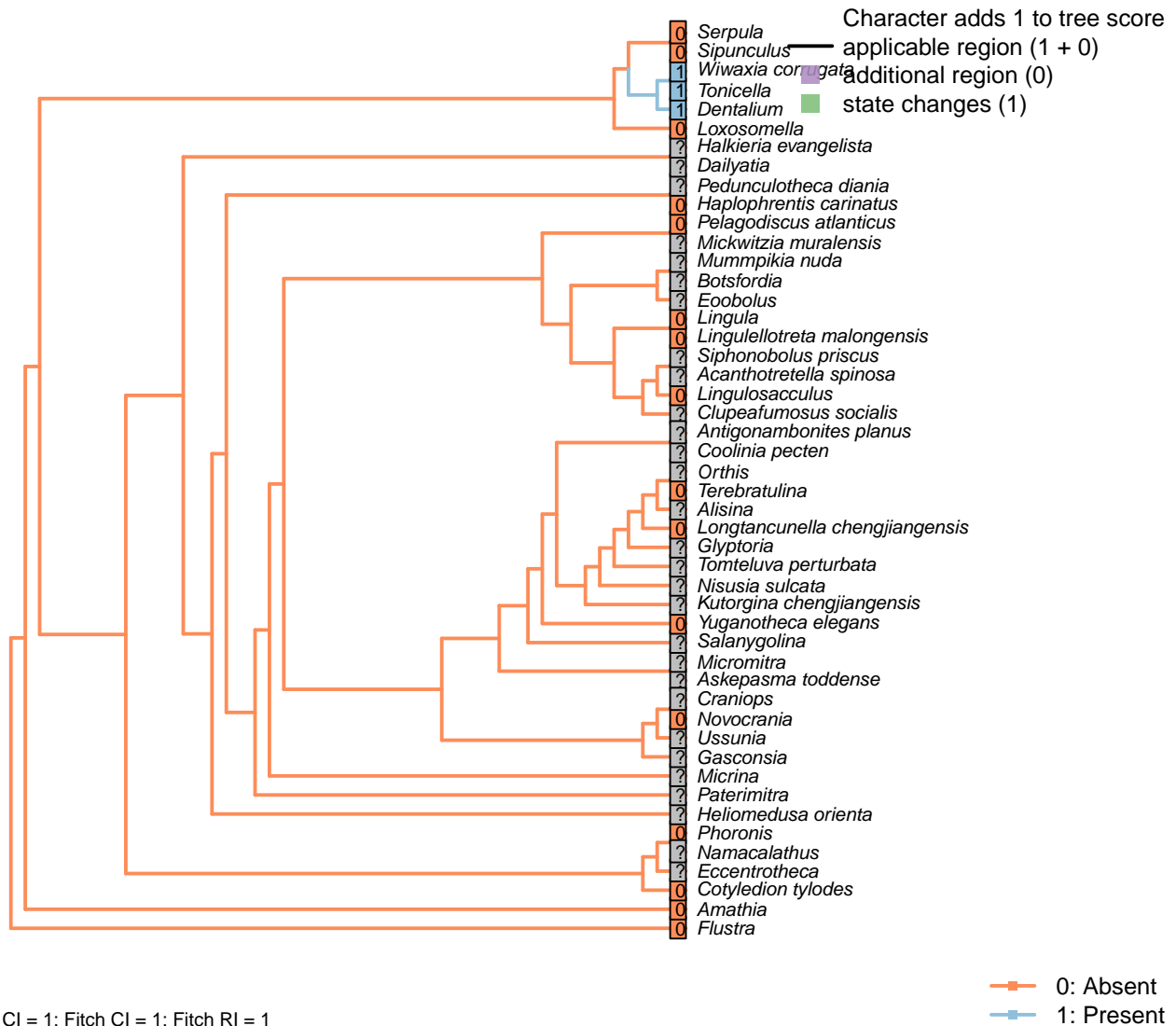
some cases serving as genital ducts (gonoducts); they replace (and may resemble) nephridia (Goodrich, 1945).

Lingula: Two coelomoducts pass outwards, meet, and open by a common pore (Goodrich, 1945).

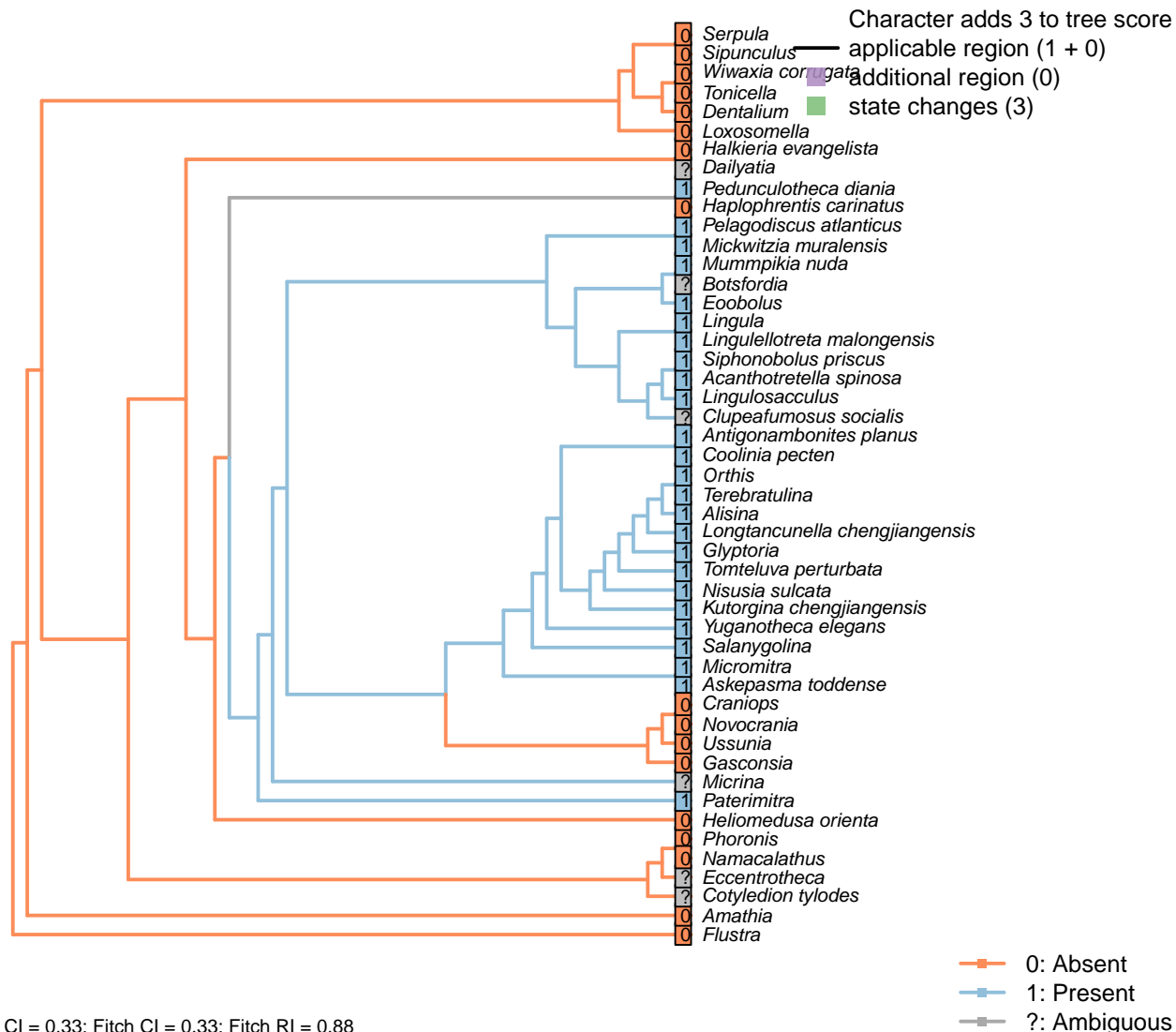
Phoronis: Multiple ciliated ducts leading to a common gonopore (Goodrich, 1945).

Wiwaxia corrugata: “large coelomic funnels serving as genital ducts” (Goodrich, 1945).

3.7 Body organization: Gills [20]



3.8 Pedicle [21]



suggest its interpretation as a pedicle sheath that is superseded as an attachment structure. On the other hand, its continuity with the internal pedicle tube suggests that it may represent an independent organ.

Gasconsia: Pedicle foramen was not necessarily occupied by a pedicle (though it presumably was).

Glyptoria: Attached apically by cementation.

Halkieria evangelista: Absent; there is no clear basis to homologise the larval attachment structure of certain sipunculans with a pedicle.

Lingula: The stalk corresponds to the molluscan foot, rather than a pedicle.

Mickwitzia muralensis: The absence of a pedicle is inferred from the absence of an internal pedicle tube, and the absence of a pedicle at the hinge.

Micrina: “It seems unlikely that *H. orientalis* possessed a pedicle that attached it to the soft seafloor, like most other Chengjiang brachiopods.” ...

“The putative pedicle illustrated by Chen *et al.* (2007, Figs 4, 6, 7) in fact is the mold of a three-dimensionally preserved visceral cavity” – Zhang *et al.* (2009).

Namacalathus: There is no obvious way to homologise the attachment structure with the ventral pedicle of brachiopods.

Phoronis: Grows directly onto the substrate.

Salanygolina: An attachment structure is inferred based on the presence of an opening (Balthasar, 2004); this is assumed to have been homologous with the brachiopod pedicle.

Terebratulina: The stalk is conceivably homologous with the brachiopod pedicle, but this possibility is impossible to test.

Tomteluva perturbata: Has a pedicle, rather than a pedicle sheath as in *Kutorgina* (Holmer *et al.*, 2018a,b).

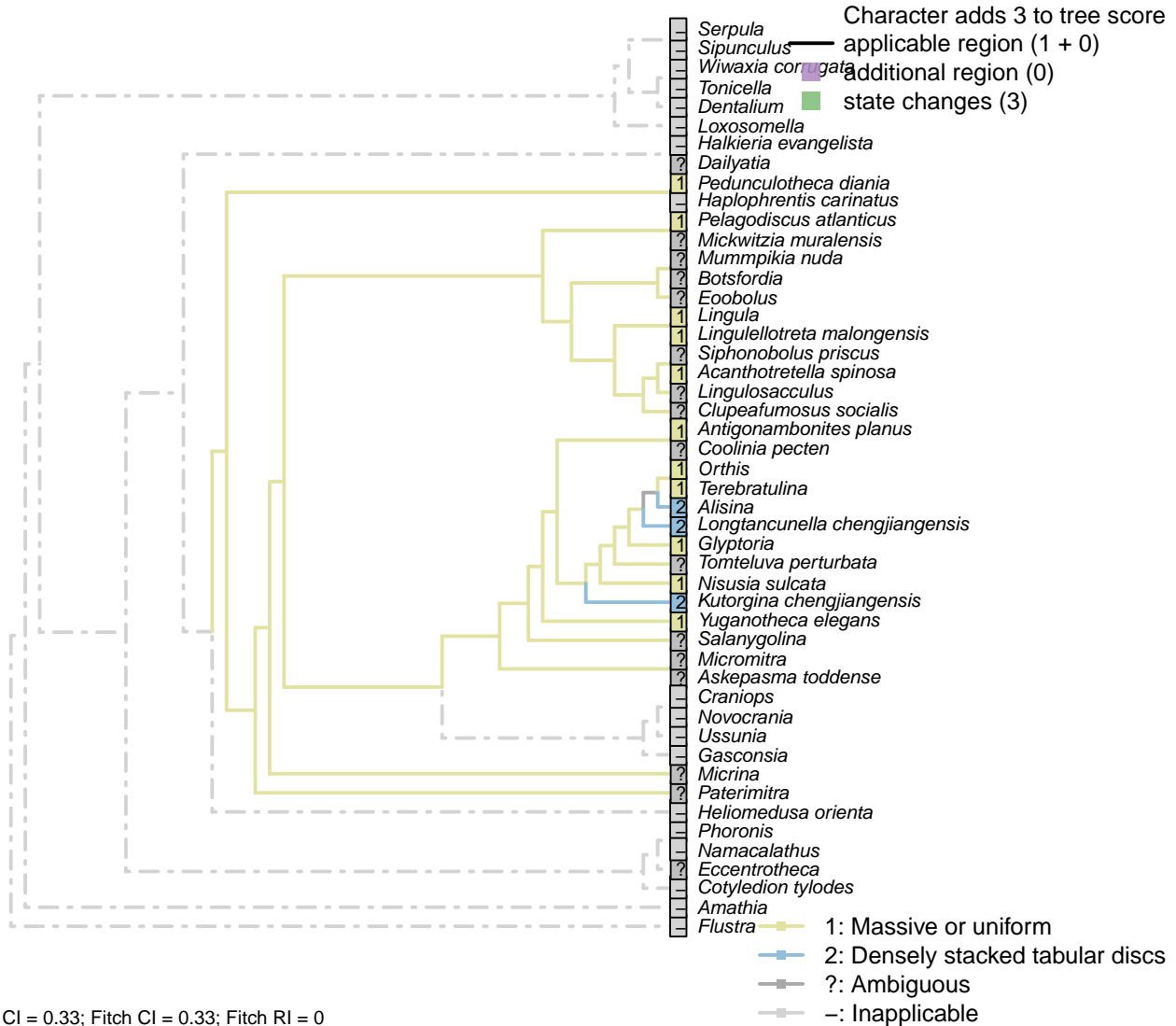
Ussunia: A pedicle was presumably present, but only the foramen is preserved.

Wiwaxia corrugata: The tube-bearing stalk of phoronids arises as an eversion of the metastomal sac, a markedly different origin from the brachiopod pedicle, which arises from a terminal attachment disc (Young, 2002); the structures are of dubious homology.

NA: “*Paterimitra* is interpreted to have attached to hard substrates via a pedicle that emerged through the small posterior opening” – Skovsted *et al.* (2009).

NA: Presumed present, based on ventral foramen with colleplax.

[22] Constitution

**Character 22: Pedicle: Constitution**

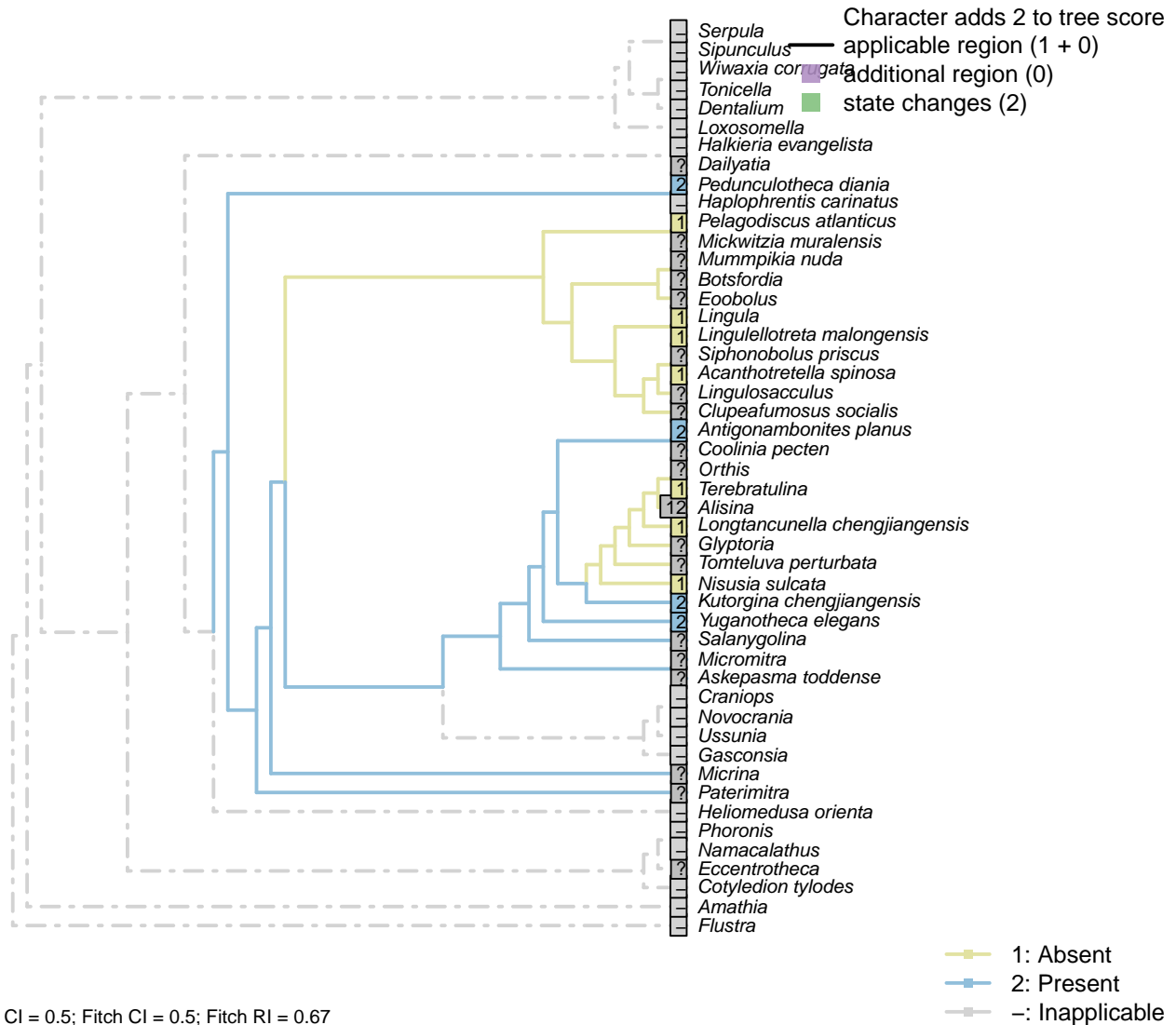
- 1: Massive or uniform
 - 2: Densely stacked tabular discs
- Transformational character.

The pedicle of certain chengjiang rhynchonelliforms comprises “densely stacked, three dimensionally preserved, tabular discs” (Holmer et al., 2018a).

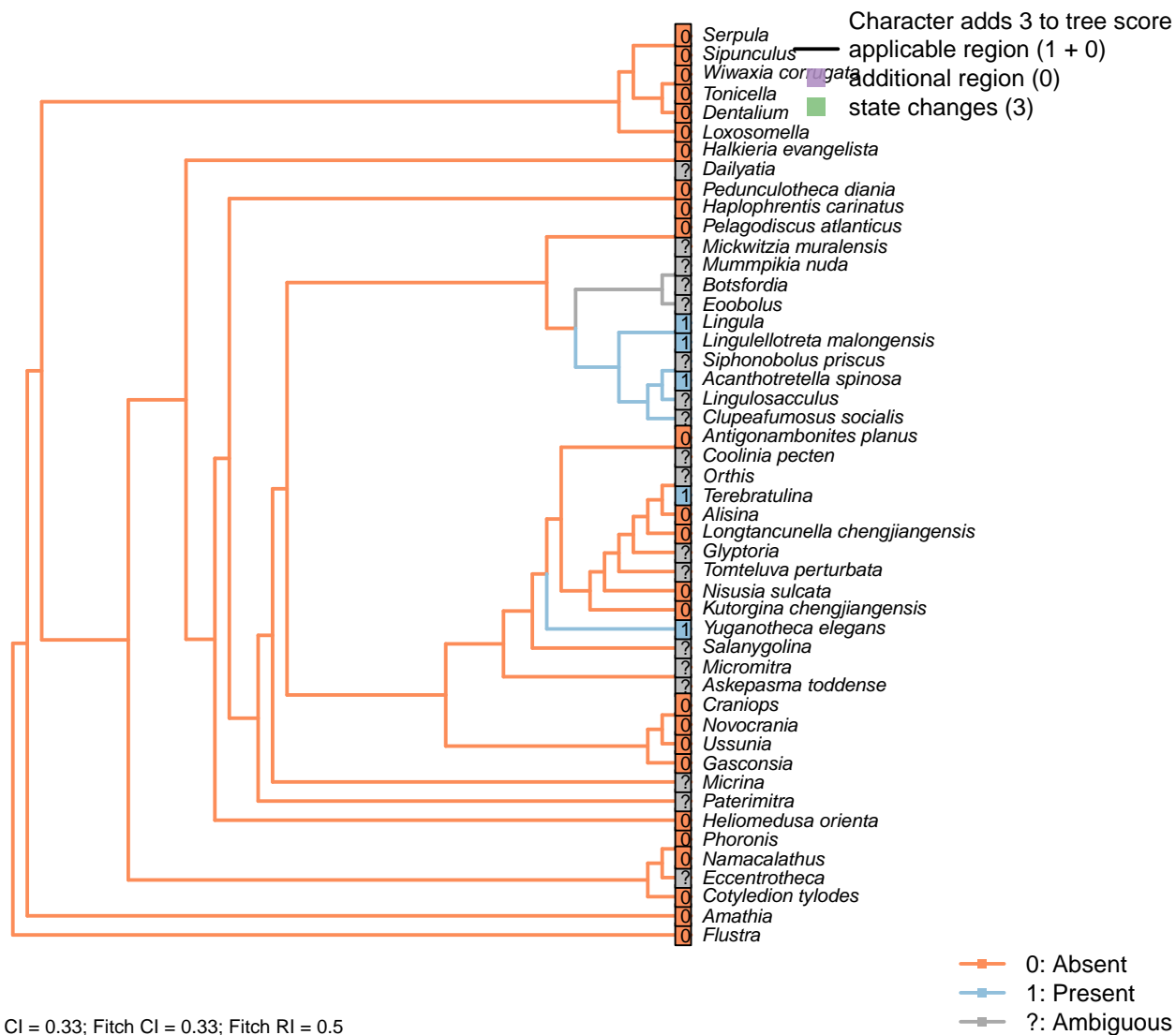
This contrasts with the uniform (‘massive’) pedicles of living taxa.

Tonicella: Extant rhynchonellid pedicles are massive, consisting of a thick outer chitinous cuticle, a pedicle epithelium, and a core composed of collagen fibres and cartilage-like connective tissue (Holmer et al., 2018a).

[23] Biomineralization



[24] Bulb

**Character 24: Pedicle: Bulb**

0: Absent

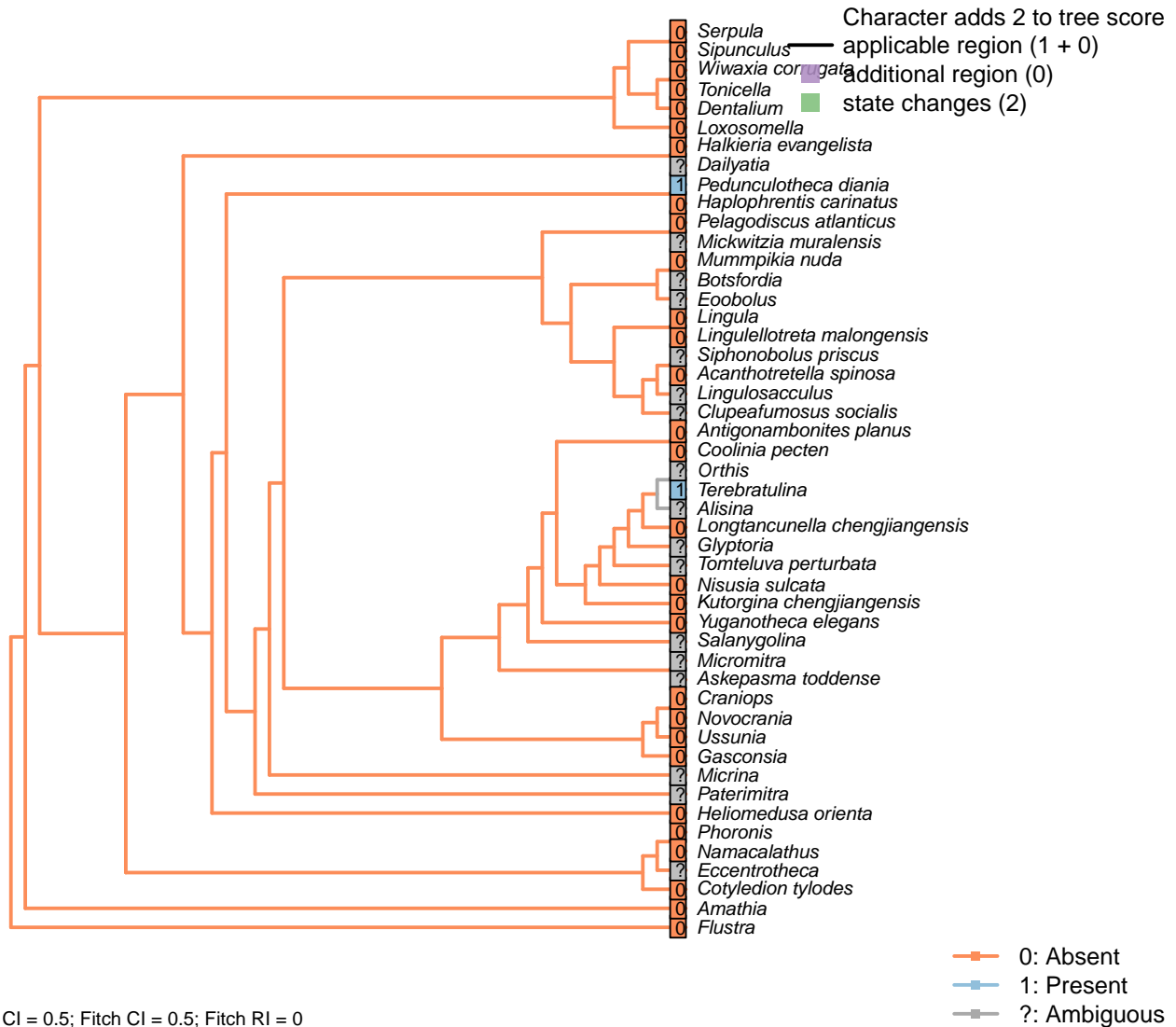
1: Present

Neomorphic character.

A bulb is an expanded region of the distal pedicle, often embedded into the sediment to improve anchorage.

Clupeafumosus socialis: Holmer and Caron (2006) interpret the presence of a bulb as tentative; we score it as ambiguous.

[25] Distal rootlets

**Character 25: Pedicle: Distal rootlets**

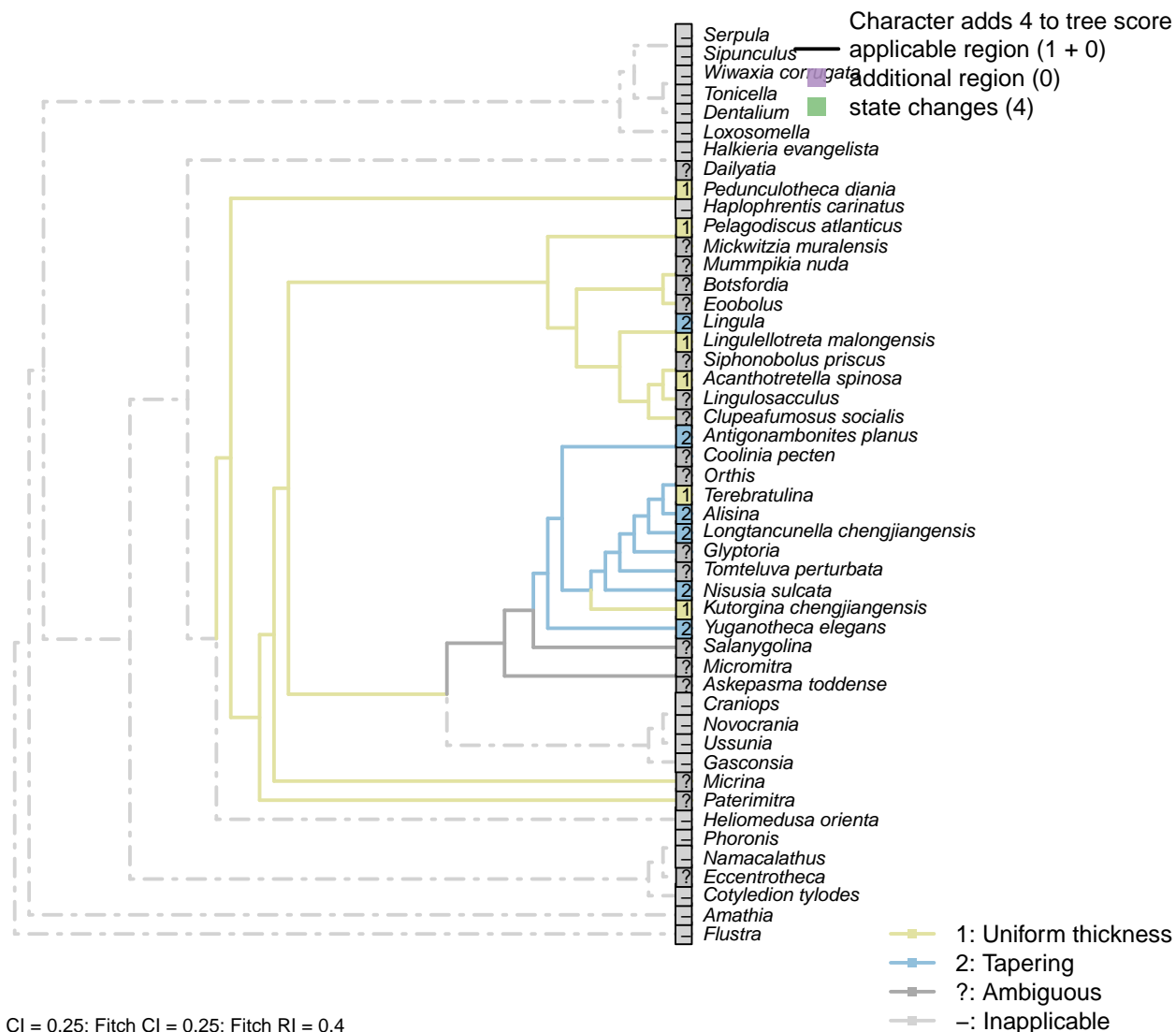
0: Absent

1: Present

Neomorphic character.

Observed in *Pedunculotheca* and *Bethia* (Sutton et al., 2005).

[26] Tapering

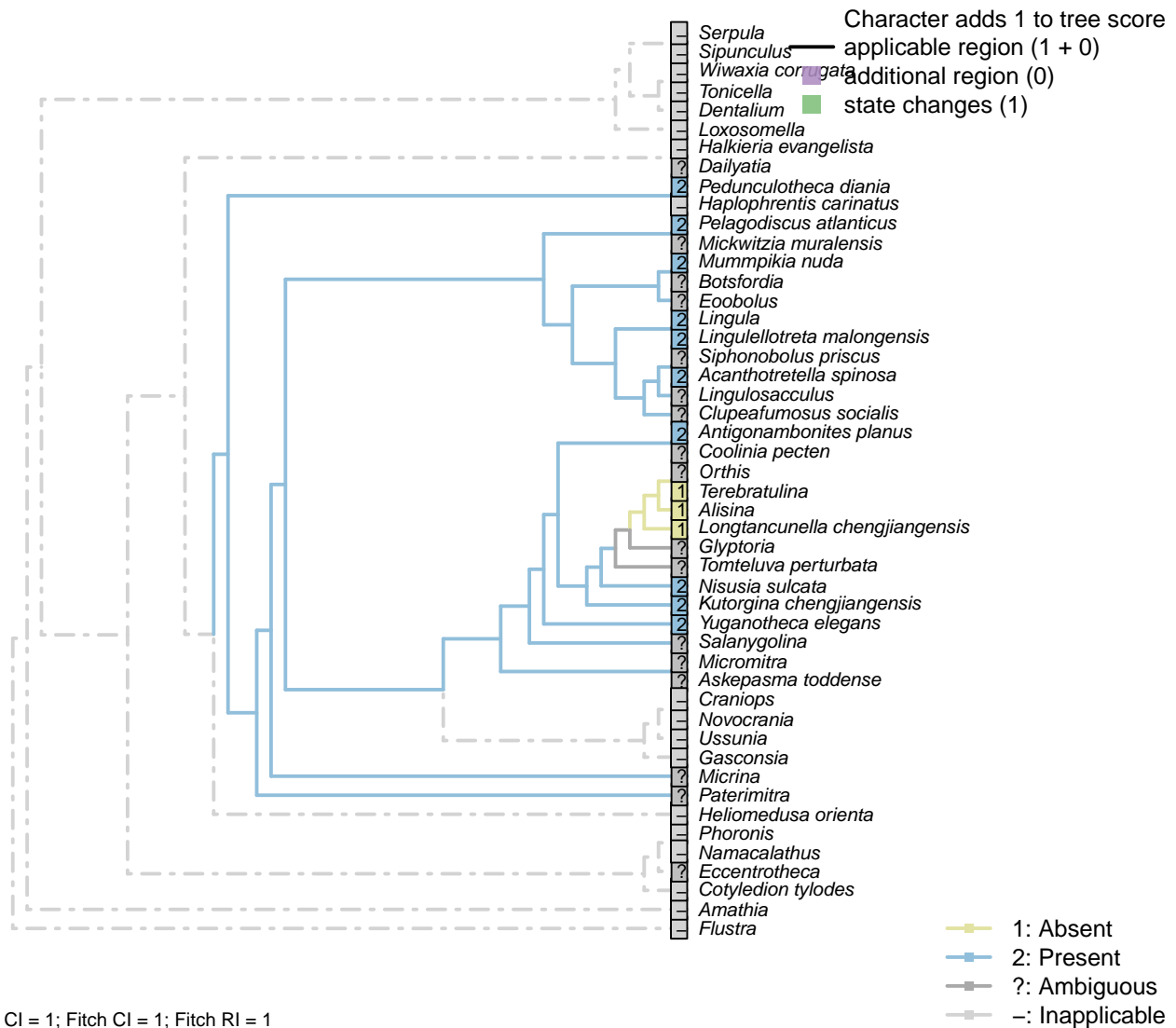


Holmer *et al.* (2018b) remark that the tapering aspect of the *Nisusia* pedicle recalls that of certain Chengjiang taxa (*Alisina*, *Longtancunella*) whilst distinguishing it from many other taxa (*Eichwaldia*, *Bethia*) in which the pedicle is a constant thickness.

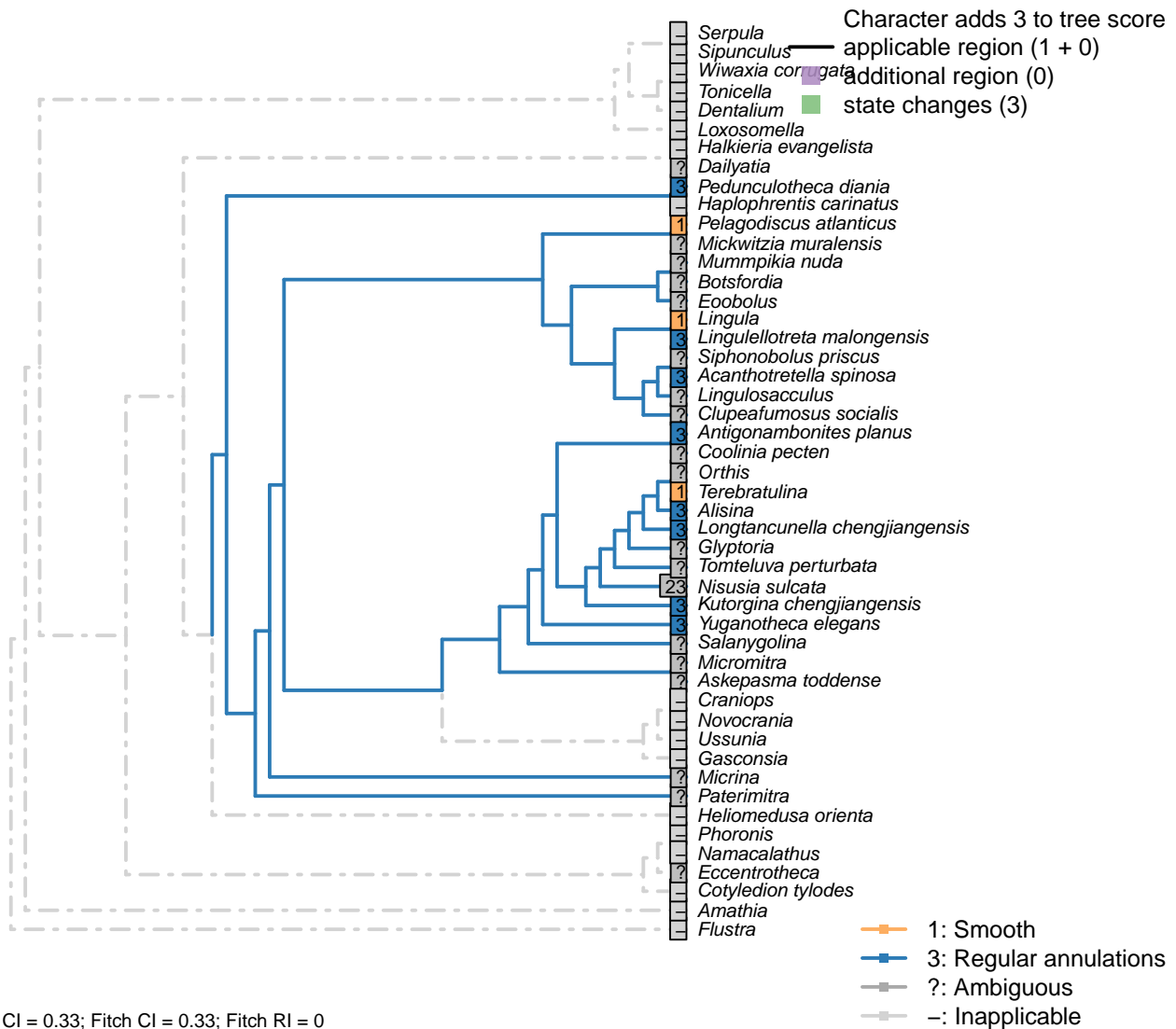
Craniops: Tapered pedicle sheath with holdfast.

Pelagodiscus atlanticus: The pedicle thickness does not obviously change between the apex of the shell and the holdfast.

[27] Coelomic region



[28] Surface ornament

**Character 28: Pedicle: Surface ornament**

- 1: Smooth
 - 2: Irregular wrinkles
 - 3: Regular annulations
- Transformational character.

Annulations are regular rings that surround the pedicle, and are distinguished from wrinkles, which are irregular in magnitude and spacing, and may branch or fail to entirely encircle the pedicle.

Clupeafumosus socialis: “The pedicle surface is ornamented with pronounced annulated rings, disposed at intervals of about 0.2 mm”.

Coolinia pecten: “It appears that the pedicle lacks a coelomic space and is distinctly annulated, with densely stacked tabular bodies” – Zhang et al. (2011b).

Craniops: “The emerging pedicle has a consistent shape in all the available specimens and is strongly

annulated and distally tapering” – Holmer et al. (2018a).

Micromitra: “Pronounced concentric annular discs disposed at intervals of 0.6–1.0 mm” – Zhang et al. (2007b).

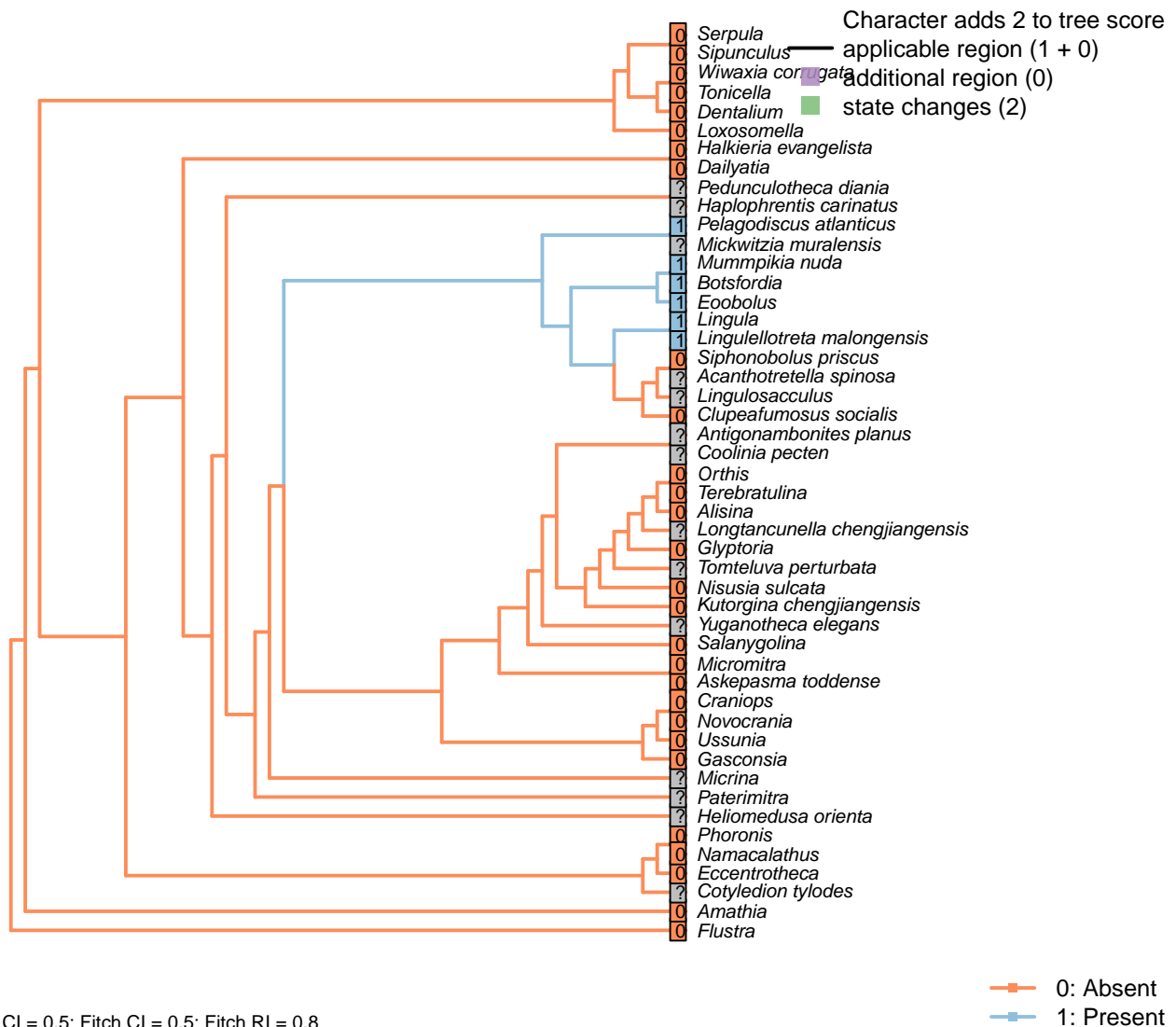
Mummpikia nuda: Regularly annotated (see fig. 14.9 in Hou et al., 2017).

Nisusia sulcata: “The preserved pedicle has condensed annulations” – Zhang et al. (2011a).

Tomteluva perturbata: The “strong annulations” vary significantly in transverse thickness (Holmer et al., 2018a), so it is not clear whether these represent true annulations or wrinkles.

NA: Annulations present in median collar.

[29] Nerve impression



Character 29: Pedicle: Nerve impression

0: Absent

1: Present

Neomorphic character.

In certain taxa the impression of the pedicle nerve is evident in the shell. See character 28 in Williams *et al.* (1998) appendix 1. Care must be taken not to code an impression as absent when the preservational quality is insufficient to safely infer a genuine absence. Treated as neomorphic as the presence of an innervation is considered a derived state.

Coolinia pecten: Not described by Williams *et al.* (2000).

Dentalium: Present in many lingulids (Williams *et al.*, 2000), and coded as present in Lingulidae (Williams *et al.*, 2000, table 6).

Gasconsia: Documented by Skovsted *et al.* (2017).

Longtancunella chengjiangensis, *Micromitra*, *Novocrania*, *Paterimitra*, NA: Following Williams *et al.* (1998), appendix 2.

Mummpikia nuda: Coded as present in Lingulelloretidae (Williams *et al.*, 2000, table 6).

Serpula: Coded as present in Discinidae (Williams *et al.*, 2000, table 6).

Siphonobolus priscus: Balthasar (2008, p. 274) identifies a canal as a probable impression of a pedicle nerve.

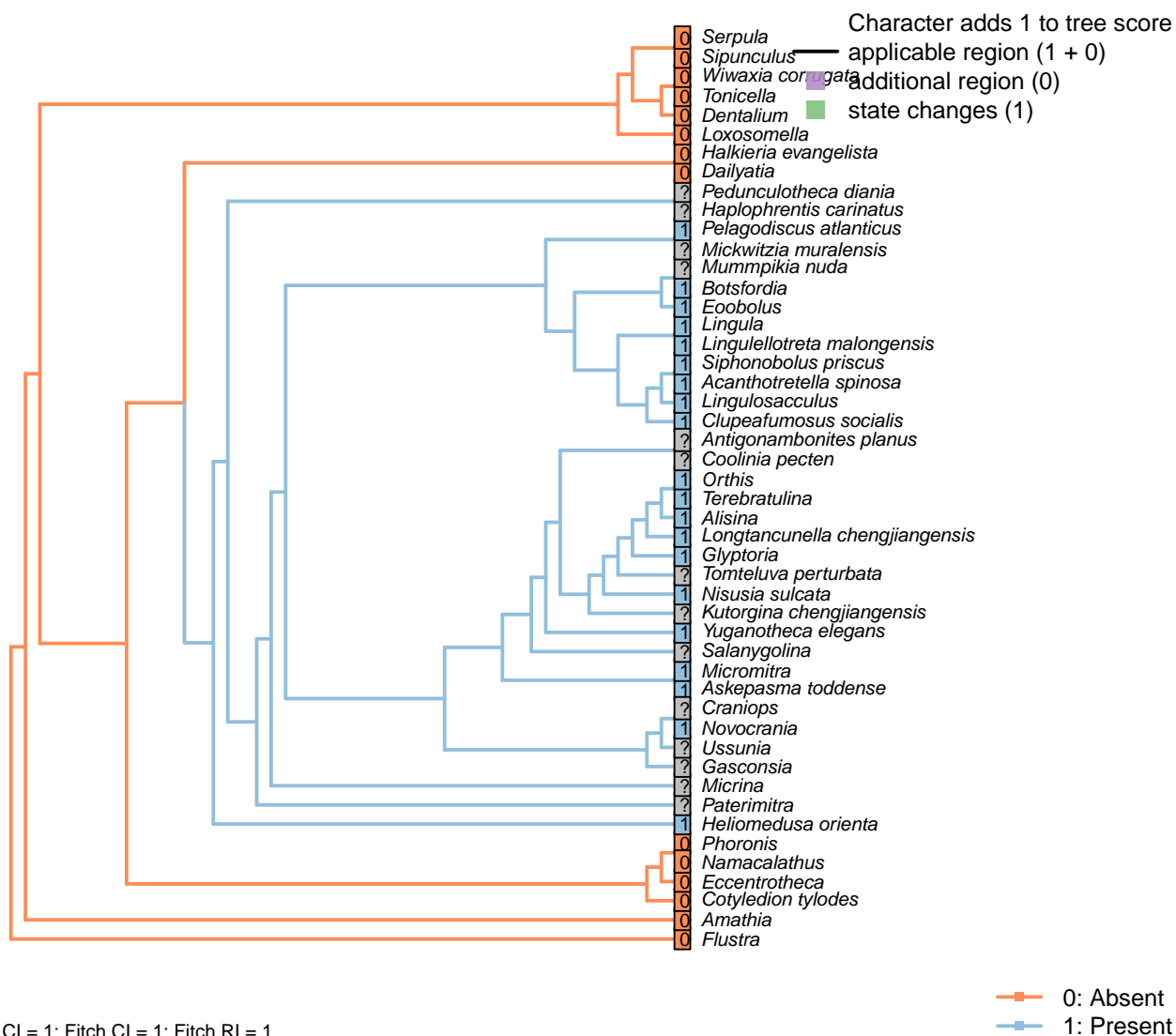
Tomteluva perturbata, *Yuganotheca elegans*: Not reported in Williams *et al.* (2000).

Ussunia: Coded as absent in Acrotretidae (Williams *et al.*, 2000, table 6).

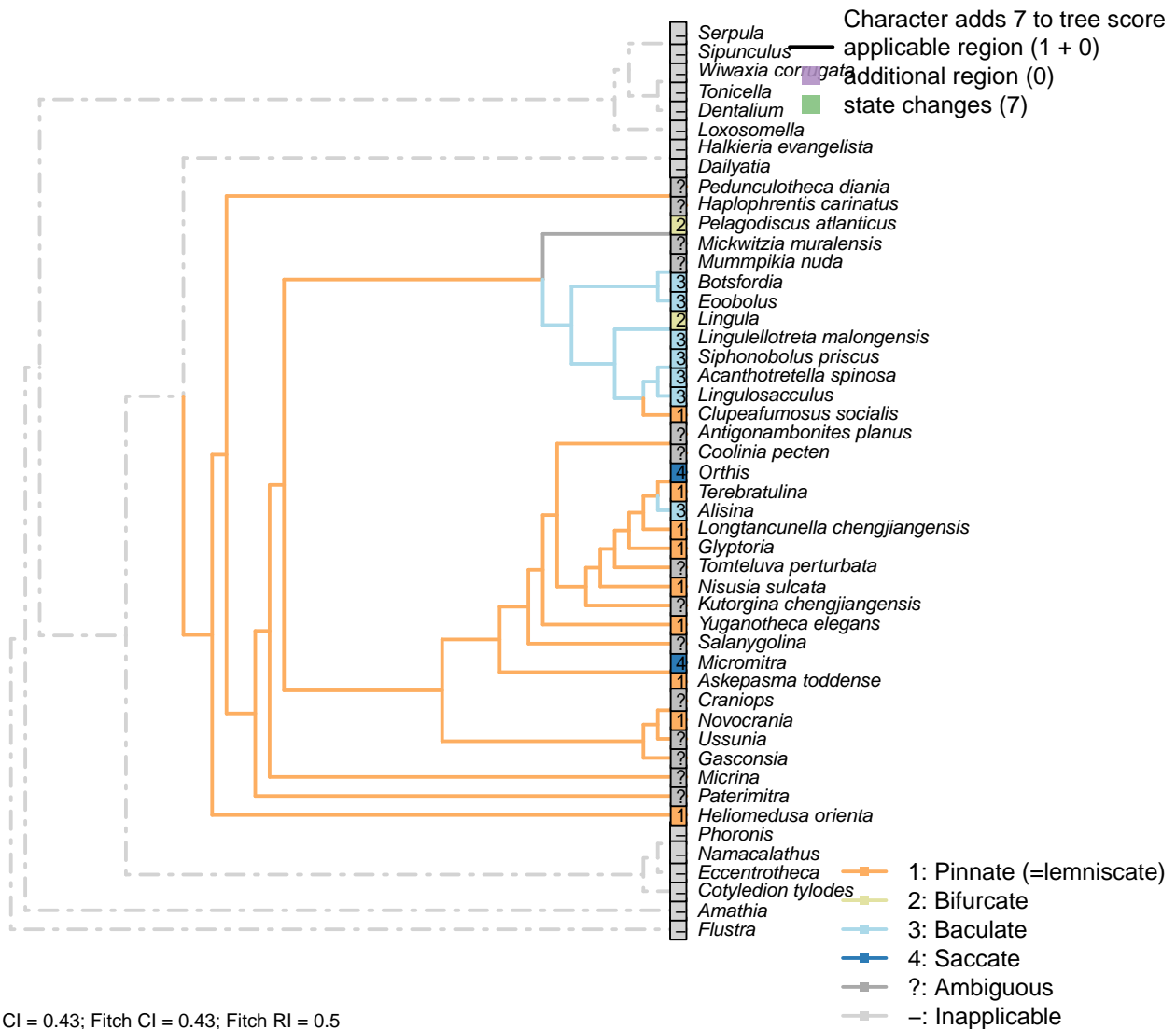
NA: Coded as absent in Siphonotretidae (Williams *et al.*, 2000, table 6).

3.9 Mantle canals

[30] Presence



[31] Morphology

**Character 31: Mantle canals: Morphology**

- 1: Pinnate (=lemniscate)
- 2: Bifurcate
- 3: Baculate
- 4: Saccate

Transformational character.

The morphology of dorsal and ventral canals is identical in all included taxa, so is assumed not to be independent – hence the use of a single character (contra Williams et al., 2000).

For a description of terms see Williams *et al.* (1997, 2000).

Pinnate = “rapidly branch into a number of subequal, radially disposed canals”

Bifurcate = “*vascula lateralia* in both valves divide immediately after leaving the body cavity”

Baculate = “extend forward without any major dichotomy or bifurcation” (Williams et al., 1997, p. 418)

Saccate = “pouchlike sinuses lying wholly posterior to the arcuate *vascula media*” (ibid., p412).

Clupeafumosus socialis: Following Table 6, for Siphonotretidae, in Williams *et al.* (2000).

Coolinia pecten, *Tomteluva perturbata*: Following Table 15 in Williams *et al.* (2000).

Craniops: Not reported in Treatise (Williams *et al.*, 2000).

Dentalium, *Mummpikia nuda*: Following table 6 in Williams *et al.* (2000).

Eccentrotheca: Not reported in Williams *et al.* (2000).

Eoobolus, *Micromitra*: Following table 15 in Williams *et al.* (2000) (for *Neocrania*).

Gasconsia, *Lingulellotreta malongensis*: Following Williams *et al.* (1998), appendix 2, and Williams *et al.* (2000), table 8.

Glyptoria: Not reported from fossil material.

Heliomedusa orienta: Williams *et al.* (2000, table 15) appear to use Palaeotrimerella (as drawn in Williams *et al.*, 1997) as a model for *Gasconsia*, which pre-supposes a close relationship. We are not aware of any report of mantle canals from *Gasconsia* itself.

Longtancunella chengjiangensis: Following appendix 2 (char. 21) in Williams *et al.* (1998).

Mickwitzia muralensis: Baculate *vascula media* – Balthasar & Butterfield (2009).

Micrina: Described as pinnate by Jin & Wang (1992).

Nisusia sulcata: Reported by Zhang *et al.* (2007c, 2011T) though the interpretation is tentative.

Novocrania: Described as pinnate (at least in ventral valve) by Williams *et al.* (1998, p. 250).

Paterimitra: Described as saccate by Williams *et al.* (1998).

Serpula: Following table 6, for Discinidae, in Williams *et al.* (2000).

Siphonobolus priscus: “Poorly resolved” – Balthasar (2008).

Tonicella: “In modern terebratulides, the *vascula media* are subordinate to the lemniscate or pinnate *vascula genitalia*” – Williams *et al.* (1997).

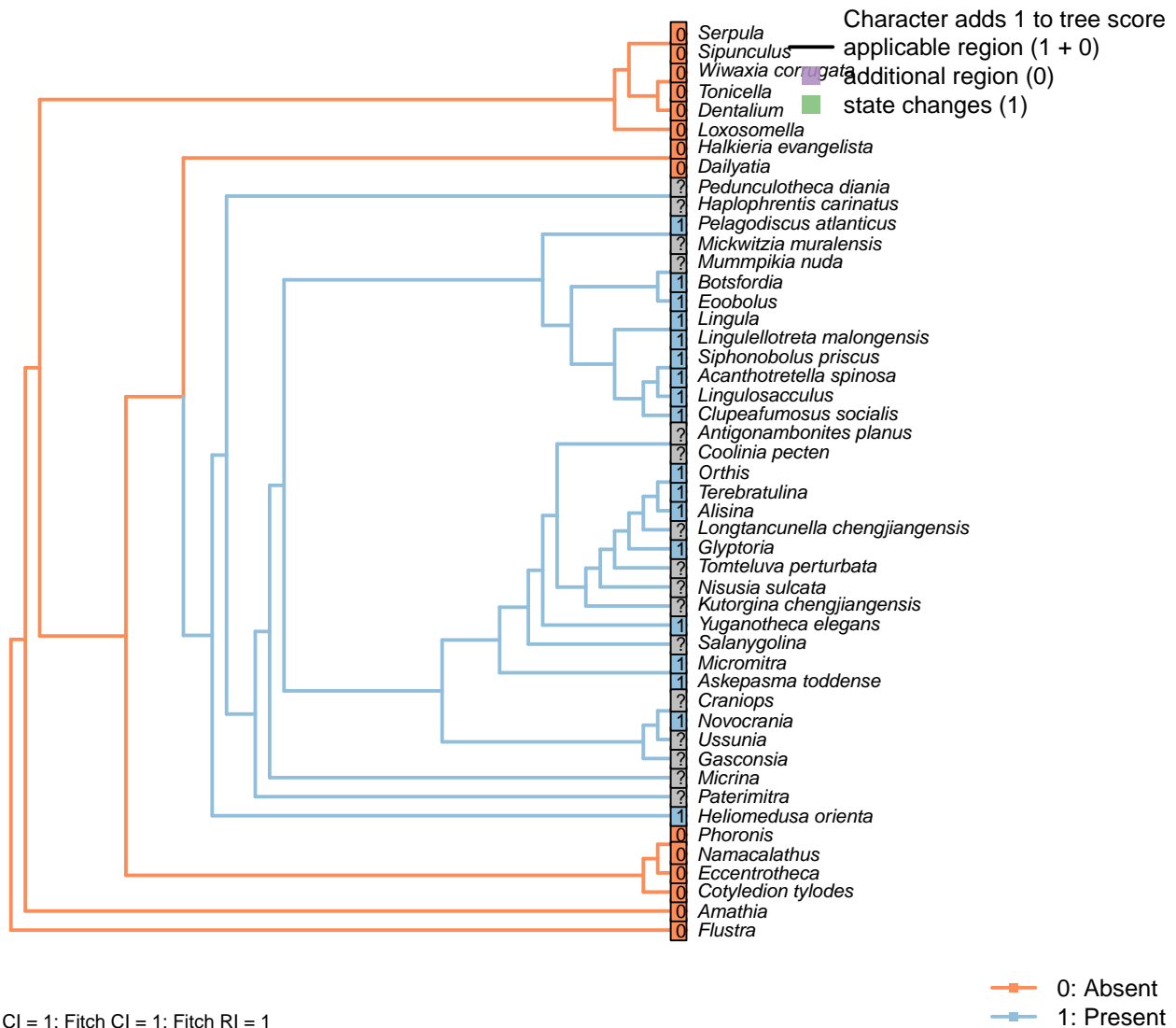
Ussunia: Following Table 8 (for Acrotreta) in Williams *et al.* (2000), and the general pinnate condition for acrotretoids stated in Williams *et al.* (1997), p. 420.

Yuganotheca elegans: Sacculate (sometimes digitate in dorsal valve) (Williams *et al.*, 2000, p716).

NA: Preservation not adequate to evaluate (Streng *et al.*, 2016).

NA: Coded uncertain in appendix 2 in Williams *et al.* (1998).

NA: Interpreted as baculate, following Havlicek (1982).

[32] *vascula lateralia*

We treat the *vascula lateralia* as equivalent to the *vascula genitalia* of articulated brachiopods, allowing phylogenetic analysis to test their proposed homology.

Williams *et al.* (1997) write: “The mantle canal system of most of the organophosphate-shelled species consists of a single pair of main trunks in the ventral mantle (*vascula lateralia*) and two pairs in the dorsal mantle, one pair (*vascula lateralia*) occupying a similar position to the single pair in the ventral mantle and a second pair projecting from the body cavity near the midline of the valve. This latter pair may be termed the *vascula media*, but whether they are strictly homologous with the *vascula media* of articulated brachiopods is a matter of opinion. It is also impossible to assert that the *vascula lateralia* are the homologues of the *vascula myaria* or *genitalia* of articulated species, although they are likely to be so as they arise in a comparable position.”

“In inarticulated brachiopods, two main mantle canals (*vascula lateralia*) emerge from the main body cavity through muscular valves and bifurcate distally to produce an increasingly dense array of blindly ending branches near the periphery of the mantle (fig. 71.1–71.2).”

Clupeafumosus socialis: Following table 8 (which records presence in Siphonotreta) in Williams *et al.* (2000).

Coolinia pecten, *Micromitra*, *Tomteluva perturbata*: Following table 15 in Williams *et al.* (2000).

Eoobolus: Following table 15 in Williams *et al.* (2000) (for *Neocrania*), who write that “Holocene craniides have only a single pair of main trunks in both valves, corresponding to the *vascula lateralia*”. Williams *et al.* (2007) reiterate this position (p. 2875), at least for the ventral valve.

Gasconsia: Following Popov (1992).

Heliomedusa orienta: Williams *et al.* (2000, table 15) appear to use *Palaeotrimerella* (as drawn in Williams *et al.*, 1997) as a model for *Gasconsia*, which pre-supposes a close relationship. We are not aware of any report of mantle canals from *Gasconsia* itself.

Micrina: Present: Williams *et al.* (2000); Jin & Wang (1992).

Mummpikia nuda: Present (Williams *et al.*, 2000).

Nisusia sulcata: Presence is possible but requires interpretation that is not unambiguous:

“In the dorsal valve, there can be seen two baculate grooves that arise from the anterior body wall at an antero-lateral position. These two grooves (Figs 4H, 5D) could be taken to represent the *vascula lateralia*” – Zhang *et al.* (2007c).

Novocrania, *Paterimitra*: “Laurie (1987) has shown that arcuate *vascula media* were present in the mantles of both valves as were pouchlike *vascula genitalia*, especially in the ventral valve” – Williams *et al.* (1997).

Serpula: Following *Lochkothele* (Discinidae), Fig. 43.4a in Williams *et al.* (2000).

Tonicella, *Yuganotheca elegans*: = *vascula genitalia*.

Ussunia: Presence indicated in Table 8 (for *Acrotreta*) in Williams *et al.* (2000).

NA: Preservation not adequate to evaluate (Streng *et al.*, 2016).

NA: Based on the figures and sketches in Zhang *et al.* (2014) (and supplementary material), the mantle canals are interpreted as lateral, with no clear *vascula media* present.

NA: Noted in *Siphonobolus* by Williams *et al.* (2000), with reference to Havlicek (1982).

But in contrast, Williams et al. (2007), p. 2875, identify the dorsal valve’s canals as a *vascula media* in living cranids (though both are *lateralia* in Ordovician craniids). This character is therefore coded as ambiguous.

Gasconsia: Following Popov (1992, fig. 2).

Heliomedusa orientalis: Williams et al. (2000, table 15) appear to use Palaeotrimerella (as drawn in Williams et al., 1997) as a model for *Gasconsia*, which pre-supposes a close relationship. We are not aware of any report of mantle canals from *Gasconsia* itself.

Lingulellotreta malongensis: Fig. 5 in Balthasar (2009).

Longtancunella chengjiangensis: Present and divergent (Williams et al., 2000).

Micrina: Present: Williams et al. (2000) p162, Jin & Wang (1992).

Nisusia sulcata: Reported by Zhang et al. (2007c) though the interpretation is tentative.

Novocrania: Following table 6 (for Paterinidae) in Williams et al. (2000).

Paterimitra: Reported by Williams et al. (1998).

Serpula: Following table 6 (for Discinidae) in Williams et al. (2000).

Tonicella: “In modern terebratulides, the *vascula media* are subordinate to the lemniscate or pinnate *vascula genitalia*” – Williams et al. (1997) p417.

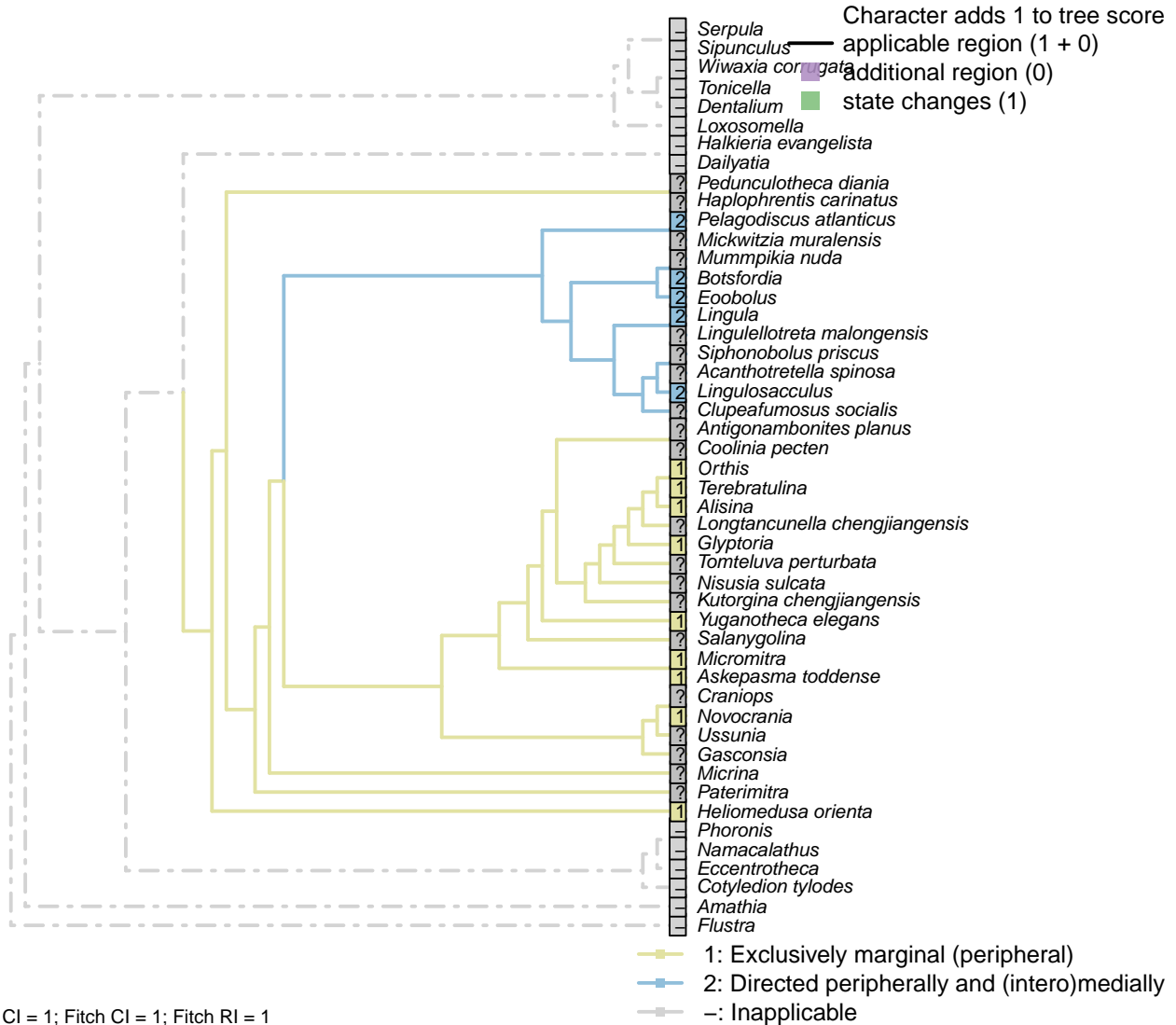
Ussunia: Following *Hadrotreta* schematic in Williams et al. (2000).

Yuganotheca elegans: From idealised morphology in Williams et al. (2000).

NA: Preservation not adequate to evaluate (Streng et al., 2016).

NA: Based on the figures and sketches in Zhang et al. (2014) (and supplementary material), the mantle canals are interpreted as lateral, with no clear *vascula media* present.

NA: Noted in *Siphonobolus* by Havlicek (1982).

[34] *vascula terminalia***Character 34: Mantle canals: *vascula terminalia***

- 1: Exclusively marginal (peripheral)
 - 2: Directed peripherally and (intero)medially
- Transformational character.

Presumed to be connected with setal follicles in life (Williams et al., 1998). See Williams *et al.* (2000) for

discussion.

Clupeafumosus socialis: Preservation not clear enough to score with certainty (Holmer and Caron, 2006).

Coolinia pecten: Interomedial *vascula terminalia* not reported by Williams *et al.* (2000).

Dentalium: Peripheral and medial for all Lingulata (Williams *et al.*, 2000).

Eoobolus: Peripheral only (Williams *et al.*, 2000, p.158).

Gasconsia, *Lingulellotreta malongensis*: Following Williams *et al.* (1998), appendix 2.

Longtancunella chengjiangensis: Following appendix 2 in Williams *et al.* (1998).

Mickwitzia muralensis: Strong indication of medially directed *vascula terminalia* from *vascula lateralia*; see fig. 1.A1 in Balthasar and Butterfield (2009).

Micrina: Inferred from Jin & Wang (1992).

Micromitra, NA: Coded uncertain in appendix 2 in Williams *et al.* (1998).

Mummpikia nuda: Not described in Williams *et al.* (2000).

Novocrania, *Paterimitra*: Peripheral only (Williams *et al.*, 1998, 2000).

Serpula: Following *Lochkothele* (Discinidae), fig. 43.4a in Williams *et al.* (2000).

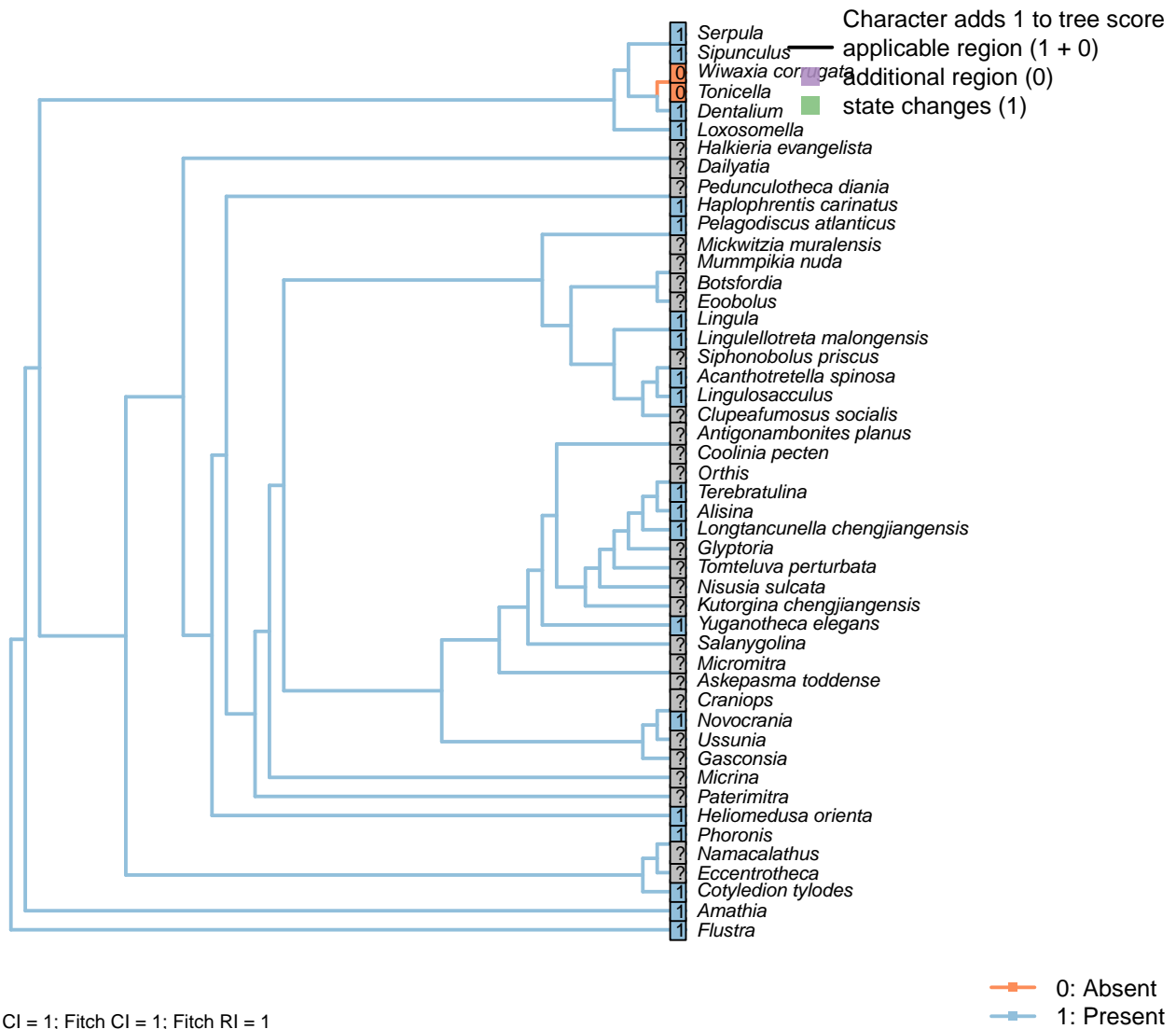
Tonicella: Following idealised plectolophous terebratulid of Emig (1992).

Yuganotheca elegans: See schematics in Williams *et al.* (2000).

NA: Not reported in Havlicek (1982) or Williams *et al.* (2000).

3.10 Perioral tentacular apparatus

[35] Presence



Character 35: Perioral tentacular apparatus: Presence

0: Absent

1: Present

Neomorphic character.

The lophophore is a ring of tentacles that surrounds the mouth. Temereva (2017) suggests that true lophophores must also encompass the anus, which excludes the tentacular apparatus of entoprocts from the definition; as homology between the tentacular apparatuses of entoprocts and other lophophorates has often been assumed, we prefer to take a more inclusive stance and code the structures as potentially homologous.

It is unlikely that the tentacles of annelids and sipunculans correspond to the lophophore, yet homology is not inconceivable. In order that the tentacular apparatus of *Haplophrentis* can be compared with both organs without prejudice, we capture the presence of a tentacular apparatus in this very broad character,

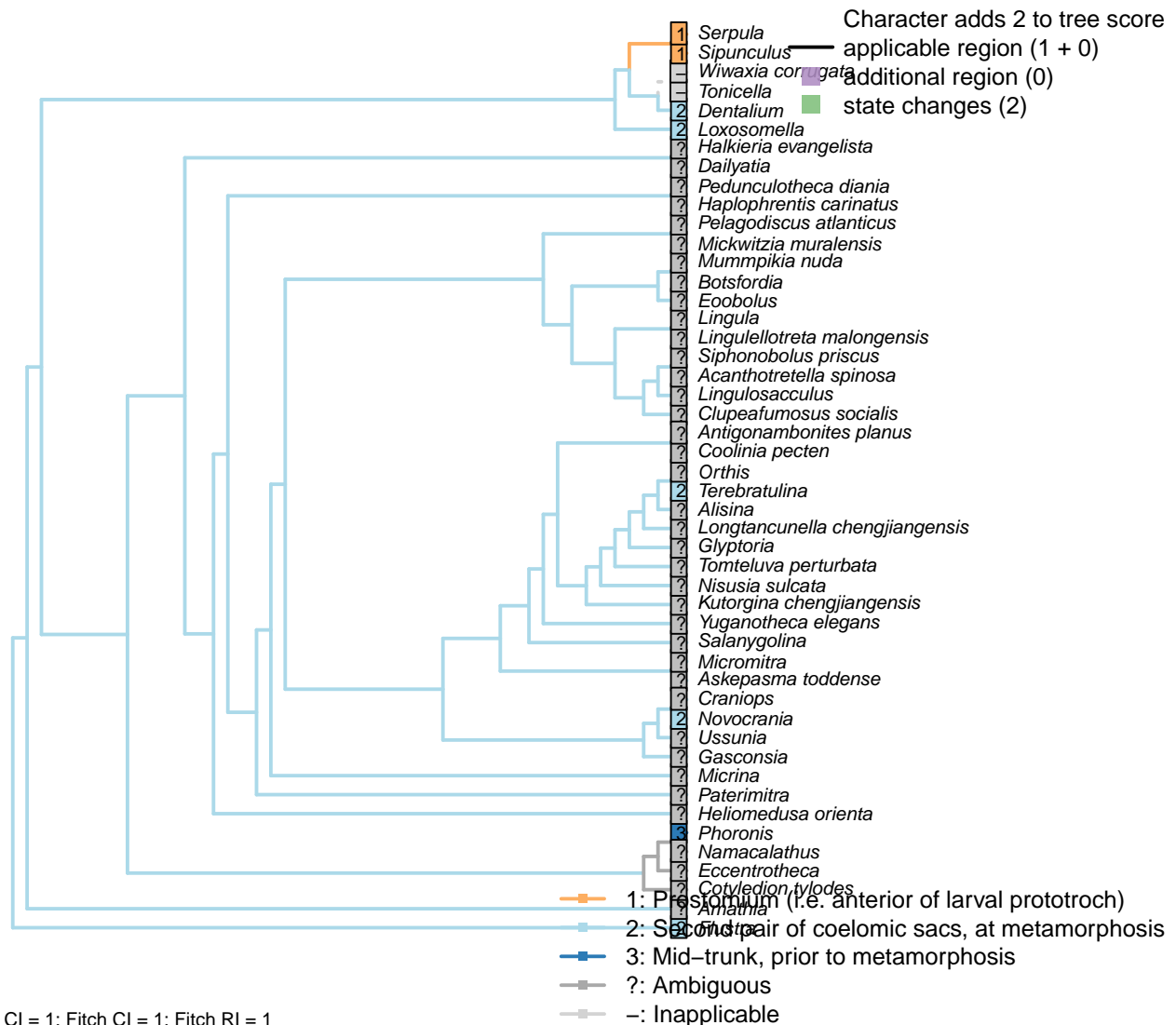
with arguments against homology reflected in separate transformation series.

Alisina: The scaphopod captacula is conceivably equivalent to the tentacular apparatus of other lophotrochozoans. It is developmentally pre-oral, and has tentatively been homologised with the pre-oral tentacles of Monoplacophora and Gastropoda (Steiner, 1992), though their musculature and late development suggests instead that they may derive from the molluscan foot, as do the arms of cephalopods (Wanninger and Haszprunar, 2002b).

Amathia: Moysiuk et al. (2017).

Terebratulina: The tentacular crown (Zhang et al., 2013) is interpreted as a lophophore.

[36] Origin



Character 36: Perioral tentacular apparatus: Origin

- 1: Prostomium (i.e. anterior of larval prototroch)
 - 2: Second pair of coelomic sacs, at metamorphosis
 - 3: Mid-trunk, prior to metamorphosis
- Transformational character.

The tentacles of annelids and sipunculans originate from a dorsal pair of buds on the prostomium (Adrianov et al., 2006), whereas the brachiopod lophophore arises from the second pair of coelomic sacs (Nielsen, 1991).

Alisina: The captacula arise close to the mouth after metamorphosis (Wanninger and Haszprunar, 2002b), in a position not dissimilar from that of the phoronid tentacles (Santagata, 2004).

Eoobolus: “At metamorphosis [...] the second pair of coelomic sacs develop small attachment areas at the edge of the dorsal valve and become the lophophore coelom” (Nielsen, 1991)

“The larval lobes are retained during the first steps of metamorphosis and are subsequently remodeled to form the lophophore and other adult organs” – Altenburger et al. (2013).

Halkieria evangelista: (Adrianov et al., 2006).

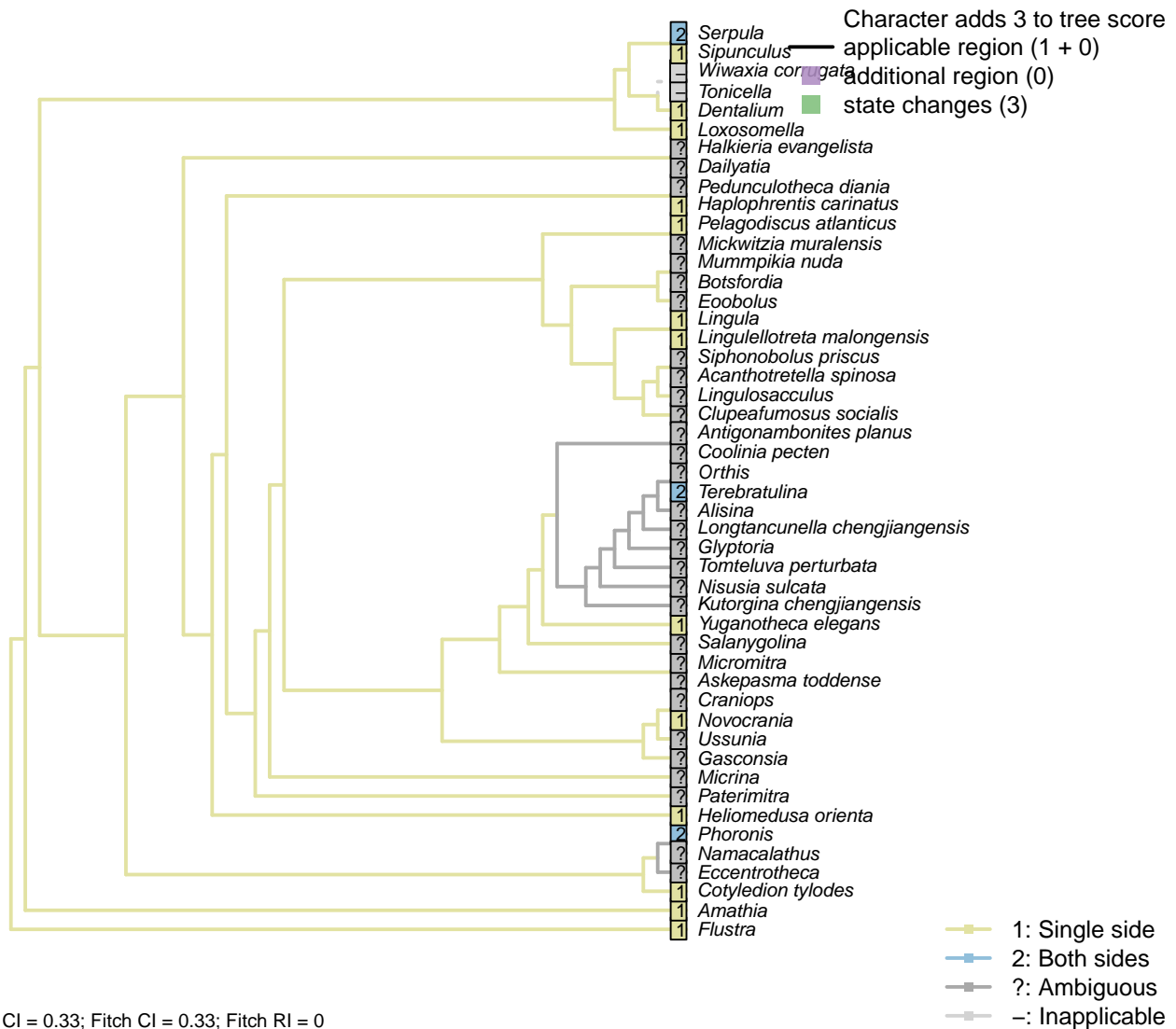
Lingula: Arising after metamorphosis (Nielsen, 1971).

Phoronis: The tentacles appear at metamorphosis, seemingly from below the corona (=prototroch) (Young, 2002).

Tonicella: Lophophore of *Terebratalia* arises post metamorphosis (Young, 2002); lophophore conceivably arising from vesicular bodies at base of apical lobe?.

Wiwaxia corrugata: At the posterior of the head, at the late larval stage (Santagata, 2004).

[37] Tentacle disposition

**Character 37: Perioral tentacular apparatus: Tentacle disposition**

1: Single side

2: Both sides

Transformational character.

Tentacles may occur along one or both sides of the axis of the lophophore arm (Carlson, 1995).

Alisina: On rim of basal lobe only (Morton, 1959).

Clupeafumosus socialis: Preservation insufficient to evaluate (Holmer and Caron, 2006).

Coolinia pecten, *Mickwitzia muralensis*, *Nisusia sulcata*: Preservation inadequate.

Dentalium, *Eoobolus*, *Serpula*, *Tonicella*, *Wiwaxia corrugata*: Following coding for higher group in Carlson (1995), appendix 1, character 36.

Halkieria evangelista: Both sides in tentacle-breathers such as *Themiste* (Ruppert and Rice, 1995; Adrianov

et al., 2006); only one side in *Sipunculus* (Ruppert and Rice, 1995; Adrianov et al., 2006).

Lingula: Single side (Nielsen, 1966).

Micrina: “Each lophophoral arm bears a row of long, slender flexible tentacles” – Zhang et al. (2009).

Micromitra: Tentacles “cannot be confidently demonstrated in the available specimens.” – Zhang et al. (2007b).

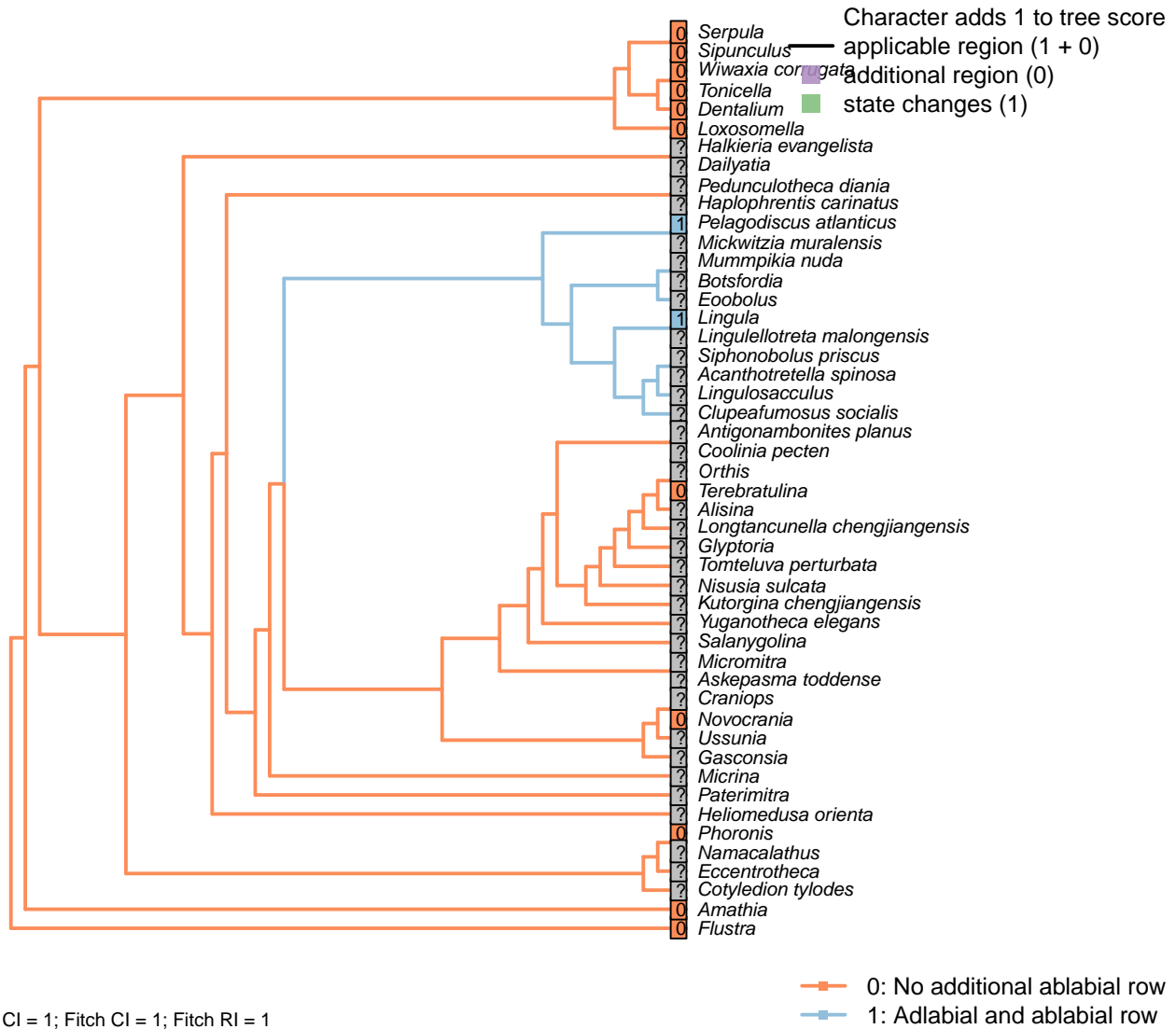
Mummpikia nuda: “The tentacles are clearly visible, and closely arranged in a single palisade” – Zhang et al. (2004).

Phoronis: Both sides (Schwaha and Wanninger, 2015; Shunkina et al., 2015).

Sipunculus: Single side (Temereva and Kosevich, 2016).

Terebratulina: Tentacles seemingly occupy a single side of the lophophore (Zhang et al., 2013).

[38] Tentacle rows per side in trocholophe stage



Character 38: Perioral tentacular apparatus: Tentacle rows per side in trocholophe stage

0: No additional ablabial row

1: Adlabial and ablabial row

Neomorphic character.

After Carlson (1995), character 37. Lophophore tentacles are commonly arranged into an ablabial and adlabial row, with ablabial tentacles sometimes added later in development.

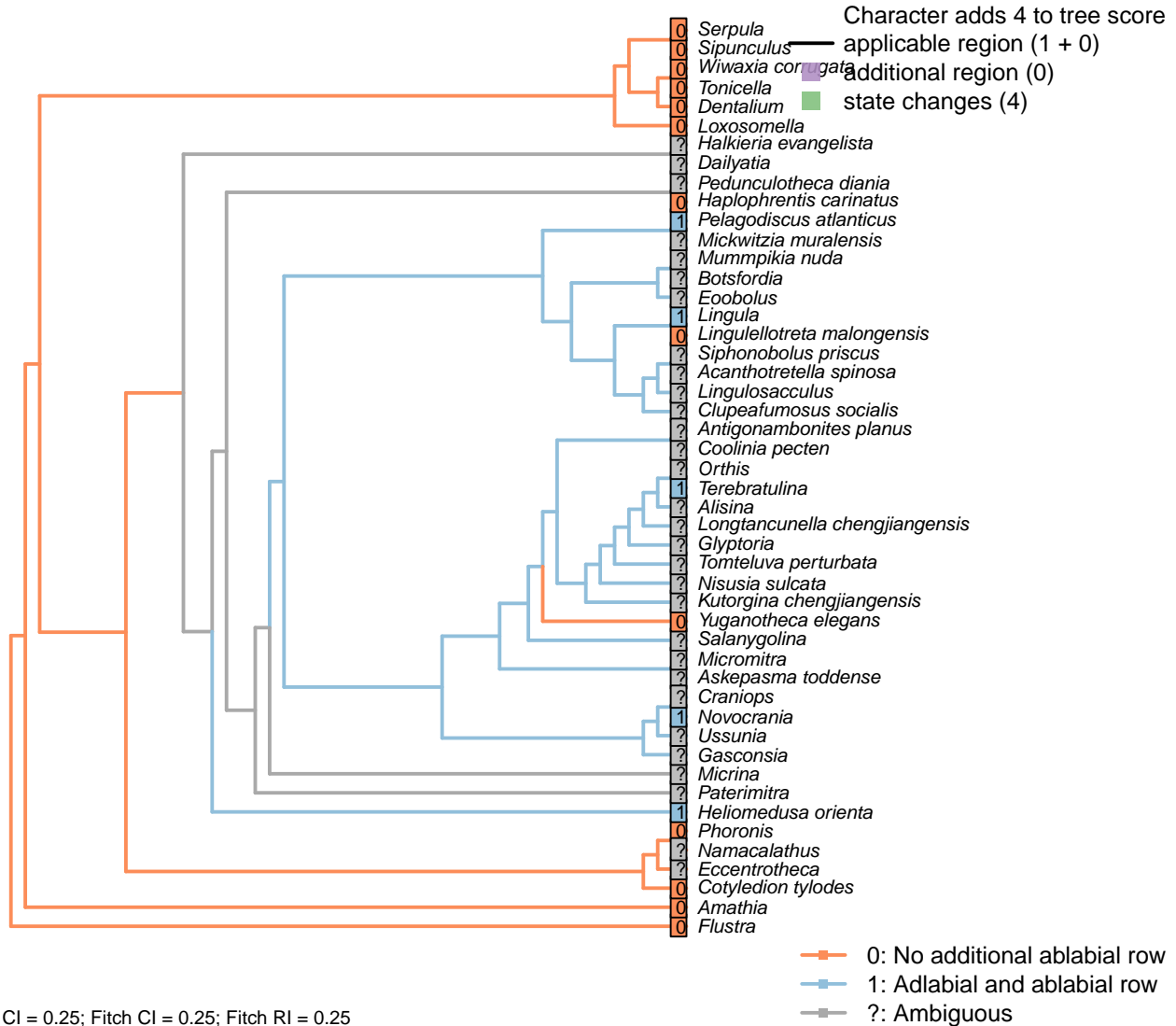
Dentalium, *Serpula*, *Tonicella*, *Wiwaxia corrugata*: Following coding for higher taxon in Carlson (1995), appendix 1, character 37.

Eoobolus: Following coding for higher taxon in Carlson (1995), appendix 1, character 37. Also states in Williams et al. (2000), p. 158.

Lingula, *Phoronis*: Inapplicable.

Sipunculus: (Temereva and Kosevich, 2016).

[39] Tentacle rows per side in post-trocholophe stage

**Character 39: Perioral tentacular apparatus: Tentacle rows per side in post-trocholophe stage**

0: No additional ablabial row

1: Adlabial and ablabial row

Neomorphic character.

After Carlson (1995), character 37. Lophophore tentacles are commonly arranged into an ablabial and adlabial row, with ablabial tentacles sometimes added later in development (and thus interpreted as a neomorphic addition).

Clupeafumusus socialis: Preservation insufficient to evaluate (Holmer and Caron, 2006).

Dentalium, *Eoobolus*, *Serpula*, *Tonicella*, *Wiwaxia corrugata*: Following coding for higher taxon in Carlson

(1995), appendix 1, character 37.

Lingula: Nielsen (1966).

Mickwitzia muralensis: Preservation insufficient to evaluate.

Micrina: “The lophophoral arms bear laterofrontal tentacles with a double row of cilia along their lateral edge, as in extant lingulid brachiopods” – Zhang et al. (2009).

Micromitra: Tentacles “cannot be confidently demonstrated in the available specimens.” – Zhang et al. (2007b).

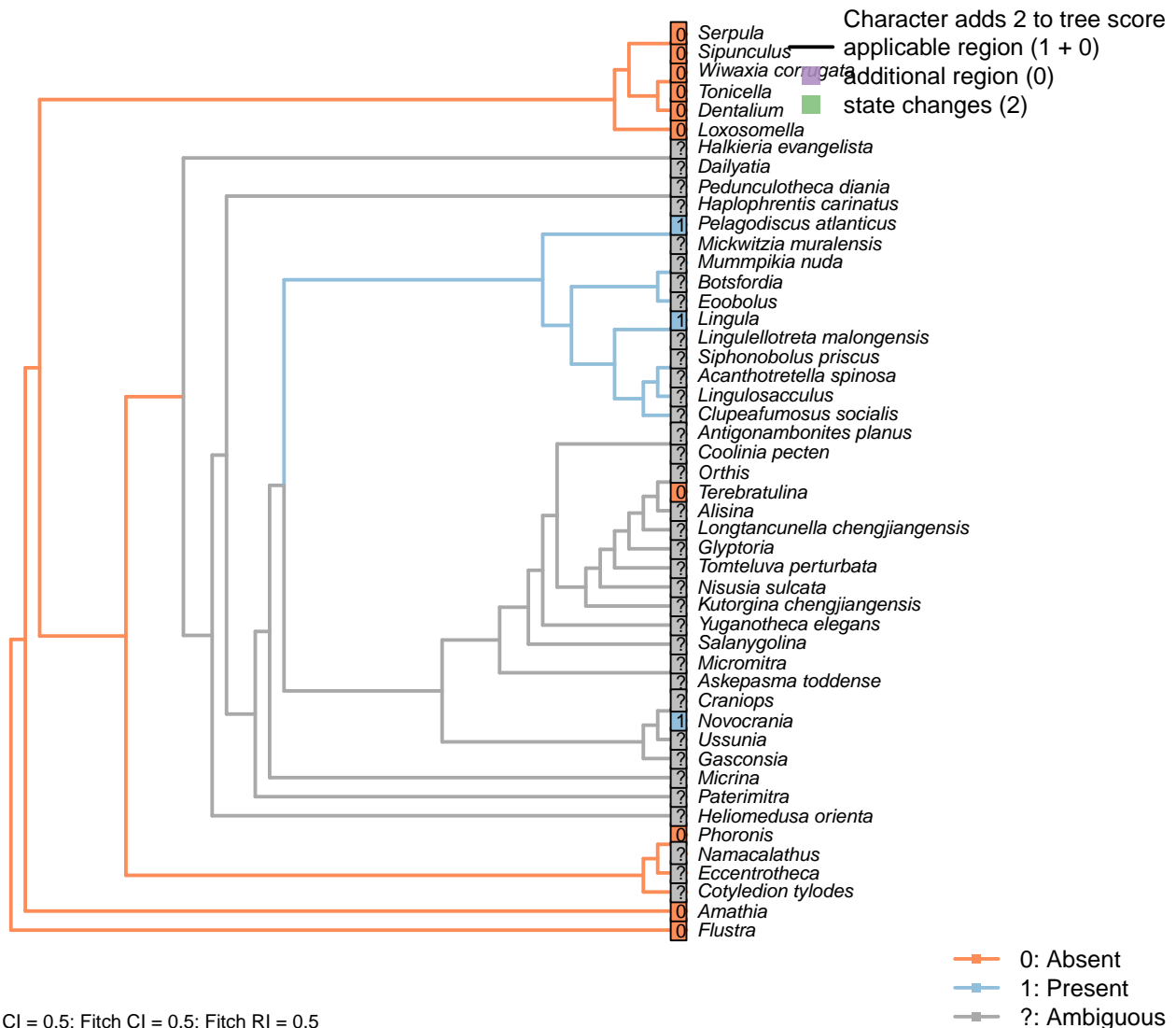
Mummpikia nuda: Single palisade (Zhang et al., 2004).

Sipunculus: (Temereva and Kosevich, 2016).

Terebratulina: Additional row not evident (Zhang et al., 2013).

NA: “helical lophophore fringed with a single row of thick, widely spaced, parallel-sided and hollow tentacles” – Zhang et al. (2014).

[40] Median tentacle in early development

**Character 40: Perioral tentacular apparatus: Median tentacle in early development**

0: Absent

1: Present

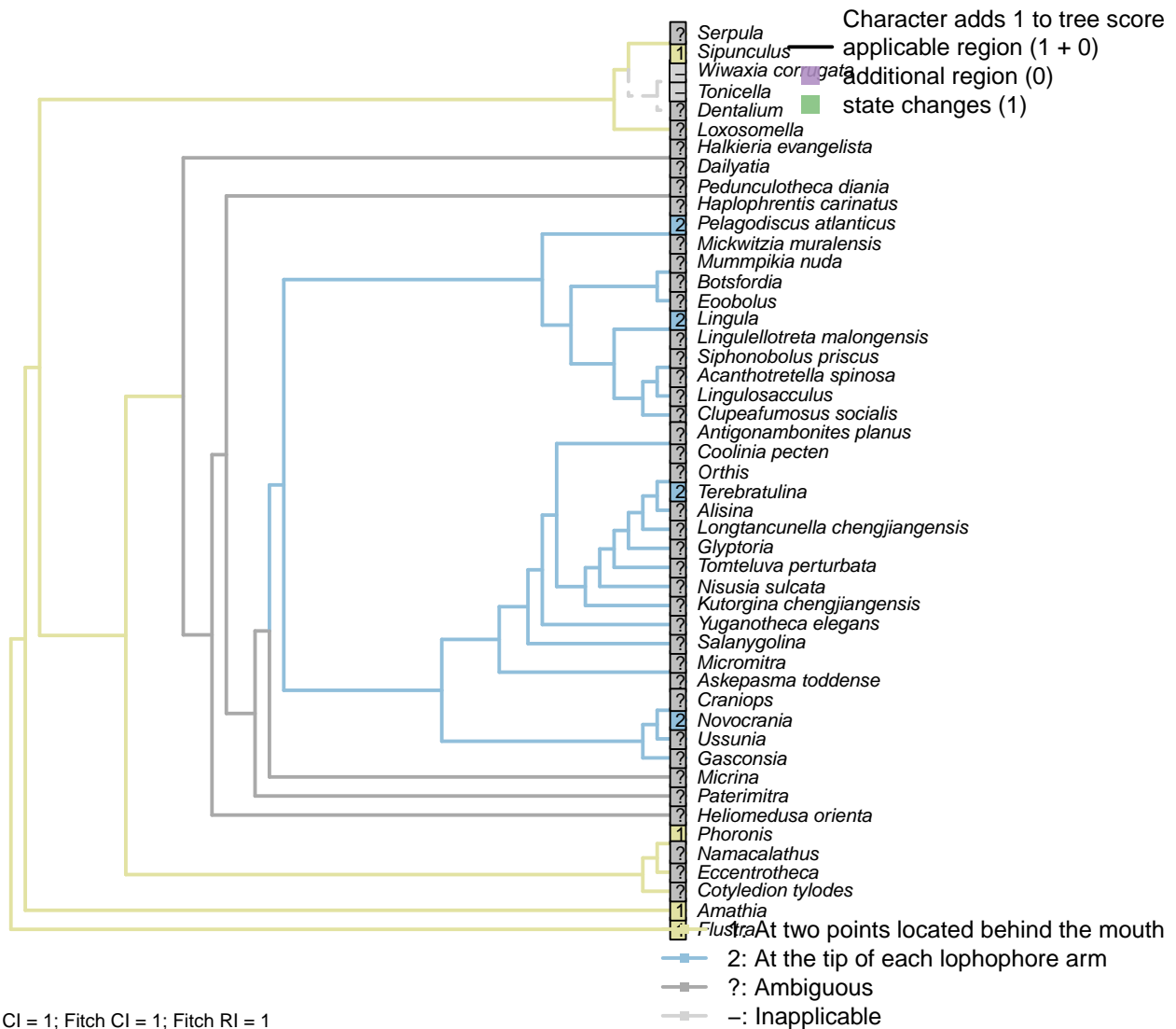
Neomorphic character.

Following character 28 in Carlson (1995). Certain taxa exhibit a median tentacle early in development that is lost during ontogeny.

Amathia, *Botsfordia*, *Clupeafumosus socialis*, *Coolinia pecten*, *Craniops*, *Eccentrotheca*, *Heliomedusa orienta*, *Lingulosacculus*, *Longtancunella chengjiangensis*, *Mickwitzia muralensis*, *Micrina*, *Micromitra*, *Mummipikia nuda*, *Namacalathus*, *Nisusia sulcata*, *Novocrania*, *Orthis*, *Paterimitra*, *Pelagodiscus atlanticus*, *Siphonobolus priscus*, *Tomteluva perturbata*, *Ussunia*, *Yuganotheca elegans*, NA, NA, NA, NA: Lophophore ontogeny presently unknown.

Lingula: Nielsen (1966).

[41] Site of tentacle addition

**Character 41: Perioral tentacular apparatus: Site of tentacle addition**

1: At two points located behind the mouth

2: At the tip of each lophophore arm

Transformational character.

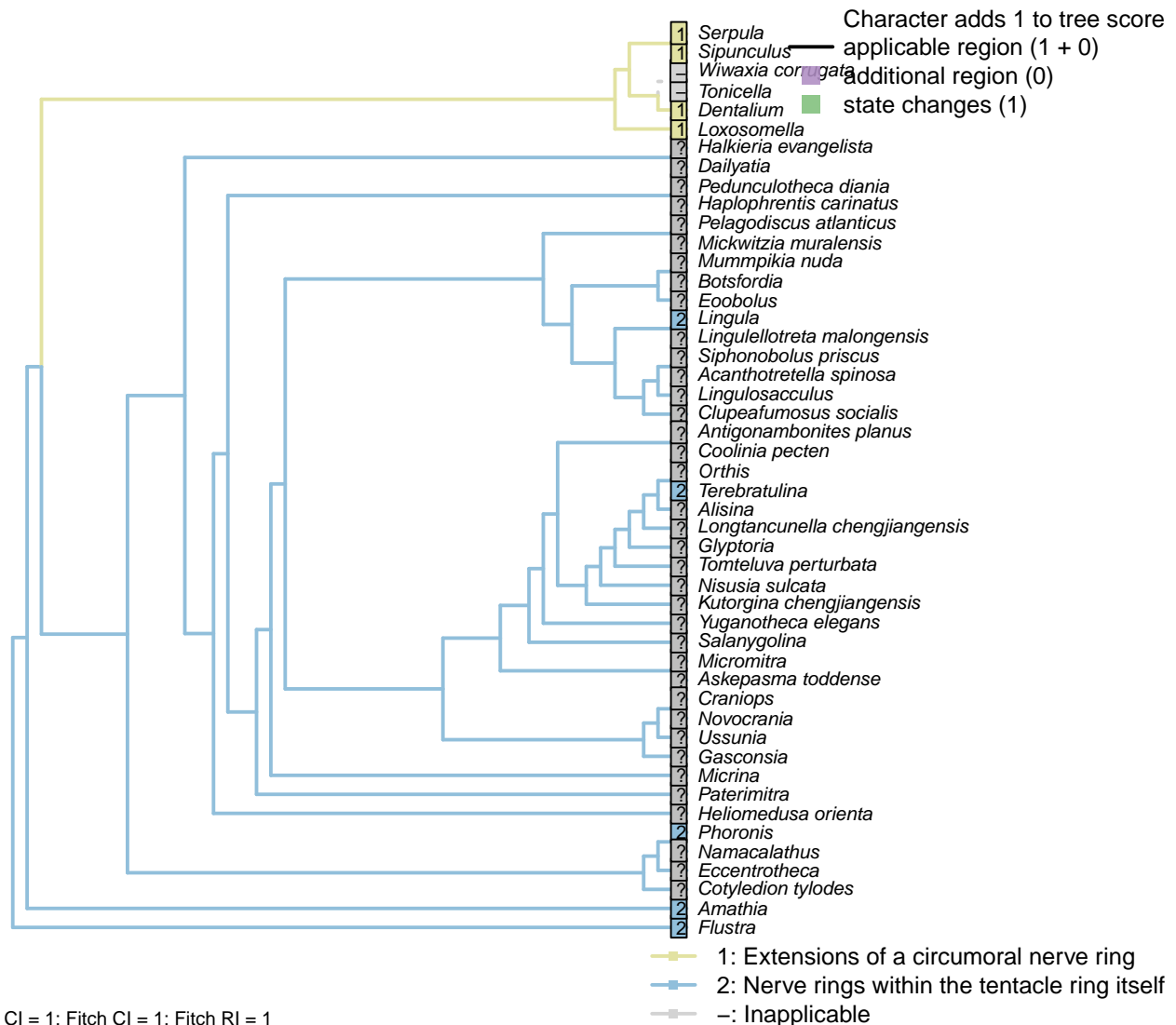
Following Temereva (2017).

Dentalium, *Eoobolus*, *Phoronis*, *Serpula*, *Sipunculus*, *Tonicella*: Following Temereva (2017).

Halkieria evangelista: New branches added at each lateral extreme, behind mouth (Adrianov et al., 2006).

Wiwaxia corrugata: Following Temereva (2017) – though in larvae, tentacles are added at the tips of the developing lophophore.

[42] Innervation

**Character 42: Perioral tentacular apparatus: Innervation**

- 1: Extensions of a circumoral nerve ring
 - 2: Nerve rings within the tentacle ring itself
- Transformational character.

Annelid tentacles are innervated by palp nerves (Orrhage and Müller, 2005); lophophores ancestrally contained a pair of nerve rings (Temereva, 2017).

Alisina: The captacula each bear an individual nerve fibre emanating from the cerebral ganglia, which is also associated with the circumoesophageal nerve ring (Sumner-Rooney et al., 2015), recalling the situation in annelids and sipunculans.

Dailyatia: Orrhage and Müller (2005).

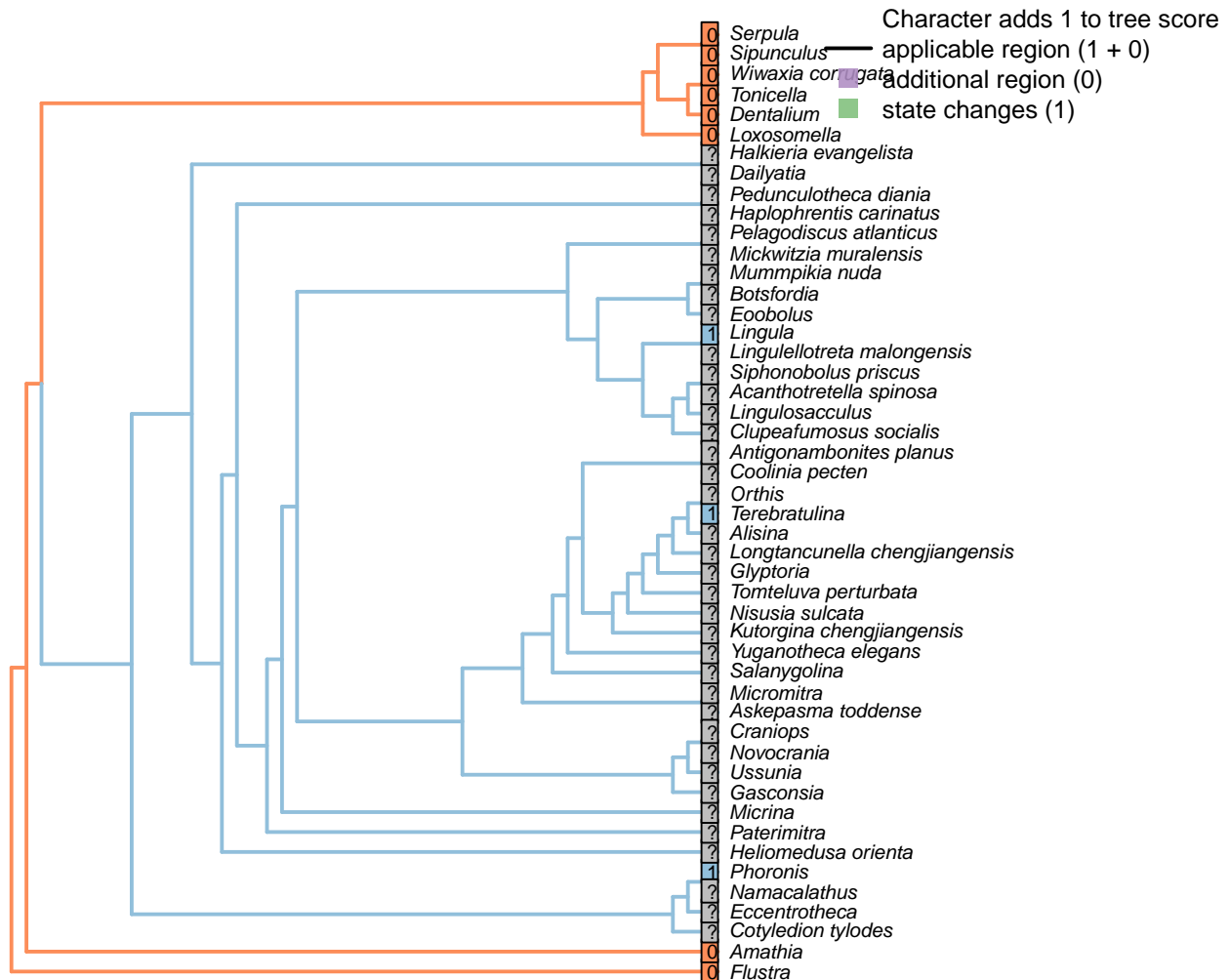
Halkieria evangelista: Rice (1993).

Lingula: Tentacle nerves originate laterally from the cerebral ganglion, branching three times and leading to

a single nerve within each tentacle (Fuchs et al., 2006).

Phoronis, *Sipunculus*: Following Temereva (2017).

[43] Inner nerve ring



0: Not reduced (whether present or absent due to absence of lophophore nerve rings)
 1: Reduced, weakly developed or absent in adults

Character 43: Perioral tentacular apparatus: Inner nerve ring

0: Not reduced (whether present or absent due to absence of lophophore nerve rings)

1: Reduced, weakly developed or absent in adults

Neomorphic character.

Juvenile lophophorates exhibit two nerve rings in the tentacles; one of these rings is often reduced or lost at adulthood (Temereva, 2017).

Dentalium: Temereva and Kuzmina (2017).

Eoobolus: Probably only a single ring is present, but only available illustrations are 19th century sketches

(Lüter, 2016).

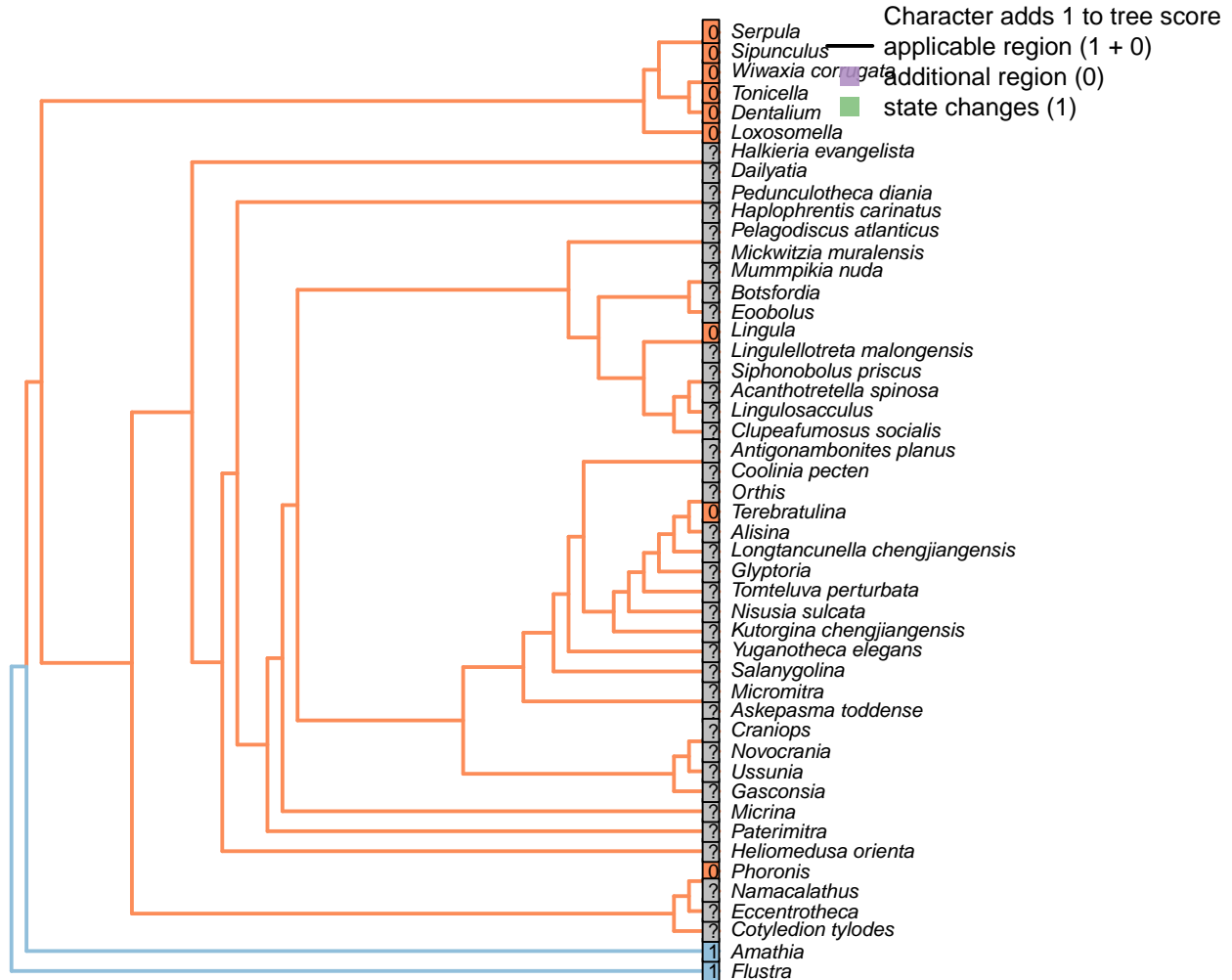
Lingula: Nerves present in tentacles, but not forming rings (Fuchs et al., 2006).

Phoronis, *Sipunculus*: Following Temereva (2017).

Tonicella: In *Gryphus* (Temereva and Kuzmina, 2017).

Wiwaxia corrugata: (Temereva, 2017).

[44] Outer nerve ring



0: Not reduced (whether present or absent due to absence of lophophore nerve rings)
 1: Reduced, weakly developed or absent in adults

Character 44: Perioral tentacular apparatus: Outer nerve ring

0: Not reduced (whether present or absent due to absence of lophophore nerve rings)

1: Reduced, weakly developed or absent in adults

Neomorphic character.

Juvenile lophophorates exhibit two nerve rings in the tentacles; one of these rings is often reduced or lost at

adulthood (Temereva, 2017).

Dentalium, *Tonicella*: Temereva (2017).

Eoobolus: Probably only a single ring is present, but only available illustrations are 19th century sketches (Lüter, 2016).

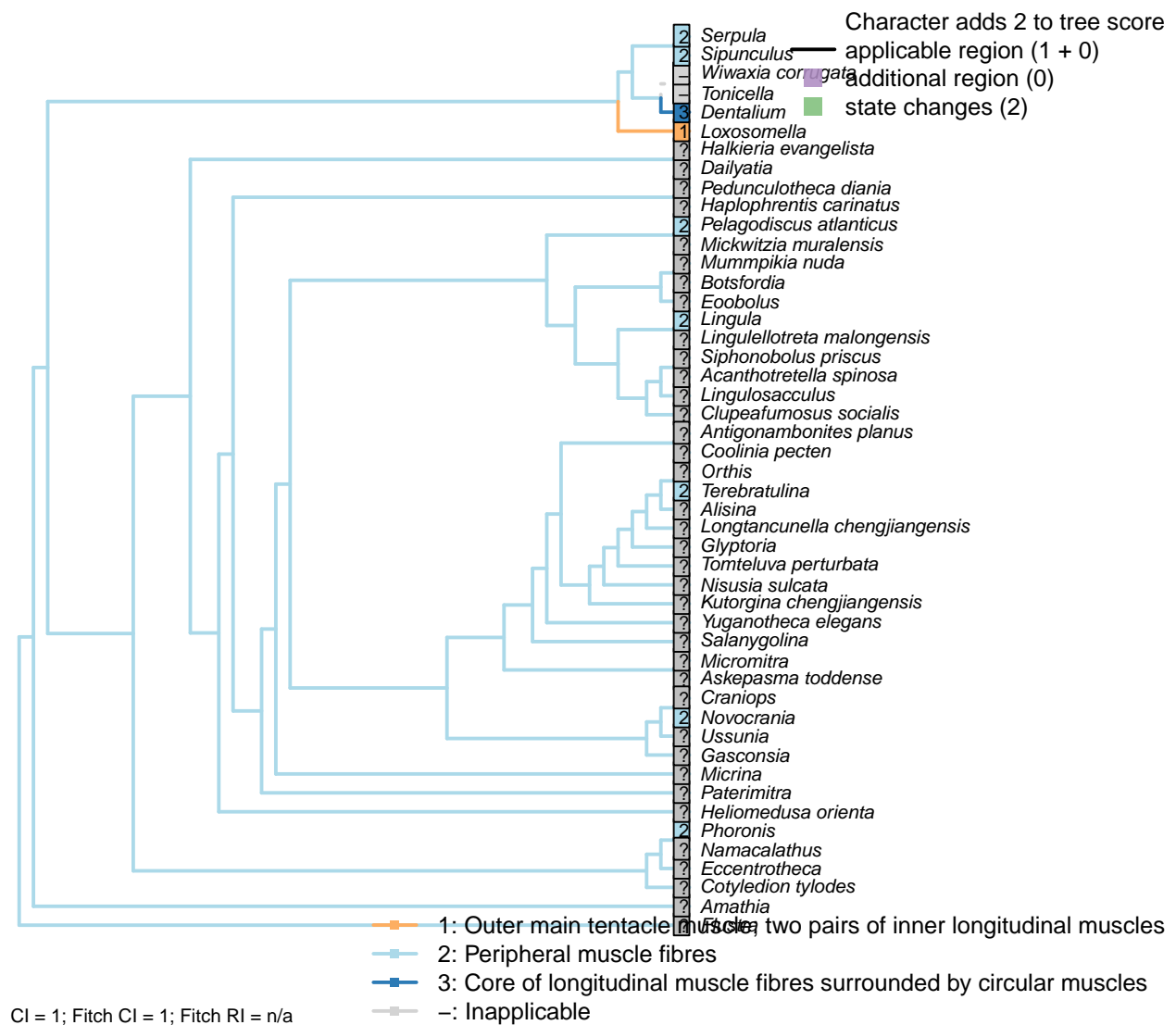
Lingula: Nerves present in tentacles, but not forming rings (Fuchs et al., 2006).

Phoronis: “Most species of bryozoans have only the inner” nerve ring – Temereva (2017).

Sipunculus: Following Temereva (2017); only one tentacle nerve ring evident in Temereva and Kosevich (2016).

Wiwaxia corrugata: Temereva and Kuzmina (2017).

[45] Musculature



Character 45: Perioral tentacular apparatus: Musculature

- 1: Outer main tentacle muscle; two pairs of inner longitudinal muscles
 - 2: Peripheral muscle fibres
 - 3: Core of longitudinal muscle fibres surrounded by circular muscles
- Transformational character.

Alisina: Six to eight elongate muscle cells in core (Shimek, 1988), surrounded by circular muscles (Byrum and Rupert, 1994).

Dailyatia: Peripheral muscle fibres (Hanson, 1949).

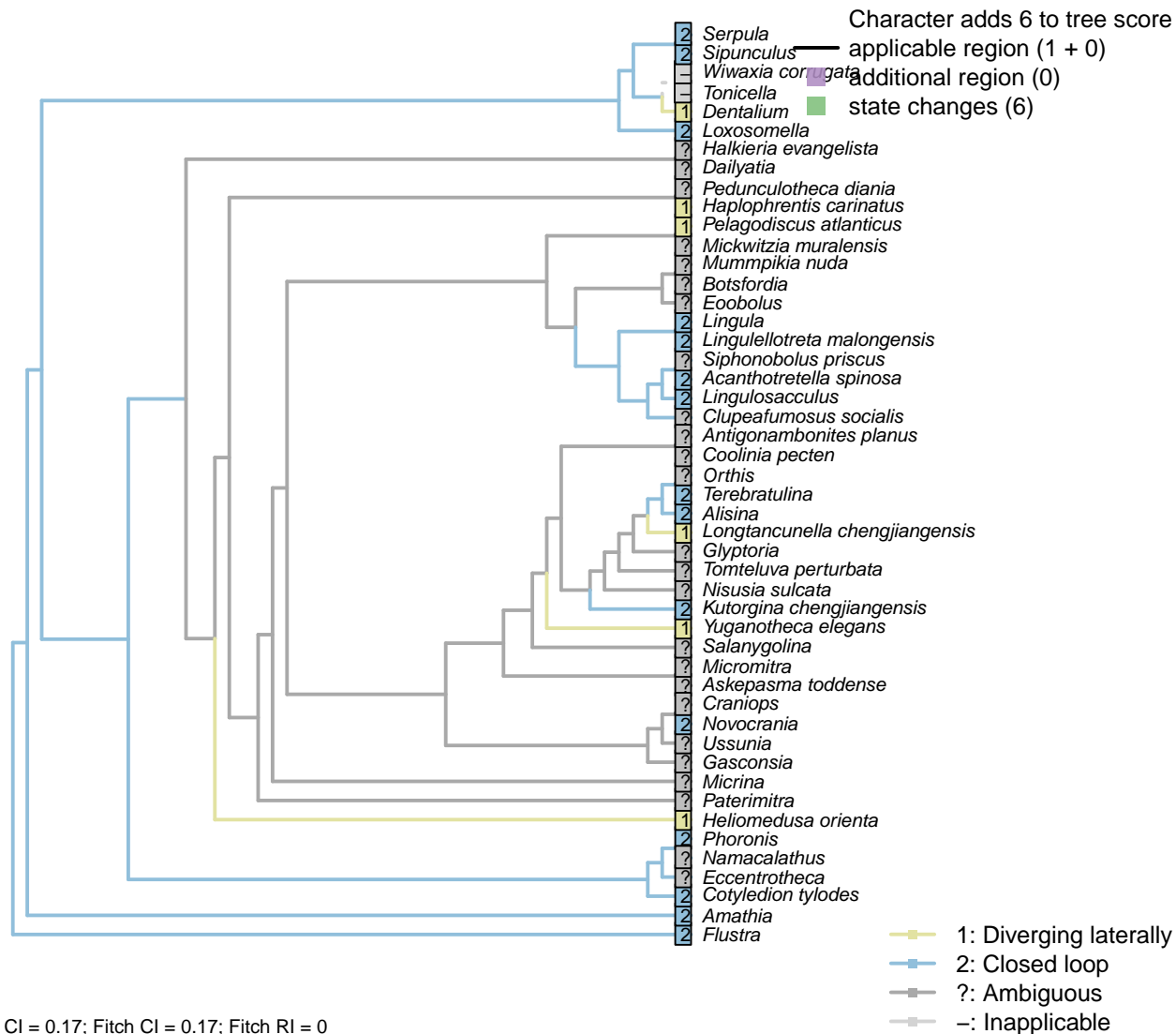
Dentalium, *Eoobolus*, *Serpula*, *Tonicella*: “Inner coelomic epithelium underlain by muscle fibers, or in the tentacles, myoepithelial cells.” – Williams et al. (1997).

Halkieria evangelista: Peripheral to main tentacle cavity (Pilger, 1982).

Lingula: Outer main tentacle muscle; two pairs of inner longitudinal muscles (Fuchs et al., 2006).

Wiwaxia corrugata: (Pardos et al., 1991).

[46] Forms closed loop



Character 46: Perioral tentacular apparatus: Forms closed loop

1: Diverging laterally

2: Closed loop

Transformational character.

Whereas the lophophore of crown-group brachiopods typically forms a closed loop, those of *Haplophrentis* and *Heliomedusa* diverge laterally (Moysiuk et al., 2017).

Dailyatia, *Halkieria evangelista*: Growing to encircle mouth in adults.

Lingula: Nielsen (1966).

Mickwitzia muralensis: Two diverging arms of the lophophore are preserved (Balthasar and Butterfield, 2009).

Namacalathus: The existence of a lophophore is speculative.

Nisusia sulcata: Two distinct, diverging arms reconstructed by Zhang et al. (2007c).

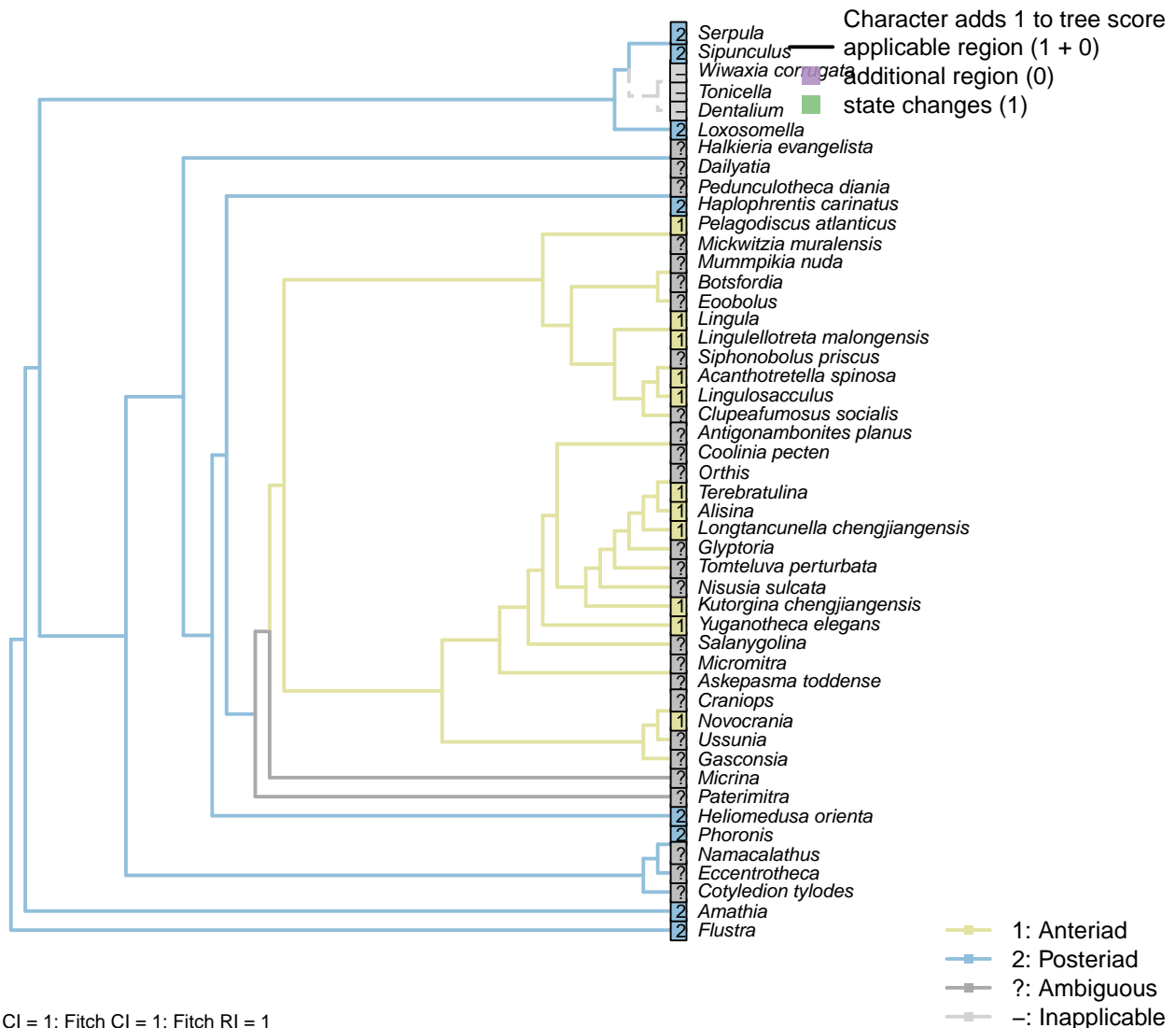
Sipunculus: Ends of arms meet to form closed loop (Temereva and Kosevich, 2016).

Terebratulina: Tentacles form almost complete circular crown.

Tomteluva perturbata: No specimens of *Nisusia* preserve the lophophore.

Wiwaxia corrugata: Two lophophore arms rather than a single continuous loop, but with tips close together to form functional loop (Torrey, 1901).

[47] Coiling direction

**Character 47: Perioral tentacular apparatus: Coiling direction**

1: Anteriad

2: Posteriad

Transformational character.

The lophophore arms of *Heliomedusa* and *Haplophrentis* arch posteriad, rather than anteriad as in lingulids. See Zhang et al. (2009); Moysiuk et al. (2017).

Clupeafumusus socialis, *Mummpikia nuda*: Arms proceed anteriad before recurving.

Lingula: Posterior (anal side) of lophophore has short stretch lacking tentacles.

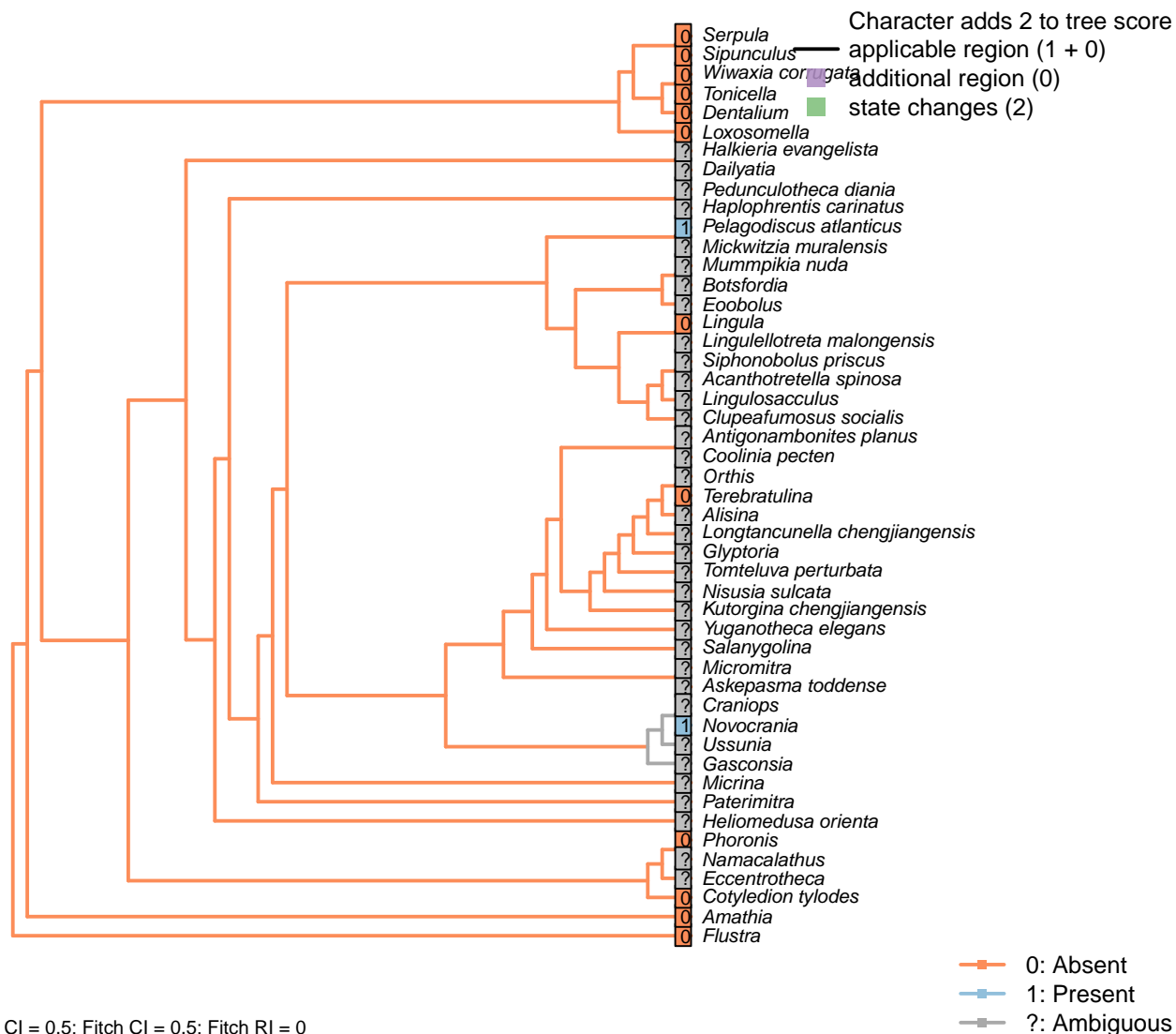
Phoronis, *Sipunculus*: Bryozoan arms reach in anal (i.e. posterior) direction (Shunkina et al., 2015).

Serpula: “converging anteriorly and coiling anterior to the body cavity” – Zhang et al. (2009).

Terebratulina: Cannot establish without distinguishing gut from anus.

Wiwaxia corrugata: Coiling in direction of anus (i.e. posteriad).

[48] Adjustor muscle

**Character 48: Perioral tentacular apparatus: Adjustor muscle**

0: Absent

1: Present

Neomorphic character.

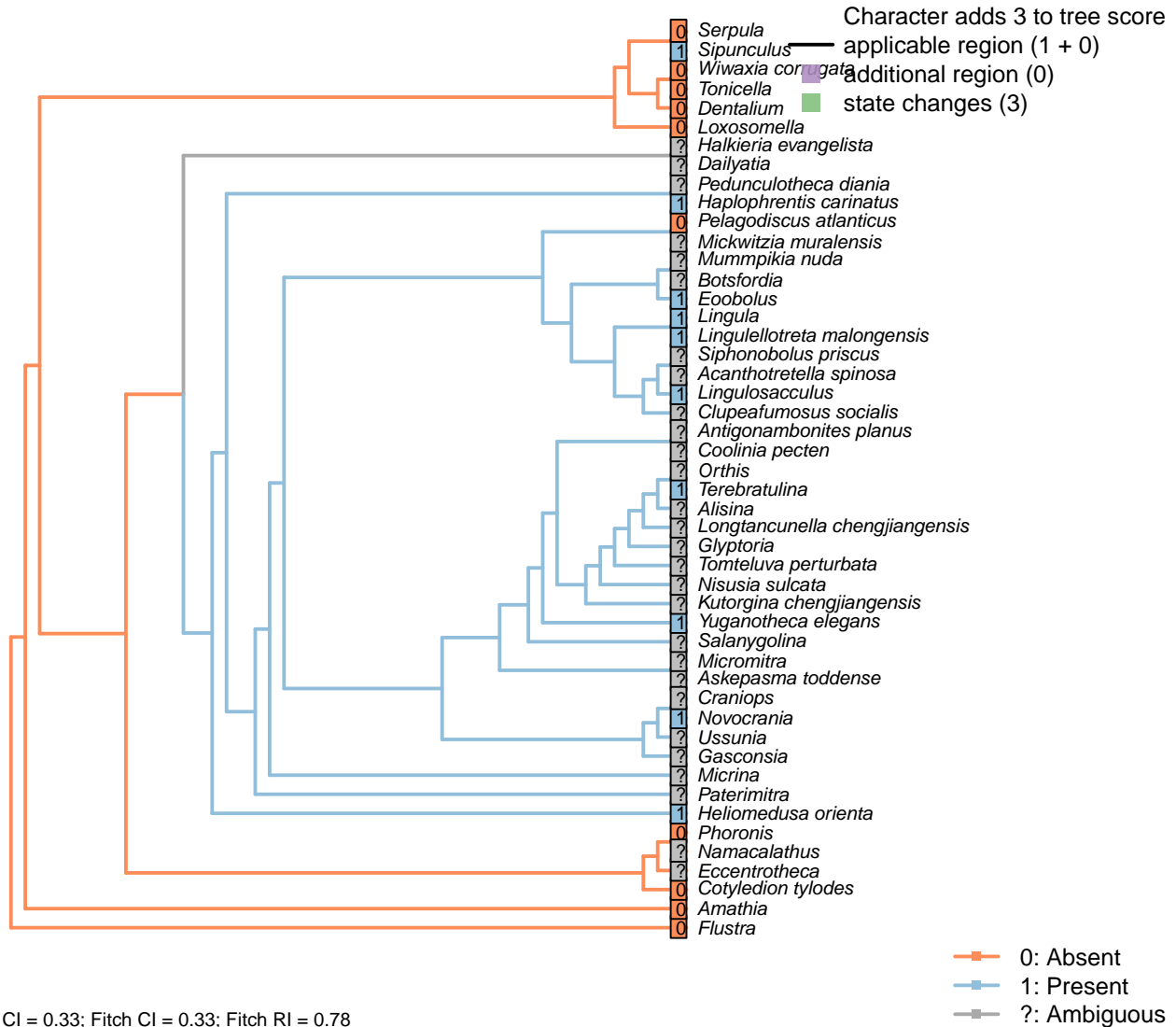
Following character 55 in Carlson (1995). Not possible to code in most fossil taxa.

Amathia, *Botsfordia*, *Clupeafumosus socialis*, *Coolinia pecten*, *Craniops*, *Eccentrotheca*, *Heliomedusa orienta*, *Lingulosacculus*, *Longtancunella chengjiangensis*, *Mickwitzia muralensis*, *Micrina*, *Micromitra*, *Mummpikia nuda*, *Namacalathus*, *Nisusia sulcata*, *Novocrania*, *Orthis*, *Paterimitra*, *Pelagodiscus atlanticus*, *Siphonobolus priscus*, *Tomteluva perturbata*, *Ussunia*, *Yuganotheca elegans*, NA, NA, NA, NA: Preservation not adequate to evaluate presence or absence of this muscle.

Dentalium, *Euobolus*, *Serpula*, *Tonicella*, *Wiwaxia corrugata*: Following coding for higher taxon in Carlson (1995), appendix 1, character 55.

3.11 Digestive tract

[49] Prominent pharynx



Character 49: Digestive tract: Prominent pharynx

0: Absent

1: Present

Neomorphic character.

Hyoliths exhibit a prominent protrusible muscular pharynx at the base of the lophophore (Moysiuk et al., 2017). This is considered as potentially equivalent to the anterior projection of the visceral cavity in *Heliomedusa*, and, by extension, in *Lingulosacculus* and *Lingulotreta*.

Halkieria evangelista: Eversible pharynx (introvert).

Lingulellotreta malongensis: Prominent extension of dorsal visceral platform (Balthasar, 2009).

Mickwitzia muralensis: The prominent anterior extension of the visceral area noted by Balthasar & Butterfield (2009) is considered as potentially homologous with that of *Heliomedusa* (Zhang et al., 2009) and, by

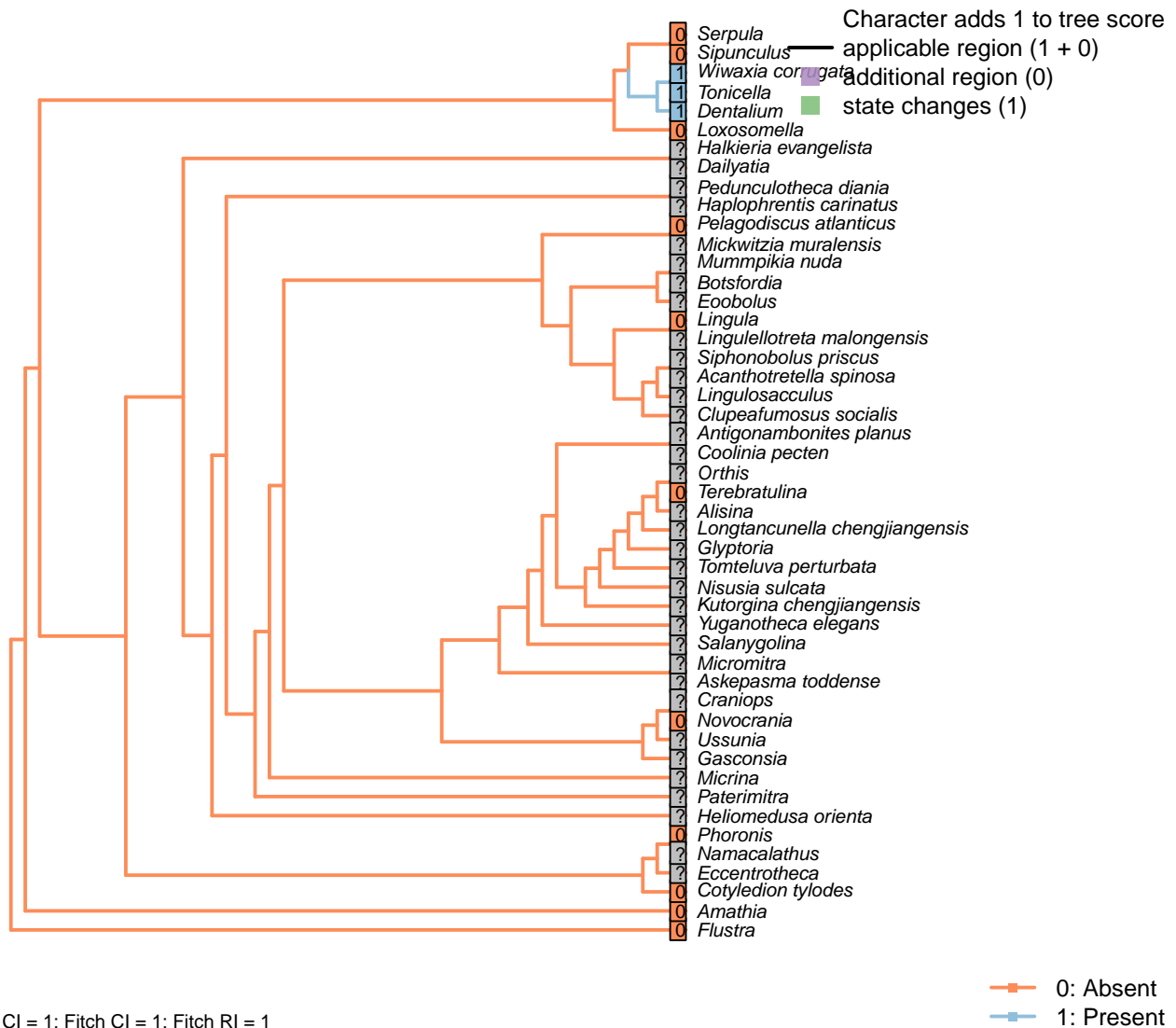
extension, *Haplophrentis* (Moysiuk et al., 2017).

Micrina: Corresponding to the “neck” of the vase-shaped visceral cavity reported by Zhang et al. (2009).

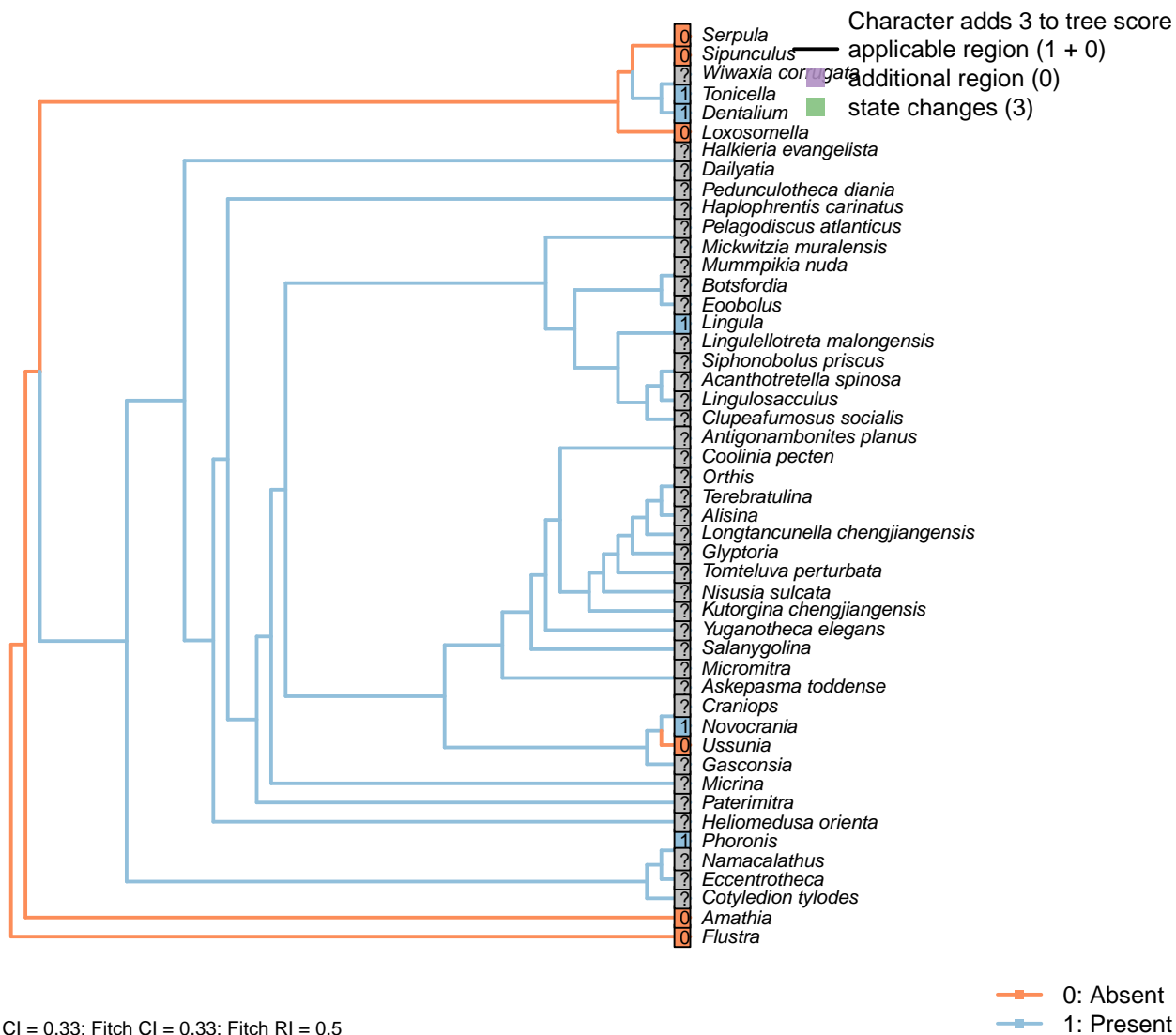
Mummpikia nuda: An anterior projection of the visceral area is noted by Williams *et al.* (2000) and considered equivalent to that observed in *Lingulosacculus* (Balthasar and Butterfield, 2009).

NA: Possibly present, following interpretation of mouth (see fig. 2c, d in Zhang et al., 2014).

[50] Radula



[51] Oesophageal folds

**Character 51: Digestive tract: Oesophageal folds**

0: Absent

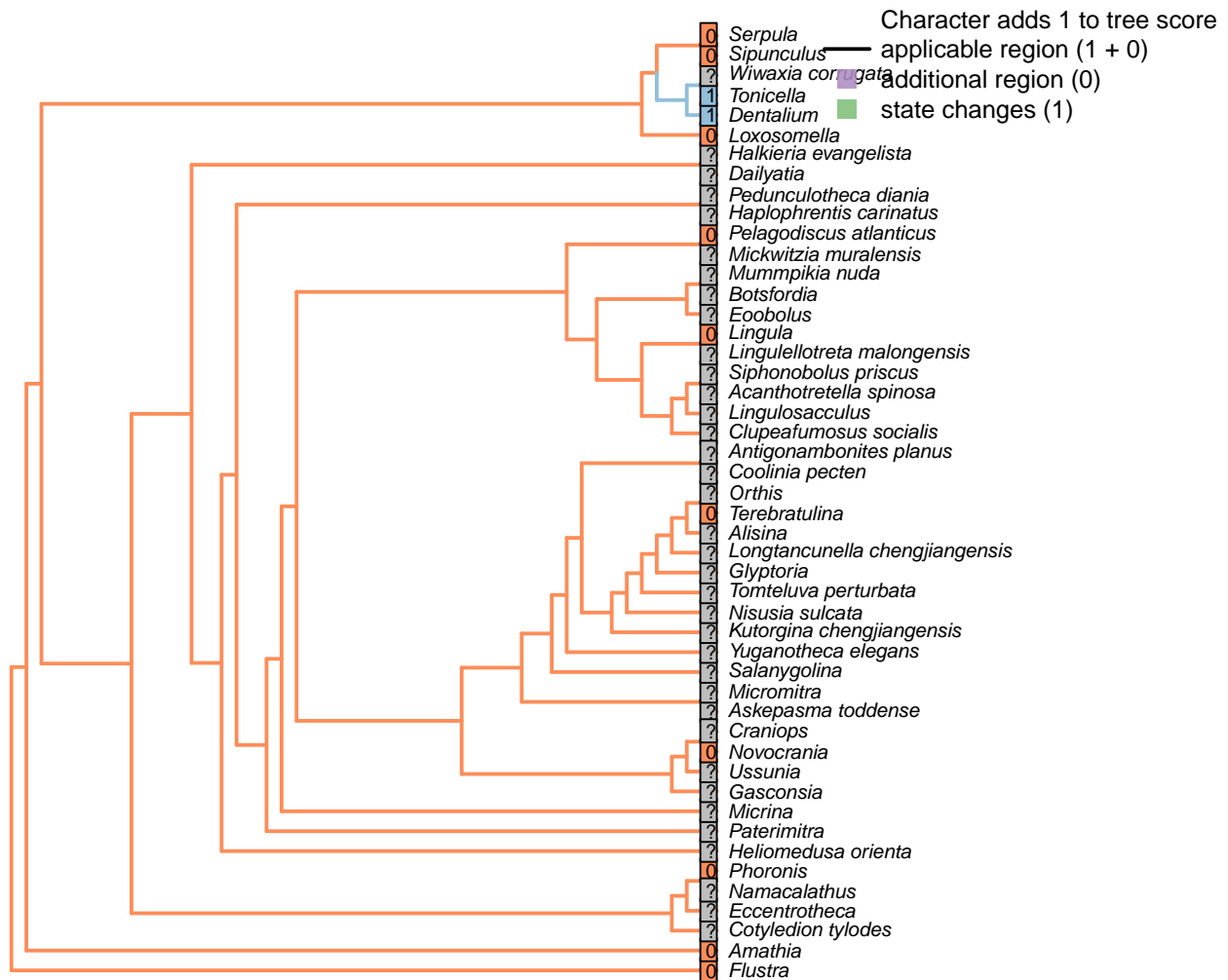
1: Present

Neomorphic character.

Following character 86 in Giribet and Wheeler (2002).

Wiwaxia corrugata: Ciliated ridge in oesophagus (Torrey, 1901).

[52] Oral sphincter



CI = 1; Fitch CI = 1; Fitch RI = 1

Character 52: Digestive tract: Oral sphincter

0: Absent

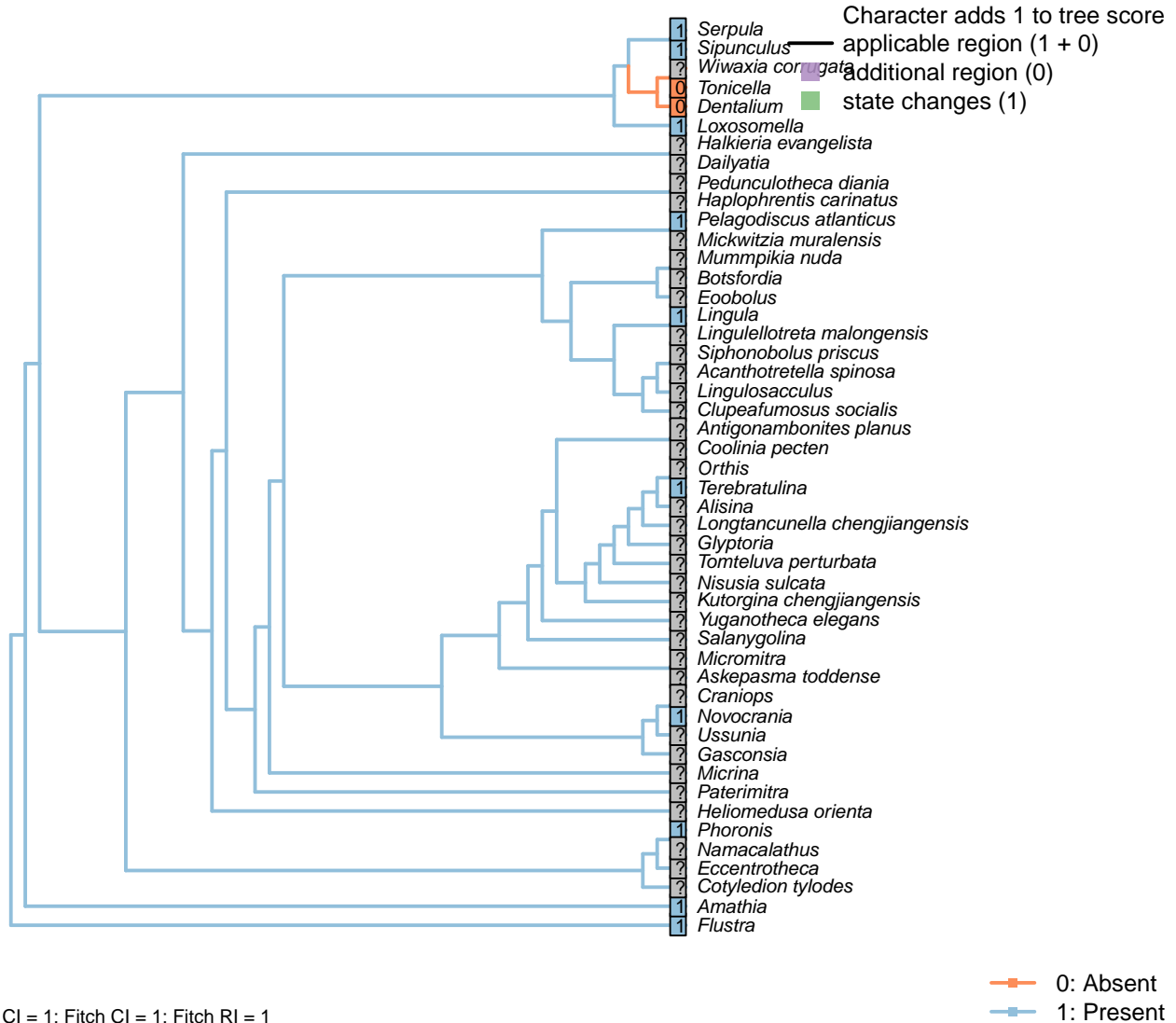
1: Present

Neomorphic character.

Character 133 in Grobe (2007).

Alisina: Present, but secondarily reduced.

[53] Locomotory cilia

**Character 53: Digestive tract: Foregut: Locomotory cilia**

0: Absent

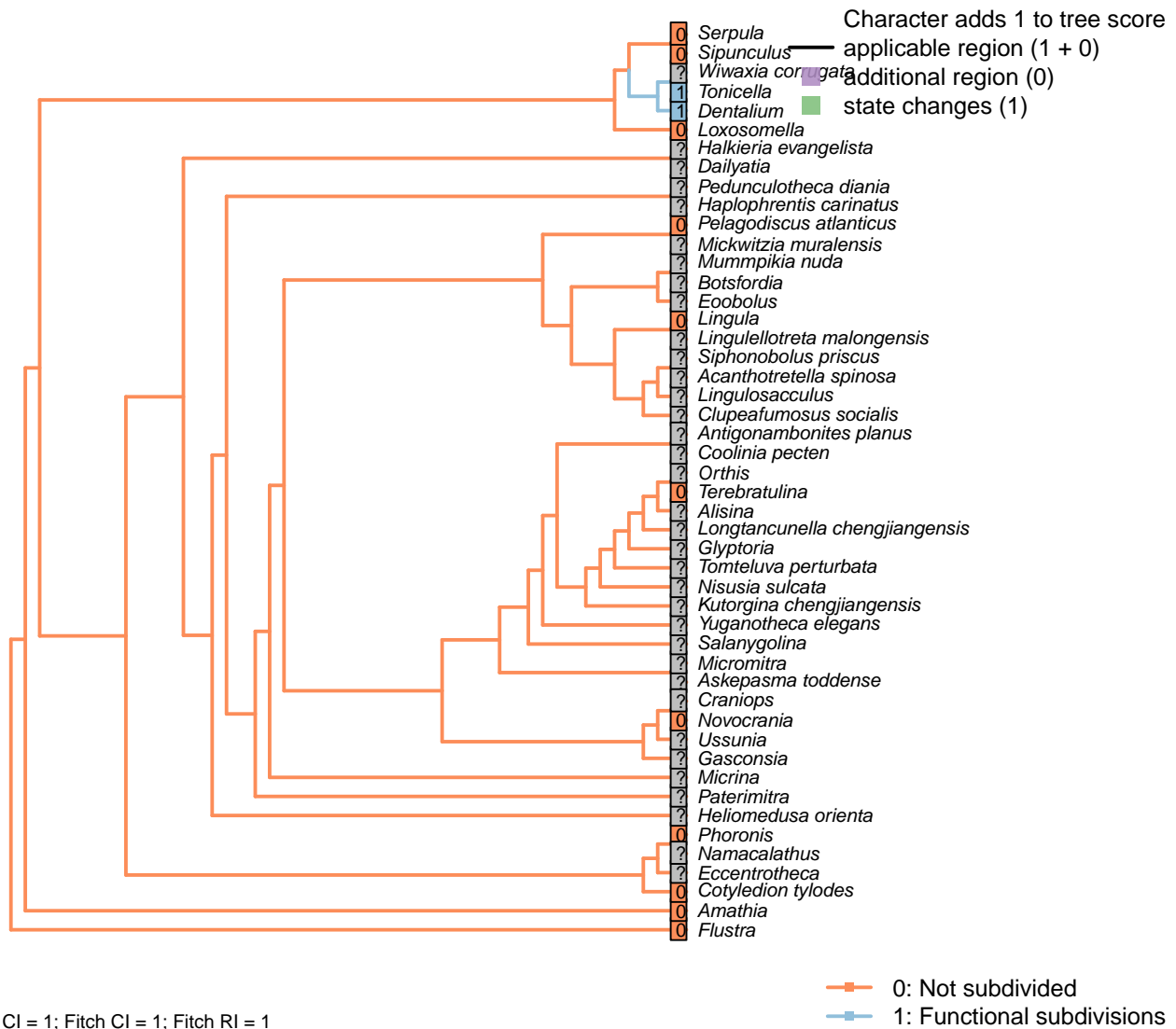
1: Present

Neomorphic character.

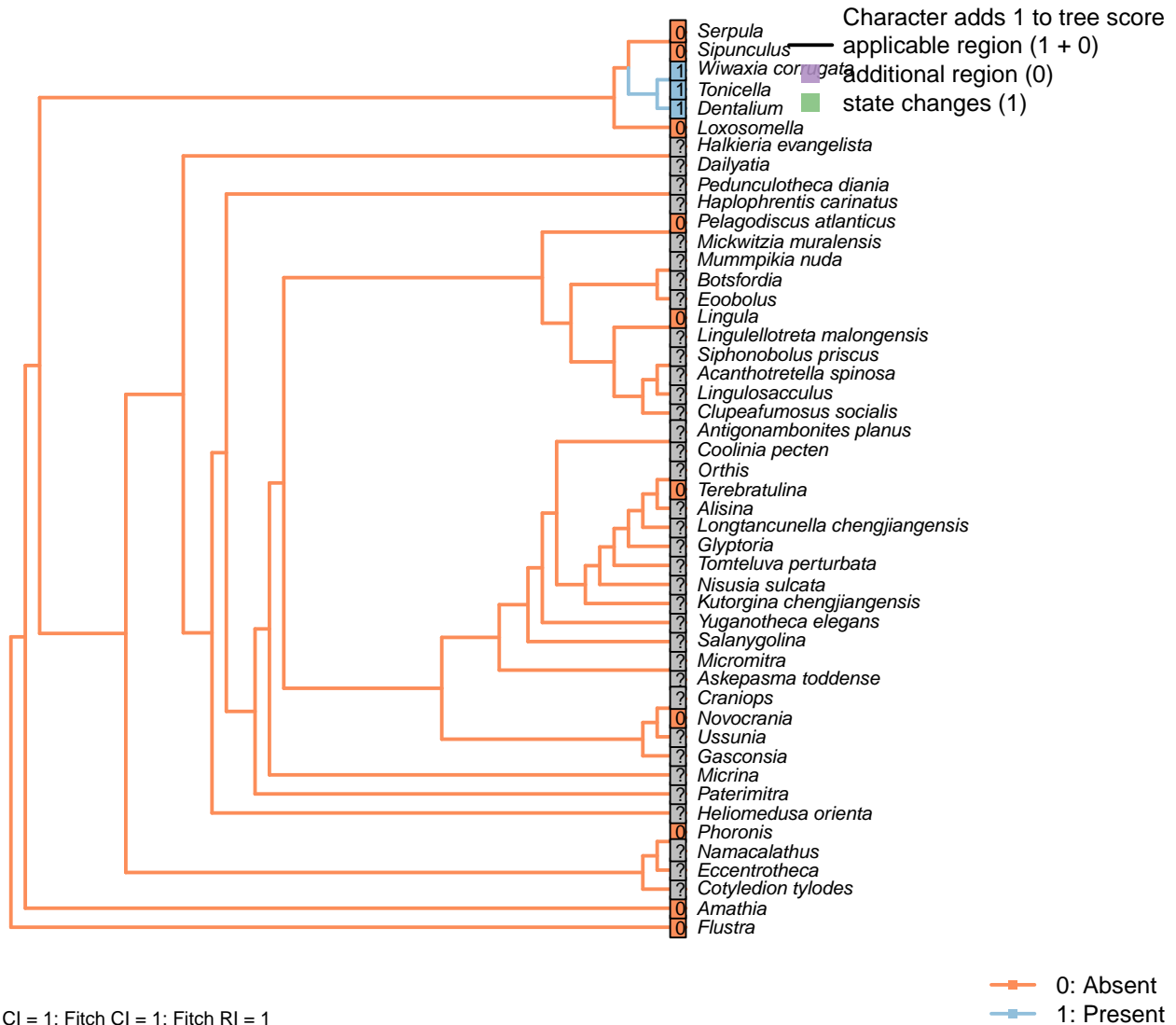
Character 66 in Haszprunar (2000).

3.12 Digestive tract: Midgut

[54] Subdivisions



[55] Glands

**Character 55: Digestive tract: Midgut: Glands**

0: Absent

1: Present

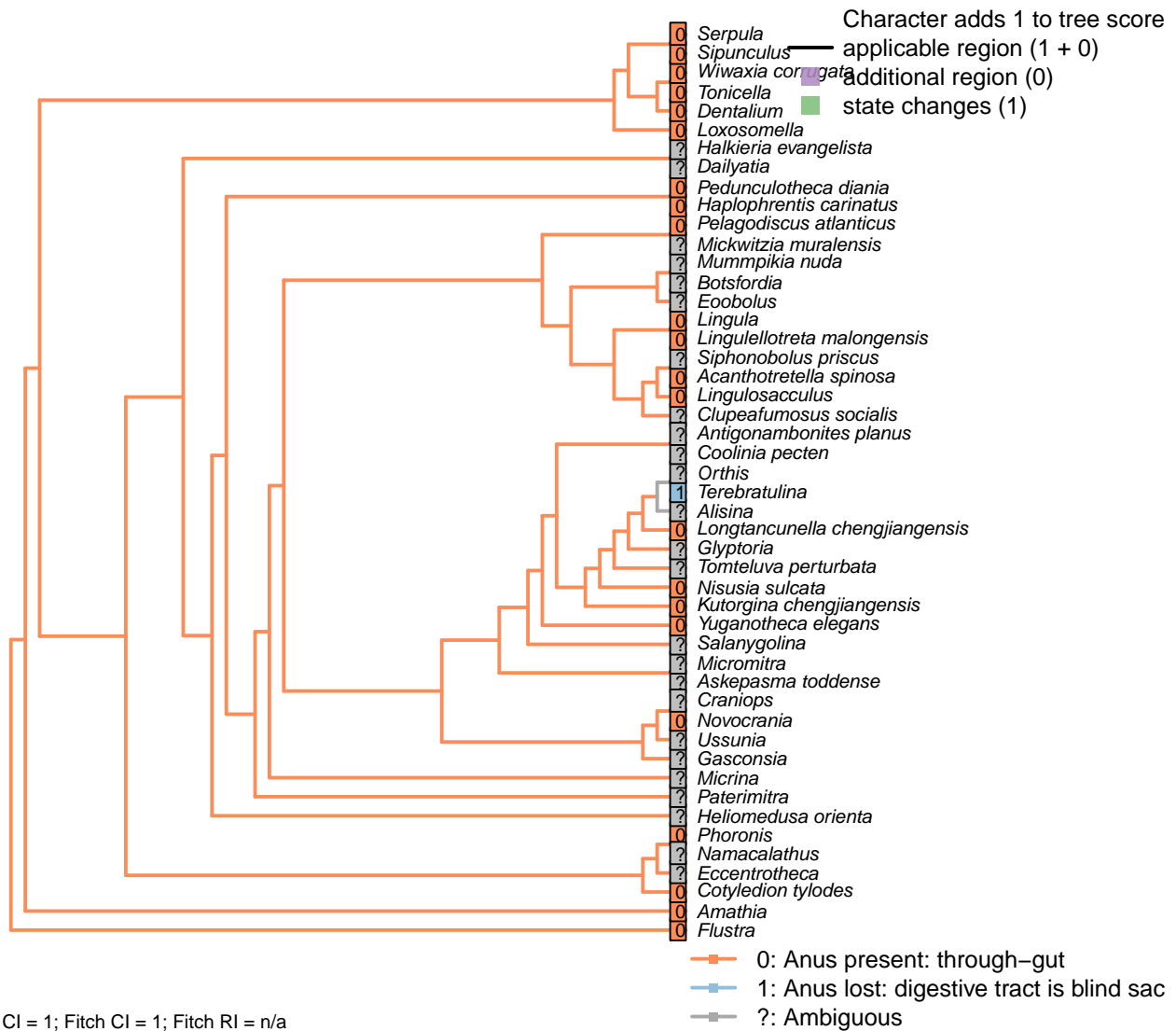
Neomorphic character.

Characters 1.40, 2.30 and 4.59 in von Salvini-Plawen and Steiner (1996); 42 in Haszprunar (2000).

Askepasma toddense: Annex to midgut interpreted as a gland (Smith, 2012b).

3.13 Digestive tract: Anus

[56] Presence



Character 56: Digestive tract: Anus: Presence

0: Anus present: through-gut

1: Anus lost: digestive tract is blind sac

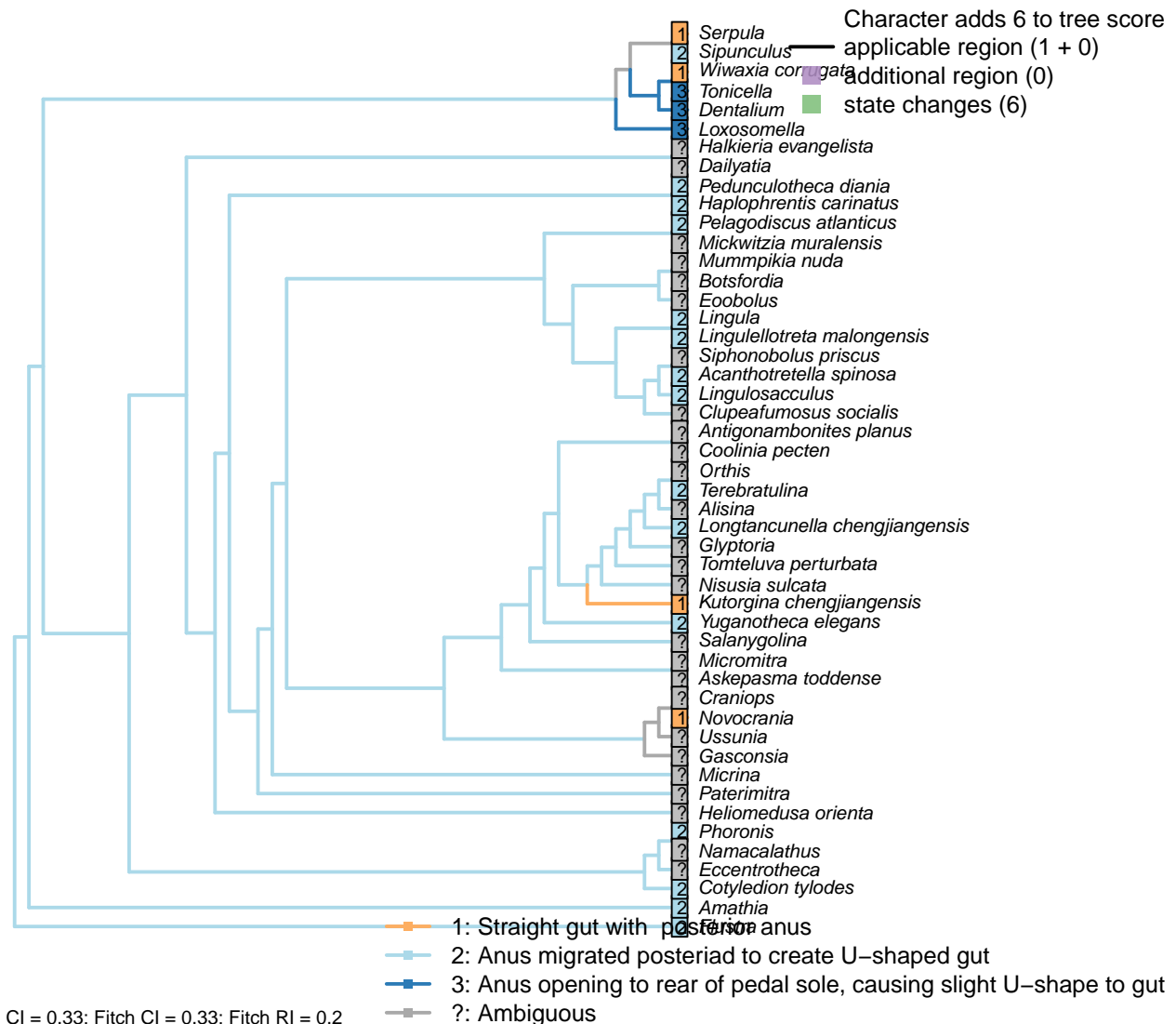
Neomorphic character.

The digestive tract may either constitute a blind sac, or a through gut with anus. The loss of an anus is known to be derived within spiralia, so this character is treated as neomorphic.

Longtancunella chengjiangensis: Scored according to familial level feature.

Micromitra: Although “the possibility of a blind ending may not be completely eliminated [...] the weight of evidence [...] leads us to reject the possibility of a blind-ending intestine” – Zhang et al. (2007b), p. 1399.

[57] Location

**Character 57: Digestive tract: Anus: Location**

- 1: Straight gut with posterior anus
 - 2: Anus migrated posteriad to create U-shaped gut
 - 3: Anus opening to rear of pedal sole, causing slight U-shape to gut
- Transformational character.

“The relative position of the mouth and anus in the larvae of brachiopods and phoronids is similar: posterior anus and anterior mouth” – Williams et al. (2007), p. 2884
 See also character 6 in Haszprunar and Wanninger (2008).

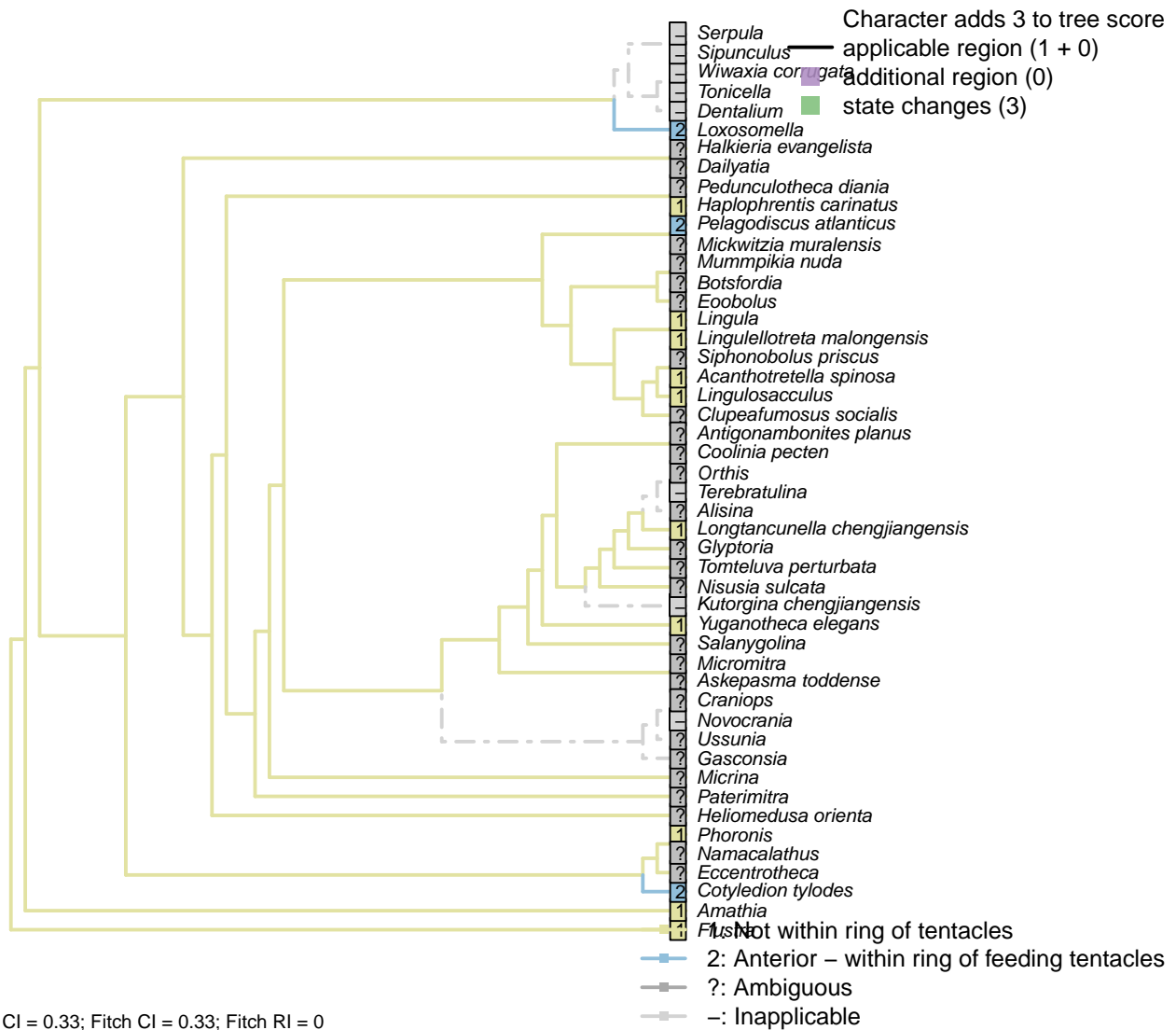
Alisina: The U-shaped gut of scaphopods arises by exaggeration of the dorsal surface, rather than migration of the anus (Steiner, 1992).

Micromitra: “Five specimens have an exceptionally preserved digestive tract, dorsally curved, with a putative dorso-terminal anus located near the proximal end of a pedicle” – Zhang et al. (2007b).

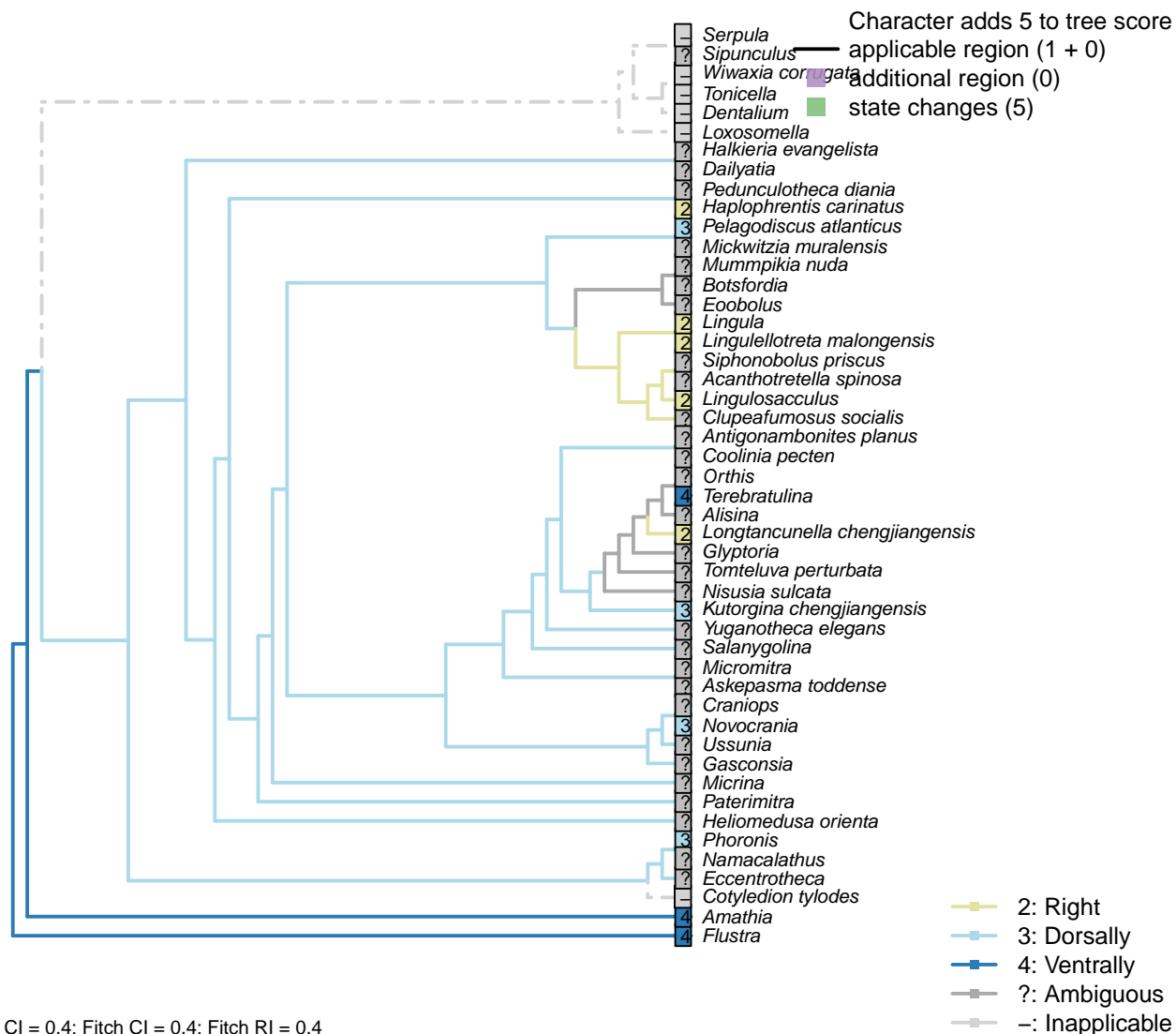
Tonicella: “In rhynchonelliforms, the gut curves somewhat into a C-shape and the (blind) anus becomes posteroventral in position.” – Williams et al. (2007), p.

2884.

[58] Migration: Within ring of tentacles



[59] Migration: Position



right body wall.” – Williams et al. (1997), p. 89.

Mickwitzia muralensis: “This same arrangement occurs in *L. nuda*, with the looped dark line tracking the same course as the exceptionally preserved guts of Chengjiang lingulellotretids, including the median position of its posterior loop and the sharp right turn as it exits the posterior extension of the ventral valve” (Balthasar and Butterfield, 2009, p.310).

Micromitra: “Five specimens have an exceptionally preserved digestive tract, dorsally curved, with a putative dorso-terminal anus located near the proximal end of a pedicle” – Zhang et al. (2007b).

Mummpikia nuda: “finally terminating in an anal opening on the right anterior body wall” (Zhang et al., 2007a, p.66).

Nisusia sulcata: “The intestine extends posteriorly, and then turns right to continue as a tortuous strand, finally terminating at the latero-median position of the anterior body wall” – Zhang et al. (2007c).

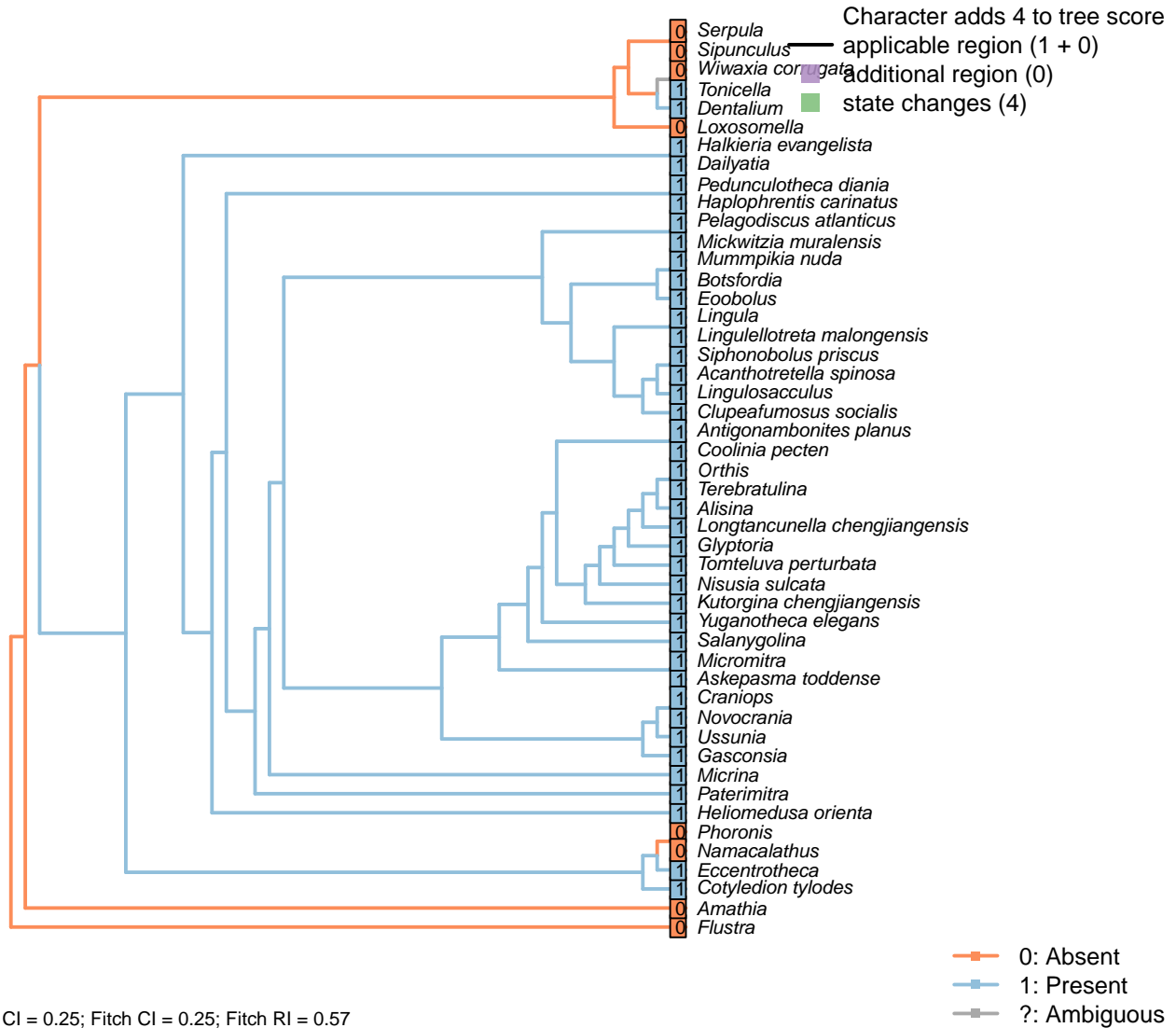
Phoronis, *Sipunculus*: Anus remains on ventral surface. Arguably, rather than the anus migrating, the dorsal surface of the animal has become extended.

Tonicella: “In rhynchonelliforms, the gut curves somewhat into a C-shape and the (blind) anus becomes posteroventral in position.” – Williams et al. (2007), p. 2884.

NA: The identification of the “very poorly impressed possible anus at the lateral side of the anterior body wall” is not yet confident, so this character is coded as not presently available.

3.14 Sclerites

[60] Present in adult



Character 60: Sclerites: Present in adult

0: Absent

1: Present

Neomorphic character.

Plate-like (wider than tall) skeletal elements, whether mineralized or non-mineralized.

The definition deliberately excludes setae (which are taller than wide).

Acanthotretella spinosa, *Alisina*: Molluscan valves are treated as potential homologues of brachiopod valves.

Antigonambonites planus: Halkieriid sclerites are interpreted as potentially homologous with those of *Dailyatia* and hence the brachiopods (Zhao et al., 2017).

Askepasma toddense: The scales of *Wiwaxia* are treated as homologous with the chaetae of annelids and

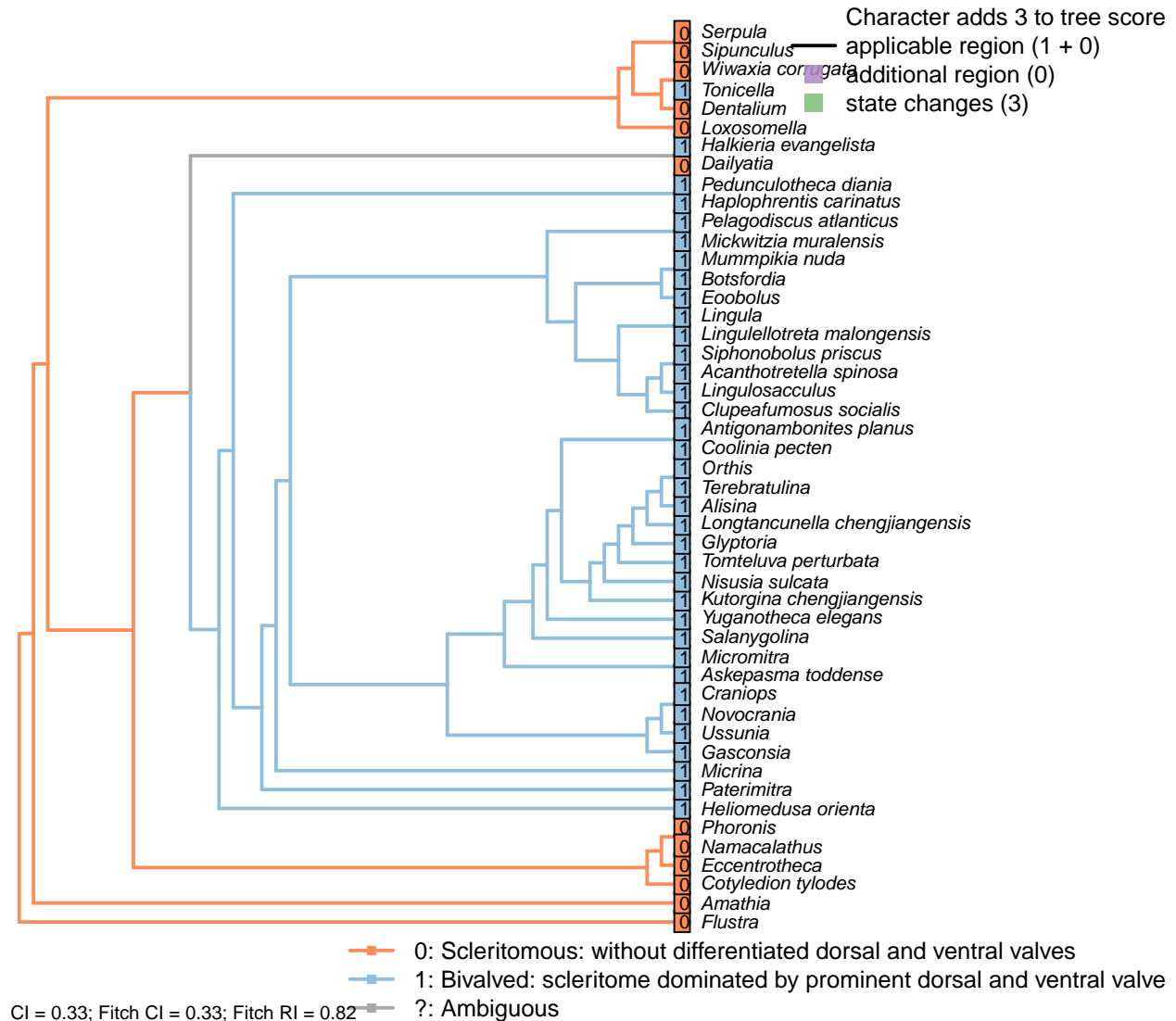
brachiopods (Butterfield, 1990; Smith, 2014; Zhang et al., 2015), rather than brachiopod shell.

Daliyatia: Annelid setae are not considered to represent potential homologues with the brachiopod shell.

Halkieria evangelista: Hooks are present, though the absence of chitin or microvillar impressions indicates that they are not homologous with those of other lophotrochozoans.

Namacalathus: The mineralized endoskeleton of *Namacalathus* is not interpreted as a sclerite.

3.15 Sclerites: Bivalved [61]



Character 61: Sclerites: Bivalved

0: Scleritinous: without differentiated dorsal and ventral valves

1: Bivalved: scleritome dominated by prominent dorsal and ventral valve

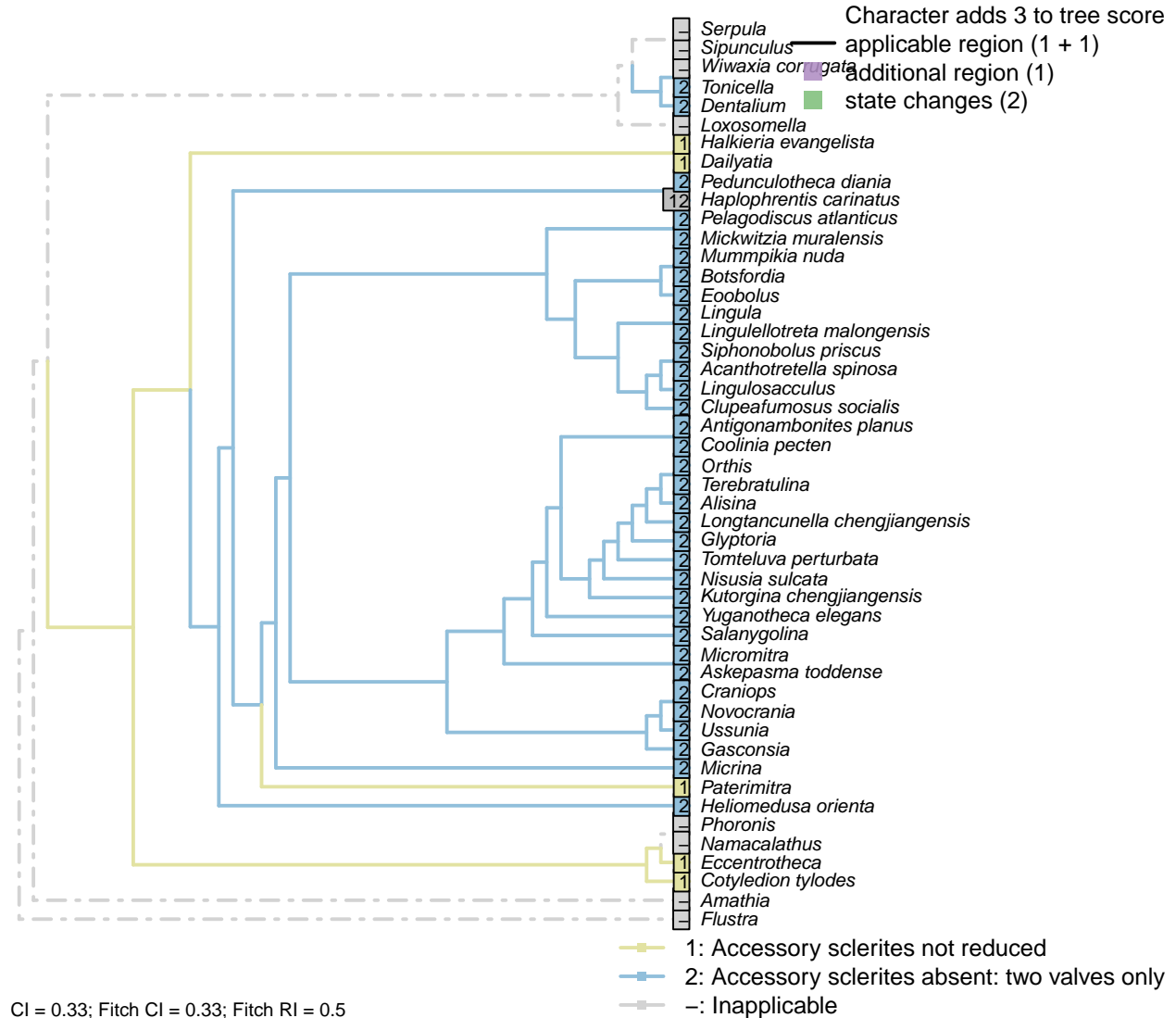
Neomorphic character.

Scleritome dominated by prominent differentiated dorsal and ventral valves.

Acanthotretella spinosa: As larvae, polyplacophorans exhibit an anterior and a posterior shell field (Wan-

ninger and Haszprunar, 2002a); subsequent subdivision of the posterior field gives rise to the posterior seven valves. *Tonicella* is thus tentatively coded as ‘bivalved’ to reflect the potential (if perhaps unlikely) homology with the paired elements of brachiopods.

[62] Accessory sclerites reduced



Character 62: Sclerites: Bivalved: Accessory sclerites reduced

- 1: Accessory sclerites not reduced
 - 2: Accessory sclerites absent: two valves only
- Transformational character.

Taxa in the bivalved condition may retain sclerites as small additional elements, such as the L-elements of *Paterimitra* (Skovsted et al., 2015).

This character is treated as neomorphic, with accessory sclerites ancestrally present, recognizing the likely origin of brachiozoans (and Lophotrochozoans more generally) from a scleritinous organism.

Acanthotretella spinosa: The intermediate shell plates arise by subdivision of the posterior shell field (Waninger and Haszprunar, 2002a), and are thus treated as equivalent to the posterior valve rather than as

distinct elements.

The girdle elements are homologous with annelid chaetae / brachiopod setae (Leise and Cloney, 1982), rather than sclerites.

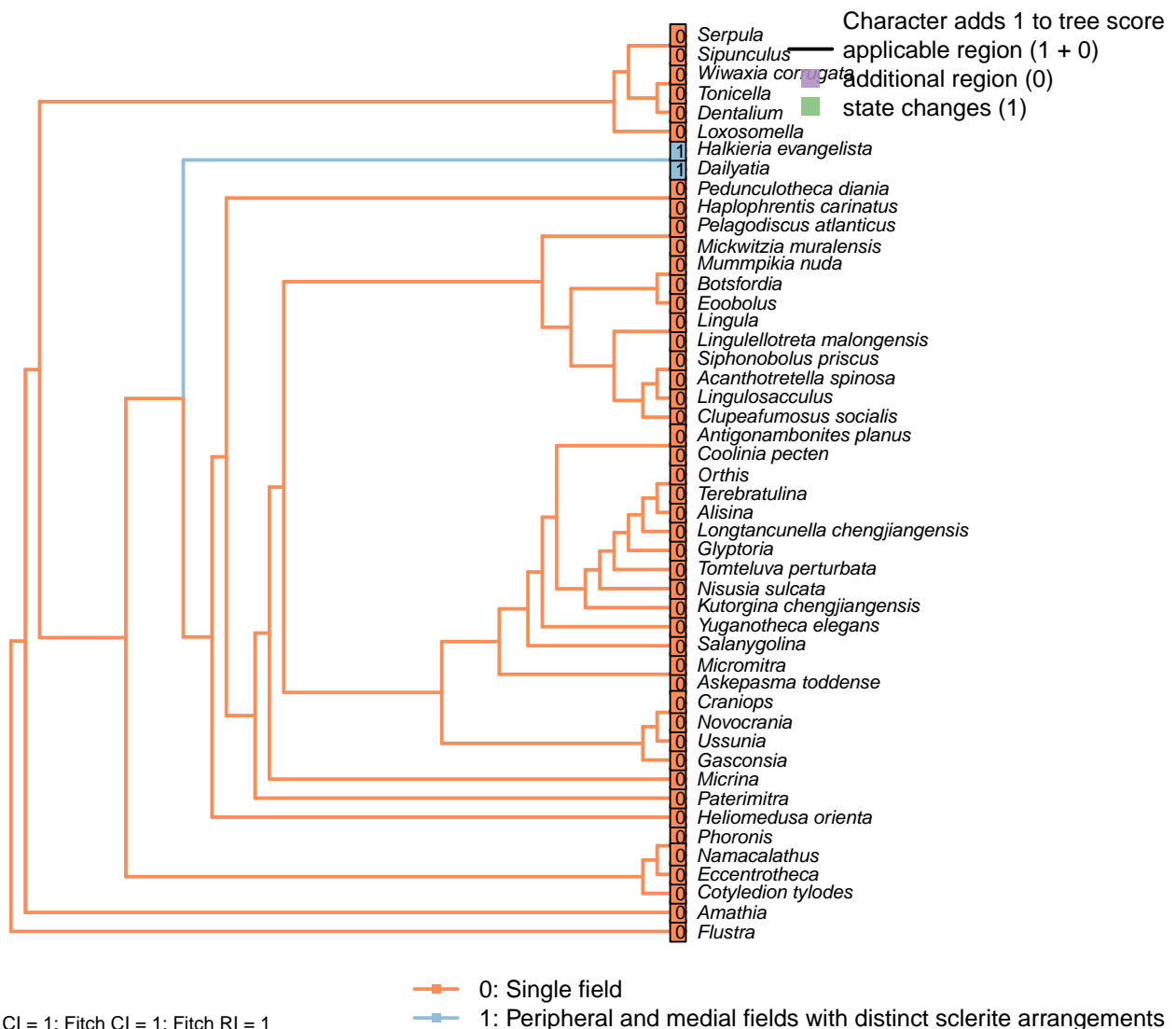
Alisina: The scaphopod valve arises posterior of the prototroch and is thus homologous with the posterior valves of Chiton, assuming that molluscan shell fields are homologous features.

Amathia: Coded as ambiguous to recognize the possibility that helens may correspond to L-elements of *Paterimitra* (Moysiuk et al., 2017).

NA: L-sclerites (Skovsted et al., 2009).

3.16 Sclerites: Accessory sclerites

[63] Arrangement



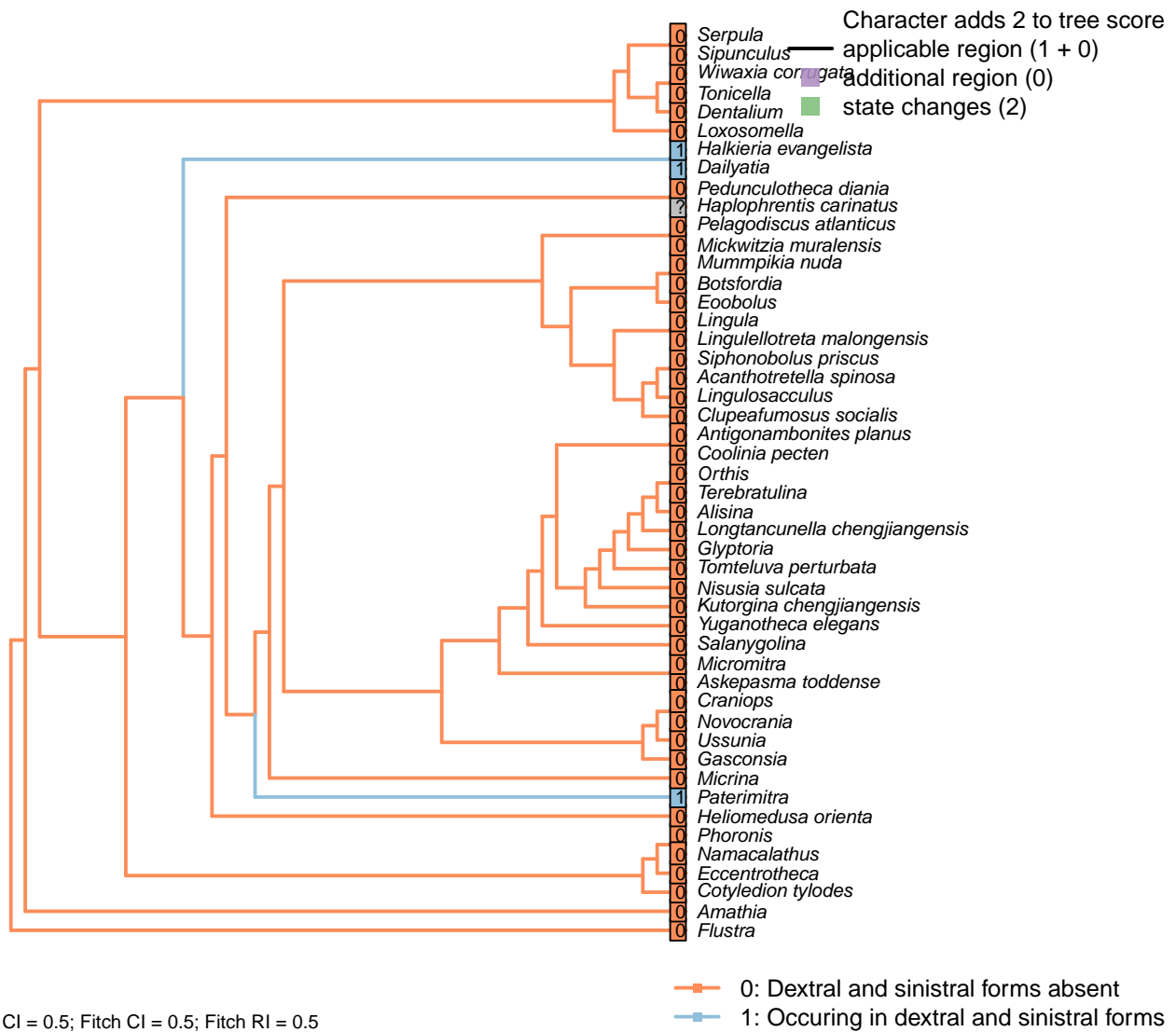
Character 63: Sclerites: Accessory sclerites: Arrangement

- 0: Single field
 1: Peripheral and medial fields with distinct sclerite arrangements
 Neomorphic character.

Following Zhao et al. (2017).

Botsfordia: Following the reconstruction of Skovsted et al. (2015).

[64] Symmetry

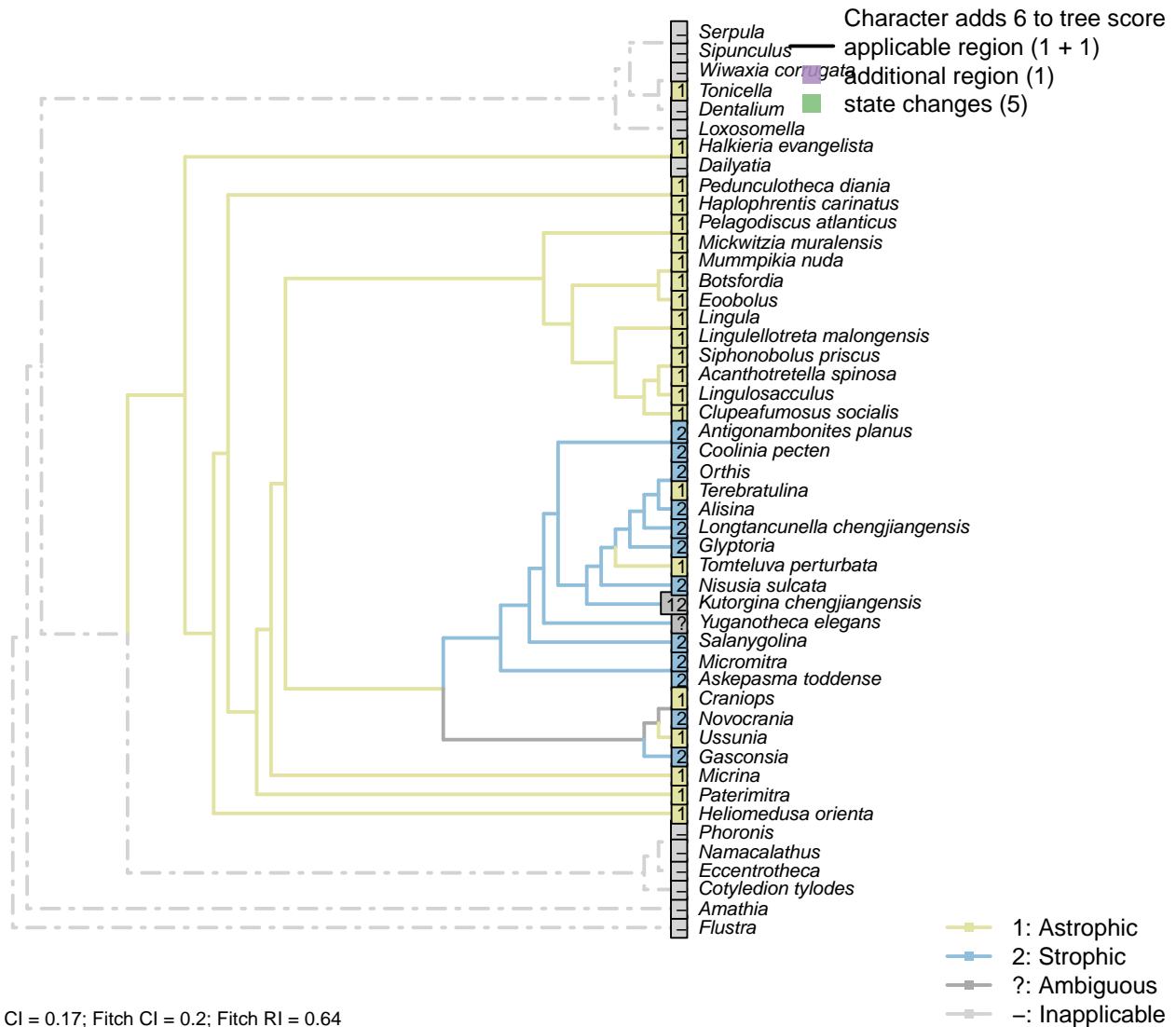


Paterimitra (Moysiuk et al., 2017).

Lingulosacculus: Skovsted et al. (2008).

3.17 Sclerites: Bivalved

[65] Hinge line shape



Character 65: Sclerites: Bivalved: Hinge line shape

1: Astrophic

2: Strophic

Transformational character.

Acanthotretella spinosa: A linear hinge articulation does not exist between valves 1 and 2; nor would it exist

between valves 1 and 8 were these adjacent (Connors et al., 2012).

Antigonambonites planus, *Salanygolina*: Non-strophic.

Eoobolus: Craniides have a strophic posterior valve edge (Williams et al., 2007, table 39 on p. 2853): *Novocrania*’s “dorsal posterior margin” is “straight” (Williams et al., 2000, p. 171).

Gasconsia: Coded as dissociated in Williams et al. (1998), appendix 2.

Glyptoria: Astrophic: rounded posterior margin (see fig. 91 in Williams et al., 2000).

Heliomedusa orientalis: The straight posterior margin of *Gasconsia* contributes to an overall resemblance with the Chileids (?).

Micromitra: Williams et al. (2000, p. 208) consider the hinge of *Kutorgina* to be stropic, whereas Bassett et al. (2001) argue for an astrophic interpretation – whilst noting that the arrangement is prominently different from other astrophic taxa. We therefore code this taxon as ambiguous.

Nisusia sulcata: “*Longtancunella* has an oval to subcircular shell with a very short strophic hinge line” – Zhang et al. (2011a).

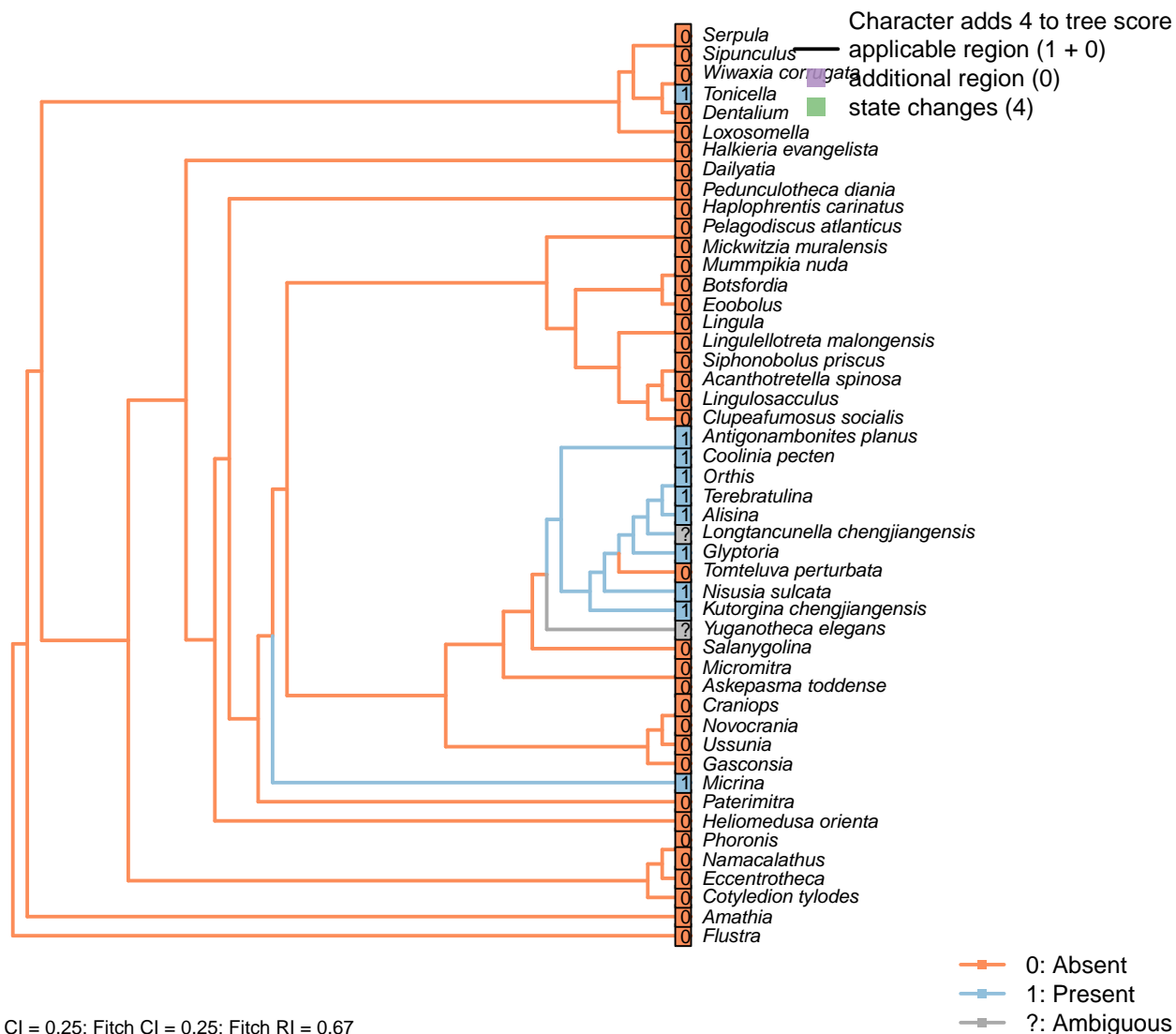
Orthis: Non-strophic: see Holmer et al. (2008).

Tomteluva perturbata: “The strophic, articulated shells of the Kutorginata rotated on simple hinge mechanisms that are different from those of other rhynchonelliforms” (Williams et al., 2000, p. 208).

NA: “Tomteluvid taxa all have a strongly ventribiconvex, astrophic shell with a unisulcate commissure” – Streng et al. (2016), p5.

NA: Not evident from fossil material; the possibility of a short strophic hinge line (as in *Longtancunella*) is difficult to discount.

[66] Apophyses

**Character 66: Sclerites: Bivalved: Apophyses**

0: Absent

1: Present

Neomorphic character.

Many brachiopods, in addition to *Micrina* and others, bear tooth-like structures or processes that articulate the two primary valves.

Caution must be applied before taxa are coded as “absent”, as teeth can be subtle and may be overlooked.

Kutorginata don’t have teeth or dental sockets, but their shells are articulated by “two triangular plates formed by dorsal interarea, bearing oblique ridges on the inner sides” (Williams et al., 2000, p. 211); this simple hinge mechanism is different from other rhynchonelliforms (Williams et al., 2000, p.208), but serves an equivalent purpose and is thus potentially homologous. We thus code kutorginids as present, using a subsequent character to capture difference in tooth morphology.

Acanthotretella spinosa: The sutural laminae correspond in function and position to brachiopod apophyses

(Connors et al., 2012), and so are coded as potentially homologous.

Coolinia pecten: “Strophic articulation with paired, ventral denticles, composed of secondary shell” – definition of family Trematobolidae in Williams et al. (2000).

Heliomedusa orienta: “Articulatory structure comprising ventral cardinal socket and dorsal hinge plate [...] The shape of the shell probably correlates strongly with the unique type of articulation, which consists of a dorsal hinge plate that fits tightly into a cardinal socket in the ventral valve, with a concave homeodeltidium in the center of the ventral interarea” – Williams et al. (2000), p.184, concerning order Trimerellida.

Kutorgina chengjiangensis: “articulatory structures poorly developed” – Williams et al. (2000), p. 192.

Micromitra: “Articulation characterized by two triangular plates formed by dorsal interarea, bearing oblique ridges on the inner sides” – Williams et al. (2000), p. 211.

Salanygolina: Not reported by or evident in Balthasar (2004).

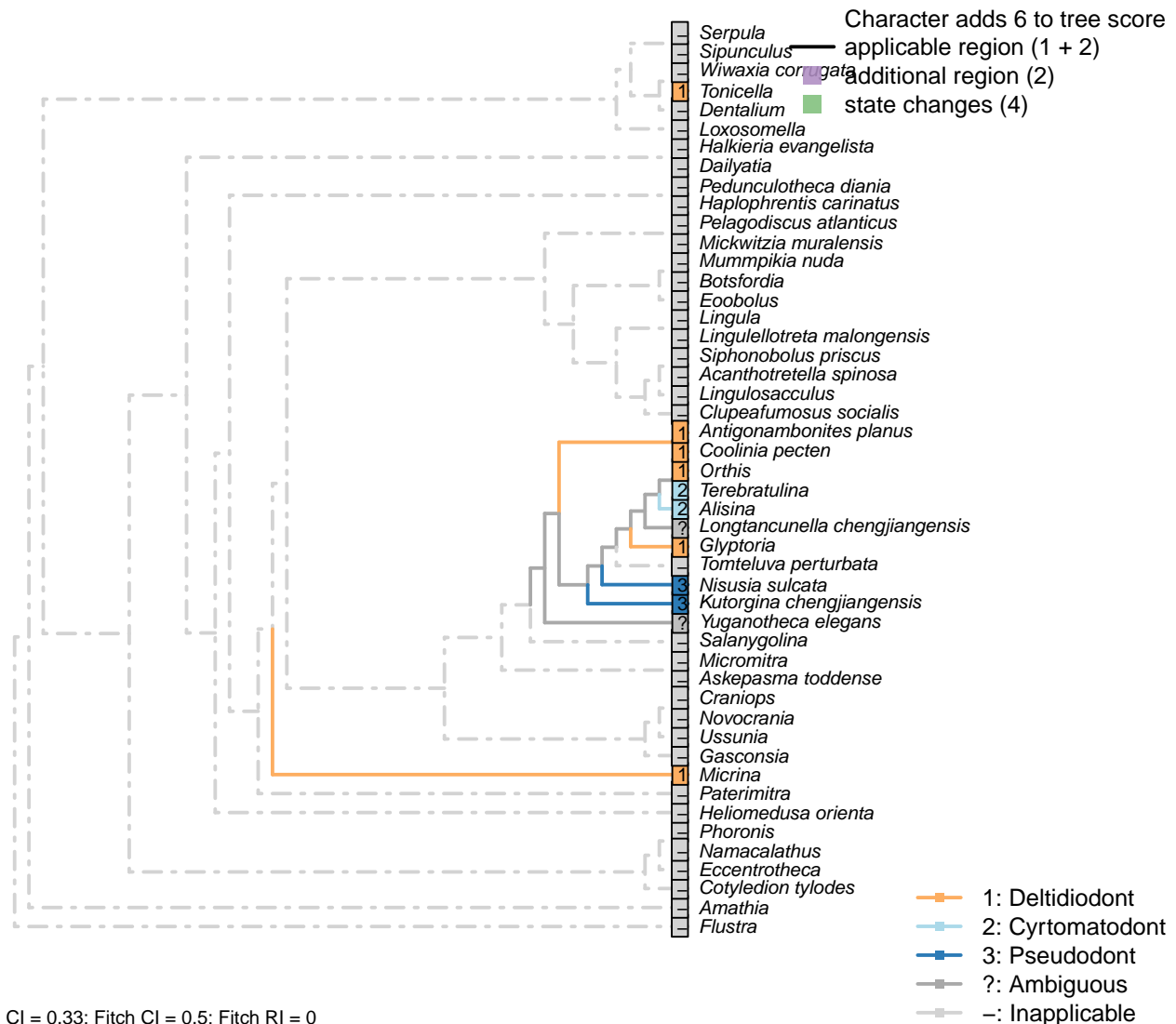
Siphonobolus priscus: No articulation structures are evident; instead, the propareas are rotated inwards (Balthasar, 2008). The definition of Family Obolellidae in Williams *et al.* (2000) notes that articulation may be lacking or vestigial in the group.

Tomteluva perturbata: Pseudodont articulation: teeth formed by distal lateral extensions from the ventral pseudodeltidium – Holmer et al. (2018a).

Ussunia: No articulating processes evident or reported by Topper *et al.* (2013a).

NA: Tomteluvids [...] lack articulation structures such as teeth and sockets (Streng et al., 2016).

[67] Apophyses: Morphology

**Character 67: Sclerites: Bivalved: Apophyses: Morphology**

- 1: Deltidodont
- 2: Cyrtomatodont
- 3: Pseudodont

Transformational character.

Deltidodont teeth are simple hinge teeth developed by the distal accretion of secondary shell; Cyrtomatodont teeth are knoblike or hook-shaped hinge teeth developed by differential secretion and resorption of the secondary shell (fig. 322 in Williams et al., 1997).

Kutorginata (here represented by *Kutorgina* and *Nisusia*) don't have teeth (apophyses) or dental sockets, but their shells are articulated by "two triangular plates formed by dorsal interarea, bearing oblique ridges on the inner sides" (Williams et al., 2000, p. 211); this simple hinge mechanism is different from other rhynchonelliforms [Williams et al. (2000), p.208; table 13 character 30], and is described as a "pseudodont articulation" (Holmer et al., 2018a).

Acanthotretella spinosa: Chiton apophyses (sutural laminae) are accretions deriving from the ventral shell

layer of the intermediate and tail valves (Schwabe, 2010), so correspond to the deltidiodont situation in brachiopods.

Craniops, *Longtancunella chengjiangensis*: Coded as deltidiodont in Benedetto (2009).

Micromitra: “Articulation characterized by two triangular plates formed by dorsal interarea, bearing oblique ridges on the inner sides” – Williams et al. (2000), p. 211.

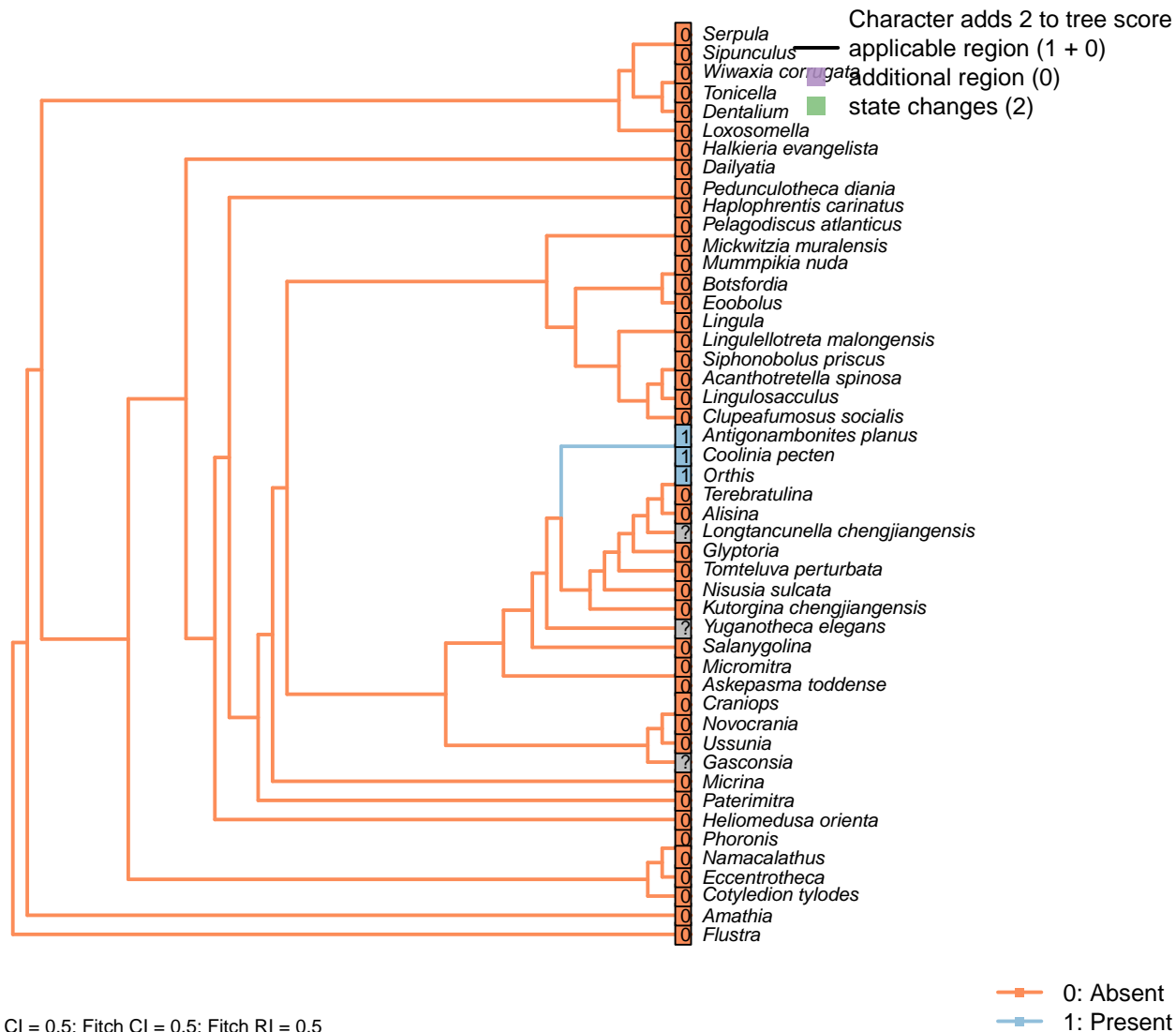
Orthis: The simple knob-like teeth of *Micrina* show no evidence of resprobtion or the hook-like shape that characterises Cyrtomatodont teeth.

Tomteluva perturbata: The ‘teeth’ are formed by the distal lateral extensions from the ventral pseudodeltidium fitting into the ‘sockets’ on the inner side of the dorsal interarea (Holmer et al., 2018a). [Coded as “deltidiodont teeth absent” in Benedetto (2009).]

Tonicella: Cyrtomatodont – see fig. 322 in Williams et al. (2000).

Yuganotheca elegans: Coded as deltidiodont (in *Eoorthis*) in Benedetto (2009).

[68] Apophyses: Dental plates



Character 68: Sclerites: Bivalved: Apophyses: Dental plates

0: Absent

1: Present

Neomorphic character.

Williams et al. (1997) (p362) write: “Teeth [...] are commonly supported by a pair of variably disposed plates also built up exclusively of secondary shell and known as dental plates (Fig. 323.1, 323.3).”

Dewing (2001) elaborates: “Dental plates are near-vertical, narrow sheets of shell tissue between the antero-median edge of the teeth and floor of the ventral valve. They are a composite structure, resulting from the growth of teeth over the ridge that bounds the ventral-valve muscle field.”

Williams et al. (2000) (p.201) write: “The denticles lack supporting structures in all Obolellida, but in Naukatida they are supported by an arcuate plate below the interarea, the anterise (Fig. 119.3a)”.

The anterise is conceivably homologous with the dental plates, thus the presence of either is coded “present” for this character.

Craniops: Coded as present (well developed) in Benedetto (2009).

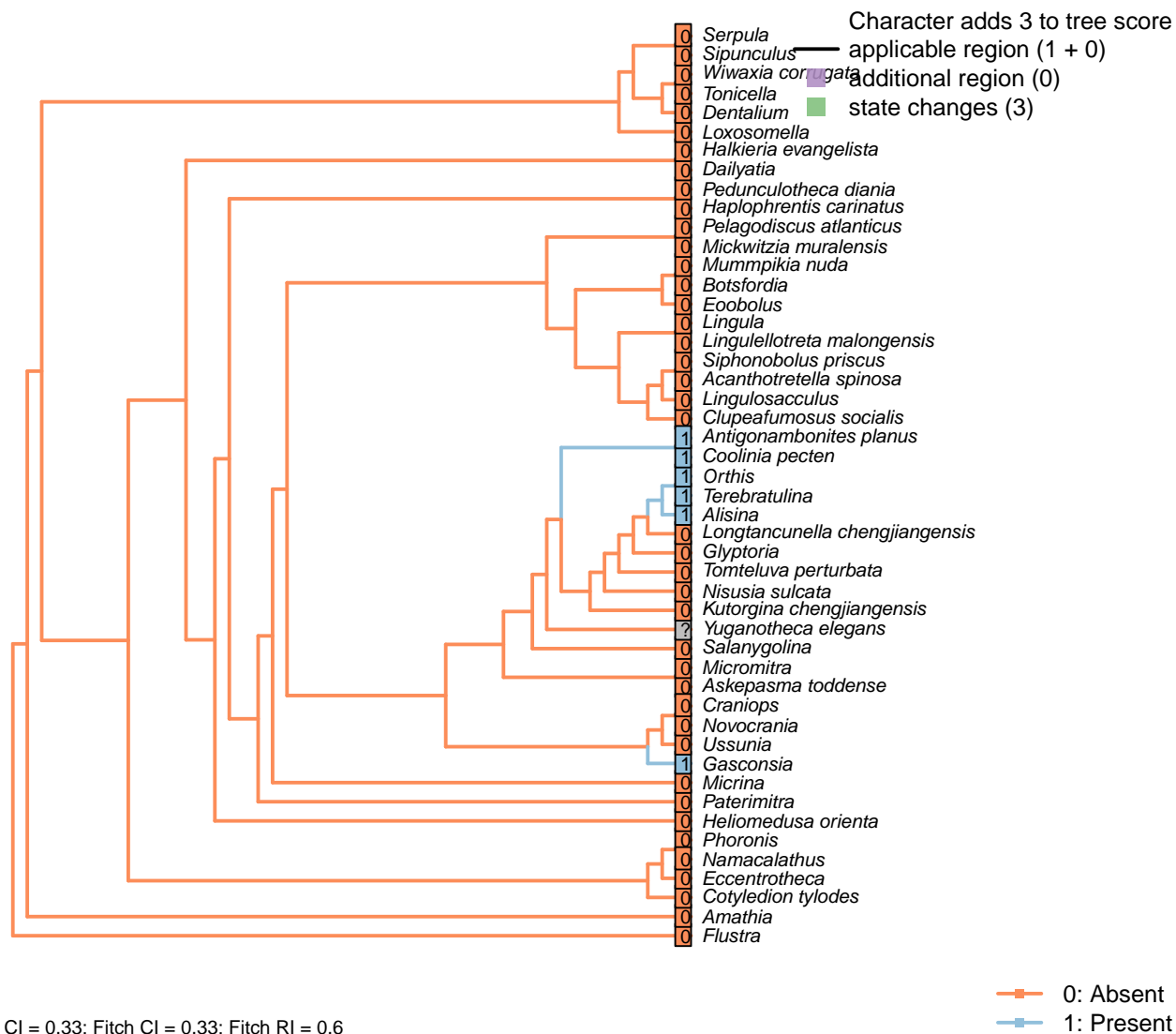
Eccentrotheca: Coded as present following Dewing (2001), who seems to use the term Strophomenoids to encompass *Coolinia*, and attests to the presence of dental plates.

Heliomedusa orientalis: Coded ambiguous to reflect the possibility that the hinge plate in trimerellids is homologous to the dental plates of other taxa, and has replaced the teeth themselves as the primary articulatory mechanism (see Williams et al., 2000, p. 184, for details of the articulation).

Longtancunella chengjiangensis, *Tomteluva perturbata*: Coded as absent in Benedetto (2009).

Yuganotheca elegans: Coded as present (short and recessive, in *Eoorthis*) in Benedetto (2009).

[69] Sockets



Williams et al. (2000), p. 184.

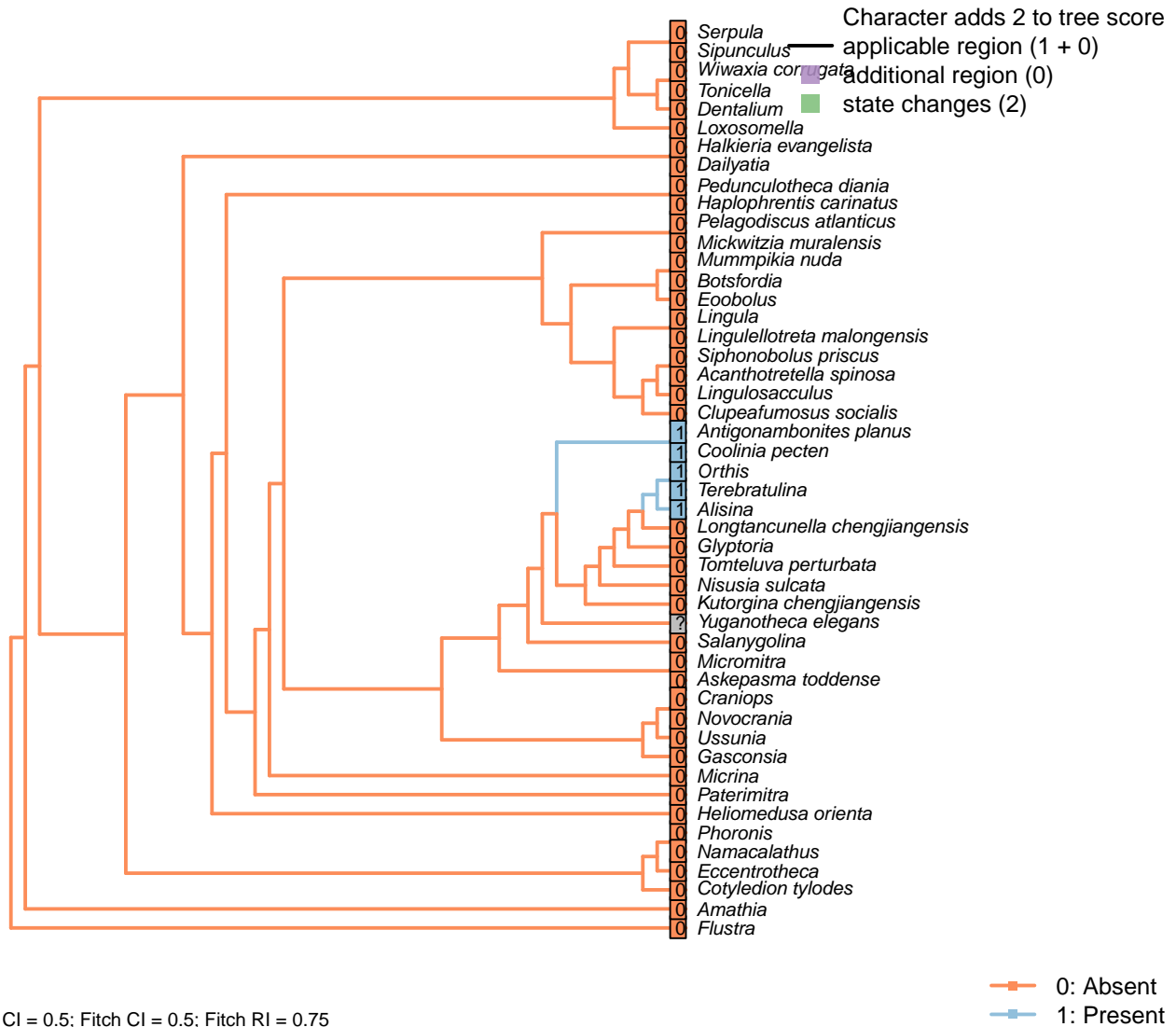
Kutorgina chengjiangensis: Following table 15 in Williams et al. (2000).

Longtancunella chengjiangensis, *Tomteluva perturbata*: Coded as absent in Benedetto (2009).

Salanygolina: Not reported by or evident in Balthasar (2004).

NA: Tomteluvids [...] lack articulation structures such as teeth and sockets (Streng et al., 2016).

[70] Socket ridges



Character 70: Sclerites: Bivalved: Socket ridges

0: Absent

1: Present

Neomorphic character.

After Bassett *et al.* (2001) character 17. May be difficult to distinguish from a brachiophore (see Fig 323 in

Williams et al., 1997), so the two structures are not distinguished here.

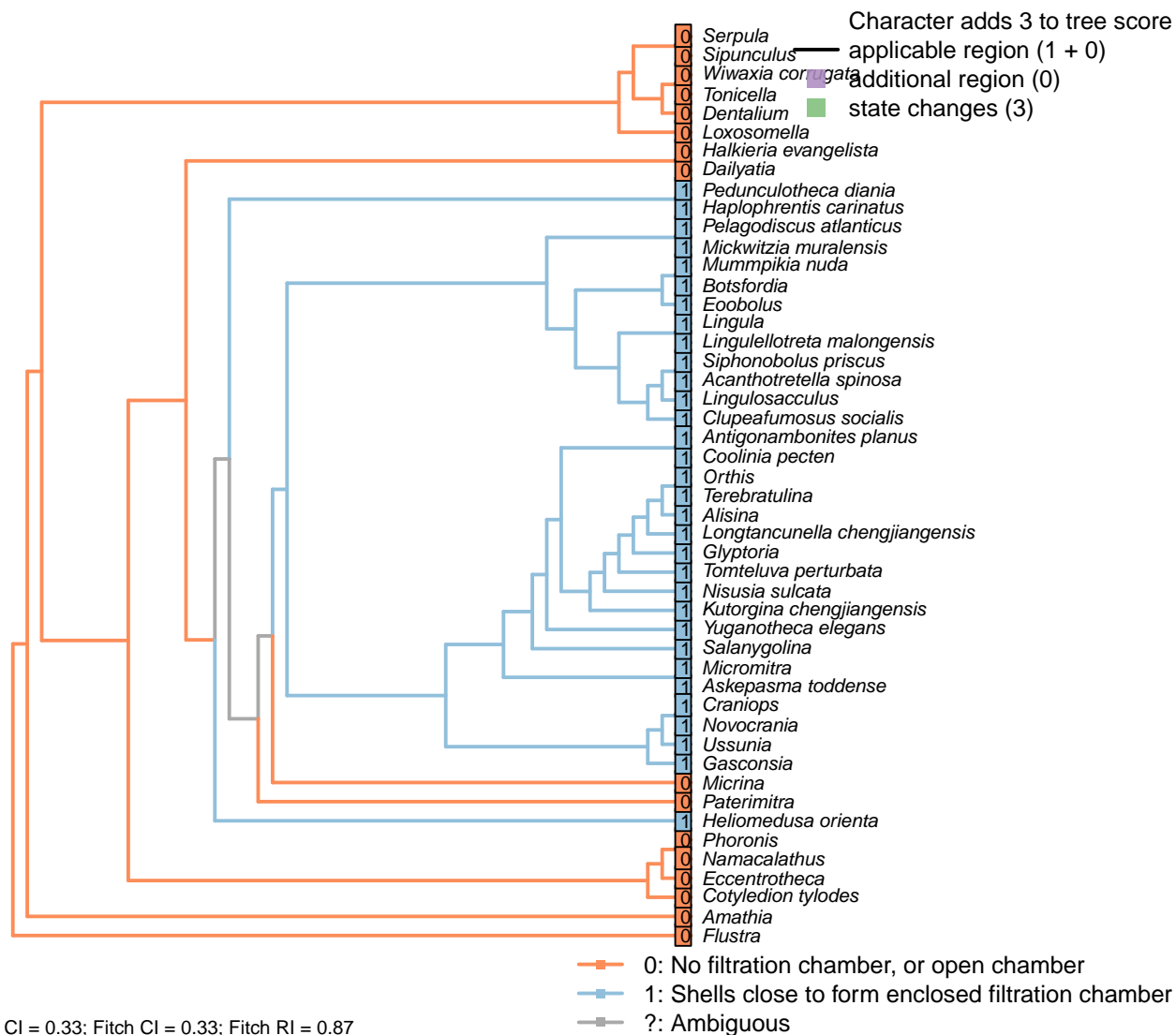
Coolinia pecten: “bearing sockets, bounded by low ridges” – Williams et al. (2000).

Craniops: Coded as present in Benedetto (2009).

Longtancunella chengjiangensis, *Tomteluva perturbata*: Coded as absent in Benedetto (2009).

NA: Tomteluvids [...] lack articulation structures such as teeth and sockets (Streng et al., 2016).

[71] Enclosing filtration chamber



Character 71: Sclerites: Bivalved: Enclosing filtration chamber

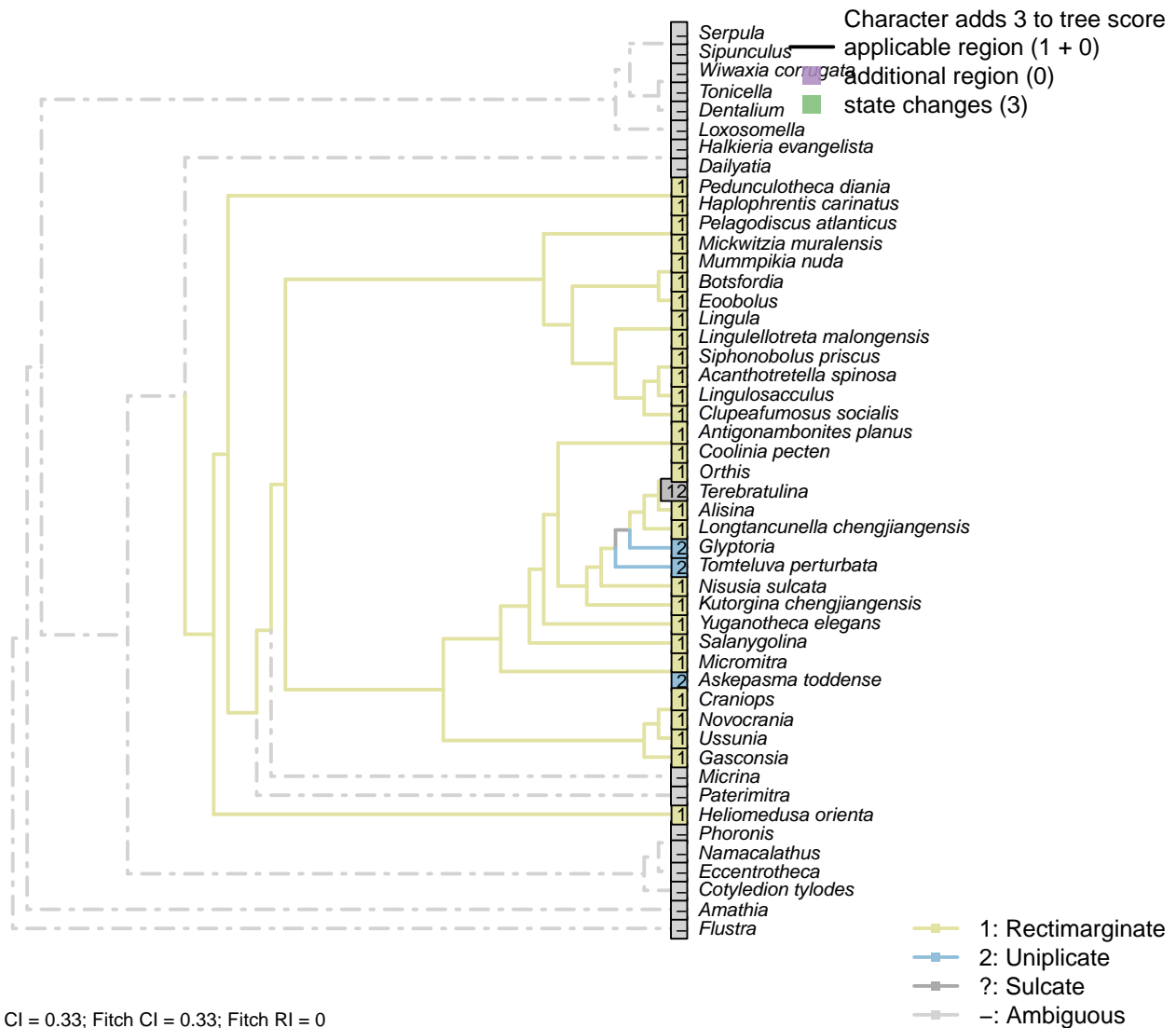
0: No filtration chamber, or open chamber

1: Shells close to form enclosed filtration chamber

Neomorphic character.

In crown-group brachiopods, the two primary shells close to form an enclosed filtration chamber. Further down the stem, taxa such as *Micrina* do not.

[72] Commissure

**Character 72: Sclerites: Bivalved: Commissure**

1: Rectimarginate

2: Uniplicate

3: Sulcate

Transformational character.

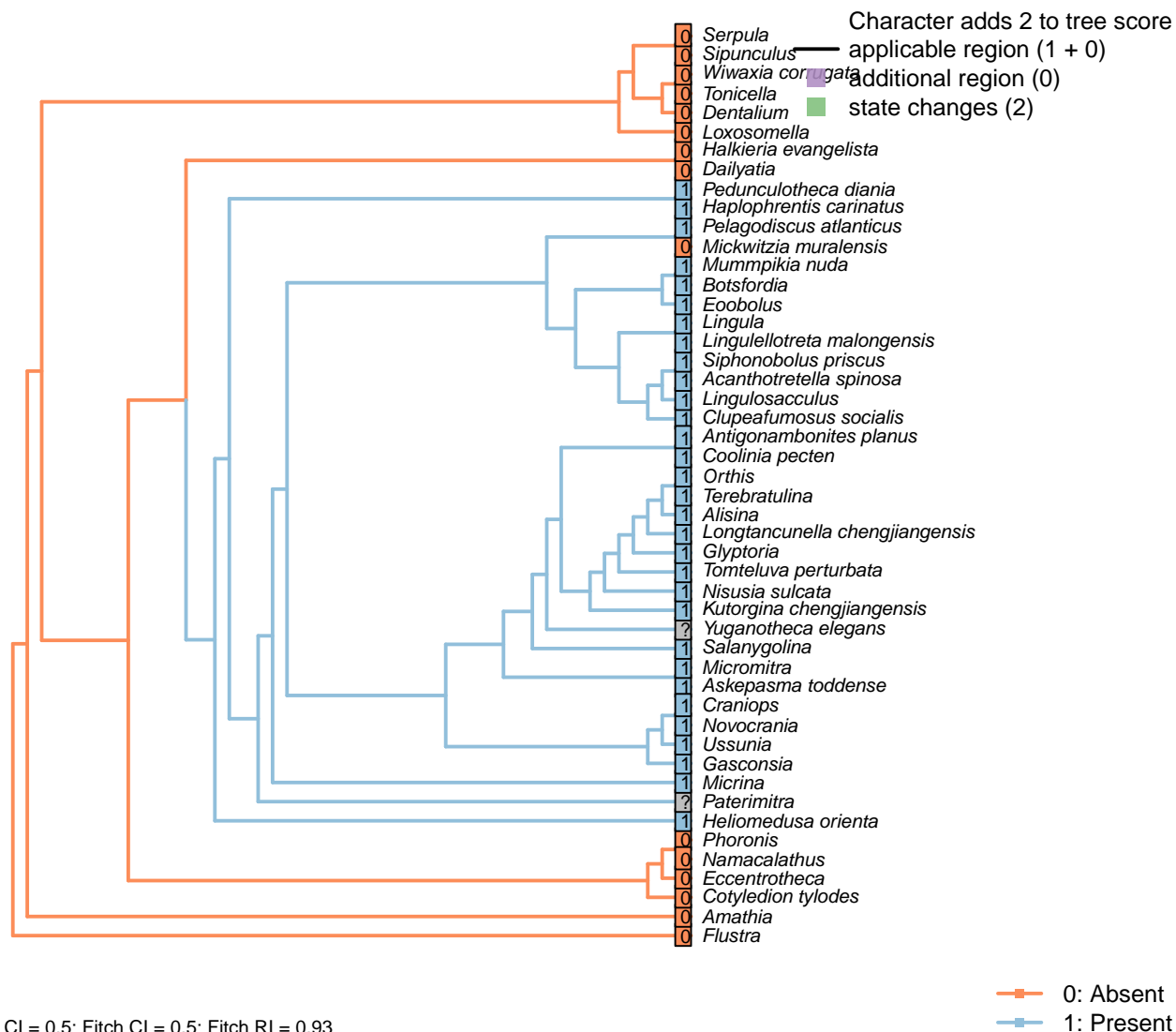
The anterior commissure can be rectimarginate (i.e. straight), uniplicate (i.e. median sulcus in ventral valve), or sulcate (with median sulcus in dorsal valve).

Longtancunella chengjiangensis, *Micromitra*, *Paterimitra*, NA: Following appendix 2 in Williams *et al.* (1998).

Novocrania: “ventral valve weakly to moderately sulcate” (Topper *et al.*, 2013b); a similar description is provided by Williams *et al.* (2000).

Tonicella: “Anterior commissure rectimarginate to uniplicate” – uniplicate in fig. 1425.1c of Williams *et al.* (2006).

[73] Muscle scars: Ventral

**Character 73: Sclerites: Bivalved: Muscle scars: Ventral**

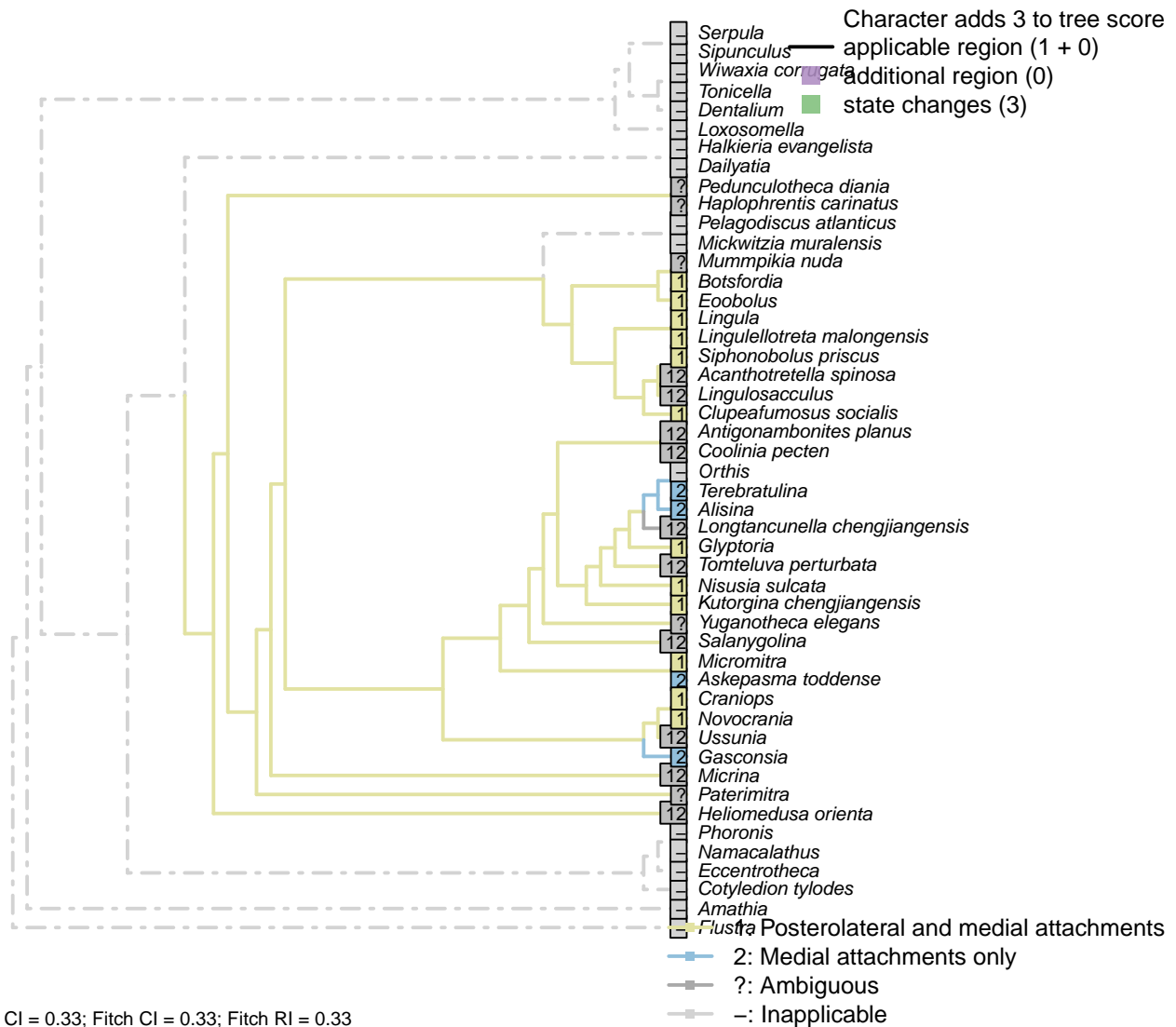
0: Absent

1: Present

Neomorphic character.

After Bassett *et al.* (2001) character 6.*Acanthotretella spinosa*: Absent (Schwabe, 2010).*Antigonambonites planus*: Muscle scars are known from the Type A, but not Type B, morphs of the halkieriid *Oikozetetes* (Paterson *et al.*, 2009; Jacquet *et al.*, 2014).*Coolinia pecten*: Muscle scars scored based on *Alisina comleyensis* (Bassett *et al.*, 2001).*Kutorgina chengjiangensis*: Scars preserved on ventral valve (Nikitin and Popov, 1984).*Orthis*: Prominent ventral muscle scars – see e.g. Holmer *et al.* (2008), fig. 1f.*Salanygolina*: Scars absent; instead, cones ornament shell's internal surface.

[74] Muscle scars: Ventral: Position

**Character 74: Sclerites: Bivalved: Muscle scars: Ventral: Position**

1: Posterolateral and medial attachments

2: Medial attachments only

Transformational character.

Muscles can attach to the ventral valve posterolaterally to, as well as between, the *vascula lateralia* (Popov,

1992).

Clupeafumosus socialis: “Individual muscle scars cannot be distinguished” – Holmer and Caron (2006).

Coolinia pecten: Following reconstruction of Gorjansky & Popov (1986).

Eoobolus: Posterior adductor muscles attach posterolaterally to ventral mantle canal (Robinson, 2014).

Glyptoria: See fig. 89 in Williams *et al.* (2000).

Heliomedusa orientalis: Musculature described in Hanken & Harper (1985).

Kutorgina chengjiangensis: Internal anatomy not adequately preserved to evaluate (Nikitin and Popov, 1984).

Lingulellotretra malongensis: The ‘laterals’ of Balthasar (2009, fig. 5) are situated almost upon the *vascula lateralia*; they are interpreted as sitting posterolateral to them.

Longtancunella chengjiangensis: Posterolateral reflected by diductor attachments; see fig. 18.3.2 in Bassett *et al.* (2001).

Micromitra: Following situation in *Nisusia*; see fig. 18.2 in Bassett *et al.* (2001).

Mummpikia nuda: See fig. 5 in Holmer *et al.* (1997).

Novocrania: Restricted to medial field, following the interpretation of the musculature presented by Williams *et al.* (2000), fig. 81.

Paterimitra: Posteromedial muscle field (Williams *et al.*, 1998, text-fig. 6) treated as equivalent to posterolateral muscles.

Serpula: Inapplicable as vascular system not directly equivalent to the canonical; see. fig 6b in Balthasar (2009).

Tomteluva perturbata: Posterolateral diductors (fig. 18.2 in Bassett *et al.*, 2001).

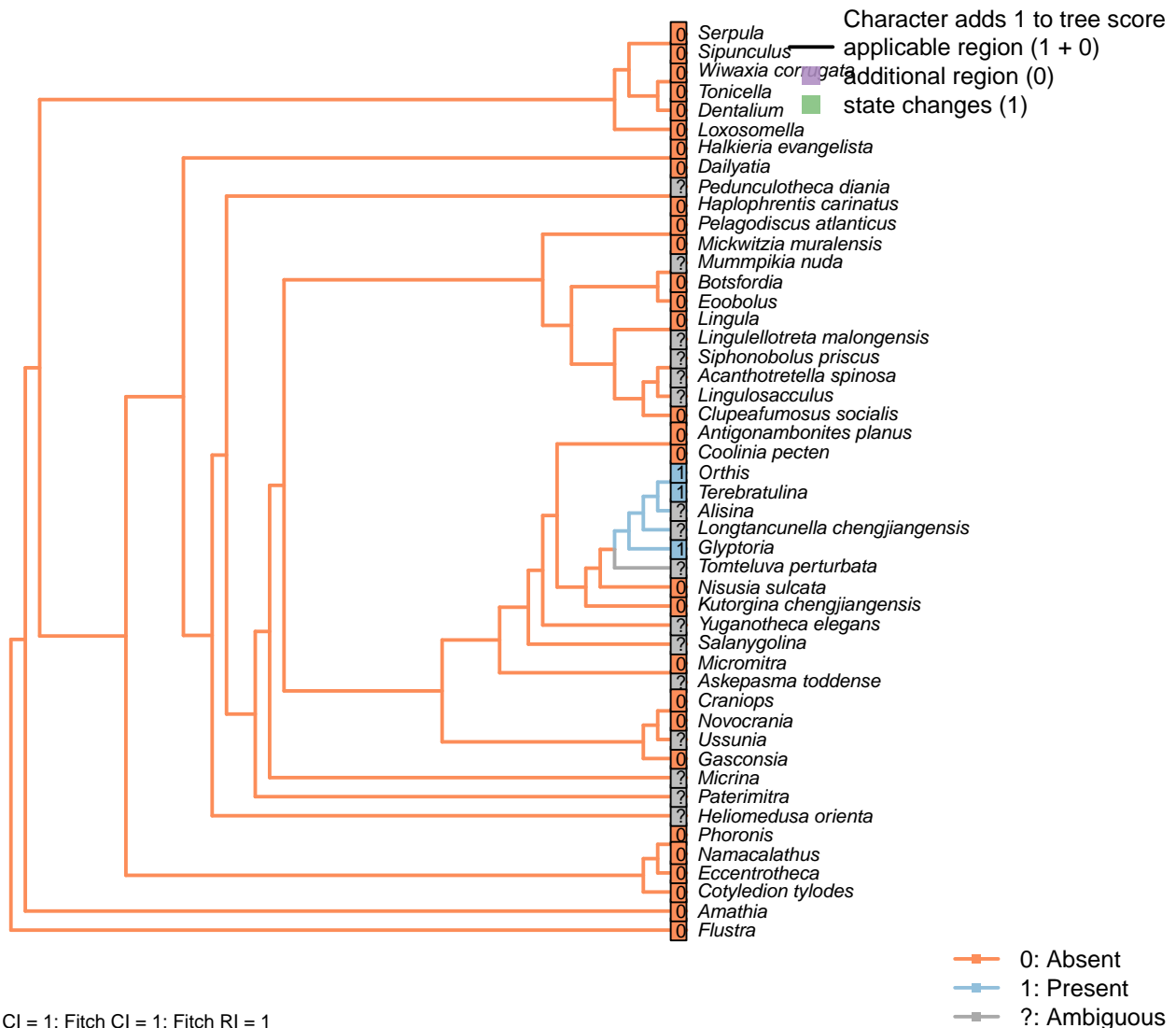
Ussunia: Coded following *Hadrotreta*, as illustrated in Popov (1992).

Yuganotheca elegans: Not applicable: *vascula lateralia* not comparable to those of other taxa.

NA: Ventral musculature not clearly constrained (Holmer *et al.*, 2009).

NA: Coded following general siphonotretid condition described by Popov (1992, p. 407).

[75] Muscle scars: Adjustor

**Character 75: Sclerites: Bivalved: Muscle scars: Adjustor**

0: Absent

1: Present

Neomorphic character.

After Bassett *et al.* (2001) character 7.

This character is contingent on the presence of a pedicle. Extreme caution must be used in inferring an absent state, as adjustor scars can be extremely difficult to distinguish from the adductor scars.

Coolinia pecten: Muscle scars scored based on *Alisina comleyensis* (Bassett *et al.*, 2001). The presence of an adjustor is marked as not presently available, as it is not clear that a scar, if present, could be distinguished from the diminutive muscle scars present.

Gasconsia: Not described in Popov (1992).

Heliomedusa orienta: No mention of an adjustor muscle in *Gasconsia* or Trimerellida more generally on

pp. 184–185 of Williams et al. (2000), nor in discussion in Williams et al. (2007) (p. 2850). Coded as absent.

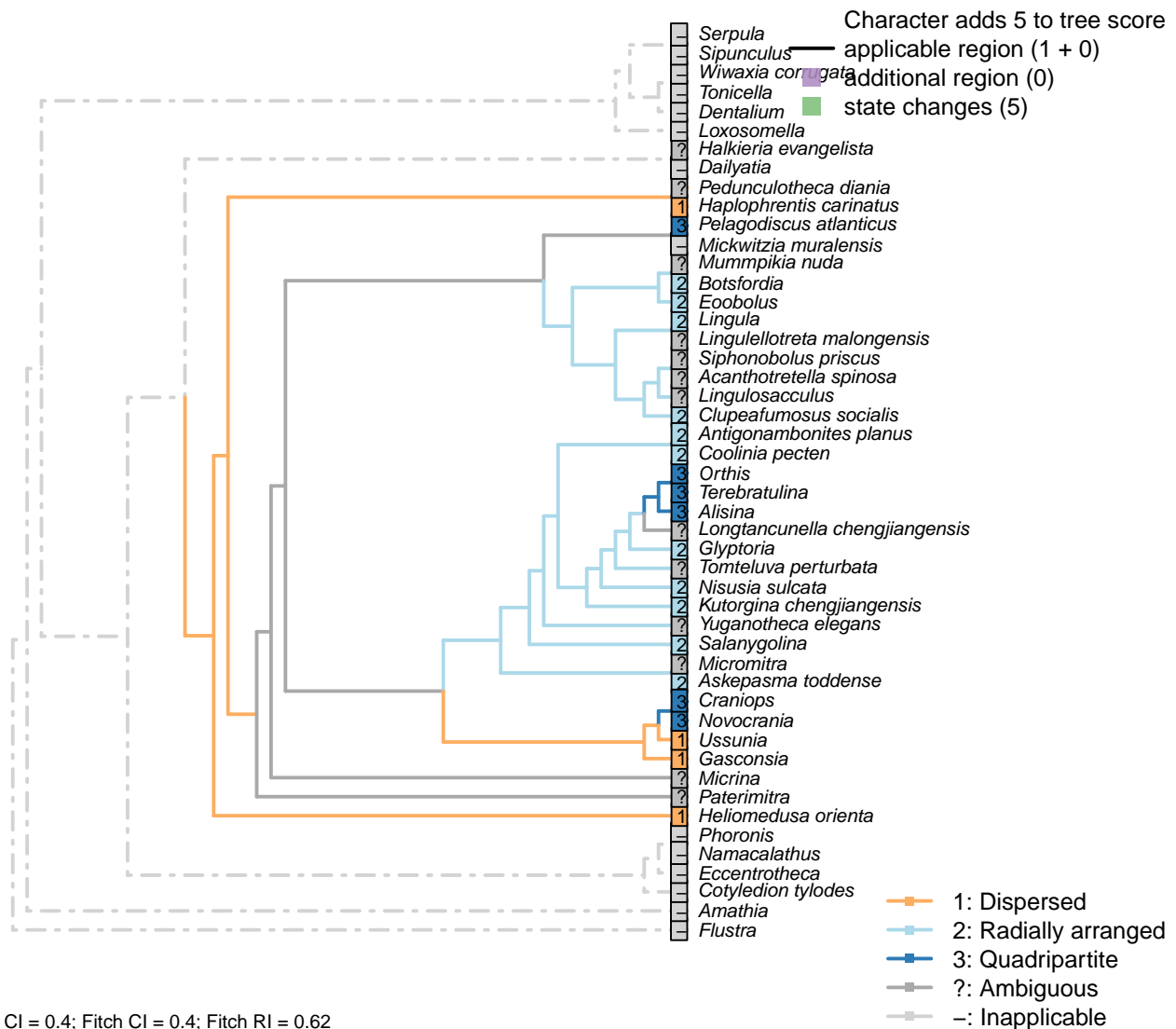
Novocrania: Following the interpretation of the musculature presented by Williams *et al.* (2000), fig. 81.

Salanygolina: Scars absent; instead, cones ornament shell's internal surface.

Ussunia: Not known in any acrotretid (Williams et al., 2000); not evident in *Clupeafumosus* (Topper et al., 2013a).

NA: Ventral musculature poorly constrained (Williams et al., 2000; Popov et al., 2009).

[76] Muscle scars: Dorsal adductors



Character 76: Sclerites: Bivalved: Muscle scars: Dorsal adductors

- 1: Dispersed
 - 2: Radially arranged
 - 3: Quadripartite
- Transformational character.

After Bassett *et al.* (2001) character 8, and Williams *et al.* [Williams *et al.* (1996), character 35; 2000, p. 160, character 54]

In the dorsal valve, the anterior and posterior adductor scars of articulated brachiopods form a single (quadripartite) muscle field (Williams *et al.*, 2000, p. 201)

In contrast, the anterior and posterior scars of e.g. trimerellids have prominently separate attachment points, with anterior and posterior muscle fields clearly distinct, and coded as “dispersed”.

In e.g. kutorginates, adductor muscles are separated into left and right fields; the same is the case in lingulids, where there are more separate muscle groups and the left and right fields conspire to produce a radial arrangement; both of these configurations are scored as “radially arranged”.

Amathia: Laterally dispersed, based on interpretation of Moysiuk *et al.* (2017), and consistent with general situation in hyoliths (see Dzik, 1980).

Antigonambonites planus: It is unclear whether the paired muscle scars of *Oikozetetes* may be homologous to brachiopod adductors.

Coolinia pecten: Following Williams *et al.* (2000) table 15 (their character 54).

Craniops: Treatise.

Eccentrotheca: “radially arranged adductor scars” – Bassett and Popov (2017), p1.

Eoobolus: Craniids scored as “open, quadripartite” by Williams *et al.* (1996).

Gasconsia: Following Williams *et al.* (1998), appendix 2.

Heliomedusa orientalis: Following the coding of Williams *et al.* (2000), table 15.

Kutorgina chengjiangensis: Following coding with state 0 (dispersed) in table 15 in Williams *et al.* (2000).

Longtancunella chengjiangensis: Scored as “dispersed” by Williams *et al.* (1998) ... but then so is *Kutorgina*, which Bassett *et al.* (2001) score as radial.

Williams *et al.* (2000) state, for superfamily Protorthida, “dorsal adductor scars probably linear”, which fits in the category of “radial” employed herein – so that’s what we follow.

Micrina: Distinct anterior and posterior fields (Chen *et al.*, 2007); coded as “dispersed” by Williams *et al.* (2000) in table 15.

Novocrania: Separate left and right fields, so radially arranged – following the interpretation of the musculature presented by Williams *et al.* (2000), fig. 81.

Paterimitra: Williams *et al.* (1998) code as “dispersed”, but have a less divided scheme of character states and disagree with other sources in some codings (e.g. Bassett *et al.*, 2001, in Kutorginates). Williams *et al.* (2000) do not describe *Micromitra* musculature and we were unable to find any reliable description of the scars, so we code as “not presently available”.

Salanygolina: Scars absent; instead, cones ornament shell’s internal surface.

Serpula: Discinids scored as “open, quadripartite” by Williams *et al.* (1996).

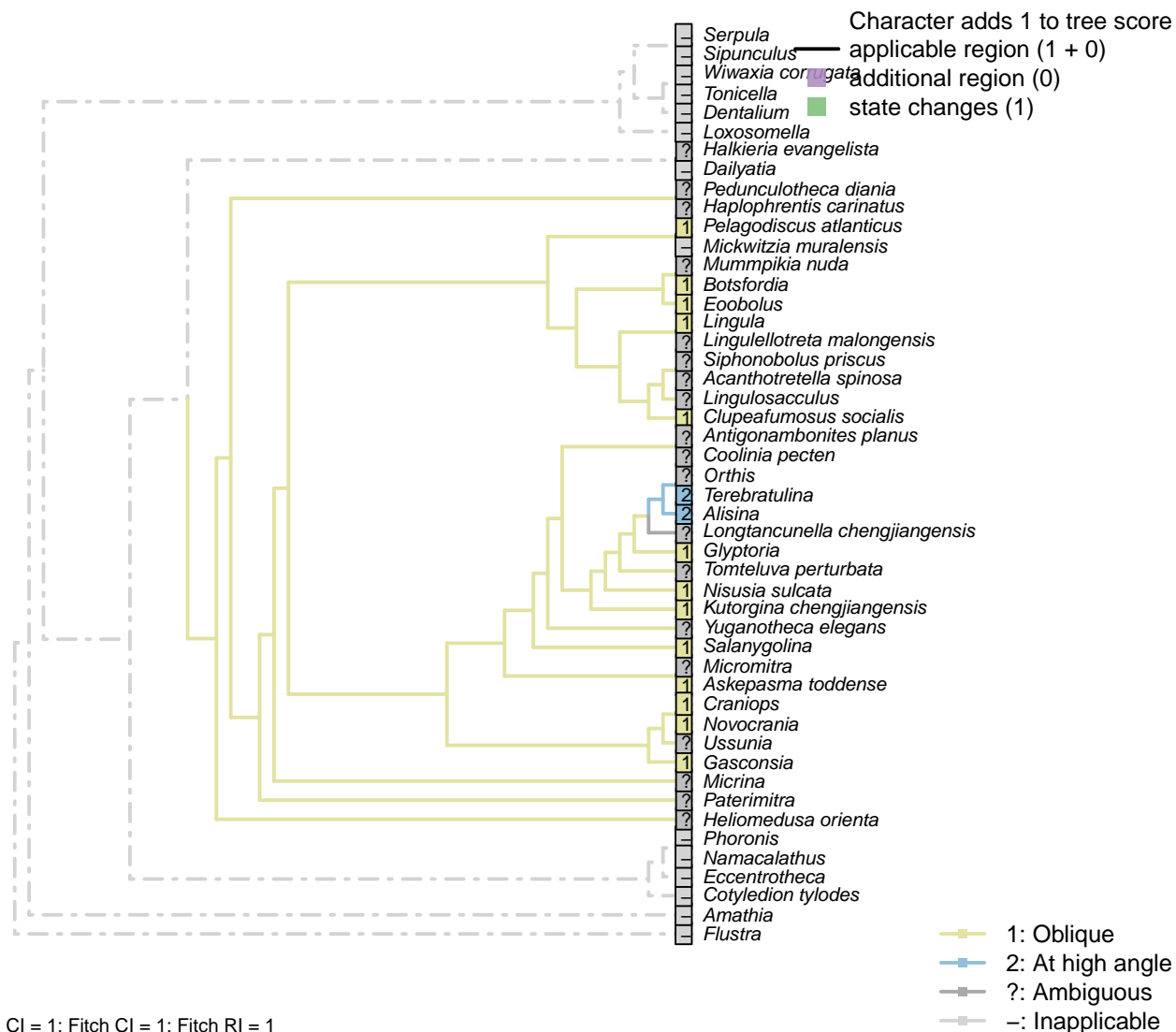
Tonicella: Coded as “grouped, quadripartite” by Williams *et al.* (1996).

Ussunia: Following reconstruction of *Hadrotreta* by Williams (2000), fig. 51, which exhibits distinct left and right fields.

NA: “The dorsal valve of *Salanygolina* has a radial arrangement of adductor muscle scars and the scars of posteromedially placed internal oblique muscles, which are also characteristic of paterinates and chileates” – Holmer *et al.* (2009).

NA: Ventral musculature poorly constrained (Williams *et al.*, 2000; Popov *et al.*, 2009).

[77] Muscle scars: Adductors: Position

**Character 77: Sclerites: Bivalved: Muscle scars: Adductors: Position**

1: Oblique

2: At high angle

Transformational character.

Position of adductor muscles relative to commissural plane.

After Bassett *et al.* (2001) character 11.*Eccentrotheca*: Not reported by Williams *et al.* (2000), nor Bassett & Popov (2017), nor explicitly by Dewing (2001).*Gasconsia*: Following description of Popov (1992).*Heliomedusa orienta*: See discussion under Trimerellida in Williams *et al.* (2000).*Lingulellotreta malongensis*: “*Eoobolus* should have anterior and posterior adductors and a variety of oblique

muscles which were probably arranged in criss-crossing pairs” – Balthasar (2009).

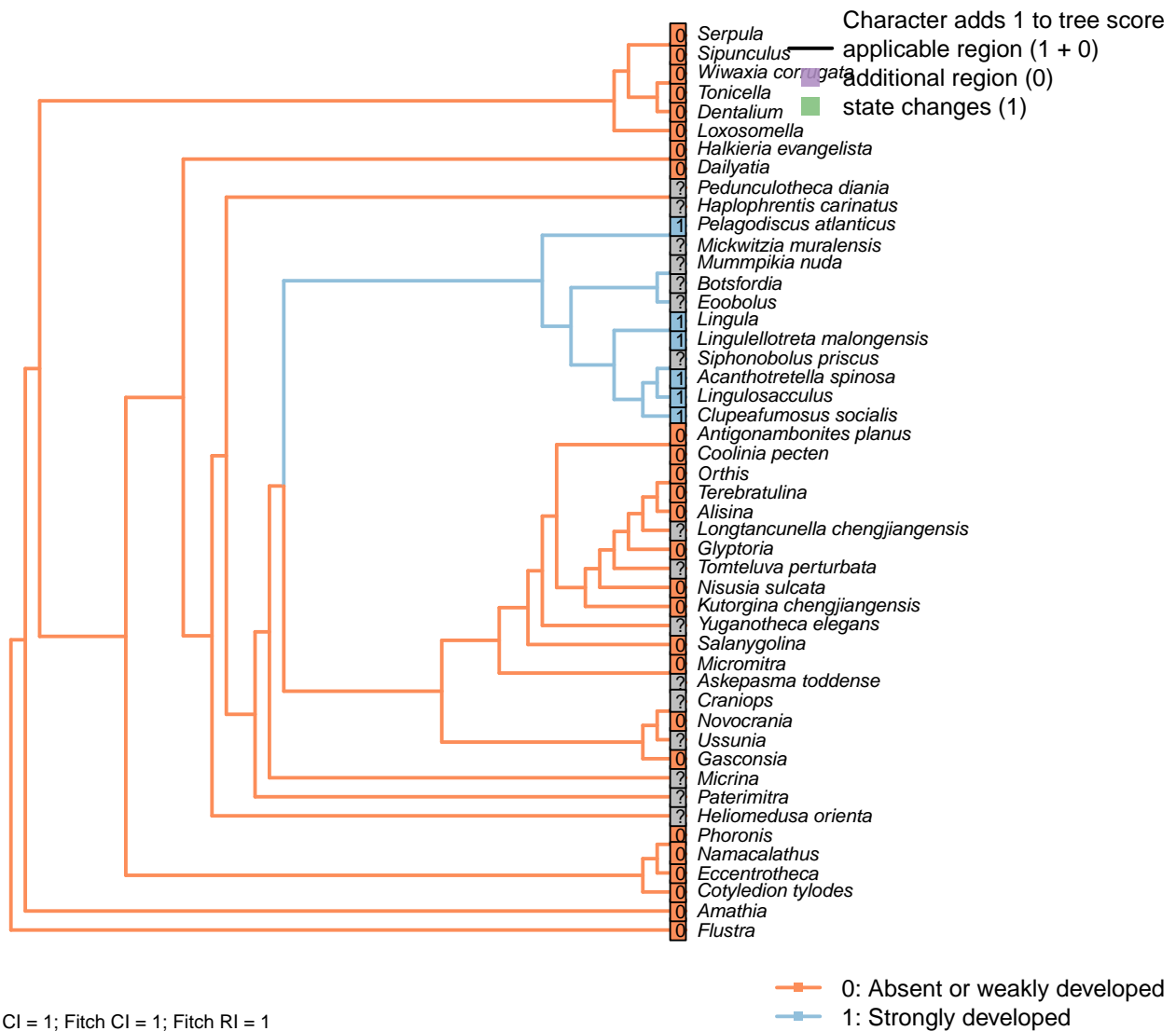
Novocrania: Following the interpretation of the musculature presented by Williams *et al.* (2000), fig. 81.

Salanygolina: Scars absent; instead, cones ornament shell's internal surface.

Serpula: Musculature considered essentially equivalent to *Lingula* by Williams *et al.* (2000), so *Lingula* coding followed here.

NA: Ventral musculature poorly constrained (Williams *et al.*, 2000; Popov *et al.*, 2009).

[78] Muscle scars: Dermal muscles



Character 78: Sclerites: Bivalved: Muscle scars: Dermal muscles

0: Absent or weakly developed

1: Strongly developed

Neomorphic character.

Based on character 11 in Zhang *et al.* (2014).

Well developed dermal muscles present in the body wall of recent lingulates, which are absent in all calcareous-

shelled brachiopods. These muscles are responsible for the hydraulic shell-opening mechanism, and possibly present in all organophosphatic-shelled brachiopods, with the possible exception of the paterinates (Williams et al., 2000, p. 32).

Coolinia pecten, *Craniops*, *Heliomedusa orientalis*, *Longtancunella chengjiangensis*, *Tomteluva perturbata*, *Yuganotheca elegans*, NA: According to the statement of Williams et al. (2000, p. 32) that these muscle are absent in all carbonate-shelled brachiopods.

Eccentrotheca: According to the statement of Williams et al. (2000, p. 32) that these muscle are absent in all carbonate-shelled brachiopods.

Eoobolus: Following Zhang et al. (2014), and the statement of Williams et al. (2000) that such muscles are absent in all calcite-shelled brachiopods.

Gasconsia: Implicitly taken as present in Popov (1992), though not marked in diagrams – suggesting not strongly developed.

Lingulellotretra malongensis: Not remarked upon by Balthasar (2009).

Micromitra: According to the statement of Williams et al. (2000, p. 32) that these muscle are absent in all carbonate-shelled brachiopods, and the coding for kutorginids in Zhang et al. (2014).

Novocrania: According to the statement of Williams et al. (2000, p. 32) that the presence of these muscles in paterinates is uncertain.

Paterimitra: Williams et al. (2000, p. 32) are uncertain about the presence of these muscles in the paterinates. Zhang et al. (2014) code absence in Paterinida, but without specifying evidence; we follow their coding here.

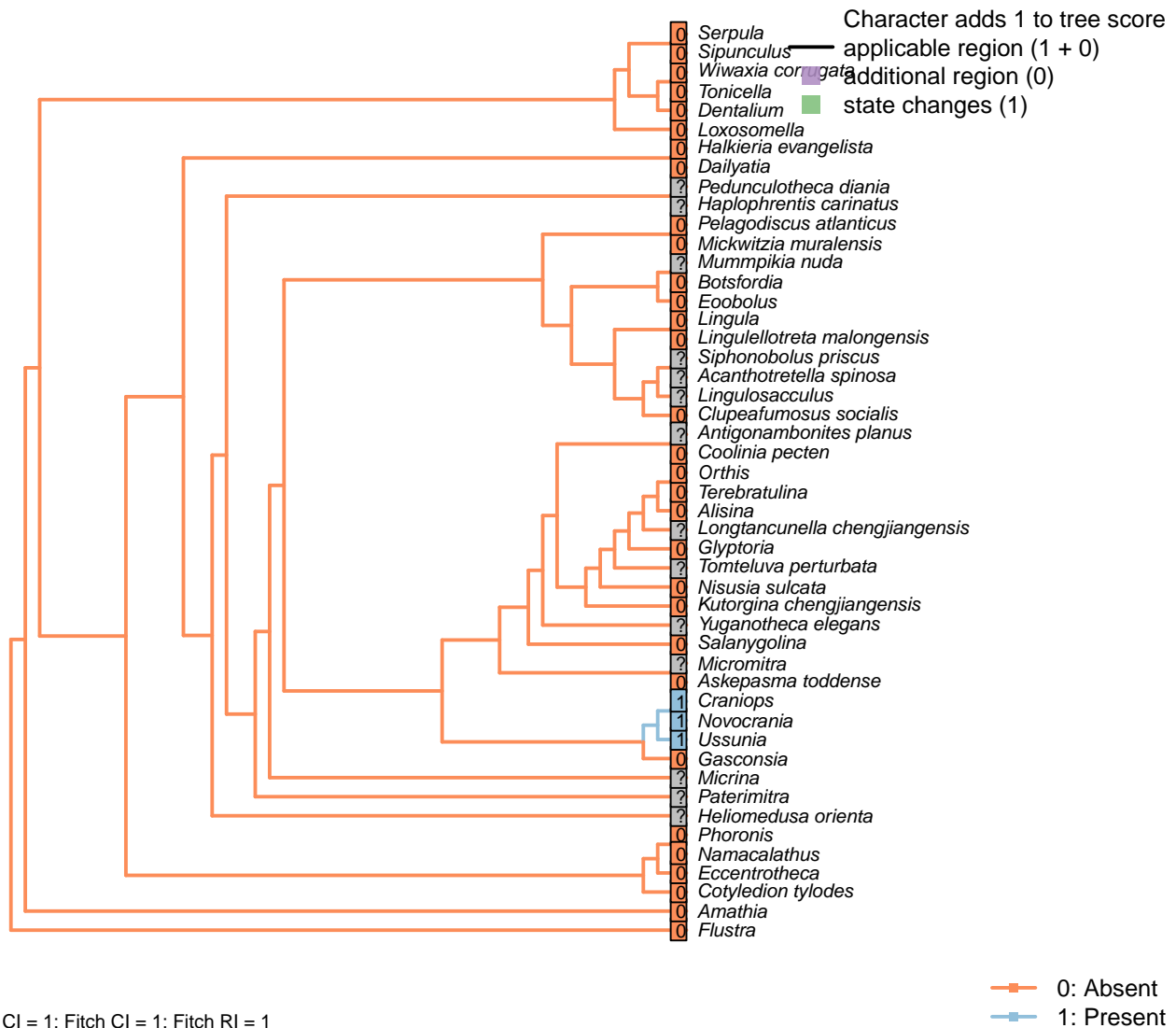
Serpula: Musculature considered essentially equivalent to *Lingula* by Williams et al. (2000), so *Lingula* coding followed here.

Siphonobolus priscus, NA: Though Williams et al. (2000, p. 32) state that these muscles are absent in all carbonate-shelled brachiopods, their existence cannot be discounted with certainty in this taxon, which is therefore coded not presently available.

Tonicella: Williams et al. (2000, p. 32) state that these muscles are absent in all carbonate-shelled brachiopods.

Ussunia: This character is coded based on the score of Acrotreta in Zhang et al. (2014), and statement in Williams et al. (2000, P.32).

NA: Ventral musculature poorly constrained (Williams et al., 2000; Popov et al., 2009).

[79] Muscle scars: Unpaired median (*levator ani*)**Character 79: Sclerites: Bivalved: Muscle scars: Unpaired median (*levator ani*)**

0: Absent

1: Present

Neomorphic character.

The *levator ani* is a diminutive unpaired medial muscle found in certain calcitic brachiopods [Williams et al. (2000); see fig. 89, character 34 in table 13].

Coolinia pecten, *Micromitra*, *Tomteluva perturbata*: Following table 13 in Williams et al. (2000).

Eccentrotheca: Not reported in Dewing (2001).

Eoobolus: Following table 13 in Williams et al. (2000) (for *Novocrania*).

Glyptoria: See fig. 90 in Williams et al. (2000).

Heliomedusa orientalis: Williams et al. (2000) code an unpaired medial muscle scar as present in their table 13, but give no reference for this coding, which perhaps arises from their interpretation of the taxon as a

trimerellid. Hanken and Harper (1985, p. 249 and text-fig. 2) explicitly identify a pair of central muscles, so we code a *levator ani* as absent.

Kutorgina chengjiangensis: Following table 15 in Williams et al. (2000).

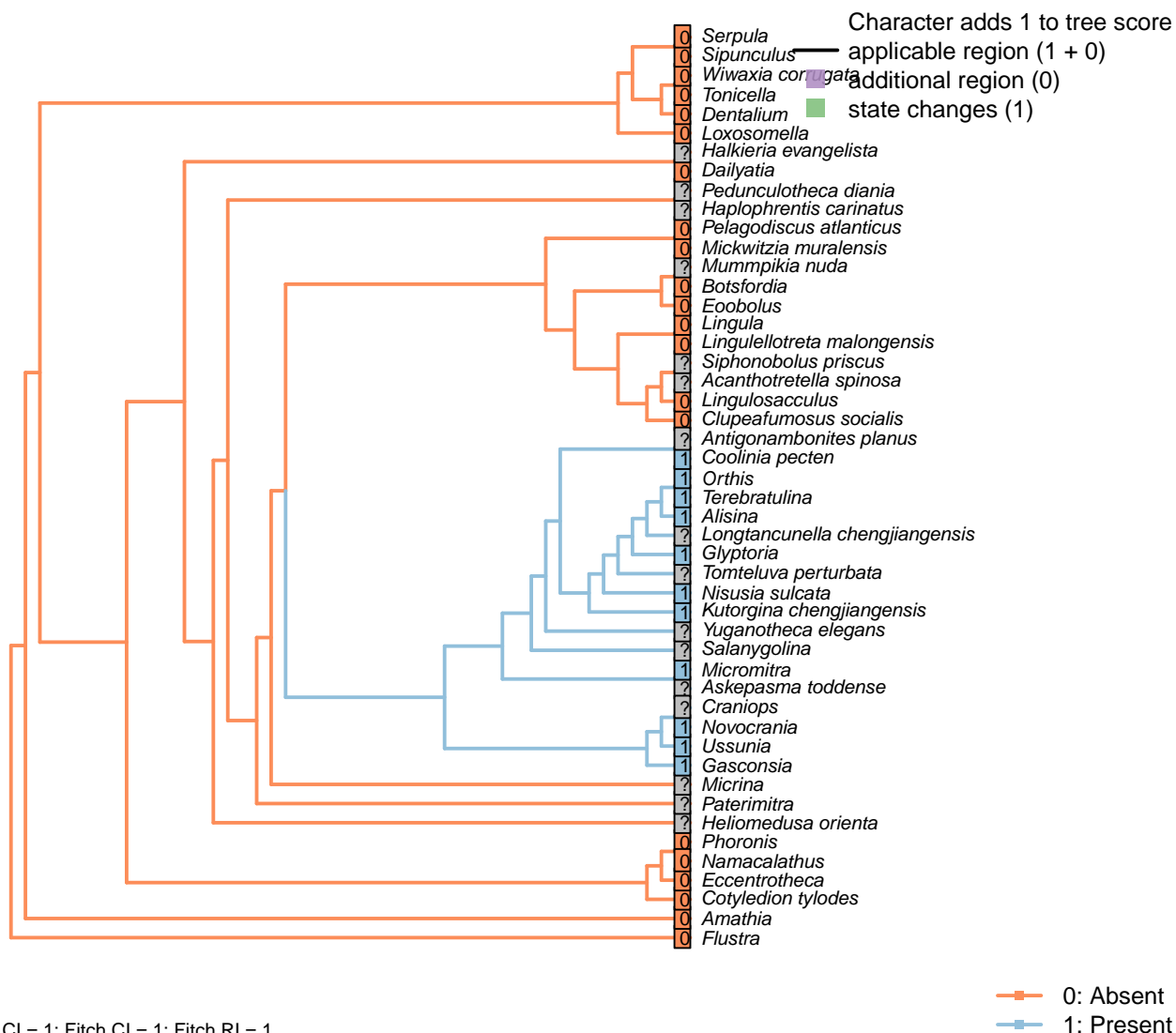
Micrina: Poor preservation of minor muscle scars noted by Chen *et al.* (2007).

Salanygolina: Scars absent; instead, cones ornament shell's internal surface.

Serpula: Musculature considered essentially equivalent to *Lingula* by Williams et al. (2000), so *Lingula* coding followed here.

NA: Ventral musculature poorly constrained (Williams et al., 2000; Popov et al., 2009).

[80] Muscle scars: Dorsal diductor



Character 80: Sclerites: Bivalved: Muscle scars: Dorsal diductor

0: Absent

1: Present

Neomorphic character.

After Bassett *et al.* (2001) character 9.

Antigonambonites planus: It is unclear whether the paired muscle scars of *Oikozetetes* are homologous to brachiopod diductors.

Clupeafumosus socialis: Not observable in *Acanthotretella* itself, so coded as ambiguous – though it is likely based on the anticipated phylogenetic affinities of *Acanthotretella* that the muscles are absent.

Heliomedusa orientalis: Internal oblique muscles serve as diductors.

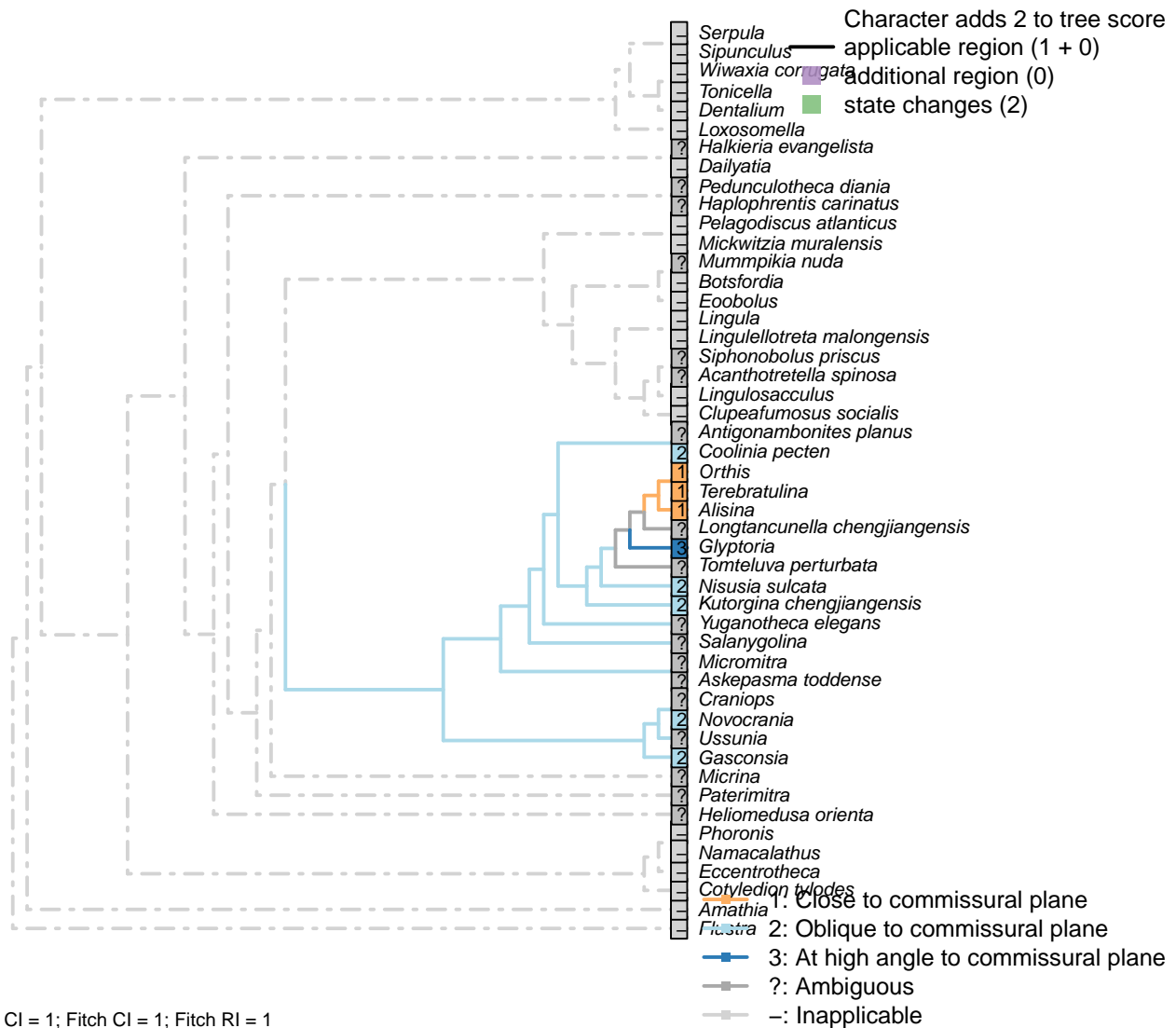
Kutorgina chengjiangensis: Internal oblique muscles present (Nikitin and Popov, 1984) and taken to serve as diductors by analogy with *Gasconsia*.

Novocrania: Not reconstructed in the the interpretation of the musculature presented by Williams *et al.* (2000), fig. 81, but presence cannot be confidently excluded.

Ussunia: Not reported by Topper *et al.* (2013a), nor reconstructed in generic acrotretid by Williams *et al.* (2000).

NA: Ventral musculature poorly constrained (Williams *et al.*, 2000; Popov *et al.*, 2009).

[81] Muscle scars: Dorsal diductor: Position

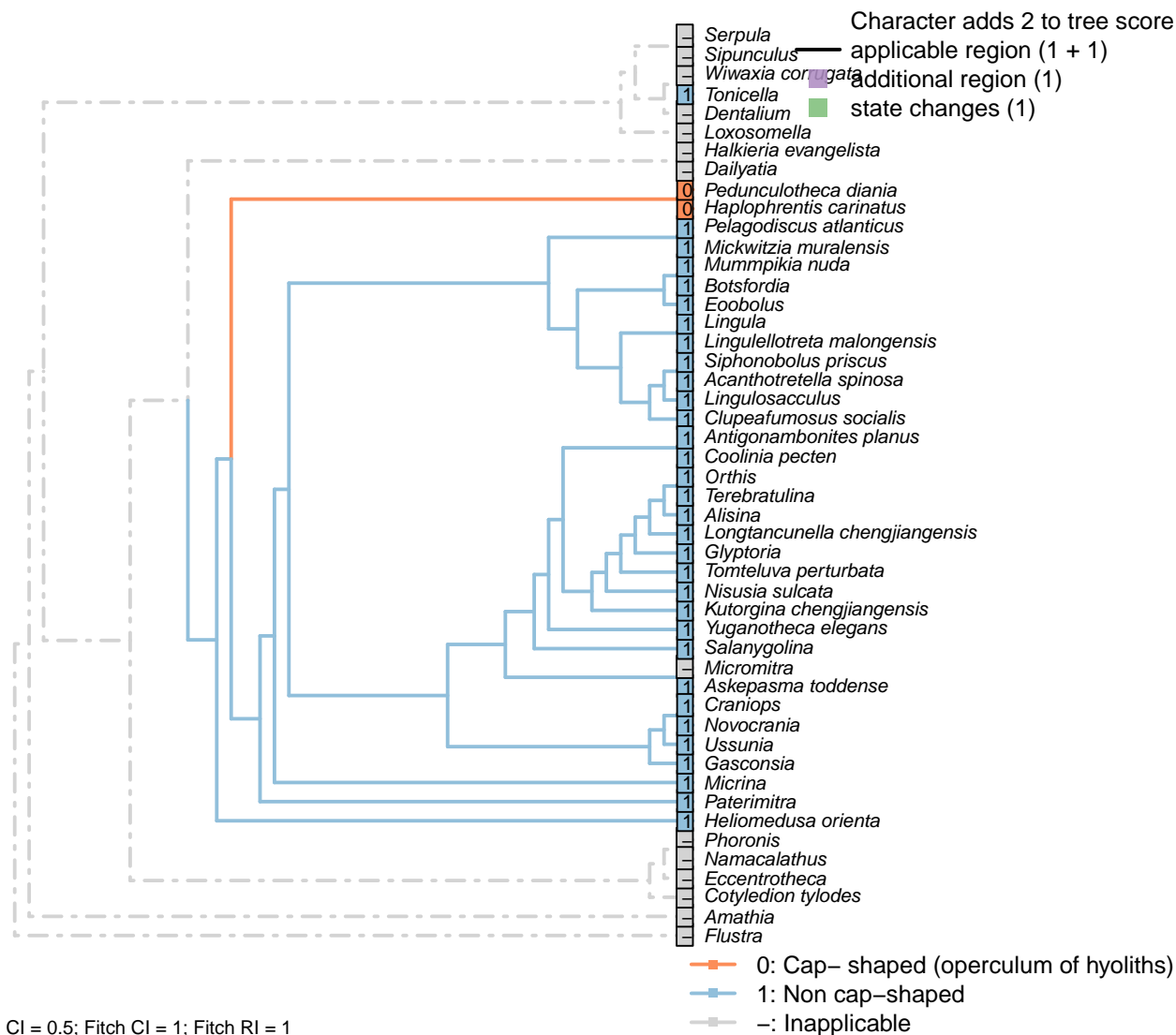


After Bassett *et al.* (2001) character 10.

NA: Ventral musculature poorly constrained (Williams *et al.*, 2000; Popov *et al.*, 2009).

3.18 Sclerite: Dorsal valve

[82] Morphology



Character 82: Sclerite: Dorsal valve: Morphology

0: Cap- shaped (operculum of hyoliths)

1: Non cap-shaped

Neomorphic character.

[NOTE: It is not clear why the shells of brachiopods, *Halkieria* etc are not scored as cap-shaped, nor why *Micromitra* is coded as inapplicable. Many other characters already exist that reflect the morphology of the dorsal valve; is this character independent? How can it be scored objectively?].

Oh dear! **You included the inapplicable token in a neomorphic character!**

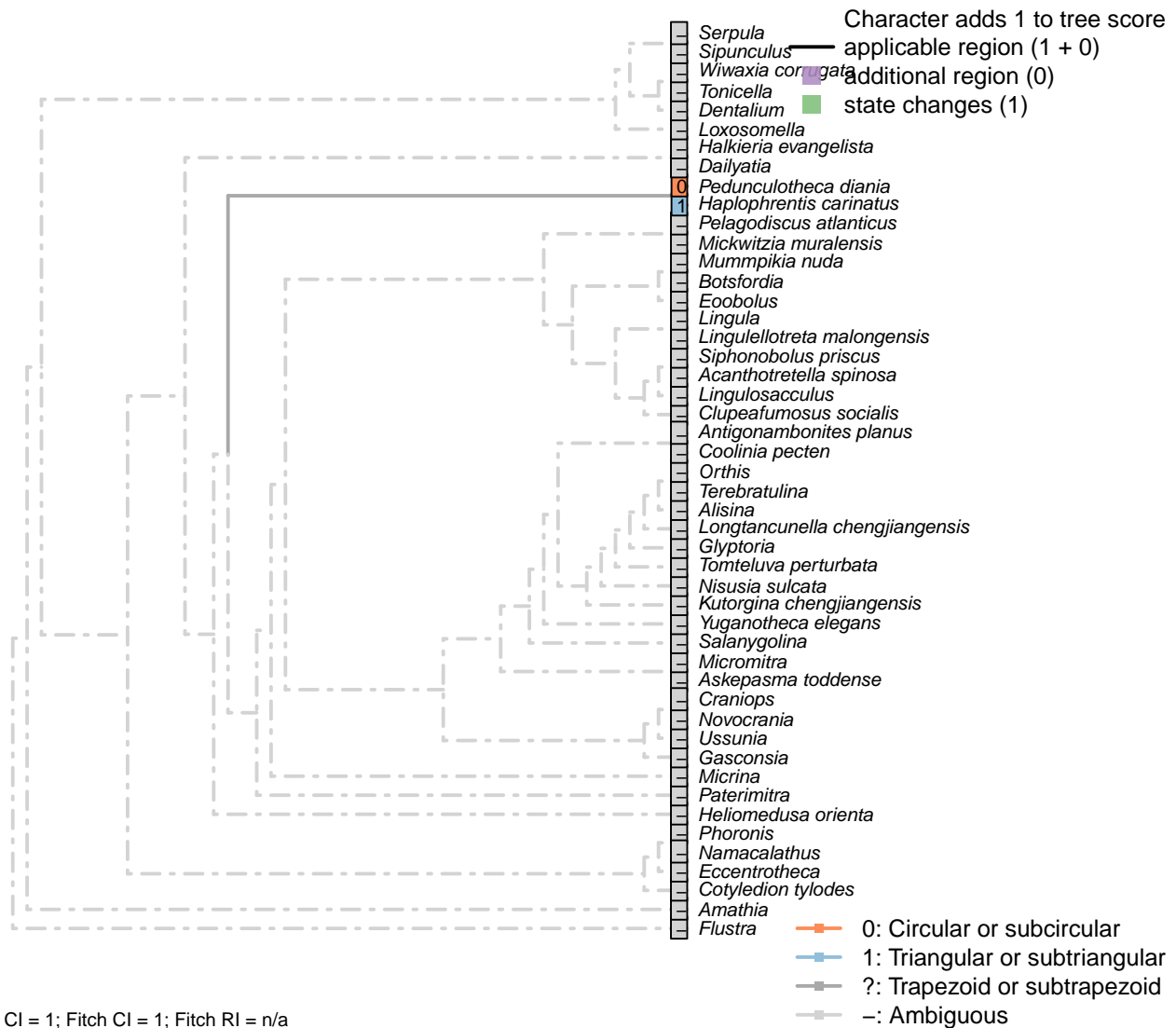
That's really very naughty, as Brazeau et al. (2018) will tell you.

Unless you are very sure that you understand the consequences, you should re-code

- Namacalathus

- Cotyledion_tyloides
- Loxosomella
- Flustra
- Amathia
- Phoronis
- Sipunculus
- Serpula
- Dentalium
- Wiwaxia_corrugata
- Halkieria_evangelista
- Dailyatia
- Eccentrotheca
- Micromitra

[83] Outline of cap-shaped shell

**Character 83: Sclerite: Dorsal valve: Outline of cap-shaped shell**

- 0: Circular or subcircular
 - 1: Triangular or subtriangular
 - 2: Trapezoid or subtrapezoid
- Neomorphic character.

[NOTE: This character seems not to be independent of other characters, for example, the shape of the hinge line and the growth of the shell. It is not clear why the character is inapplicable in non-hyolith taxa.].

Oh dear! **You included the inapplicable token in a neomorphic character!**

That's really very naughty, as Brazeau et al. (2018) will tell you.

Unless you are very sure that you understand the consequences, you should re-code

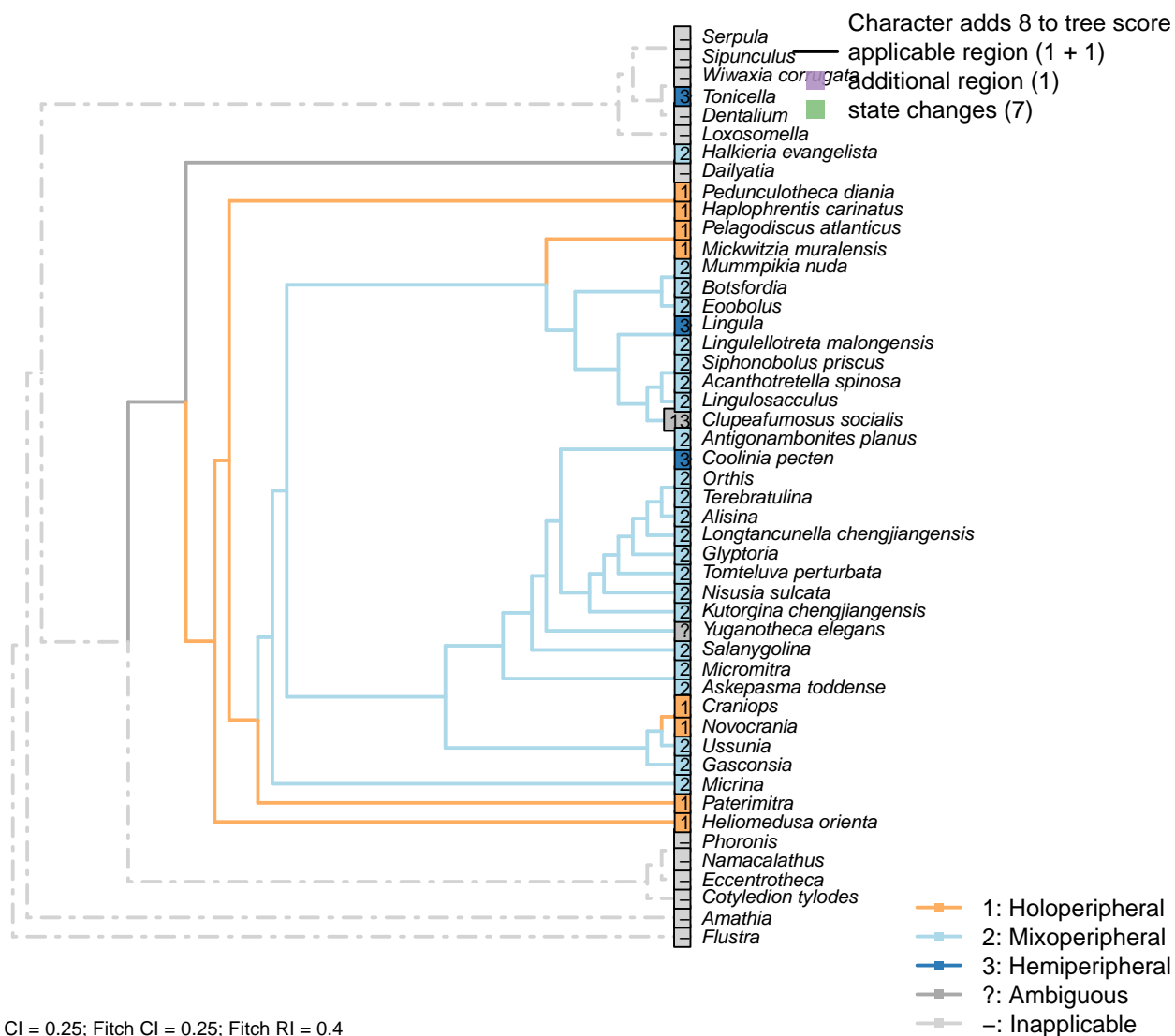
- Namacalathus
- Cotyledion_tylodes

- *Loxosomella*
- *Flustra*
- *Amathia*
- *Pelagodiscus_atlanticus*
- *Terebratulina*
- *Lingula*
- *Phoronis*
- *Sipunculus*
- *Serpula*
- *Tonicella*
- *Dentalium*
- *Wiwaxia_corrugata*
- *Halkieria_evangelista*
- *Dailyatia*
- *Acanthotretella_spinosa*
- *Alisina*
- *Askepasma_toddense*
- *Antigonambonites_planus*
- *Botsfordia*
- *Clupeafumosus_socialis*
- *Coolinia_pecten*
- *Novocrania*
- *Craniops*
- *Gasconsia*
- *Ussunia*
- *Eccentrotheca*
- *Eoobolus*

- Glyptoria
- Heliomedusa_orienta
- Kutorgina_chengjiangensis
- Lingulosacculus
- Lingulellotreta_malongensis
- Longtancunella_chengjiangensis
- Micrina
- Micromitra
- Mickwitzia_muralensis
- Mumpikia_nuda
- Nisusia_sulcata
- Orthis
- Paterimitra
- Salanygolina
- Siphonobolus_priscus
- Tomteluva_perturbata
- Yuganotheca_elegans

3.19 Sclerites: Dorsal valve

[84] Growth direction



Character 84: Sclerites: Dorsal valve: Growth direction

1: Holoperipheral

2: Mixoperipheral

3: Hemiperipheral

Transformational character.

See Fig. 284 in Williams *et al.* (1997).

The growth direction dictates the attitude of the cardinal area relative to the hinge, which does not therefore represent an independent character.

Crudely put, if, viewed from a dorsal position, the umbo falls within the outer margin of the shell, growth is holoperipheral; if it falls outside the margin, it is mixoperipheral; if it falls exactly on the margin, it is hemiperipheral.

Acanthotretella spinosa: For the purposes of this analysis, we must treat polyplacophoran and brachiopod

valves as potentially homologous.

In brachiopods, the dorsal valve bears the lophophore, which arises from the anterior lobe of the larva (Altenburger et al., 2013) – indicating that the dorsal shell field is associated with the anterior lobe.

In polyplacophorans, the head valve arises from a shell field on the anterior (pre-prototroch) lobe of the larva (Wanninger and Haszprunar, 2002a), which we therefore treat as homologous with the brachiopod dorsal valve.

In support of this hypothesis, we note that the posterior (but not anterior) valves of chitons bear apophyses (Schwabe, 2010; Connors et al., 2012), which are most prominent in the ventral (but not dorsal) valves of brachiopods (Williams et al., 1997, fig. 322), and which occur in the morph A shell of *Oikozetetes*, which is interpreted as the posterior valve of a halkieriid (Paterson et al., 2009).

As the single posterior shell field of polyplacophorans subdivides to give rise to the six intermediate valves plus the tail valve (Wanninger and Haszprunar, 2002a), we prefer to consider the intermediate valves as representing “subdivisions” of a single valve rather than additional valves added to the body plan.

Growth is hemiperipheral in the anterior valve of polyplacophorans and holoperipheral in the posterior valves (Schwabe, 2010; Connors et al., 2012).

Glyptoria: “Both valves with growth holoperipheral” – Williams et al. (2000), p. 164.

Kutorgina chengjiangensis: Growth “mixoperipheral in both valves” in trimerellids (Williams et al., 2000; Popov et al., 1997).

Micrina: “holoperipheral growth in dorsal valve” – Williams et al. (2007).

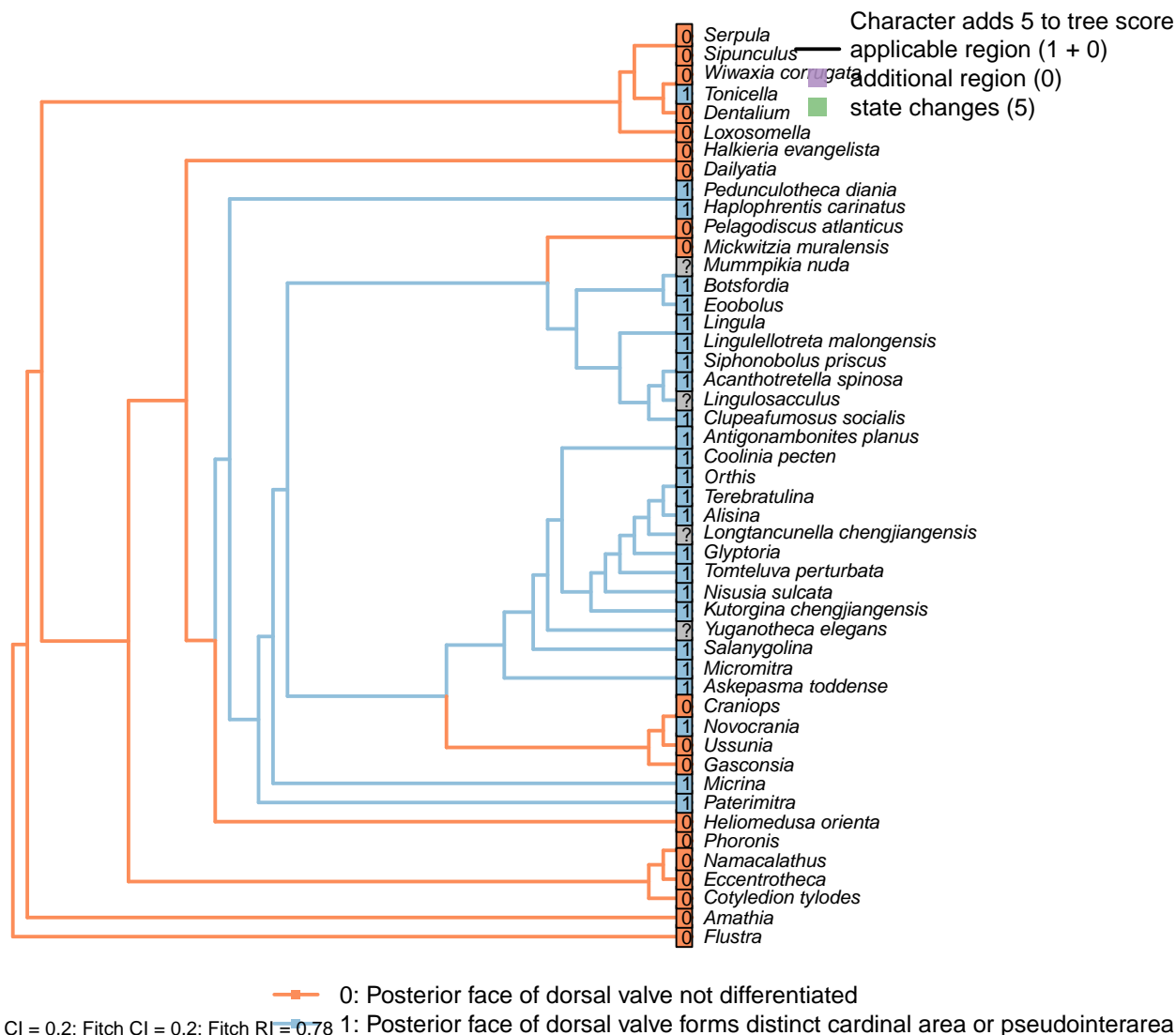
Zhang *et al.* (2009) conclude that Chen *et al.* (2007) misidentify the dorsal valve as the ventral valve.

Orthis: See Holmer *et al.* (2008).

Ussunia: Appears hemiperipheral in fig. 3 in Topper *et al.* (2013a), though bordering on holoperipheral, so scored as ambiguous.

NA: S2 and L sclerites are clearly holoperipheral. See Larsson et al. (2014), fig. 2.

[85] Posterior surface: Differentiated

**Character 85: Sclerites: Dorsal valve: Posterior surface: Differentiated**

0: Posterior face of dorsal valve not differentiated

1: Posterior face of dorsal valve forms distinct cardinal area or pseudointerarea

Neomorphic character.

In shells that grow by mixoperipheral growth, the triangular area subtended between each apex and the posterior ends of the lateral margins is termed the cardinal area. In shells with holoperipheral growth, a flattened surface on the posterior margin of the valve is termed a pseudointerarea (paraphrasing Williams et al., 1997).

In order for this character to be independent of a shell's growth direction, we do not distinguish between a "cardinal area", "interarea" or "pseudointerarea".

Acanthotretella spinosa: V-shaped notch in anterior valve (Schwabe, 2010).

Amathia: A very short pseudointerarea appears to be present (Moysiuk et al., 2017).

Clupeafumosus socialis: Pseudointerarea present, following Siphonotretidae coding in Williams et al. (2000),

table 6.

Coolinia pecten, *Craniops*, *Eccentrotheca*, *Longtancunella chengjiangensis*, *Micromitra*, *Yuganotheca elegans*, NA, NA: Cardinal area (interarea) present.

Dentalium, *Mummpikia nuda*: Pseudointerarea present, following Williams *et al.* (2000), table 6.

Eoobolus, *Pelagodiscus atlanticus*, NA: Pseudointerarea.

Gasconsia: “dorsal pseudointerarea vestigial, divided by median groove” – Williams *et al.* (2000).

Glyptoria: “Only some craniopsids (Lingulapholis, Pseudopholidops [not *Craniops*]) have well-developed pseudointerareas.” – Williams *et al.* (2000).

Heliomedusa orientalis: Absent: the dorsal (branchial) pseudointerarea of *G. schucherti* is “reduced or obsolete”; that of *G. worsleyi* “short, virtually obsolete” (Hanken and Harper, 1985).

Kutorgina chengjiangensis: Following table 15 in Williams *et al.* (2000).

Mickwitzia muralensis: Unclear from fossil material.

Micrina: Pseudointerarea in ventral valve, but not dorsal valve (Williams *et al.*, 2000, 2007).

Nisusia sulcata: Zhang *et al.* (2011a) note that “all evidence of a pseudointerarea is lacking”, but the two-dimensional preservation style of Chengjiang material makes details of dorsal valve difficult to distinguish, and the possibility of a diminutive pseudointerarea cannot be excluded with total confidence.

Novocrania: Well-defined pseudointerarea (Williams *et al.*, 2000, p153).

Orthis: = Sellate sclerite duplication (Holmer *et al.*, 2008).

Paterimitra: “Dorsal pseudointerarea usually well defined, low, anacline to catacline” – Williams *et al.* (2000).

Salanygolina: Shell flat.

Serpula: Absent, following entry for Discinidae in Williams *et al.* (2000), table 6.

Siphonobolus priscus: “Information on the dorsal interarea is inconclusive [...] no obvious interarea is recognisable; whether or not this is the primary state or a taphonomic artefact is difficult to assess” – Balthasar (2008), p. 276.

Tomteluva perturbata: Cardinal area (interarea) present – with reference to Holmer *et al.* (2018a).

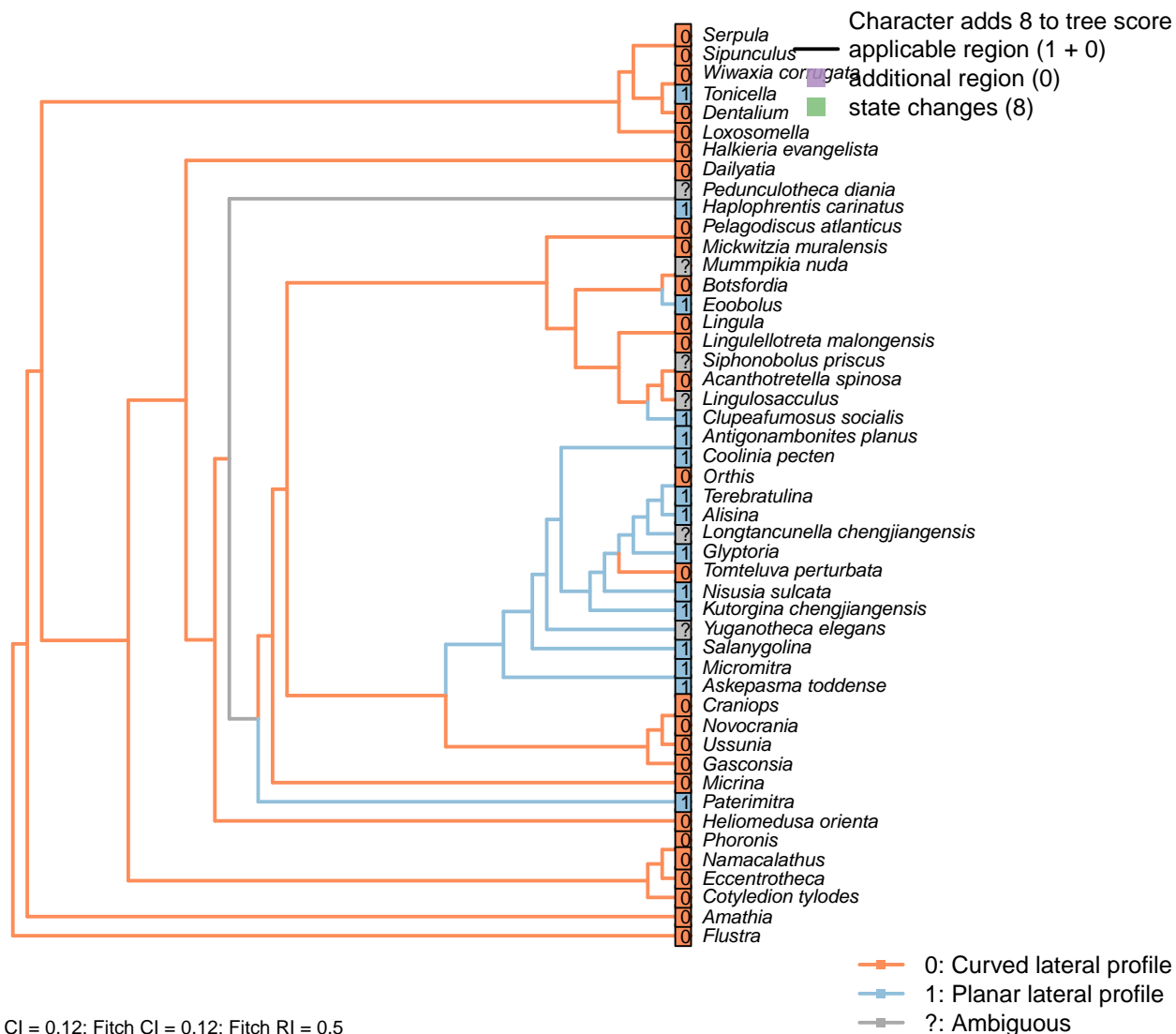
Tonicella: Interarea present.

Ussunia: Pseudointerarea present; figured by Topper *et al.* (2013a), fig. 3j.

NA: A differentiated region is not obvious in fossil material or its reconstruction (Zhang *et al.*, 2014), but the two-dimensional preservation style of Chengjiang material makes details of dorsal valve difficult to distinguish, and the possibility of a diminutive pseudointerarea cannot be excluded with confidence.

NA: “Dorsal pseudointerarea weakly anacline, undivided, elevated above the valve floor” – Popov *et al.* (2009).

[86] Differentiated posterior surface: Morphology

**Character 86: Sclerites: Dorsal valve: Differentiated posterior surface: Morphology**

0: Curved lateral profile

1: Planar lateral profile

Neomorphic character.

It is possible for a cardinal area or pseudointerarea to be distinct from the anterior part of the shell, yet to remain curved in lateral profile.

Taking an undifferentiated posterior margin as primitive, the primitive condition is curved – flattening of the posterior margin represents an additional modification that can only occur once the posterior margin is differentiated.

Acanthotretella spinosa: Essentially planar, though open in aspect (following Chiton in Schwabe, 2010).

Gasconsia: “Curved pseudointerarea” – Skovsted et al. (2017).

Heliomedusa orientalis, *Kutorgina chengjiangensis*, *Micrina*, *Salanygolina*, *Serpula*: Posterior surface cannot

be flat if it is not differentiated.

Lingulellotreta malongensis: Essentially planar; see Balthasar (2009), fig. 4a.

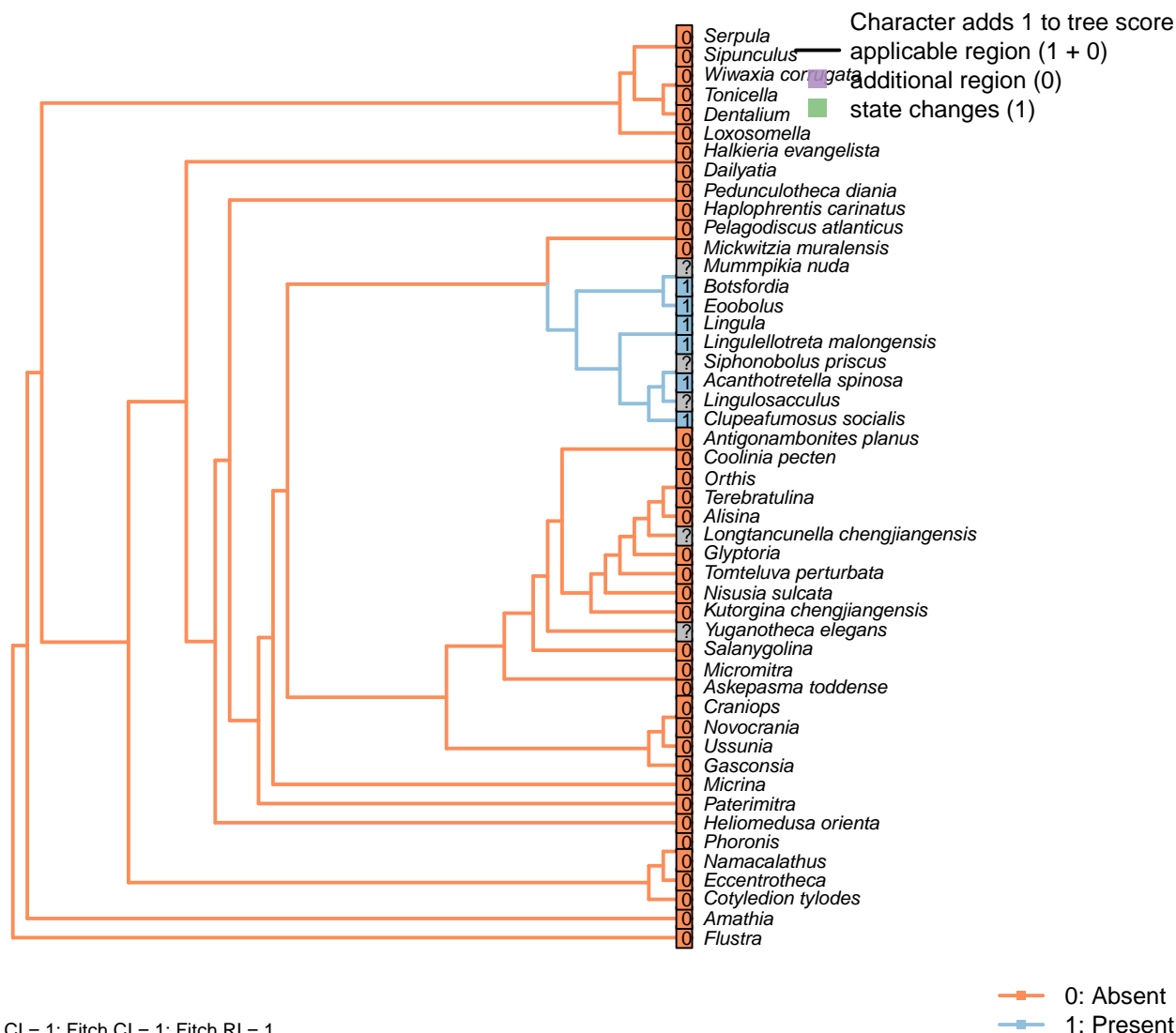
Paterimitra: Essentially straight; see fig. 3.7 in Ushatinskaya (2016).

Pelagodiscus atlanticus: Difficult to evaluate based on present material, given low nature of valve and compressed preservation.

Ussunia: Truncated but essentially planar surface; see e.g. p196 of Topper et al. (2013a).

NA: The short interarea appears planar (see for example Popov et al. 2009 fig. 6A), but its short length makes it difficult to establish whether slight curvature is present.

[87] Posterior surface: Medial groove



Character 87: Sclerites: Dorsal valve: Posterior surface: Medial groove

0: Absent

1: Present

Neomorphic character.

Following character 29 in Williams *et al.* (2000), table 9 (which relates to pseudointerarea).

Clupeafumusus socialis: The dorsal pseudointerarea is poorly preserved, but appears to have a median groove (Holmer and Caron, 2006).

Gasconsia: “dorsal pseudointerarea vestigial, divided by median groove” – Williams *et al.* (2000).

Lingulellotrete malongensis: Prominent medial groove (Balthasar, 2009).

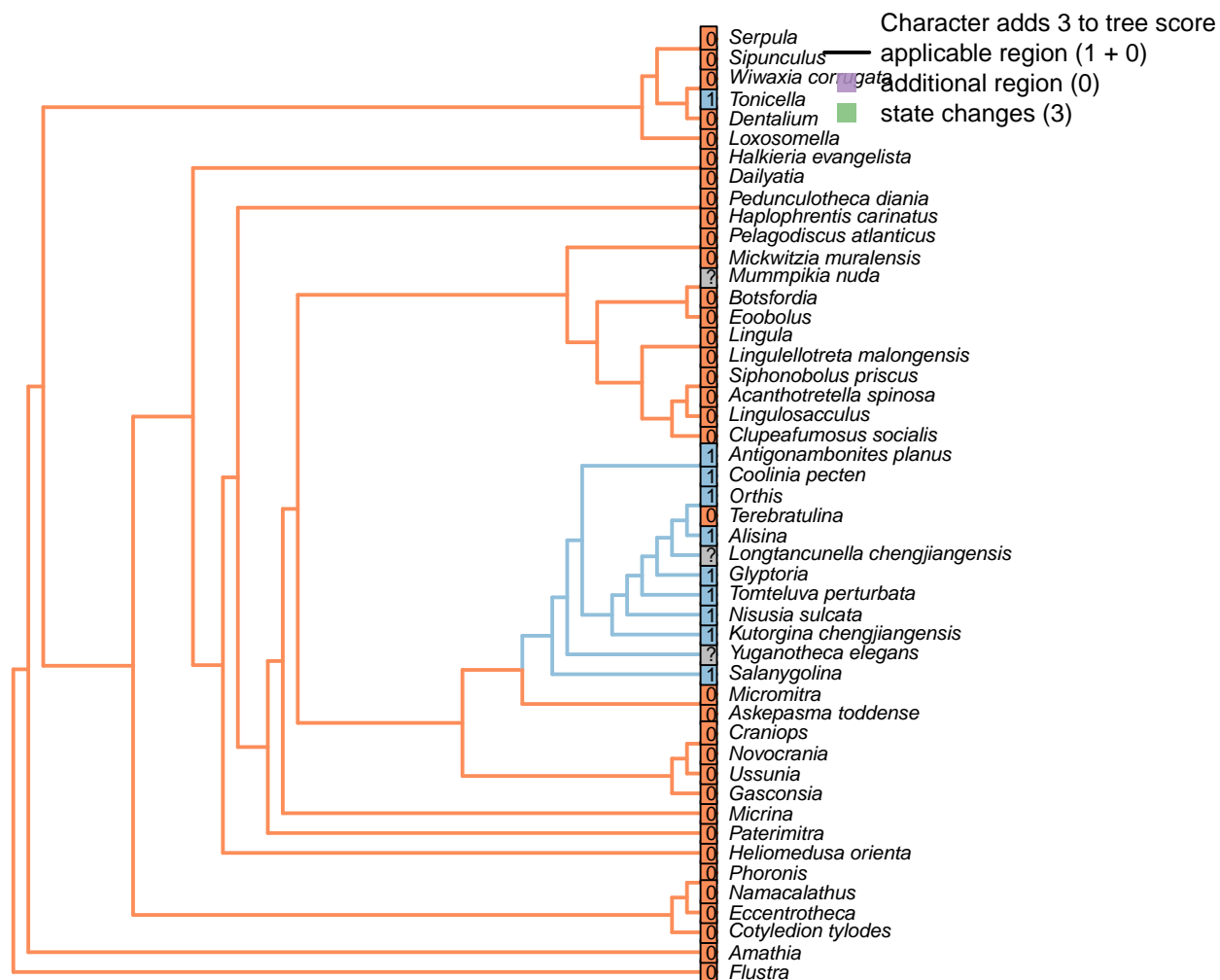
Micrina: “A posteriorly protruding dorsal pseudointerarea with no median groove and no flexure lines” – Chen *et al.* (2007).

Mummpikia nuda: Dorsal pseudointerarea with wide, concave median groove and short propareas” – Williams *et al.* (2000).

Ussunia: Present; figured by Topper *et al.* (2013a), fig. 3j.

NA: The dorsal pseudointerarea of *S. priscus* is undivided (Popov *et al.*, 2009), but in other species it is divided by a “wide, poorly defined median groove” (Williams *et al.*, 2000). Coded, therefore, as polymorphic.

[88] Posterior surface: Notothyrium



CI = 0.33; Fitch CI = 0.33; Fitch RI = 0.78

Character 88: Sclerites: Dorsal valve: Posterior surface: Notothyrium

0: Absent

1: Present

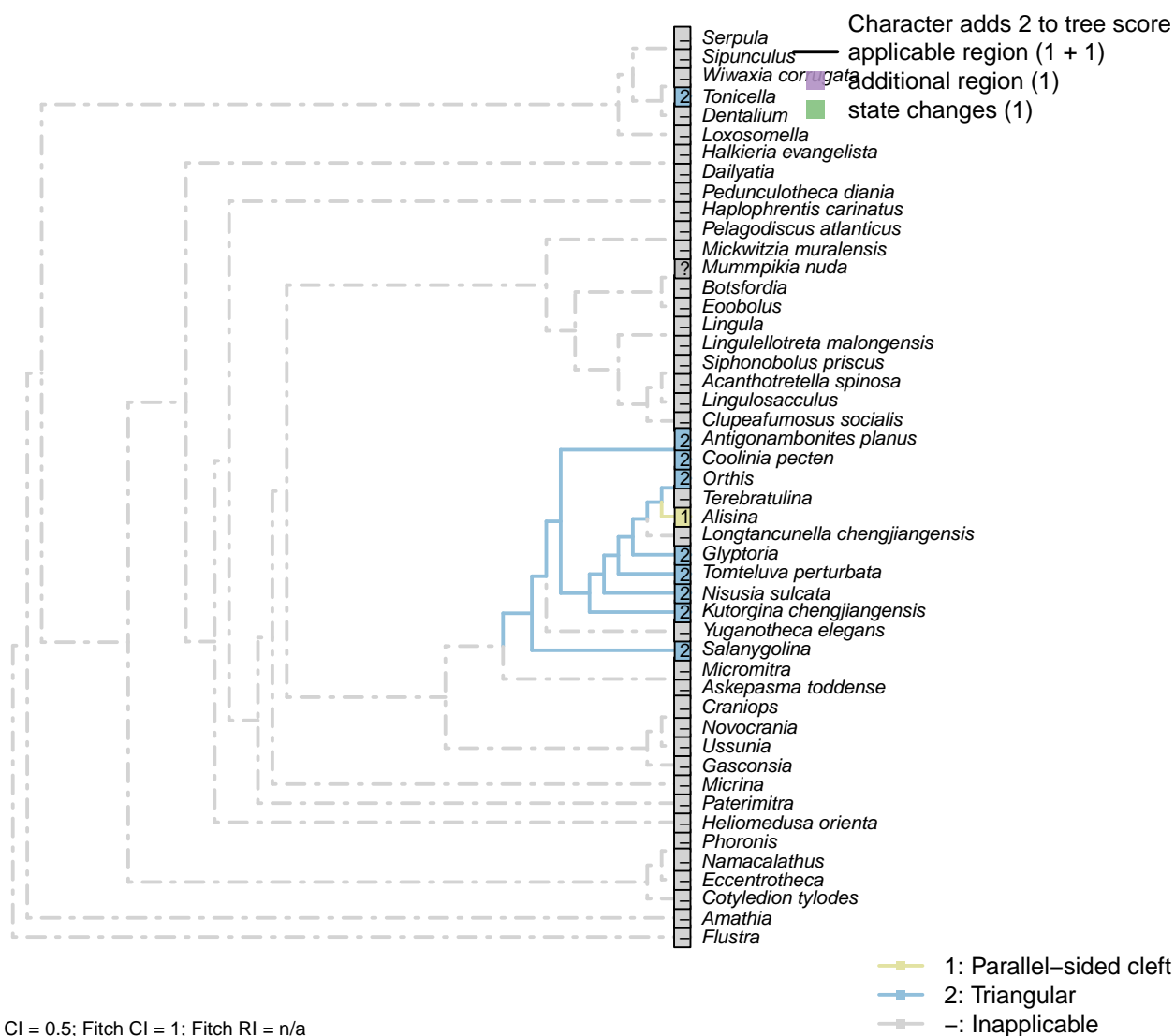
Neomorphic character.

A notothyrium is an opening in an interarea that accommodates the pedicle, and may be filled with plates.

Acanthotretella spinosa: The deep V-shaped notch (Schwabe, 2010, fig. 8) is positionally equivalent to the brachiopod notothyrium.

Gasconsia: Following Williams et al. (1998), appendix 2.

Nisusia sulcata: No evidence or report of an opening at the hinge line in fossil material in Zhang et al. (2007c) or Zhang et al. (2011a).

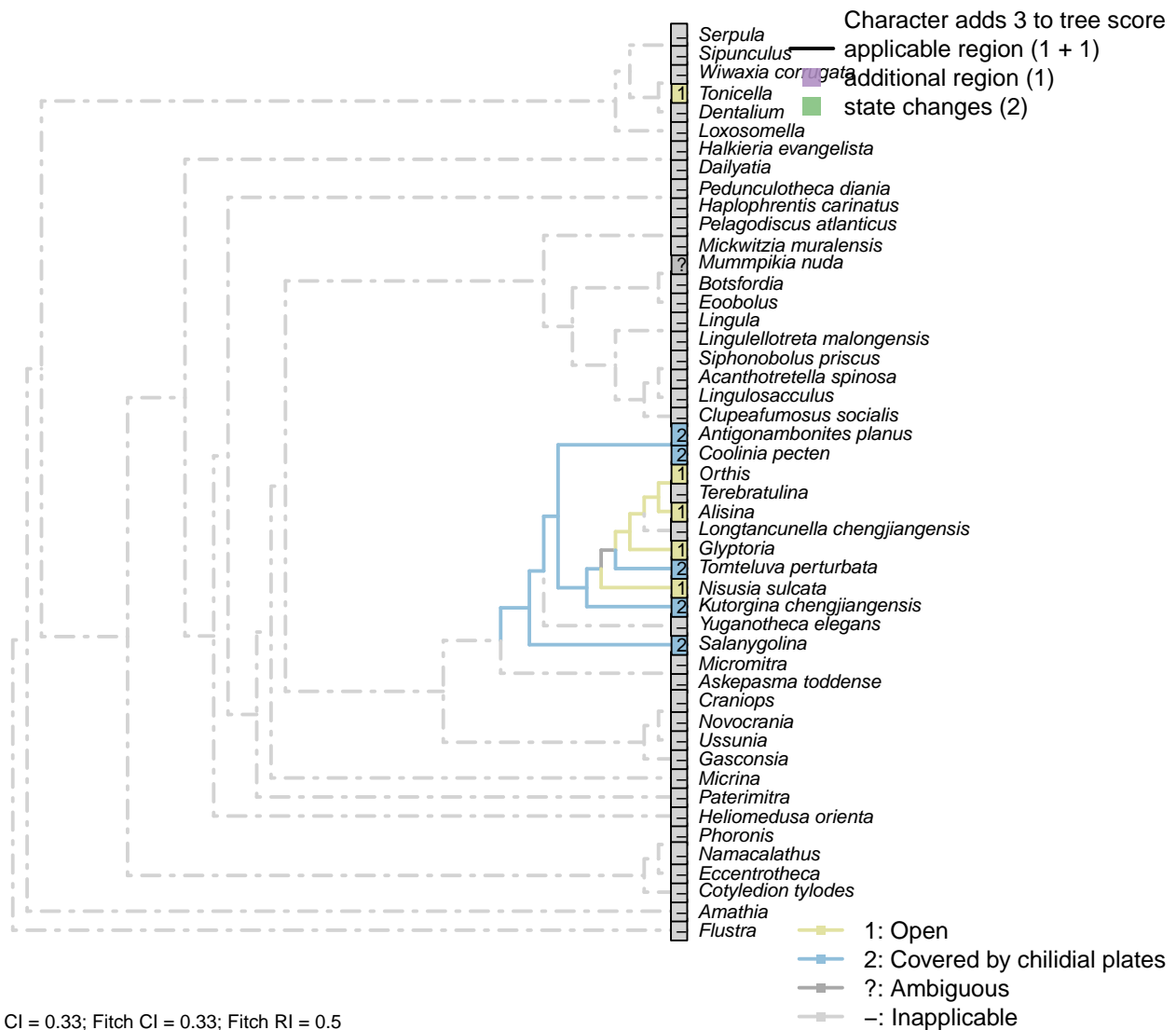
[89] Posterior surface: Notothyrium: Shape

- 1: Parallel-sided cleft
- 2: Triangular
- Transformational character.

A notothyrium is an opening in an interarea that accommodates the pedicle, and may be filled with plates.

A simplification of character 5 in Bassett et al. (2001).

[90] Posterior surface: Notothyrium: Chilidial plates



Character 90: Sclerites: Dorsal valve: Posterior surface: Notothyrium: Chilidial plates

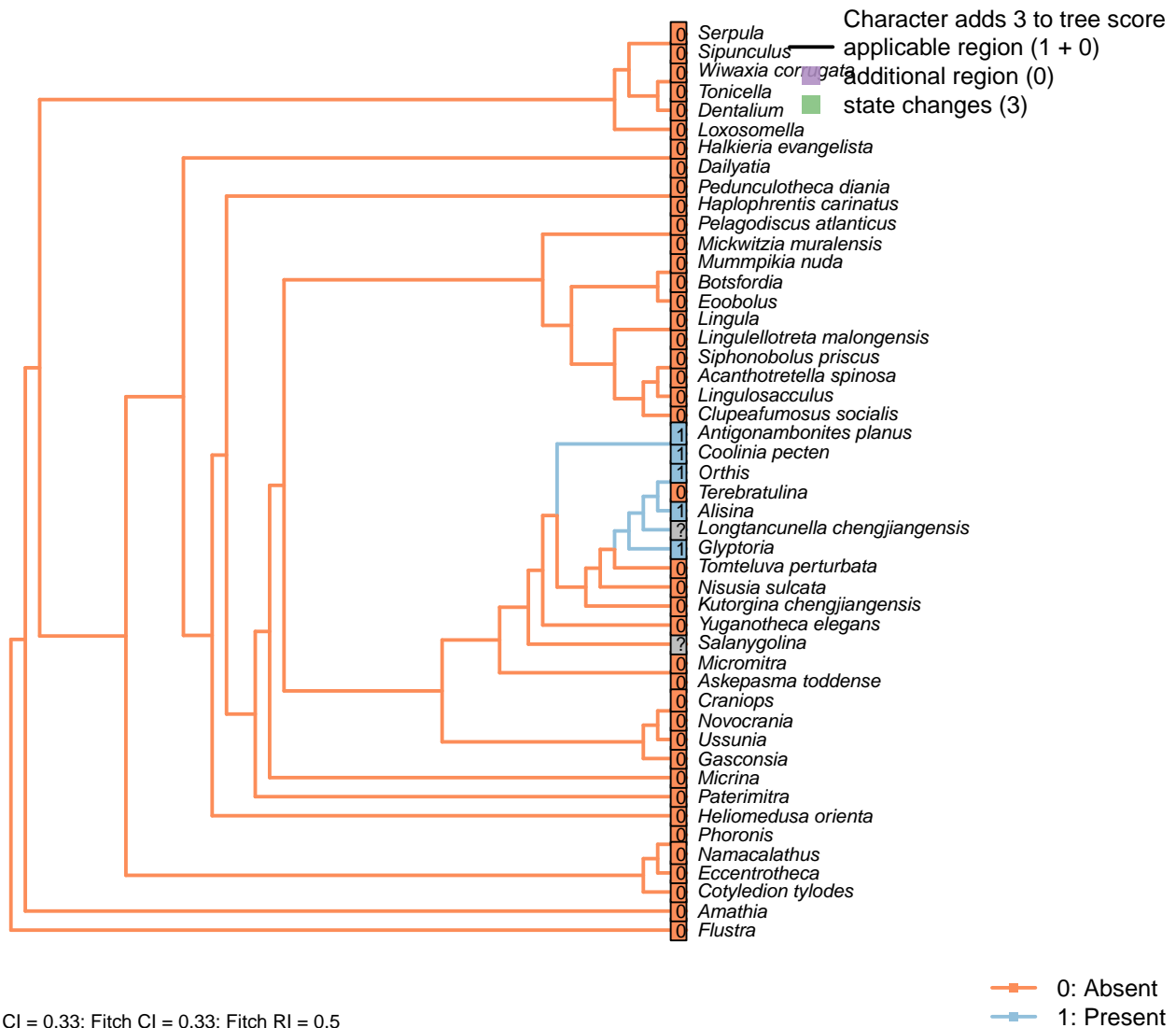
- 1: Open
- 2: Covered by chilidial plates
- Transformational character.

A notothyrium may be open or covered by a chilidium or two chilidial plates.

No included taxa exhibit more than one chilidial plate.

Transformational as it is not self-evident whether the ancestral taxon had an open or closed notothyrium.

[91] Notothyrial platform

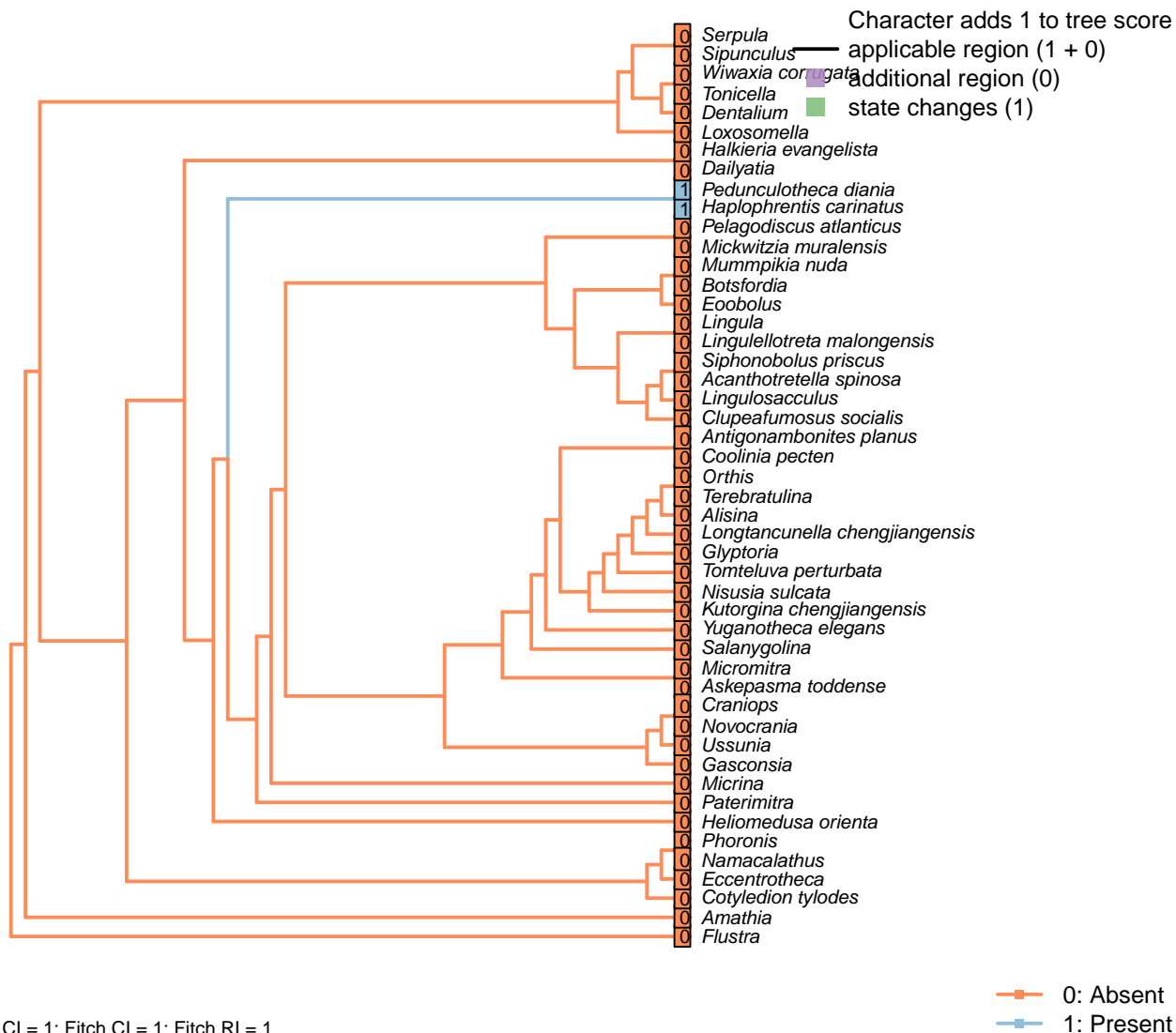


Bassett *et al.* (2001) score as absent in Table 18.1.

Tomteluva perturbata: Bassett *et al.* (2001) score as absent in Table 18.1.

“Dorsal diductor scars impressed on floor of notothyrial cavity”: Williams *et al.* (2000), regarding Kutztorginata.

[92] Cardinal shield



Character 92: Sclerites: Dorsal valve: Cardinal shield

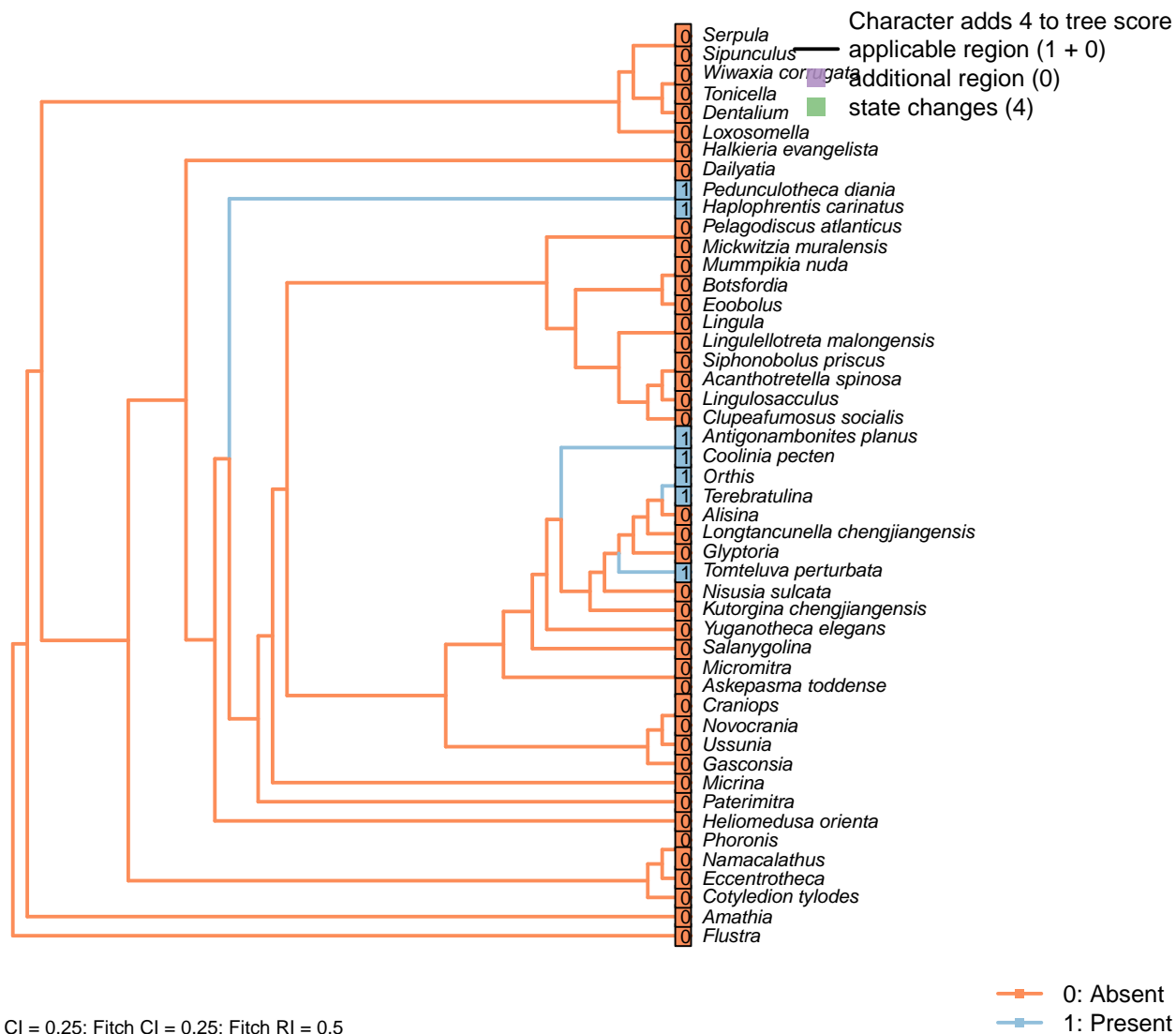
0: Absent

1: Present

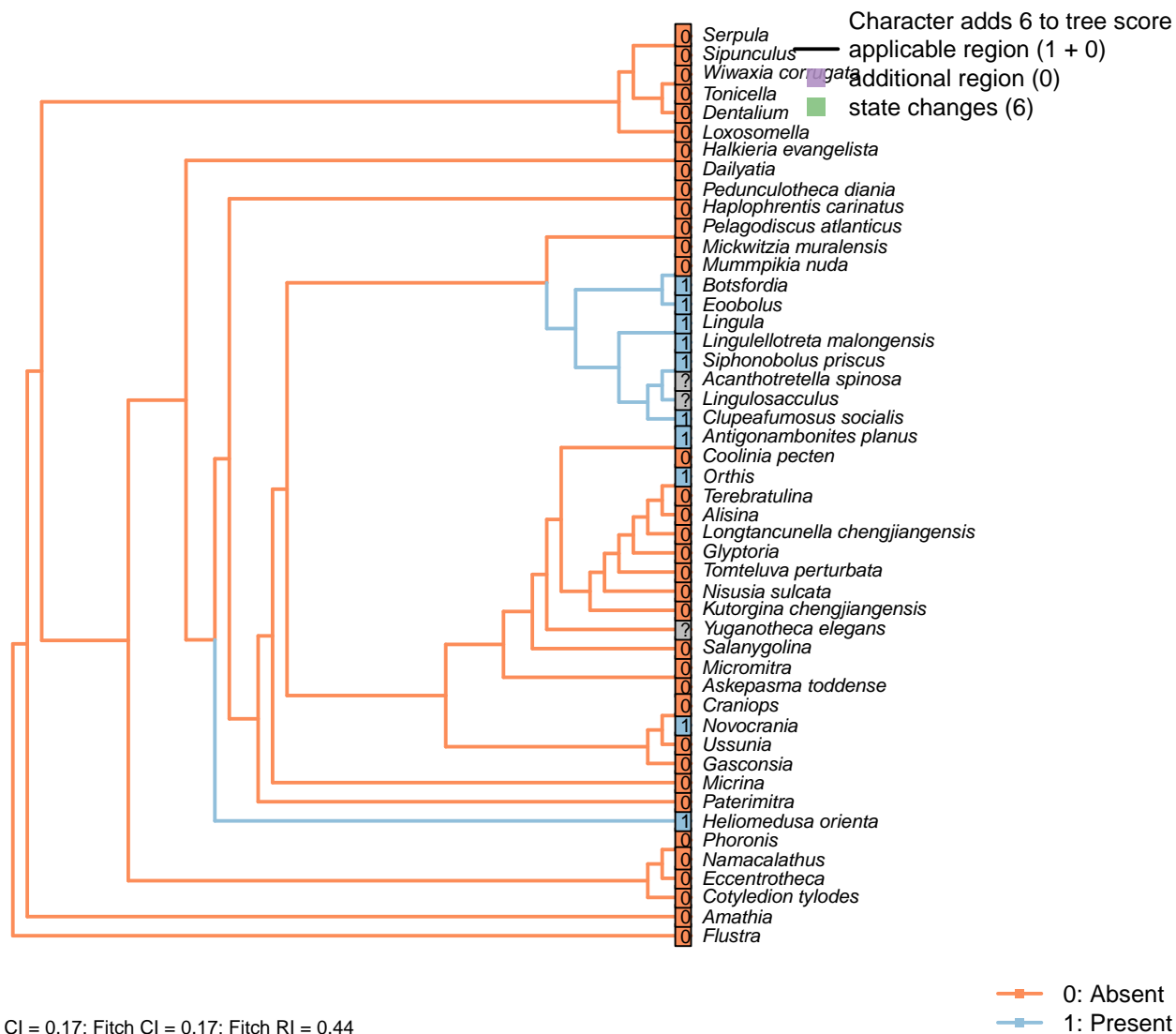
Neomorphic character.

A prominent platform in the hyolith operculum. With no obvious sites for muscle attachment, it is unlikely to be homologous to the notothyrial platform.

[93] Cardinal processes



[94] Medial septum



The dorsal valve of many taxa exhibits a septum or process (or myophragm) along the medial line. See character 25 in Benedetto (2009).

Clupeafumosus socialis: Not described by Holmer & Caron (2006), but an unannotated linear feature corresponds to the position of a median septum. Without detailed study of the specimen, we opt to score this as ambiguous.

Craniops: Weakly developed septum evident in internal cast: Williams et al. (2000), fig. 508.2e.

Eoobolus: Median process evident: Williams et al. (2000) fig. 100.2a, d.

Gasconsia: “dorsal interior with narrow anterior projection extending to midvalve, bisected by median ridge”

– Williams et al. (2000).

Kutorgina chengjiangensis: Following char 42 in table 15 in Williams et al. (2000).

Lingulellotreta malongensis: A “median projection” is present (fig. 4g in Balthasar, 2009).

Longtancunella chengjiangensis: Neither evident nor reported in Williams *et al.* (2000).

Mickwitzia muralensis: It is not possible to determine, based on the material presented in Balthasar & Butterfield (2009), whether the anterior projection of the visceral area in the dorsal valve corresponds to a medial septum in the underlying shell.

Micrina: Reported on ‘ventral’ valve by Chen *et al.* (2007); we consider their ‘ventral’ valve to be the dorsal valve.

The structure is unambiguously figured (e.g. fig. 5.1 in Chen et al., 2007), contra its coding as absent in Williams et al. (2000) and its lack of mention in Williams et al. (2007) or Zhang et al. (2009).

Micromitra: Absent – fig. 129.1f in Williams *et al.* (2000).

Mummpikia nuda: Very weakly developed but seemingly present between muscle scars in *Lingulellotreta*, more prominent in *Aboriginella* (also *Lingulellotretidae*) (Williams et al., 2000, fig. 34).

Siphonobolus priscus: See pl. 2 panel 6 in Balthasar (2008).

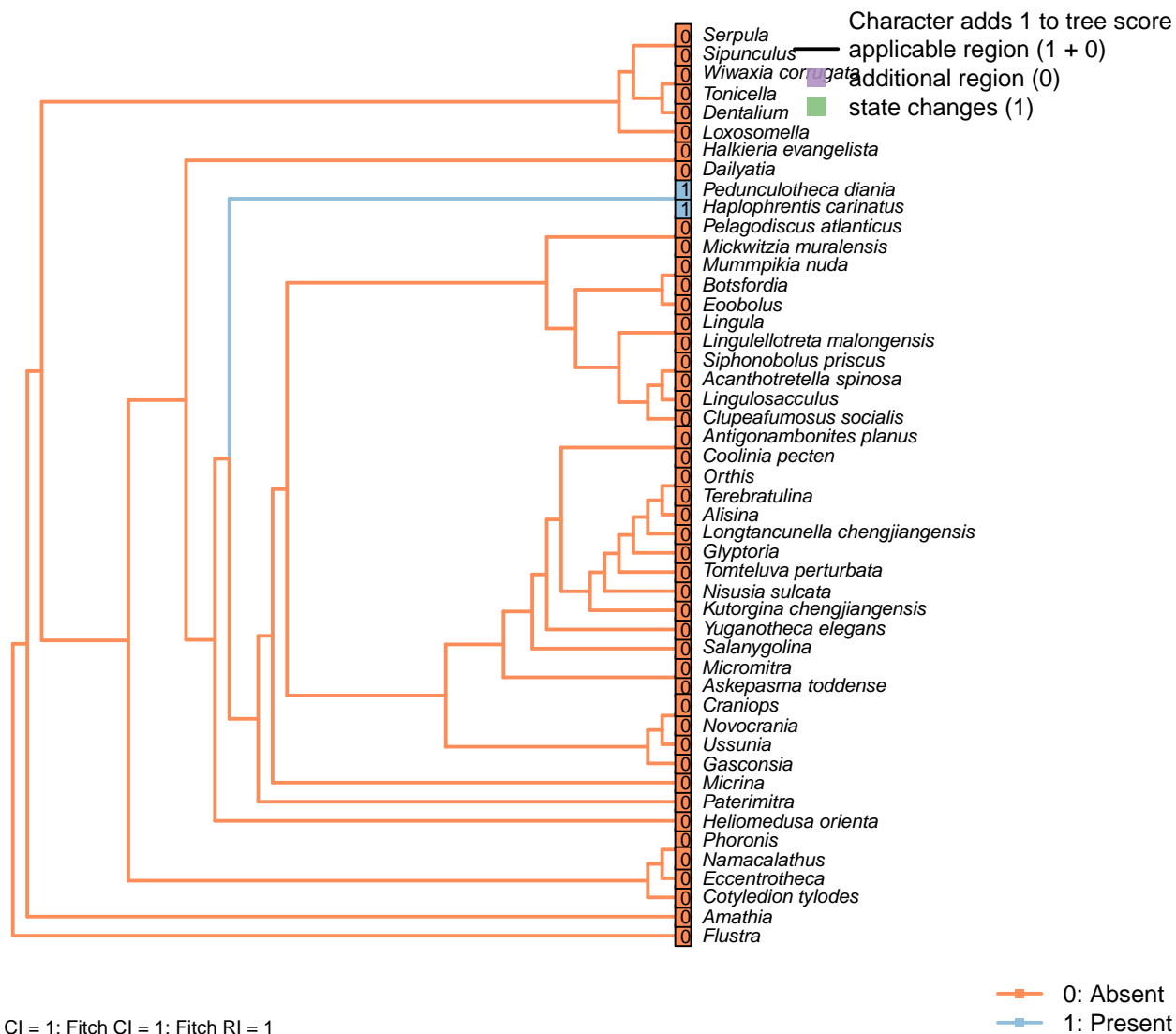
Tomteluva perturbata: Fig. 125 in Williams *et al.* (2000).

Ussunia: Prominent process evident (Topper et al., 2013a).

Yuganotheca elegans: Short medial process (“low median ridge”, p. 724) present in dorsal valve; see Fig. 523.3b in Williams *et al.* (2000).

NA: “Dorsal interior [...] bisected by a short median ridge.” – Popov et al. (2009).

[95] Clavicles

**Character 95: Sclerites: Dorsal valve: Clavicles**

0: Absent

1: Present

Neomorphic character.

Prominent symmetrical ridges on the inner surface of the hyolith operculum.

[96] Clavicles: Type of clavicles

All taxa are coded as ambiguous for this character.

Character 96: Sclerites: Dorsal valve: Clavicles: Type of clavicles

0: Monoclavicle

1: Platyclavicle

2: Biclavicle

3: Triclavicle

- 4: Tetraclavicle
- 5: Polyclavicle
- Neomorphic character.

Usually the operculum of hyoliths has one pair of clavicles, but in some taxa of hyolithida there are more than one pair of clavicles, which can be divided into six types (Marek, 1967).

Monoclavicle: one pair of clavicles with a keel-shaped or rounded, narrow cross section; Platyclavicle: one pair of broad, flat clavicles enclosing a great number of small channels;

Biclavicle: two pairs of clavicles;

Triclavicle: three pairs of clavicles;

Tetraclavicle: four pairs of clavicles;

Polyclavicle: more than four pairs of clavicles.

[NOTE: This character seems to combine two different features: the number of clavicles, and the shape of each clavicle. Would it work better as two separate characters?].

3.20 Sclerite: Helens [97]

All taxa are coded as ambiguous for this character.

Character 97: Sclerite: Helens

- 0: Absent
- 1: Present
- Neomorphic character.

Helens are a pair of curved lateral skeletal elements of hyolithide hyoliths, so far no parallel structures have been found in lophotrochozoans.

[NOTE: Hyolith helens are currently coded as being potentially homologous with the L-elements of *Paterimitra*; see character “Sclerites: Bivalved: Accessory sclerites reduced”. We should not code the presence of the same feature twice; if we treat helens as definitely not homologous with the *Paterimitra* L-sclerites, then we need to unarguably defend why the two structures cannot be homologous in the character definition. If we cannot do this then we should code hyoliths with helens as having accessory sclerites instead. We could add a separate character describing the form/shape of the accessory sclerites if this helped to group the hyolithides.].

[98] Cardinal teeth

All taxa are coded as ambiguous for this character.

Character 98: Sclerite: Dorsal valve: Cardinal teeth

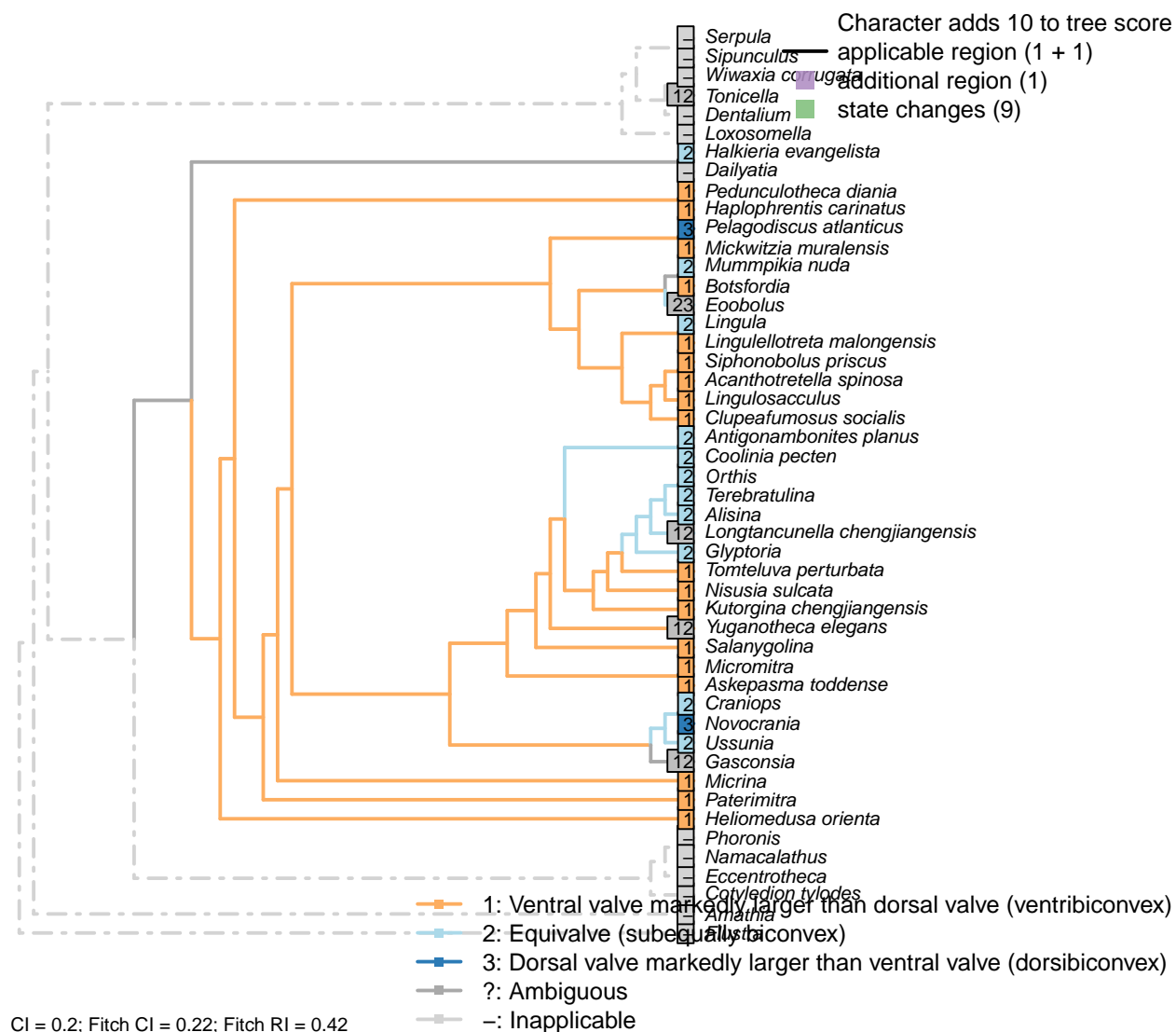
- 0: Absent
- 1: Present
- Neomorphic character.

Dentiform processes on the internal cardinal shield margin of some hyolith opercula, but no corresponding tooth sockets, which is supposed not for articulation.

[NOTE: The character description should make clear how these differ from cardinal processes, character “Sclerites: Dorsal valve: Cardinal processes”].

3.21 Sclerites: Ventral valve

[99] Relative size



Character 99: Sclerites: Ventral valve: Relative size

- 1: Ventral valve markedly larger than dorsal valve (ventribiconvex)
 - 2: Equivalve (subequally biconvex)
 - 3: Dorsal valve markedly larger than ventral valve (dorsibiconvex)
- Transformational character.

In many brachiopods, the valves are closely similar in size; in others, the ventral valve is markedly larger than the dorsal, on account of being more convex. Marginal cases are treated as ambiguous for the relevant states.

Acanthotretella spinosa: Coded as ambiguous for equivalve/ventral valve larger: the posterior embryonic

shell field, treated herein as equivalent to the ventral valve,.

Craniops: Broadly equivalve – see Williams *et al.* (2000) fig. 508.2c.

Gasconsia: After table 8 in Williams *et al.* (2000).

Glyptoria: “Shell subequally biconvex” – Williams *et al.* (2000).

Heliomedusa orientalis: Equivalve as juveniles, becoming “convexiplane” (Williams *et al.*, 2000, p. 187) as adults (Hanken and Harper, 1985).

Kutorgina chengjiangensis: Subequally biconvex (Williams *et al.*, 2000, p. 192).

Lingulellotreta malongensis: “*Eoobolus* is biconvex”, but in his amended diagnosis, Balthasar (2009) described it as “shell inequivalved, dorsibiconvex”.

Micrina: Ventral valve larger than the dorsal valve (Zhang *et al.*, 2009, p. 659).

Micromitra: Ventral valve larger (see Williams *et al.*, 2000, fig. 125.).

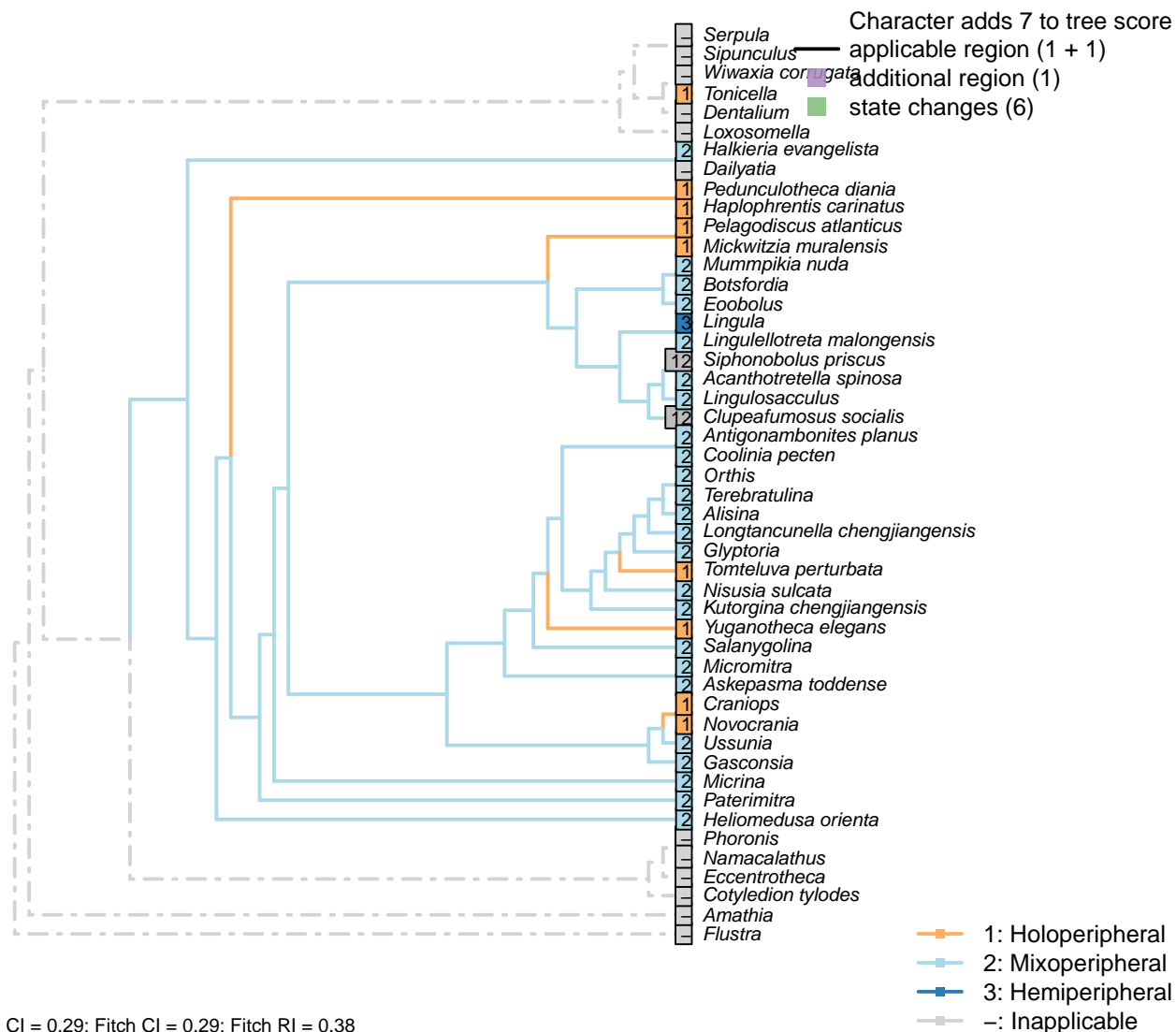
Nisusia sulcata, NA: The ventral valve is somewhat, but not markedly, larger than the dorsal; as such, this character is coded ambiguous for equivalve/ventral valve larger.

Siphonobolus priscus: Aside from hinge, valves similar in convexity and size (Balthasar, 2008).

Tomteluva perturbata: Ventral valve larger (see Williams *et al.*, 2000, fig. 126.).

NA: Ventribiconvex (Popov *et al.*, 2009).

[100] Growth direction

**Character 100: Sclerites: Ventral valve: Growth direction**

1: Holoperipheral

2: Mixoperipheral

3: Hemiperipheral

Transformational character.

See Fig. 284 in Williams *et al.* (1997) for depiction of terms.

The growth direction dictates the attitude of the cardinal area relative to the hinge, which does not therefore represent an independent character.

Crudely put, if, viewed from a dorsal position, the umbo falls within the outer margin of the shell, growth is holoperipheral; if it falls outside the margin, it is mixoperipheral; if it falls exactly on the margin, it is hemiperipheral.

Acanthotretella spinosa: Growth is hemiperipheral in the anterior valve of polyplacophorans and holoperiph-

eral in the posterior valves (Schwabe, 2010; Connors et al., 2012).

Glyptoria: “Both valves with growth holoperipheral” – Williams et al. (2000), p. 164.

Kutorgina chengjiangensis: Growth “mixoperipheral in both valves” in trimerellids (Williams et al., 2000; Popov et al., 1997).

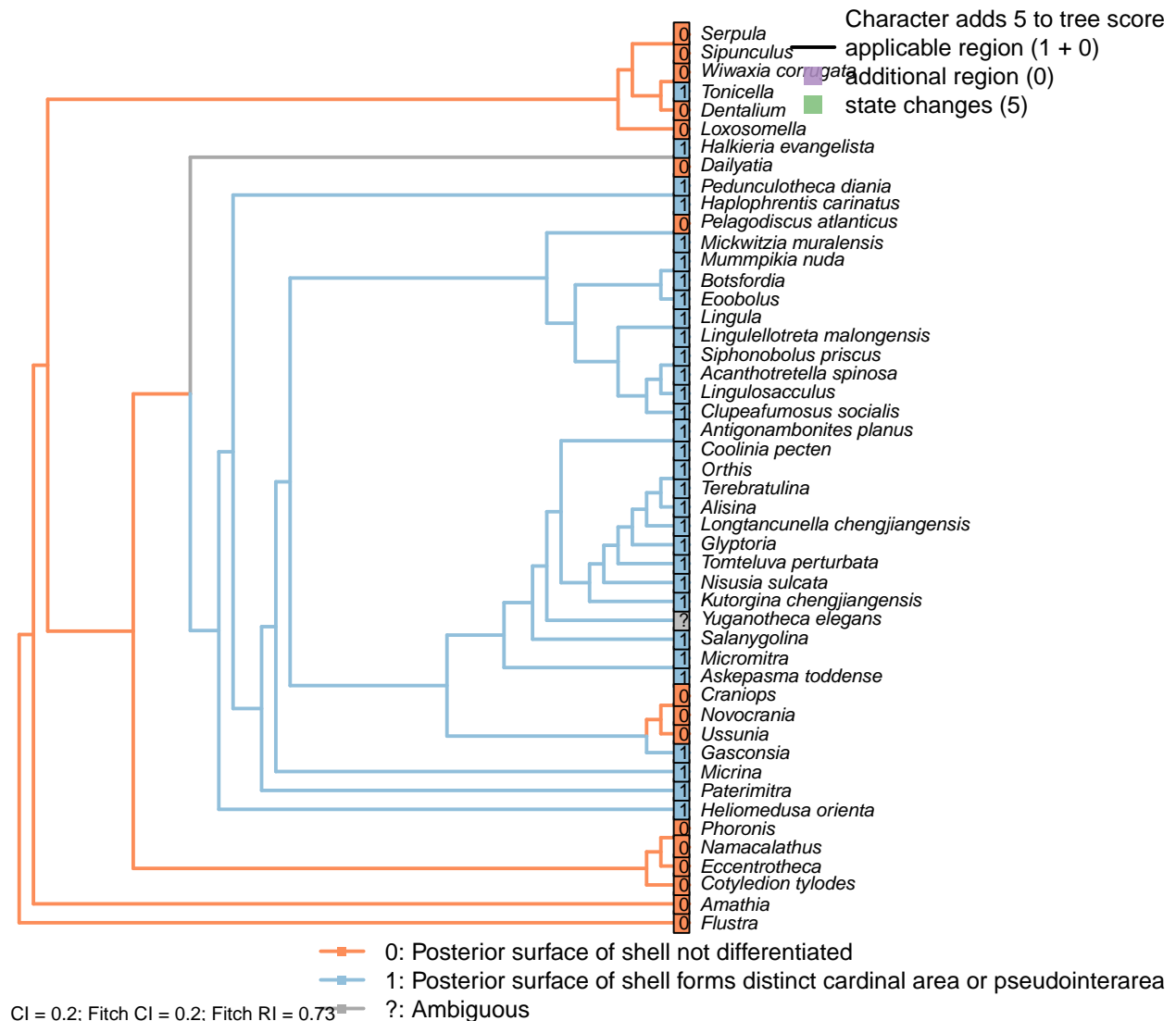
Micrina: Williams et al. (2000, 2007) reconstruct mixoperipheral growth in the ventral valve [though Chen et al. (2007) reconstruct the valves the other way round, i.e. it is the ventral valve that grows holoperipherally, and the dorsal mixoperipherally].

Ussunia: Inferred from Topper et al. (2013a).

NA: The apical flange notwithstanding, the umbo of the S1 sclerite is posterior of the hinge line and the posterior edge of the lateral plate – see Larsson et al. (2014), fig. 2a, c.

NA: Initially holoperipheral (Popov et al., 2009, p. 159), then on the brink of being mixoperipheral in adulthood, so coded as polymorphic.

[101] Posterior surface: Differentiated



Character 101: Sclerites: Ventral valve: Posterior surface: Differentiated

0: Posterior surface of shell not differentiated

1: Posterior surface of shell forms distinct cardinal area or pseudointerarea

Neomorphic character.

In shells that grow by mixoperipheral growth, the triangular area subtended between each apex and the posterior ends of the lateral margins is termed the cardinal area. In shells with holoperipheral growth, a flattened surface on the posterior margin of the valve is termed a pseudointerarea (paraphrasing Williams et al., 1997).

In order for this character to be independent of a shell's growth direction, we do not distinguish between a "cardinal area", "interarea" or "pseudointerarea".

Acanthotretella spinosa: Following the proposed homology model between the posterior valve of polyplacophorans and the ventral valve of brachiopods, the "posterior" surface of the polyplacophoran valve is taken to be the surface that would articulate with the anterior valve, which is anatomically anterior on the living organism.

Coolinia pecten, *Craniops*, *Eccentrotheca*, *Longtancunella chengjiangensis*, *Micromitra*, *Tomteluva perturbata*, *Yuganotheca elegans*, NA, NA: Interarea present.

Heliomedusa orientalis: The region corresponding to the ventral (pseudo)interarea is described as a "trimerellid ventral cardinal area" by Williams et al. (2000, p.162), who code both an interarea and a pseudointerarea as absent in trimerellids.

Kutorgina chengjiangensis: Following char 17 in table 15 of Williams et al. (2000).

Mickwitzia muralensis: The conical valve is interpreted as the ventral valve with an extended pseudointerarea.

Micrina: Zhang et al. (2009) report a moderate to somewhat developed ventral pseudointerarea, confirmed by Williams et al. (2007).

Nisusia sulcata: Though "all evidence of a pseudointerarea is lacking" – Zhang et al. (2011a) – the region of the shell between the strophic hinge line and the colleplax (fig. 2 in Zhang et al., 2011a) is distinct from the rest of the shell; the ends of the strophic hinge line are marked by prominent nicks in the shell margin. *Longtancunella* is therefore coded as having a differentiated posterior surface.

Salanygolina: Termed an interarea by Balthasar (2004).

Siphonobolus priscus: Balthasar (2008) interprets a pseudointerarea as being present – e.g. p273, "Of particular interest is the vault that bridges the most anterior portion of the ventral pseudointerarea and raises it above the visceral platform."; "This pattern is reversed in the ventral valves of *M. nuda*, where the anterior projection of the pedicle groove is raised above the valve floor whereas the lateral parts of pseudointerarea are not".

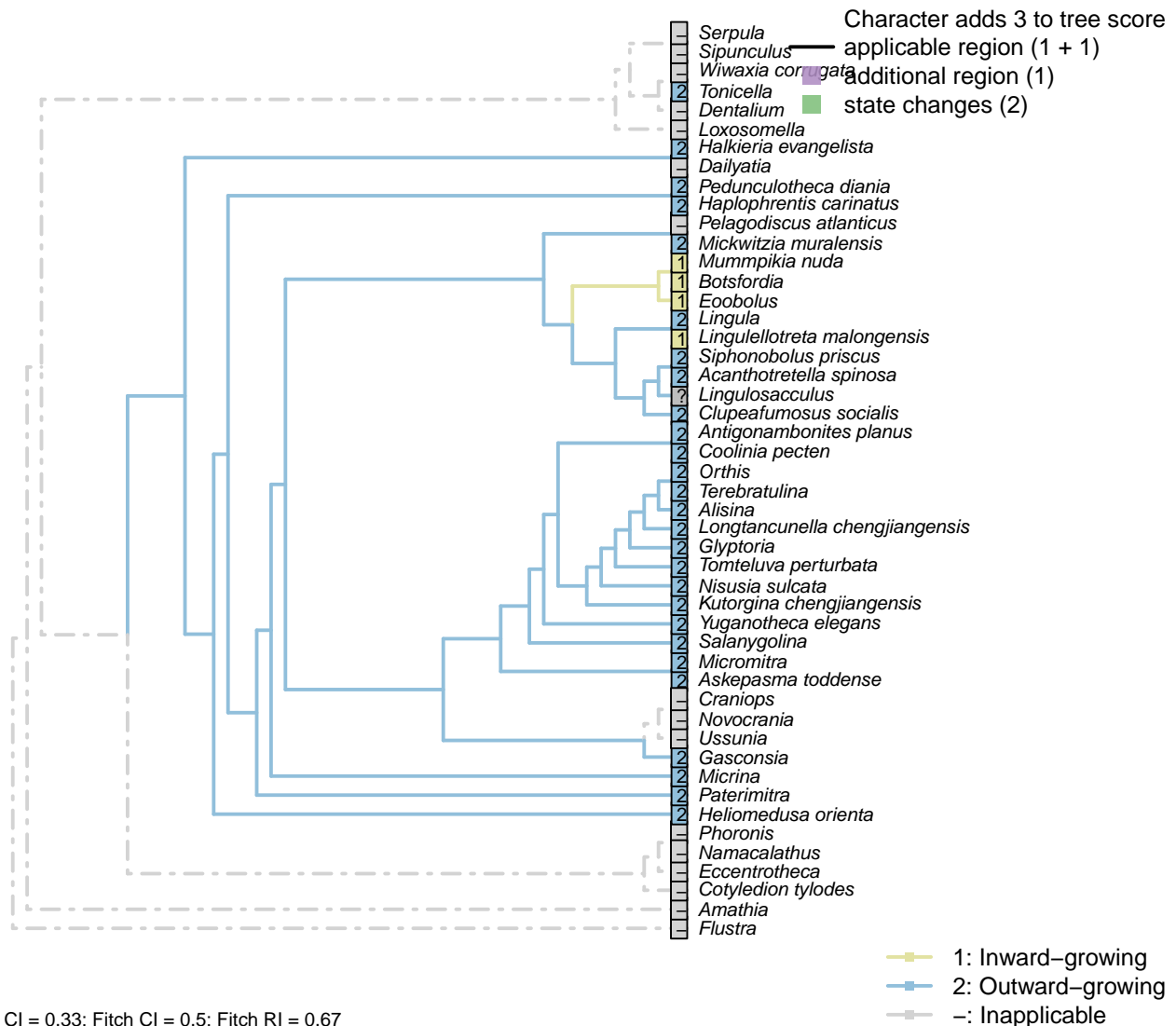
Tonicella: Interarea.

Ussunia: Described by Topper et al. (2013a).

NA: Triangular notch and subapical flange.

NA: "Ventral pseudointerarea, low, undivided, poorly defined" – Williams et al. (2000).

[102] Posterior margin growth direction

**Character 102: Sclerites: Ventral valve: Posterior margin growth direction**

1: Inward-growing

2: Outward-growing

Transformational character.

Balthasar (2008) notes an inward-growing posterior margin of the pseudointerarea as potentially linking *Mummpikia* with the linguliform brachiopods.

Coded as inapplicable in taxa without a differentiated posterior margin: the posterior margin can only grow inwards if it is differentiated from the anterior margin; else the entire shell would grow in on itself.

Gasconsia: Inward-growing; see Skovsted & Holmer (2005), pl. 4.

Lingulellotreta malongensis: See for example Skovsted & Holmer (2005), pl. 3.

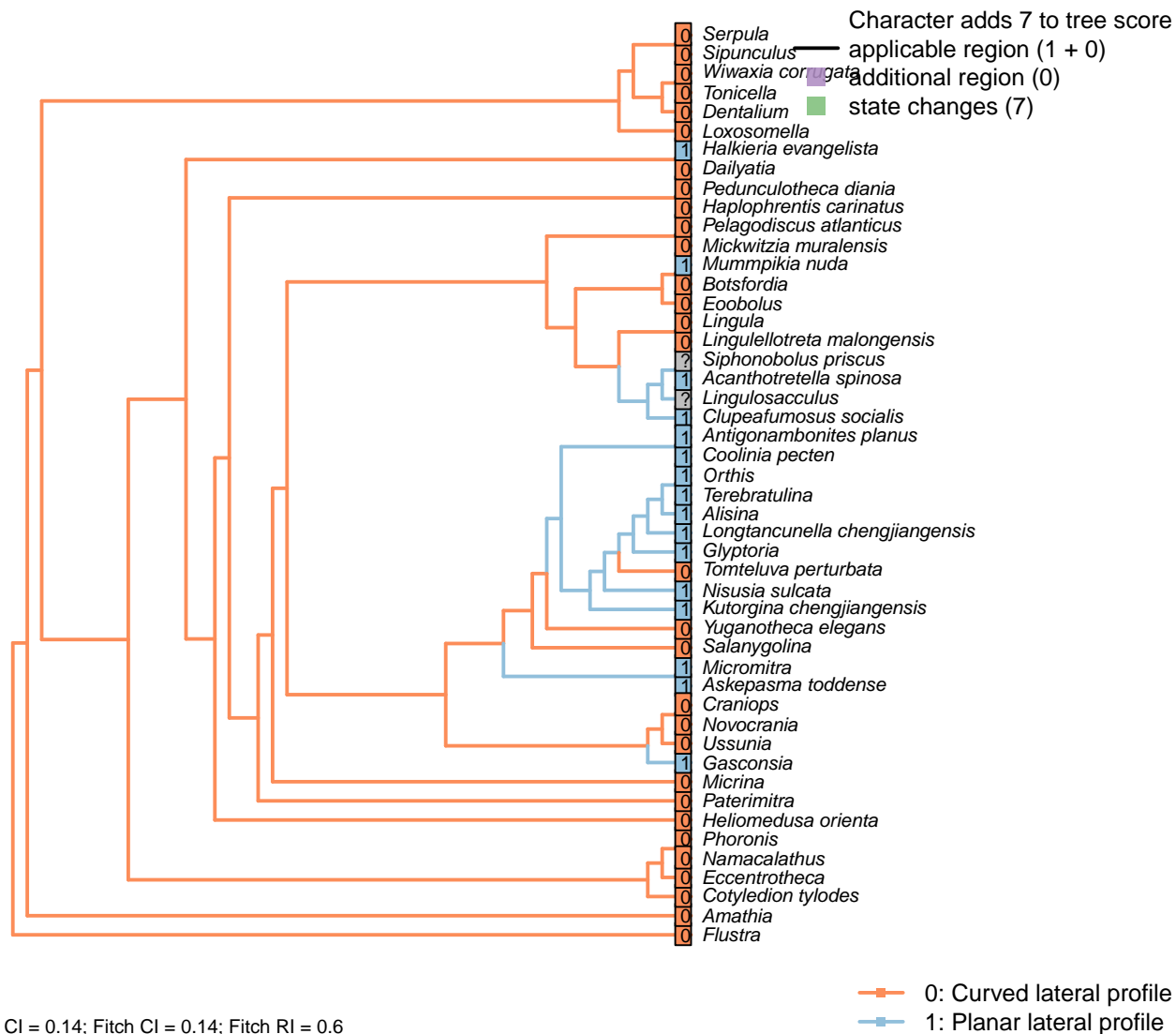
Mummpikia nuda: Transverse cross section of ventral pseudointerarea concave.

Siphonobolus priscus: Balthasar (2008) interprets an inward-growing posterior margin of the pseudointerarea – e.g. p273, “Of particular interest is the vault that bridges the most anterior portion of the ventral pseu-

dointerarea and raises it above the visceral platform [...] An inward-growing posterior margin is otherwise known only from the pseudointerareas of linguliform brachiopods”.

Ussunia: See Topper *et al.* (2013a).

[103] Posterior surface: Planar



Character 103: Sclerites: Ventral valve: Posterior surface: Planar

0: Curved lateral profile

1: Planar lateral profile

Neomorphic character.

It is possible for a cardinal area or pseudointerarea to be distinct from the anterior part of the shell, yet to remain curved in lateral profile.

Taking an undifferentiated posterior margin as primitive, the primitive condition is curved – flattening of the posterior margin represents an additional modification that can only occur once the posterior margin is differentiated.

A flat and triangular interarea links *Mummpikia* with the Obolellidae (Balthasar, 2008) – but all included taxa have triangular interareas, so this is not listed as a separate character.

Acanthotretella spinosa: (Schwabe, 2010).

Clupeafumusus socialis: ventral pseudointerareas are most similar to those found within the Order Siphonotretida.

Gasconsia: See Skovsted & Holmer (2005), pl. 3, fig. 14.

Lingulellotreta malongensis: Some curvature retained.

Mummpikia nuda: Transverse cross section of ventral pseudointerarea concave.

Nisusia sulcata: Flattened, reflecting the strophic hinge line.

Paterimitra: Essentially planar; see fig. 6 in Ushatinskaya (2016).

Ussunia: “Ventral pseudointerarea is gently procline and is flat in lateral profile”. — (Topper et al., 2013a).

NA: ‘Almost’ planar – see Popov *et al.* (2009, fig. 4). Coded as ambiguous.

[104] apertural ligular extension of conical shell

All taxa are coded as ambiguous for this character.

Character 104: Sclerites: Ventral valve: apertural ligular extension of conical shell

0: Absent

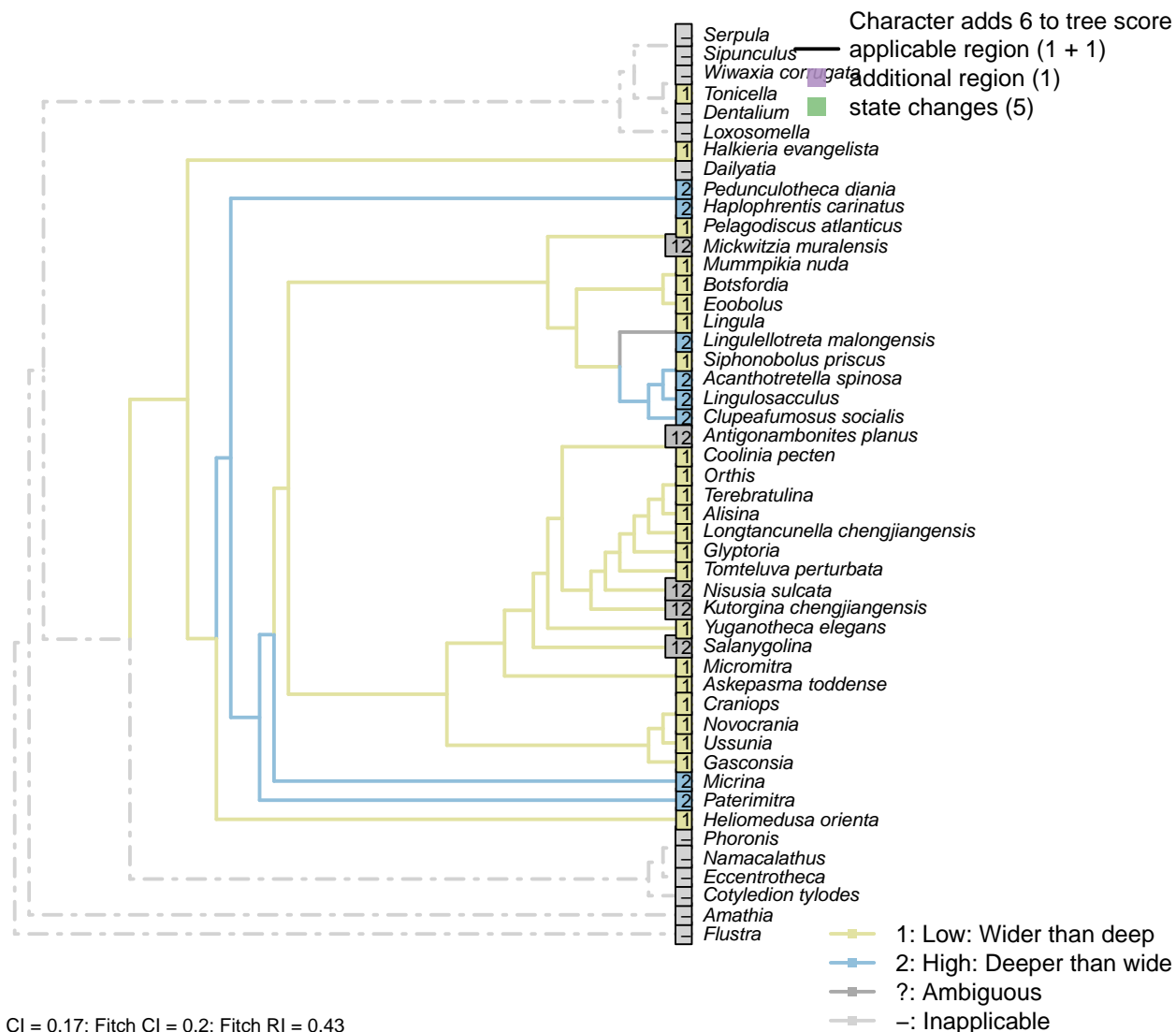
1: Present

Neomorphic character.

Ligula of conical shell is a characteristic feature of hyolithid hyoliths.

[NOTE: It is not clear from the definition how this character ought to be coded in taxa that are not hyoliths. A more general definition is needed to ensure that other taxa can be coded objectively.].

[105] Posterior surface: Extent

**Character 105: Sclerites: Ventral valve: Posterior surface: Extent**

- 1: Low: Wider than deep
 - 2: High: Deeper than wide
- Transformational character.

Distinguishes taxa whose ventral valve is essentially flat from those that are essentially conical.

Craniops: Though scored High in data matrix of Benedetto (2009), this taxon (see Williams et al., 2000, fig. 508) does not express the deeply conical ventral valve that this character is intended to reflect. It is charitably coded as ambiguous.

Eccentrotheca: See fig. 485 in Williams et al. (2000).

Eoobolus: Low cone.

Heliomedusa orientata: “ventral cardinal interarea low, apsacline, with narrow, poorly defined homeodeltidium” – Williams et al. (2000), p. 186.

Micromitra: This taxon (see Williams et al., 2000, fig. 129; Popov, 1992, fig. 1) comes close to expressing the

deeply conical ventral valve that this character is intended to reflect, though this is not always so pronounced (e.g. Williams *et al.*, 2000, fig. 125). It is therefore coded as ambiguous.

Salanygolina: Often not prominently high (Skovsted and Holmer, 2003; Balthasar, 2004), though in some cases (e.g. Butler *et al.*, 2015) the ventral valve approaches the conical shape that this character is intended to capture. Coded as polymorphic.

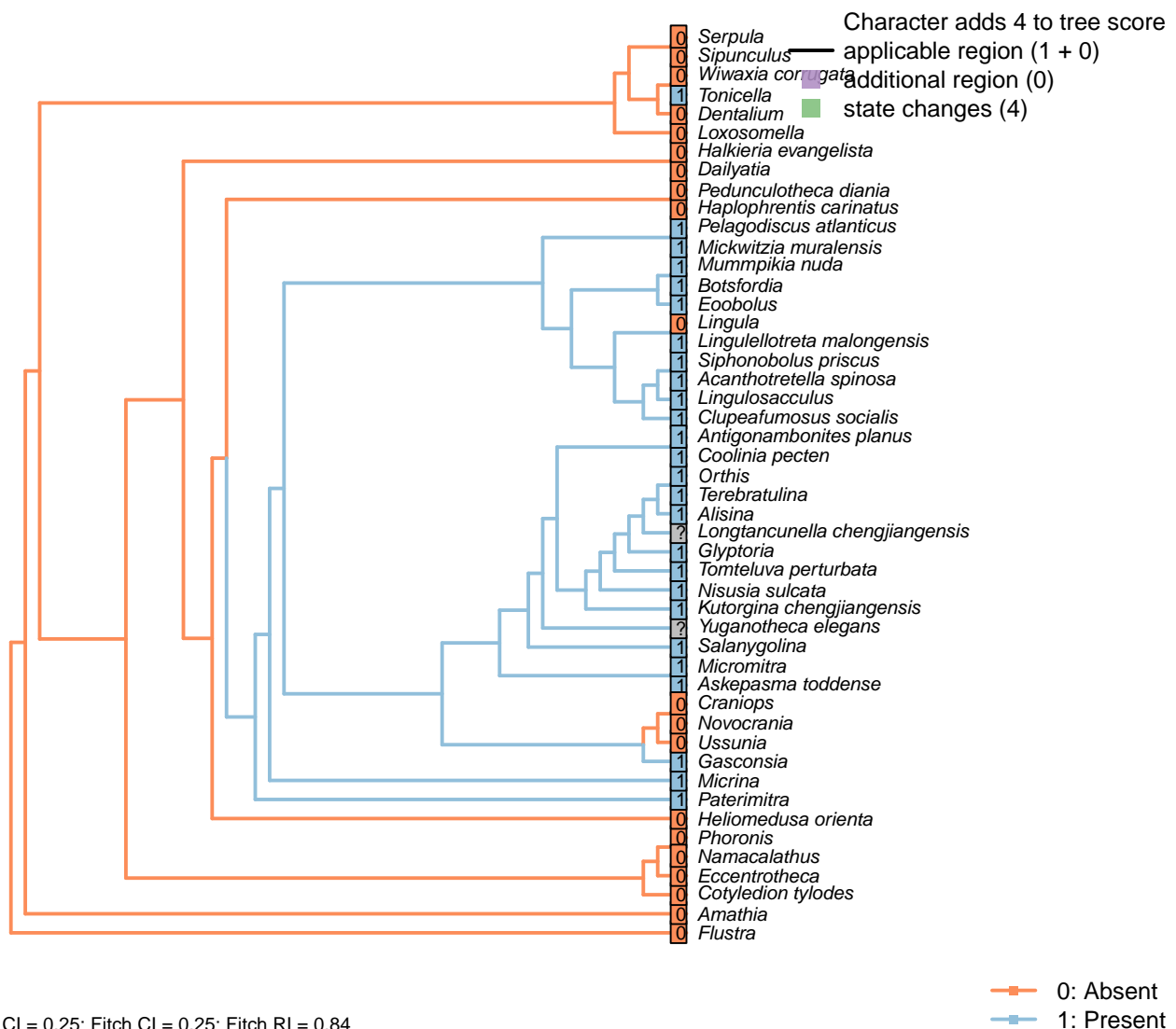
Tomteluva perturbata: Scored as high in data matrix of Benedetto (2009), and depicted as such in Williams *et al.* (2000, fig. 125) and Popov (1992, fig. 1); but not high in all specimens (e.g. Williams *et al.*, 2000, fig. 126). It is therefore coded as polymorphic.

Ussunia: Entire valve length – see schematic in Williams *et al.* (1997), fig. 286.

Yuganotheca elegans: Scored ‘Low’ for *Eoorthis* by Benedetto (2009); assumed same in *Orthis*.

NA: Whereas Williams *et al.* (2000, p. 156) describe the ventral pseudointerarea as high, the shell lacks the deeply conical aspect that this character is intended to capture; we thus code the taxon as ambiguous.

[106] Posterior surface: Delthyrium



Character 106: Sclerites: Ventral valve: Posterior surface: Delthyrium

0: Absent

1: Present

Neomorphic character.

A delthyrium is an opening in an interarea or pseudointerarea that accommodates the pedicle, and may be filled with plates.

The homology of the pedicle in the pseudointerarea of obolellids and botsfordiids with the umbonal pedicle foramen of acrotretids was proposed by Popov (1992), and seemingly corroborated by observations of Ushatinskaya & Korovnikov (2016), who note that the propareas of the *Botsfordia* ventral valve sometimes merge to form an elongate teardrop-shaped pedicle foramen.

Acanthotretella spinosa: The antemucronal area (Schwabe, 2010) is treated as equivalent to the brachiopod delthyrium.

Clupeafumosus socialis: Origin modelled on *Siphonobolus*.

Gasconsia: The homology of the triangular notch or groove in the pseudointerarea with the umbonal pedicle foramen of acrotretids was proposed by Popov (1992), and seemingly corroborated by observations of Ushatinskaya & Korovnikov (2016), who note that the propareas of the *Botsfordia* ventral valve sometimes merge to form an elongate teardrop-shaped pedicle foramen.

Lingulellotreta malongensis: See for example fig. 5 in Balthasar (2009).

Longtancunella chengjiangensis: “Delthyrium and notothyrium open, wide” – Cooper (1976).

Nisusia sulcata: Unclear: a narrow ridge that may correspond to a pseudodeltidium evident in fig 2a and sketched in fig. 2c is not discussed in the text of Zhang et al. (2011a), so the delthyrial region is coded as ambiguous.

Novocrania: Homeodeltidium absent (Williams et al., 2000, p. 153); deltidium is open (see Topper et al., 2013b, fig. 4).

Orthis: Opening inferred by Holmer *et al.* (2008).

Salanygolina: A delthyrium is present in young individuals (Balthasar, 2004).

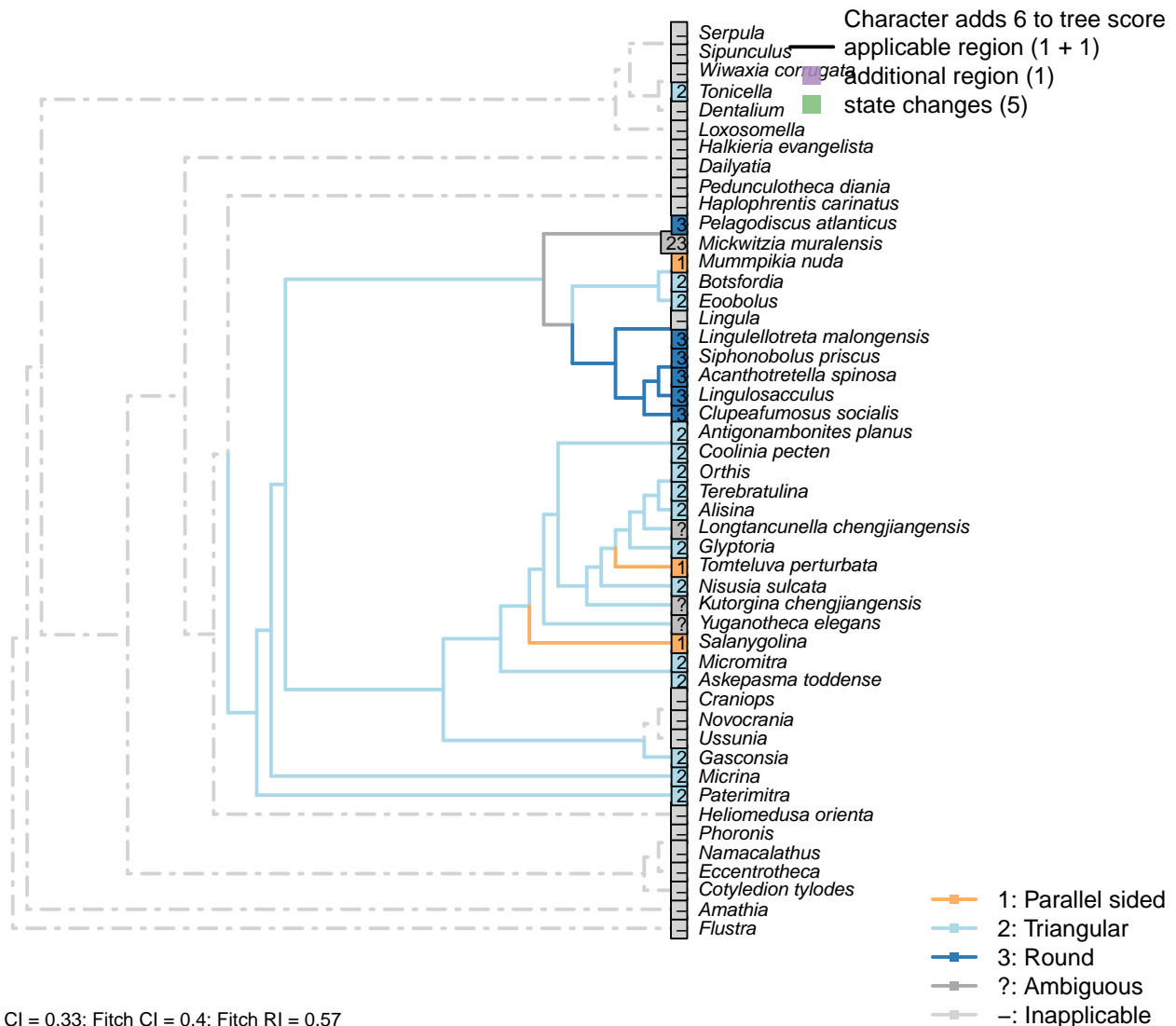
Serpula: The listrum (pedicle opening) is interpreted as originating via a similar mechanism to that of acrotretids (Popov, 1992), and hence corresponding to a basally sealed delthyrium.

Ussunia: Following Popov (1992), the larval delthyrium is sealed in adults by outgrowths of the posterolateral margins of the shell.

NA: Details of the hinge region are unclear due to the flattened and overprinted nature of fossil preservation.

NA: Ontogeny presumed to resemble that of acrotretids.

[107] Posterior surface: Delthyrium: Shape

**Character 107: Sclerites: Ventral valve: Posterior surface: Delthyrium: Shape**

- 1: Parallel sided
- 2: Triangular
- 3: Round

Transformational character.

A parallel-sided delthyrium links *Mummpikia* with the Obolellidae (Balthasar, 2008).

Following Popov (1992), the larval delthyrium of acrotretids and allied taxa is understood to be sealed in adults by outgrowths of the posterolateral margins of the shell. The resultant round or teardrop-shaped foramen corresponds the delthyrium.

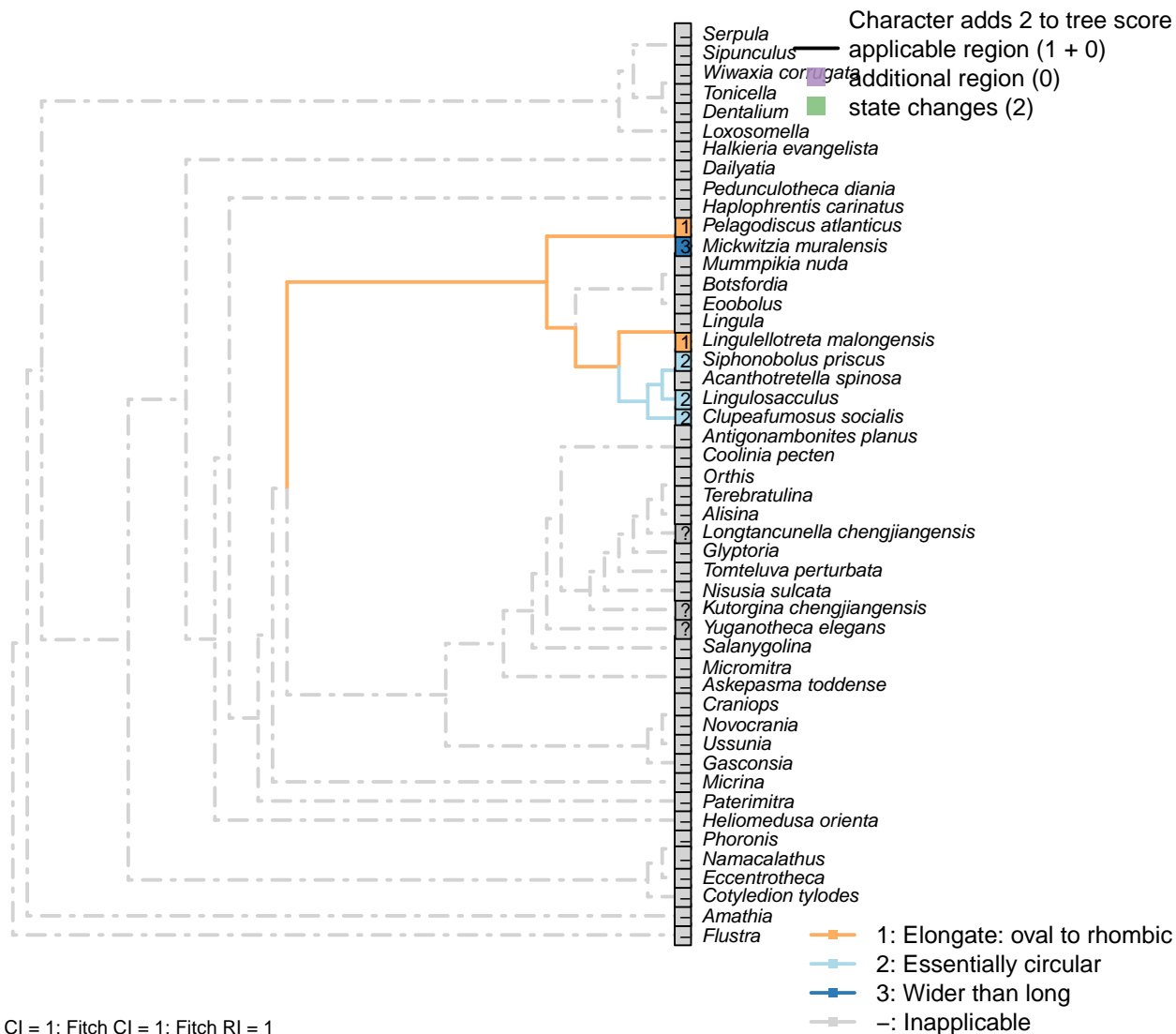
Novocrania: Prominently triangular (see Topper et al., 2013b, fig. 2).

Salanygolina: An opening is incorporated at the base of the homeodeltidium when the organism switches from early to late maturity (fig. 10 in Balthasar, 2004). This opening is conceivably homologous with the pedicle foramen of acrotretid brachiopods and their ilk. To reflect this possible homology, *Mickwitzia* is

coded as polymorphic (triangular/round).

Ussunia: Following the model of Popov (1992).

[108] Posterior surface: Delthyrium: Shape: Aspect of rounded opening

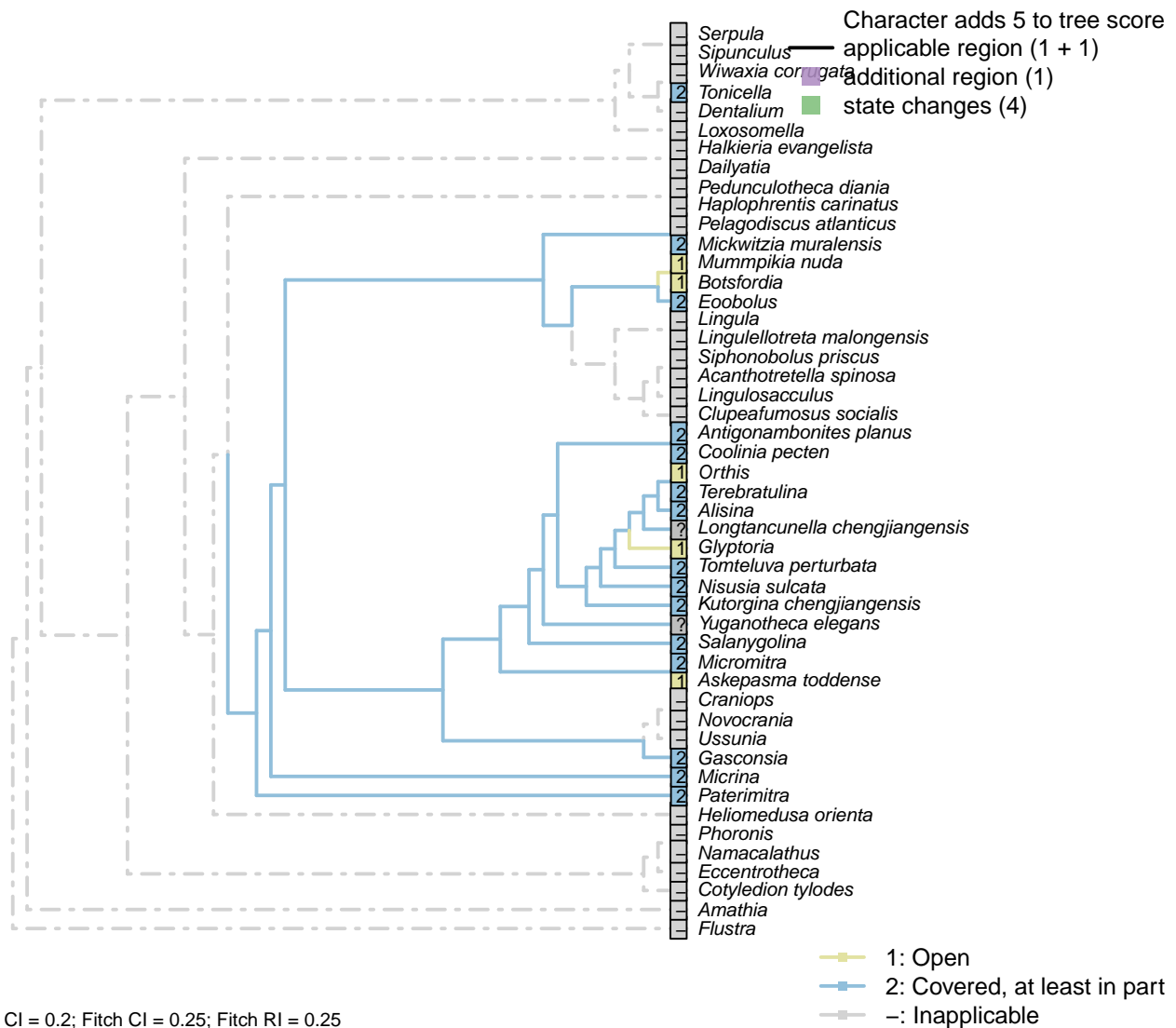


internal tissue].

Mummpikia nuda: Oval (Williams et al., 2000).

Salanygolina: Wider than long: see fig. 10 in Balthasar (2004).

[109] Posterior surface: Delthyrium: Cover



lateral parts of the shell, per Popov, 1992).

Eccentrotheca: A convex pseudodeltidium completely covers the delthyrium in *Coolinia*.

Gasconsia: See pl. 3 fig. 15 in Skovsted & Holmer (2005).

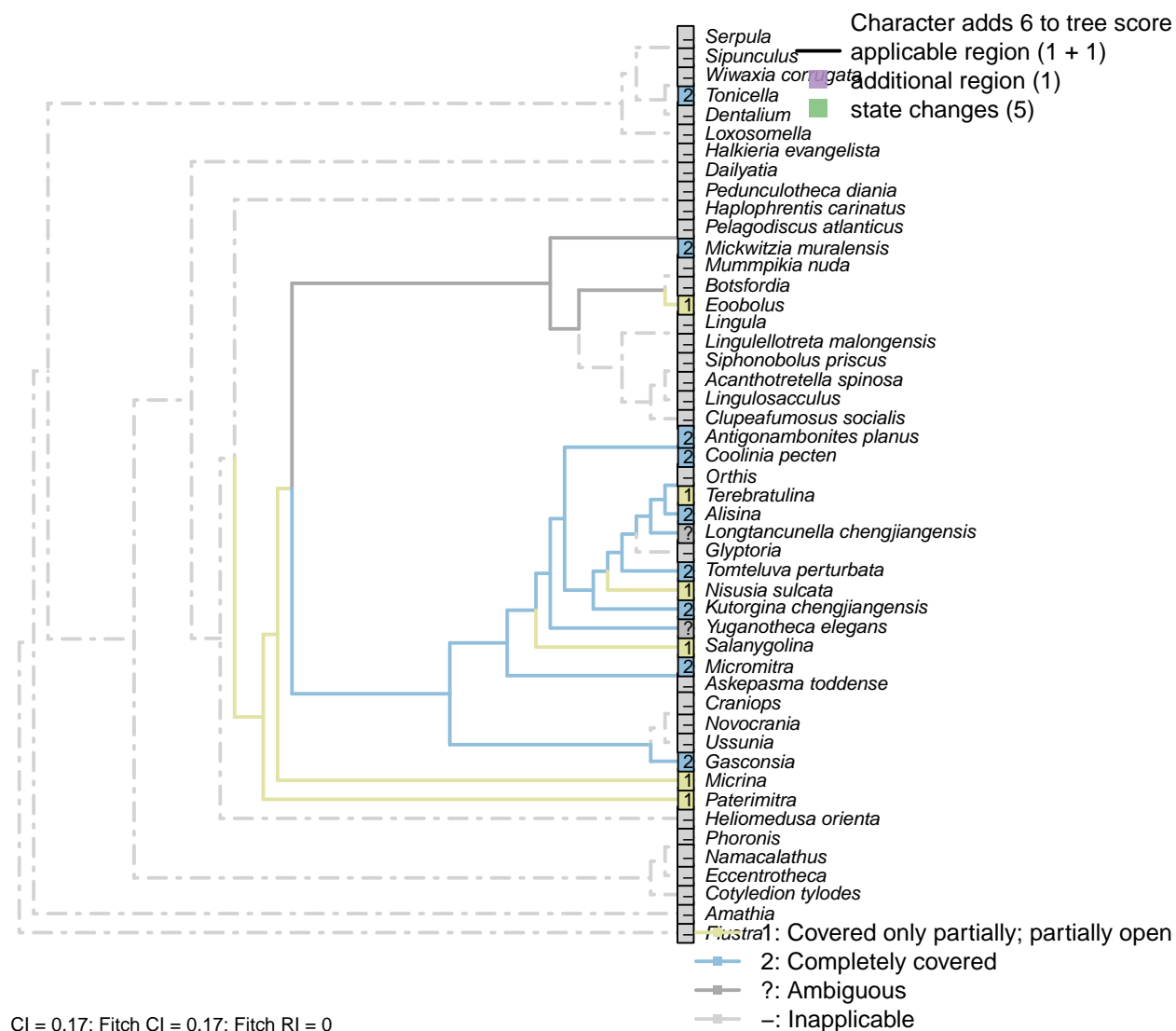
Longtancunella chengjiangensis: Coded as open by Williams *et al.* (1998).

Novocrania: Open (Topper *et al.*, 2013b).

Tomteluva perturbata: “Covered only apically by a small convex pseudodeltidium” – Holmer *et al.* (2018a).

NA: Covered by subaical flange, in part.

[110] Posterior surface: Delthyrium: Cover: Extent



Character 110: Sclerites: Ventral valve: Posterior surface: Delthyrium: Cover: Extent

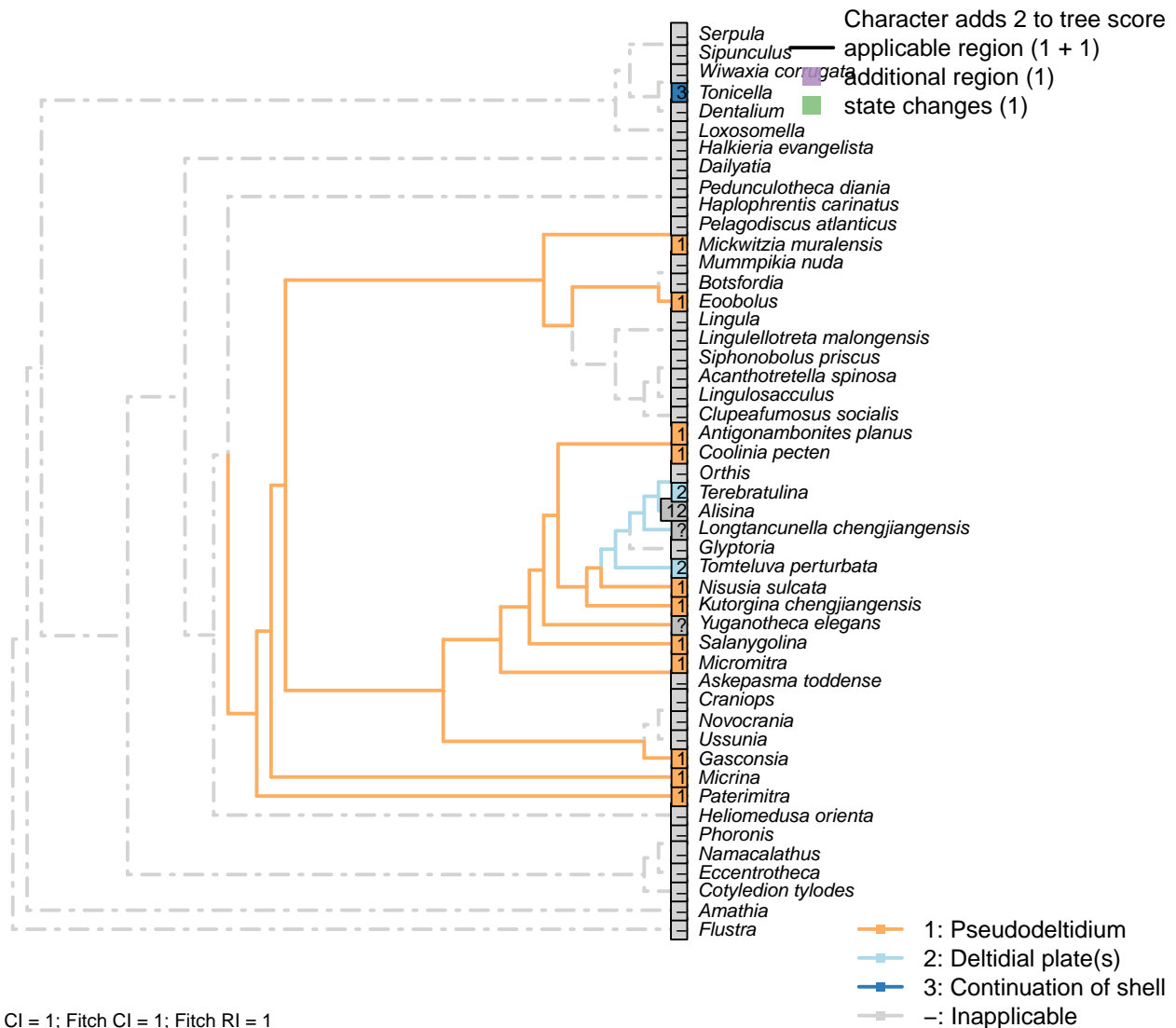
- 1: Covered only partially; partially open
- 2: Completely covered

Transformational character.

Orthis: Remains somewhat open.

Tomteluva perturbata: A well-defined pseudo-deltidium [...] closes only the apical part of the delthyrium (Rowell and Caruso, 1985).

[111] Posterior surface: Delthyrium: Cover: Identity



Character 111: Sclerites: Ventral valve: Posterior surface: Delthyrium: Cover: Identity

- 1: Pseudodeltidium
 - 2: Deltidial plate(s)
 - 3: Continuation of shell
- Transformational character.

This character has the capacity for further resolution (one or more deltidial plates), but this is unlikely to affect the results of the present study.

The pseudodelthyrium is also referred to as a homeodeltidium.

The antemucronal area of Polyplacophora is treated as equivalent to the brachiopod delthyrium, but is not depositionally distinct to the rest of the shell, so is coded with a distinct character state.

Coolinia pecten: Stated as “concave pseudodeltidium with median plication” – Williams et al. (2000)

Coded as “Pseudodeltidium: Covered by concave plate” by Bassett *et al.* (2001).

Heliomedusa orienta: A homeodeltidium is illustrated by Hanken and Harper (1985).

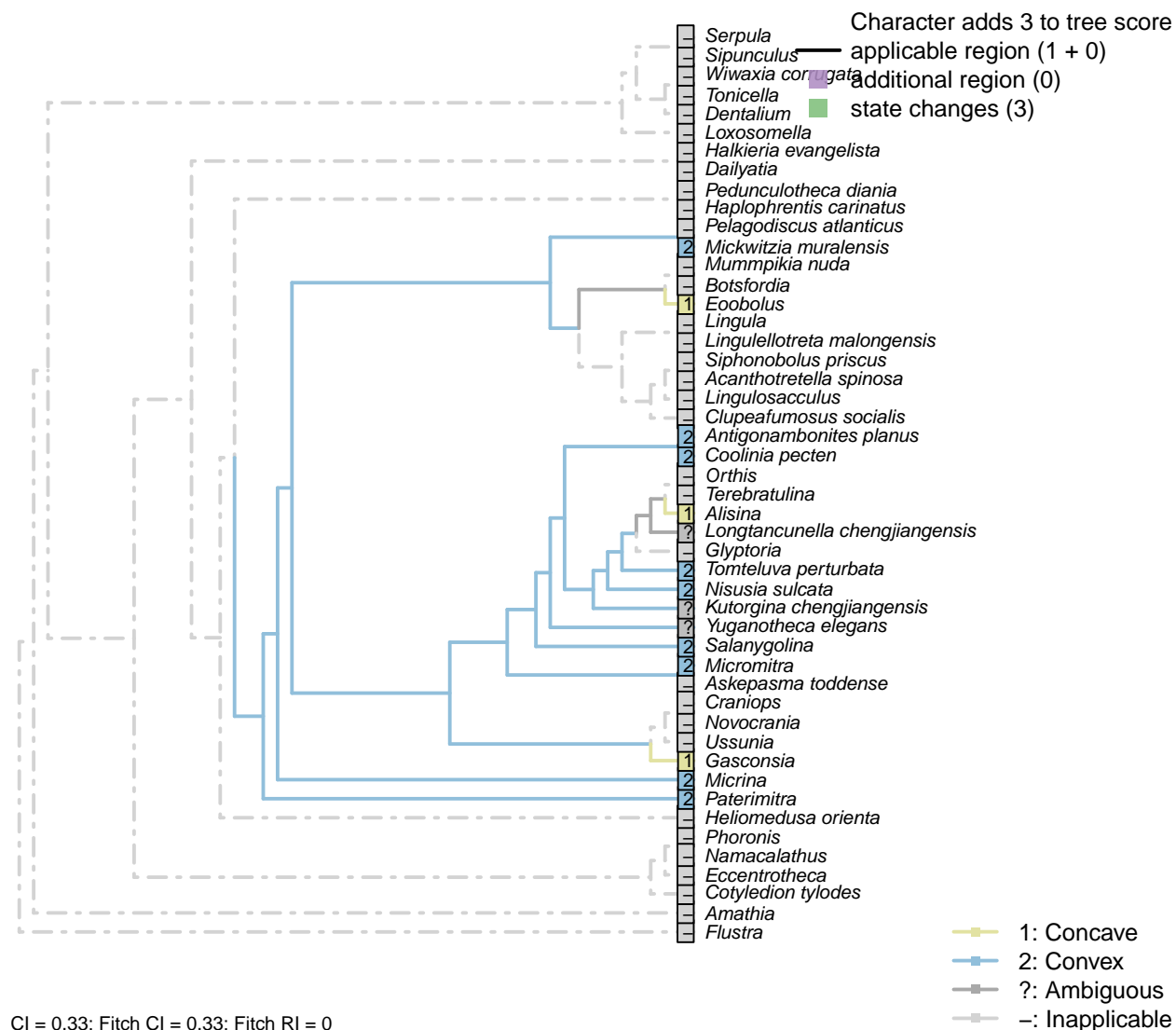
Mummpikia nuda: The subapical flange of the *Paterimitra* S1 sclerite has been homologised with the ventral homeodeltidium of *Micromitra* (Larsson et al., 2014).

Novocrania: No pseudodeltidium (Williams et al., 2000, p. 153).

Orthis: “Ventral valve convex with apsacline interarea bearing delthyrium, covered by a convex pseudodeltidium” – Holmer et al. (2008).

Salanygolina: Termed a homeodeltidium by Balthasar (2004).

[112] Posterior surface: Delthyrium: Pseudodeltidium: Shape



Character 112: Sclerites: Ventral valve: Posterior surface: Delthyrium: Pseudodeltidium: Shape

1: Concave

2: Convex

Transformational character.

A ridge-like (i.e. convex) pseudodeltidium unites *Salanygolina* with *Coolinia* and other Chileata (Holmer et al., 2009, p. 6).

Coolinia pecten: “concave pseudodeltidium with median plication” – Williams et al. (2000)

Coded as “Pseudodeltidium: Covered by concave plate” by Bassett *et al.* (2001).

Craniops: Convex (Williams et al., 2000, fig. 508).

Heliomedusa orientalis: “Narrow depressed homeodeltidium” – Hanken and Harper (1985).

Micromitra: Difficult to determine based on material presented in Zhang *et al.* (2007b), or indeed for other species in the genus (e.g. Williams et al., 2000; Skovsted and Holmer, 2005; Holmer et al., 2018b).

Orthis: Convex deltoid (Holmer et al., 2008).

Paterimitra: Gently convex (see Williams et al., 2000, fig. 83.3).

Salanygolina: Convex (see Balthasar, 2004, fig. 4B).

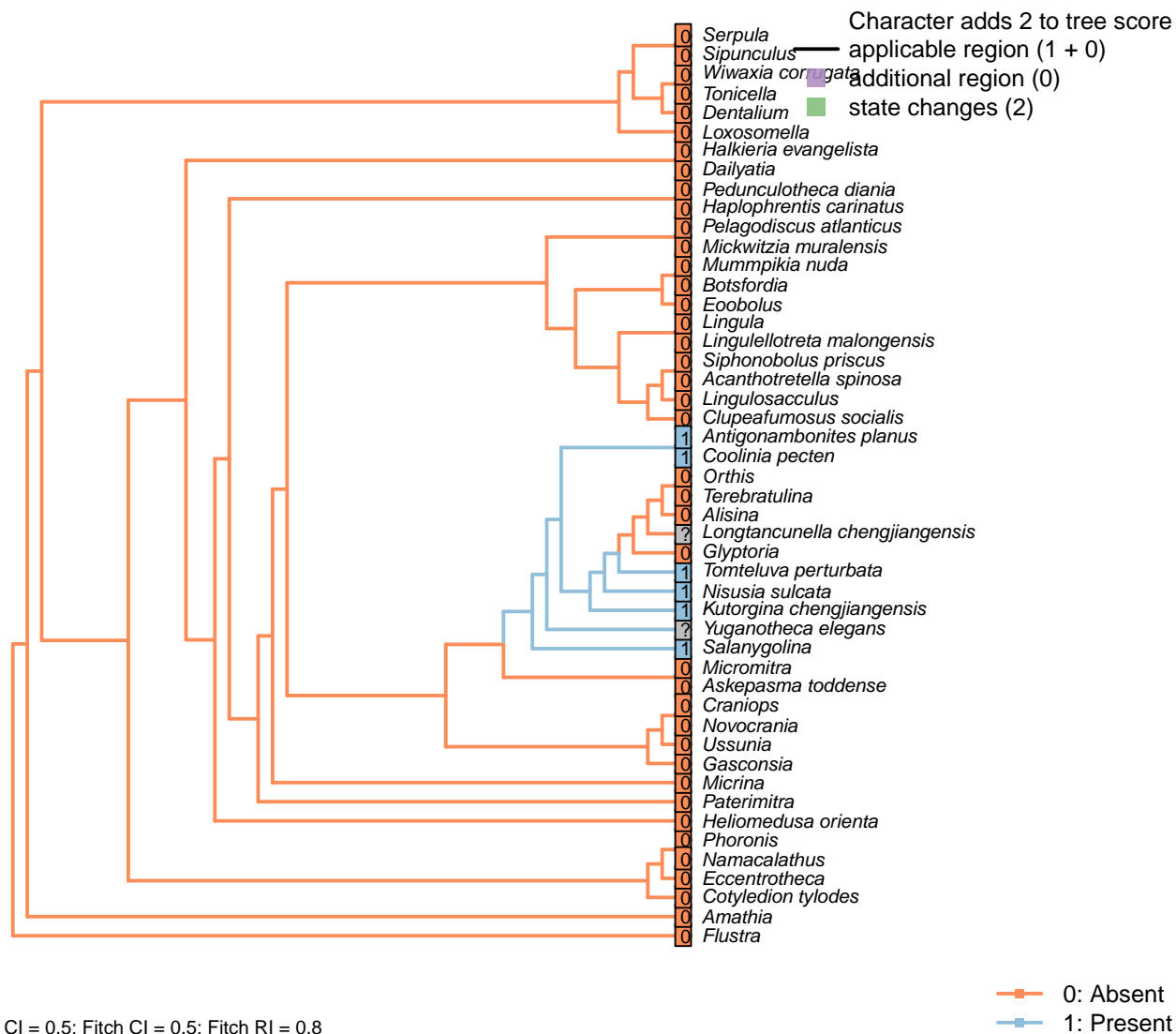
Tomteluva perturbata: Convex in *Nisusia* (see Rowell and Caruso, 1985, fig. 8.4).

NA: Gently convex (see Williams et al., 2000, fig. 83.1).

NA: Convex (Streng et al., 2016).

NA: “The presence of [...] a narrow delthyrium covered by a convex pseudodeltidium, places Salanygolinidae outside the Class Paterinata and strongly suggests affinity to the Cambrian Chileida” – Holmer et al. (2009), p. 9.

[113] Posterior surface: Delthyrium: Pseudodeltidium: Hinge furrows

**Character 113: Sclerites: Ventral valve: Posterior surface: Delthyrium: Pseudodeltidium: Hinge furrows**

0: Absent

1: Present

Neomorphic character.

After Bassett *et al.* (2001) character 18, “Hinge furrows on lateral sides of pseudodeltidium”.

Amathia, *Botsfordia*, *Clupeafumosus socialis*, *Dentalium*, *Eoobolus*, *Lingulosacculus*, *Mickwitzia muralensis*, *Micrina*, *Mummipikia nuda*, *Novocrania*, *Orthis*, *Paterimitra*, *Pelagodiscus atlanticus*, *Serpula*, *Siphonobolus priscus*, *Tonicella*, *Ussunia*, *Wiwaxia corrugata*, *Yuganotheca elegans*, NA: Absent due to inapplicability of

neomorphic character.

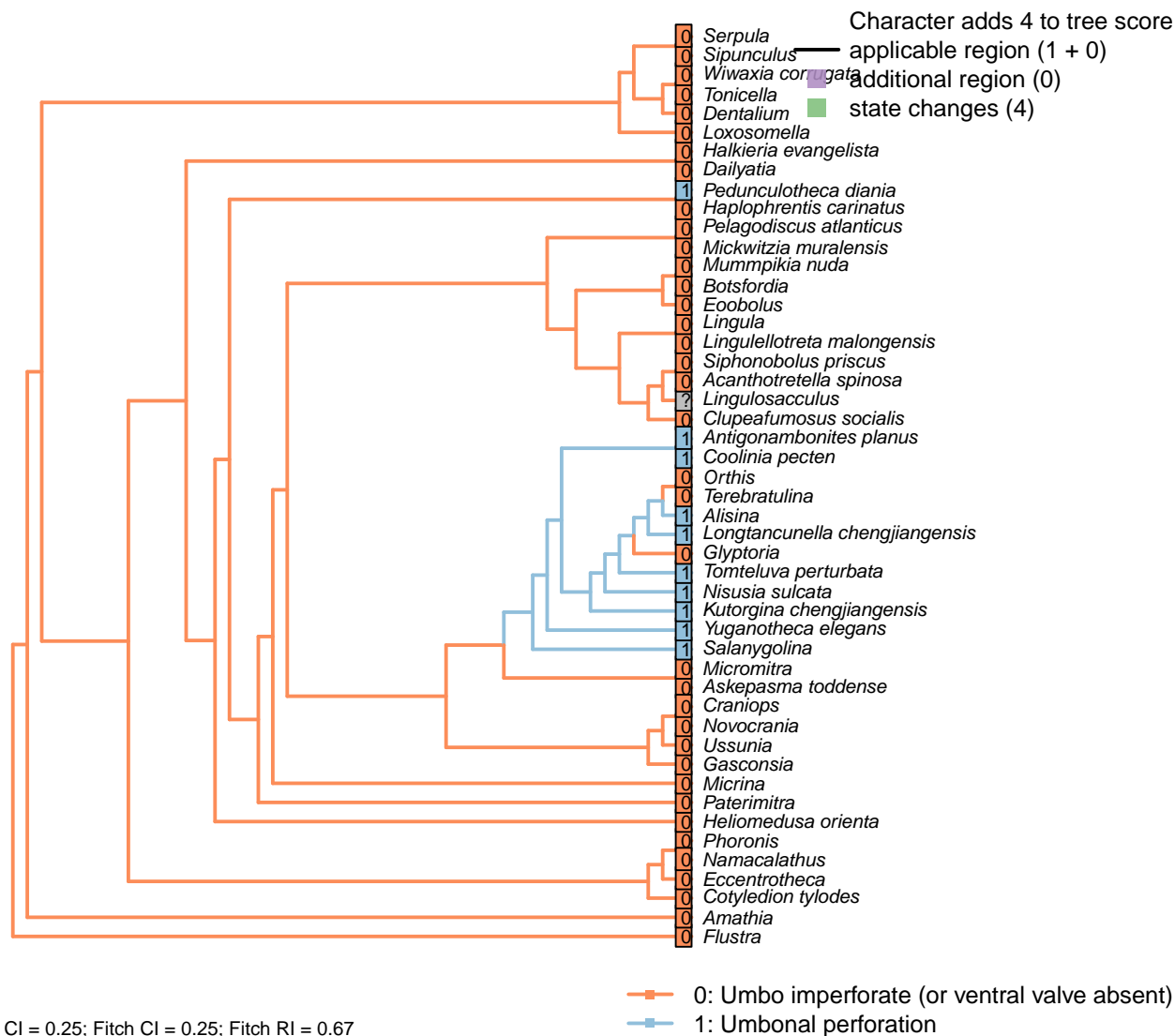
Heliomedusa orientata: Not evident or illustrated (Hanken and Harper, 1985).

Longtancunella chengjiangensis: Coded as absent in Bassett et al. (2001) (table 18.1).

Micromitra, *Tomteluva perturbata*: Coded as present in Bassett et al. (2001) (table 18.1).

NA: The presence of this feature is impossible to determine based on the available material.

[114] Umbonal perforation



Certain taxa, particularly those with a colleplax, exhibit a perforation at the umbo of the ventral valve. This opening is sometimes associated with a pedicle sheath, which emerges from the umbo of the ventral valve without any indication of a relationship with the hinge.

In contrast, the pedicle of acrotretids and similar brachiopods is situated on the larval hinge line, but is later surrounded by the posterolateral regions of the growing shell to become separated from the hinge line, and encapsulated in a position close to (or with resorption of the brephic shell, at) the umbo (see Popov, 1992, pp. 407–411 and fig. 3 for discussion). In some cases, an internal pedicle tube attests to this origin – potentially corresponding to the pedicle groove of lingulids. As such, the pedicle foramen of acrotretids and allies is not originally situated at the umbo; it is instead understood to represent a basally sealed delthyrium.

Botsfordia: The B and C sclerites of *Dailyatia* bear small umbonal perforations (Skovsted et al., 2015), but these are not considered to be homologous with the ventral valve, so this character is coded as inapplicable – though the possibility that the perforations are equivalent is intriguing.

A1 sclerites typically have a pair of perforations, which are conceivably equivalent to the setal tubes of *Micrina* (Holmer et al., 2011). The A1 sclerite of *D. bacata* has a structure that is arguably similar to the ‘colleplax’ of *Paterimitra*. But the homology of any of these structures to the umbonal aperture of brachiopods is difficult to establish.

Lingulosacculus: The sclerites of *Eccentrotheca* form a ring that surrounds the inferred attachment structure; the attachment structure does not emerge from an aperture within an individual sclerite. Thus no feature in *Eccentrotheca* is judged to be potentially homologous with the apical perforation in bivalved brachiopods.

Mickwitzia muralensis: The apical termination of the fossil is unknown.

Micrina: There is “compelling evidence to demonstrate that the putative pedicle illustrated by Chen *et al.* (2007, Figs. 4, 6, 7) in fact is the mold of a three-dimensionally preserved visceral cavity.” – Zhang et al. (2009).

Salanygolina: The umbo itself is imperforate (Balthasar, 2004).

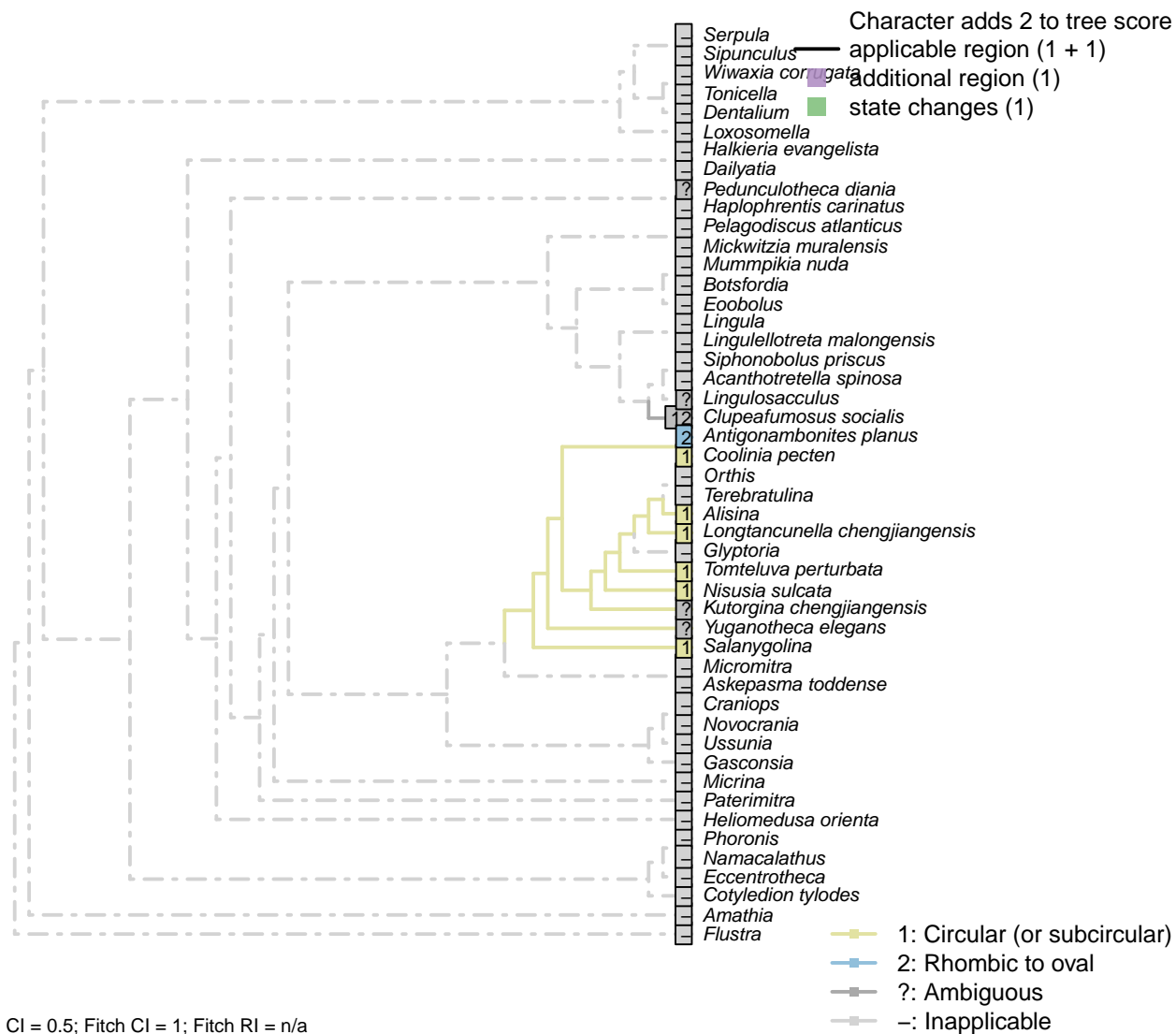
Ussunia: The presumed pedicle foramen reported by Topper *et al.* (2013a) is at the ventral valve umbo. No evidence of an internal pedicle tube is present, but we follow Popov (1992) in inferring the encapsulation of the pedicle foramen.

NA: The presumed pedicle foramen is an opening between the S1 and S2 sclerites, neither of which are perforated (Skovsted et al., 2009).

NA: Streng *et al.* (2016) observe “an internal tubular structure probably representing the ventral end of the canal within the posterior wall of the pedicle tube”, but do not consider this tomteluid dube to be homologous with the pedicle tube of acrotretids and their ilk, stating (p. 274) that it appears to be unique within Brachiopoda.

NA: Prominent subcircular perforation at umbo associated with an internal pedicle tube (Popov et al., 2009), thus presumed to share an origin with the acrotretid pedicle foramen.

[115] Umbonal perforation: Shape



score it as (sub) circular.

Micrina: Rhombic to oval – seen as evidence for a discinid affinity (Chen et al., 2007).

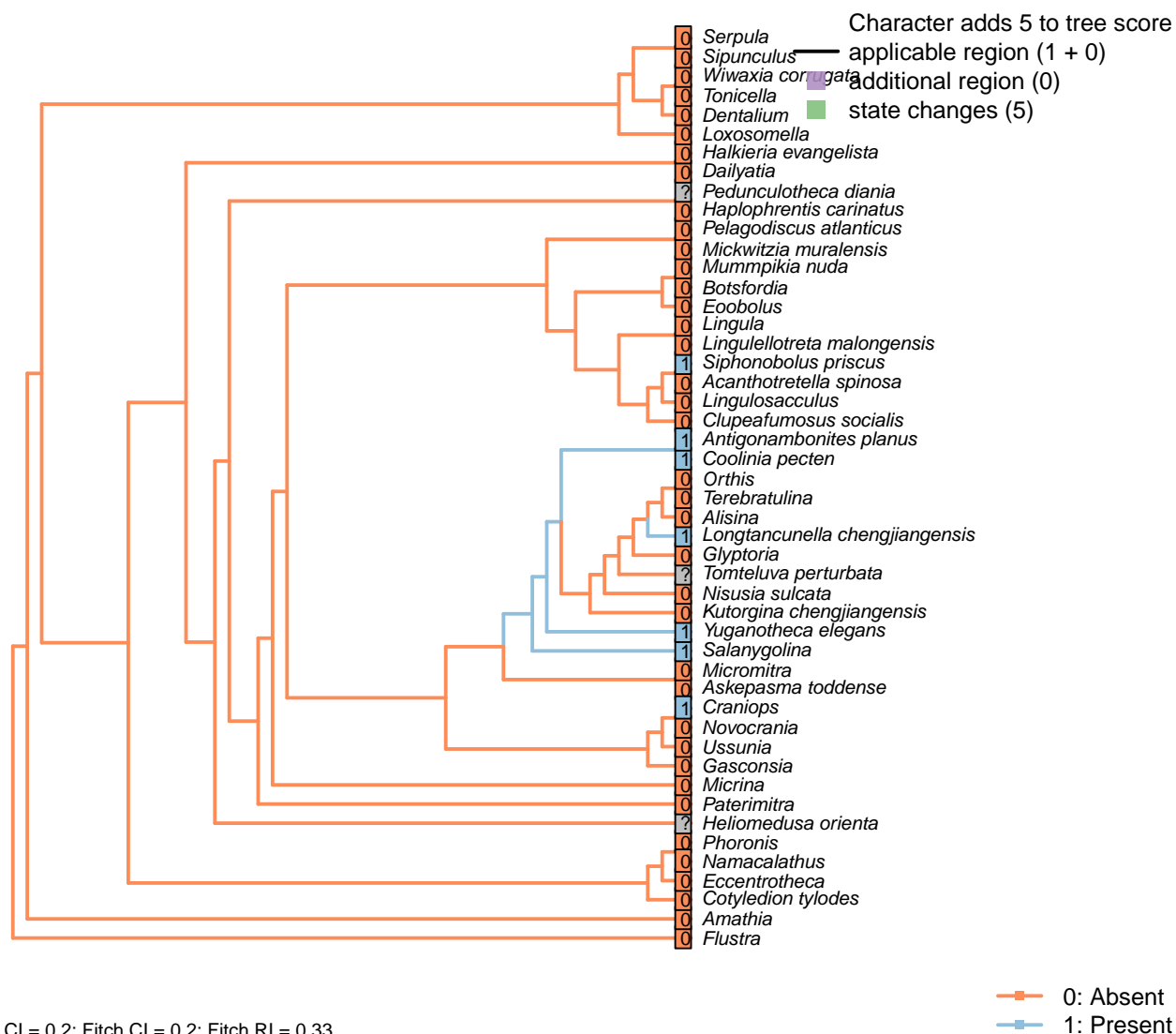
Micromitra: The exact size and shape of the apical perforation is obscured by the emerging pedicle.

Tomteluva perturbata: “close to circular” (Holmer et al., 2018a).

Ussunia: Taller than wide in some cases, but very nearly circular in others; see Topper et al. (2013a).

NA: Essentially circular (Holmer et al., 2009, fig. 4).

[116] Colleplax, cicatrix or pedicle sheath



Character 116: Sclerites: Ventral valve: Colleplax, cicatrix or pedicle sheath

0: Absent

1: Present

Neomorphic character.

In certain taxa, the umbo of the ventral valve bears a colleplax, cicatrix or pedicle sheath; Bassett *et al.* (2008) consider these structures as homologous.

Gasconsia: Following Williams *et al.* (1998), appendix 2.

Glyptoria: *Paracraniops* is “externally similar to *Craniops*, but lacking cicatrix” – indicating that *Craniops* bears a cicatrix (Williams *et al.*, 2000). Also coded as present in their table 15.

Kutorgina chengjiangensis: Following table 15 in Williams *et al.* (2000).

Micrina: A cicatrix was reconstructed by Jin and Wang (1992) (figs 6b, 7), but has not been reported by later authors; possibly, as with the ‘pedicle foramen’ of Chen *et al.* (2007), this structure represents internal organs rather than a cicatrix proper (Zhang *et al.*, 2009); as such it has been recorded as ambiguous.

Micromitra: The umbonal region of kutorginides “clearly lacks a pedicle sheath” (Holmer *et al.*, 2018b).

Mummpikia nuda: The pedicle is identified as such (rather than a pedicle sheath) by the internal pedicle tube.

Nisusia sulcata: A ring-like structure surrounding the pedicle is interpreted as a colleplax (Zhang *et al.*, 2011a), though the authors make no comparison with the pedicle capsule exhibited by extant terebratulids (see Holmer *et al.*, 2018a).

Orthis: Absent in *Micrina* (Holmer *et al.*, 2011).

Pelagodiscus atlanticus: The flat apical termination of juvenile individuals possibly functioned as colleplax for attachment, but may simply represent the brephic shell; we treat it as ambiguous to reflect this potential homology.

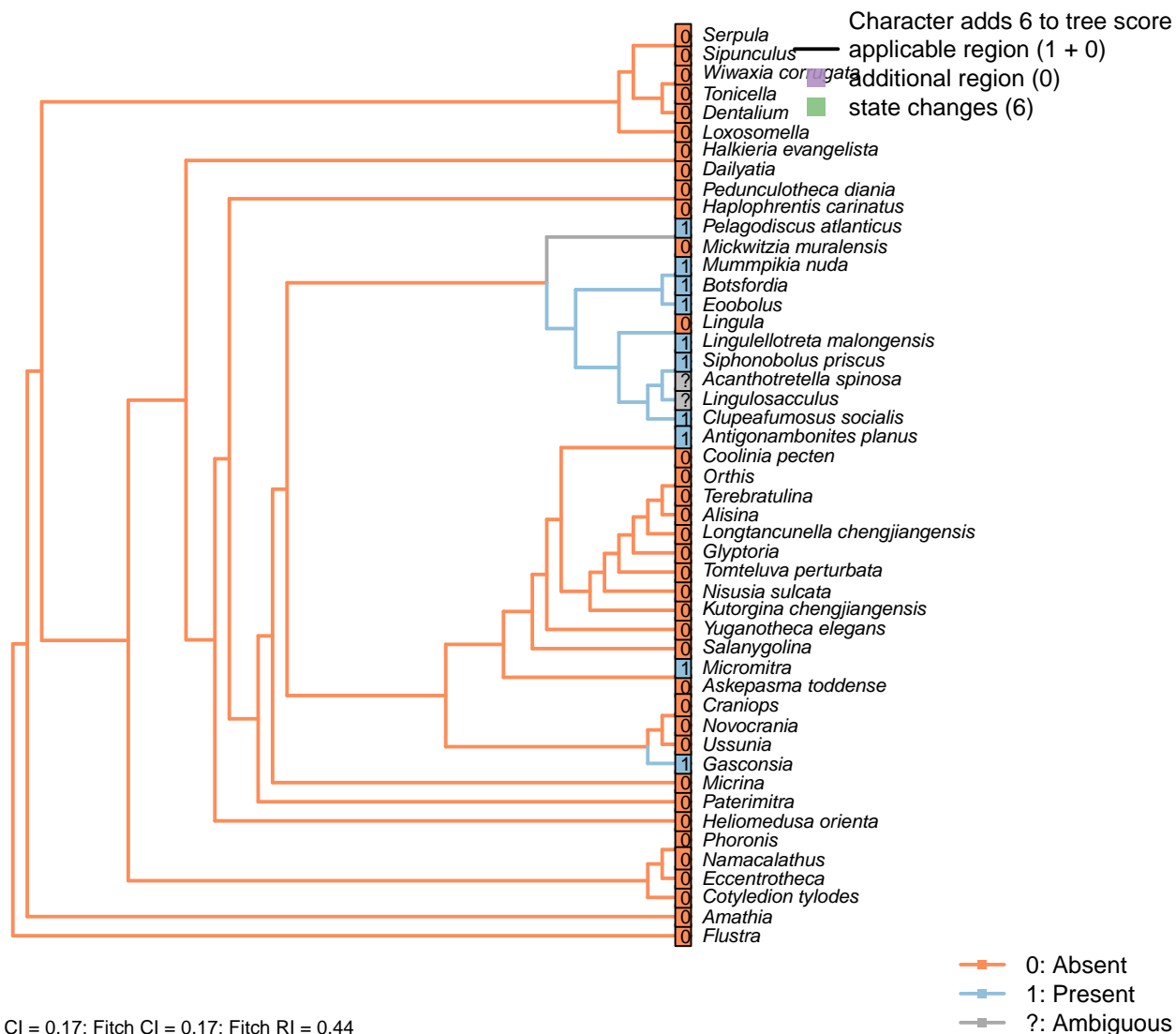
Ussunia: Not reported by Topper *et al.* (2013a).

NA: The internal canal associated with the pedicle is unique to the tomteluvids, and has an uncertain identity (Streng *et al.*, 2016). It could conceivably correspond to an internalized pedicle sheath or an equivalent structure, so this feature is coded as ambiguous here.

NA: The median collar or conical tube is conceivably homologous with the pedicle sheath.

NA: Coded as present in view of the attachment scar, which has been considered homologous with the “adult colleplax and foramen with attachment pad” in *Salanygolina* (Popov *et al.*, 2009).

[117] Median septum

**Character 117: Sclerites: Ventral valve: Median septum**

0: Absent

1: Present

Neomorphic character.

Chen *et al.* (2007) observe a median septum in what they interpret as the ventral valve of *Heliomedusa*, and the ventral valve of *Discinisca*, which they propose points to a close relationship.

Amathia: The carina of *H. carinatus* is an angular elevation of the ventral valve surface, rather than a septum growing inward on the interior of shell.

Clupeafumosus socialis: Carbonaceous preservation confounds the identification of internal shell structures;

it is possible that this feature is present, but not observable in the Burgess Shale material.

Eoobolus: Valve thin and often unmineralized.

Gasconsia: Following Williams et al. (1998), appendix 2.

Heliomedusa orientalis: Evident in moulds of ventral valve (Hanken and Harper, 1985; Watkins, 2002).

Kutorgina chengjiangensis: Following char. 42 in table 15 in Williams et al. (2000).

Lingulellotreta malongensis: Prominent median septum (fig. 4d, e in Balthasar, 2009).

Longtancunella chengjiangensis: Neither evident nor reported in Williams et al. (2000).

Micrina: Reported on ‘ventral’ valve by Chen et al. (2007); we consider the ‘ventral’ valve to be the dorsal valve.

Mummpikia nuda: Medial septum visible in ventral valve in Williams et al. (2000), fig. 34.1c.

Paterimitra: Ventral ridge characteristic of *Micromitra* (Skovsted and Peel, 2010).

Serpula: Described as present in *Discinisca* by Chen et al. (2007); assumed present also in *Pelagodiscus*.

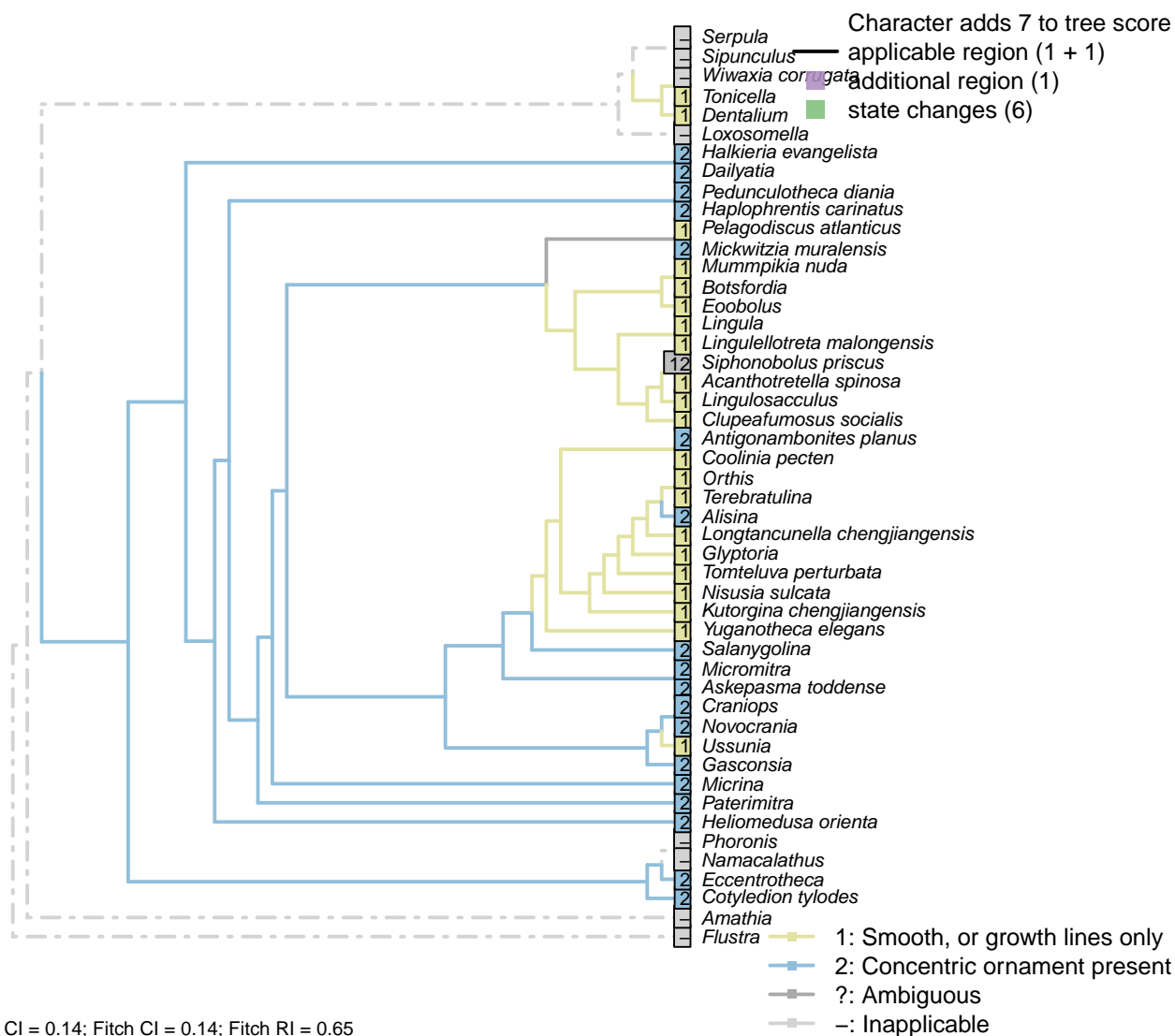
Siphonobolus priscus: “Some specimens also reveal that the vault had a slight median septum, which is now visible as a notch or a groove dividing the right from the left part” – Balthasar (2008).

Ussunia: A short medial ridge (septum) is present in the ventral valve (Topper et al., 2013a).

NA: Present; see Popov et al. (2009), fig. 5J.

3.22 Sclerites: Ornament

[118] Concentric ornament



Character 118: Sclerites: Ornament: Concentric ornament

- 1: Smooth, or growth lines only
 - 2: Concentric ornament present
- Transformational character.

After character 11 in Williams *et al.* (1998). Coded as transformational as it is possible that maintaining a smooth shell without occasional prominent ridges requires greater secretory control.

Acanthotretella spinosa: No prominent ornamentat in *Tonicella* (Connors et al., 2012).

Amathia: A series of regularly spaced concentric ridges adorn both valves (Moysiuk et al., 2017); these are

more pronounced than mere growth lines.

Antigonambonites planus: Ridges in shell parallel, but are more prominent than, growth lines.

Eoobolus: Irregular ridges externally (Williams et al., 2000).

Gasconsia: Following Williams et al. (1998), appendix 2.

Pustules are arranged along concentric growth lines (Skovsted and Holmer, 2005), so are not treated as a distinct ornamentation.

Lingulosacculus: More or less concentric ridges occur on *Eccentrotheca* sclerites (Skovsted et al., 2011).

Longtancunella chengjiangensis, *Micromitra*, *Novocrania*, *Paterimitra*, NA: Following appendix 2 in Williams et al. (1998).

Micrina: The ornament on shell exterior is described as concentric fila (Chen et al., 2007, P.43), and also scored as it in Williams et al. (2000, pp.160–163).

Pelagodiscus atlanticus: A series of regularly spaced concentric ridges adorn the ventral valve; comparatively less regular lines ornament the operculum.

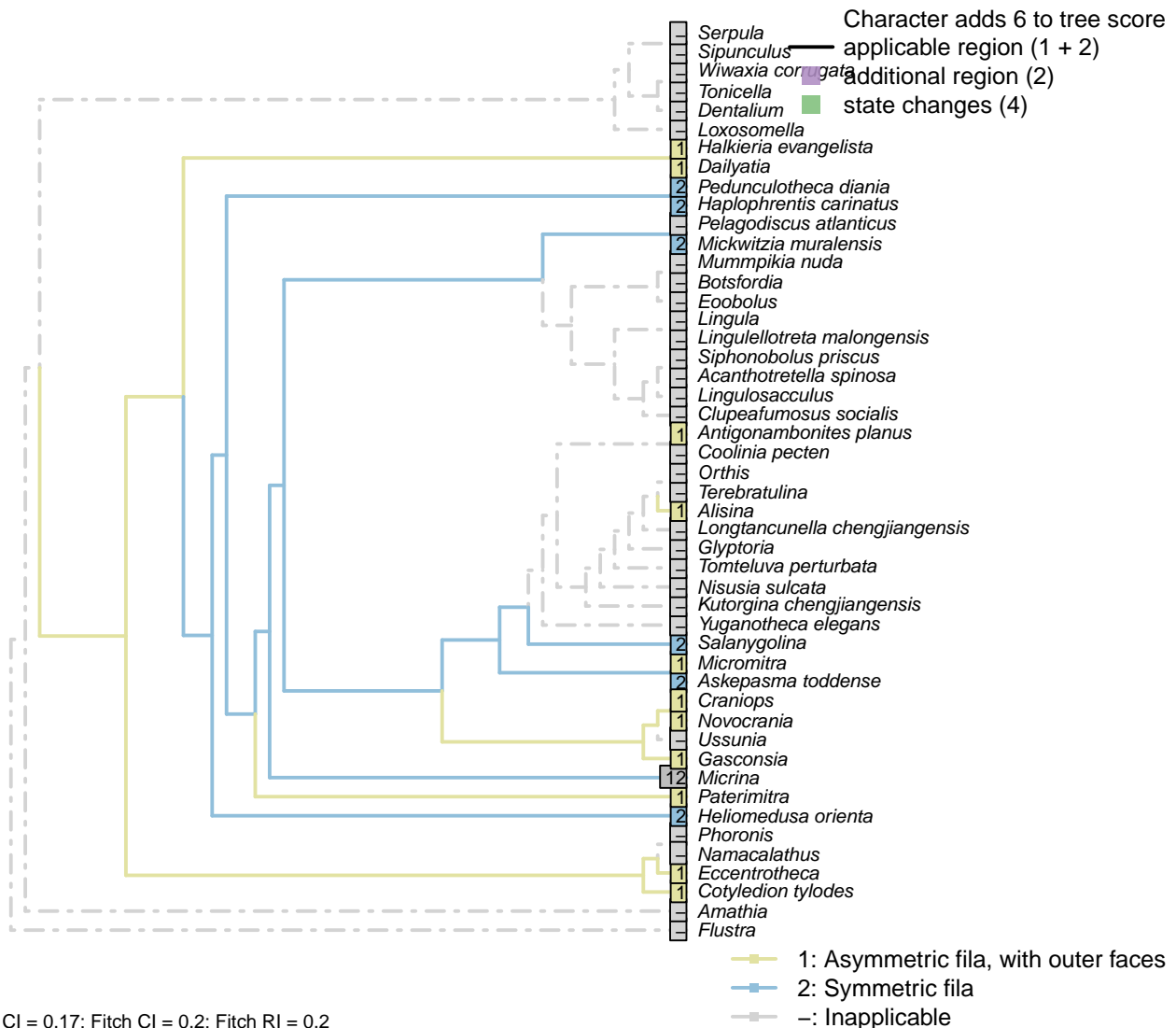
Salanygolina: Symmetric fila.

Serpula: Only growth lines evident (Williams et al., 2000).

Terebratulina: Zhang et al. (2013).

Tonicella: Single ridge evident in Williams et al. (2006) fig. 1425.1a interpreted as interruption of growth rather than inherent feature, so coded as absent (i.e. smooth).

[119] Concentric ornament: Symmetry

**Character 119: Sclerites: Ornament: Concentric ornament: Symmetry**

1: Asymmetric fila, with outer faces

2: Symmetric fila

Transformational character.

After character 11 in Williams *et al.* (1998).*Botsfordia*: Clear asymmetry (Skovsted *et al.*, 2015).*Coolinia pecten*: Seemingly asymmetric (Williams *et al.*, 2000, fig. 122.3c; Zhang *et al.*, 2011b, Fig. 1).*Eoobolus*: Clear outer faces (Williams *et al.*, 2000, fig. 100.2b).*Heliomedusa orienta*: Assymmetric (Hanken and Harper, 1985, fig. 3).*Lingulosacculus*: Ornament, such as it is, is asymmetric, with prominent outer faces (Skovsted *et al.*, 2011).*Longtancunella chengjiangensis*, *Micromitra*, *Novocrania*, *Paterimitra*, NA: Following appendix 2 in Williams

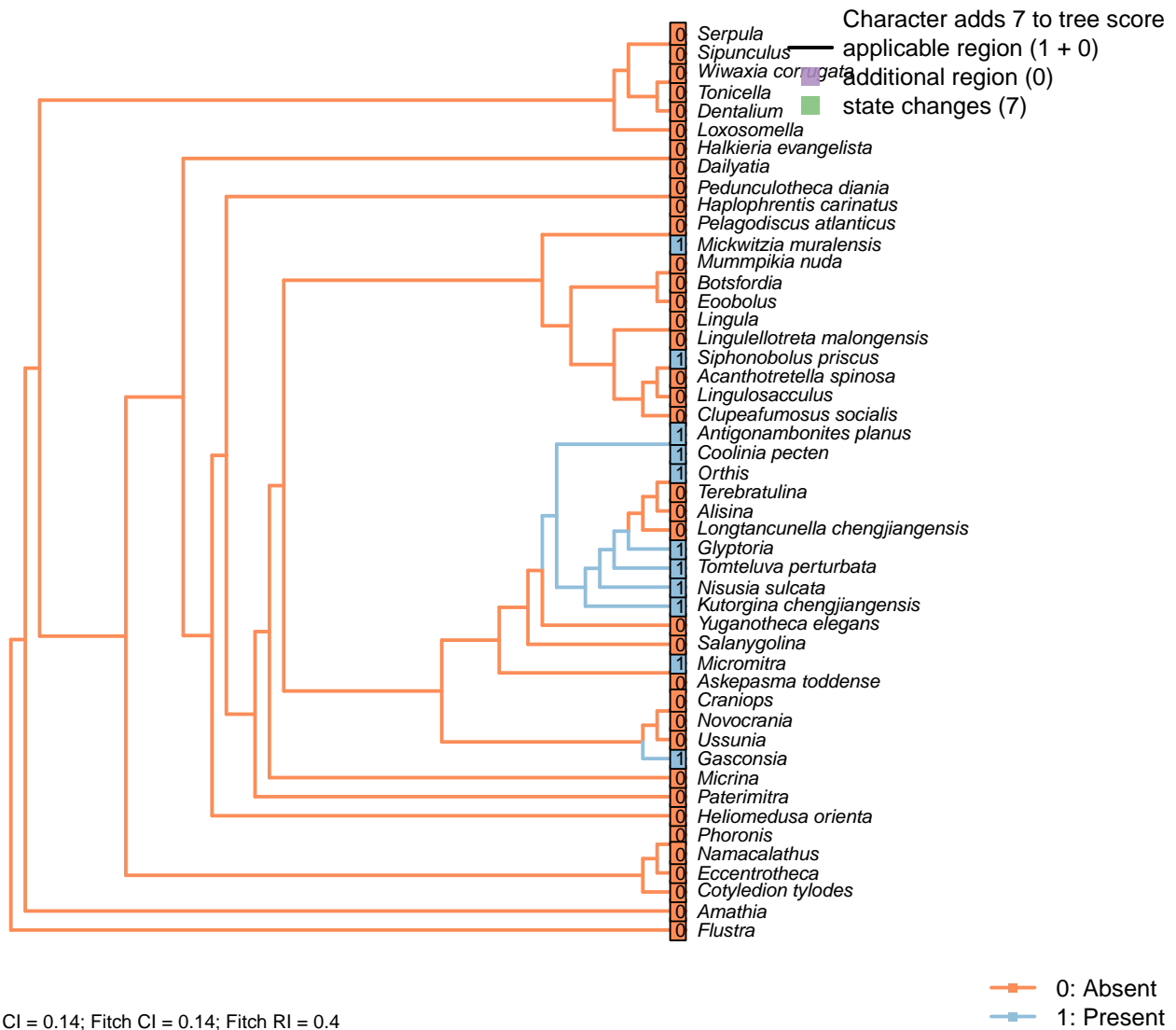
et al. (1998).

Micrina: See fig. 1715 in Williams *et al.* (2007).

Orthis: No obvious asymmetry, even if not obviously symmetric either (Holmer *et al.*, 2008). Coded as ambiguous.

Salanygolina: Symmetric fila (Balthasar, 2004).

[120] Radial ornament



Ridges radiating from umbo, i.e. ribs.

Gasconsia: Following Williams et al. (1998), Appendix 2.

Heliomedusa orientalis: “Ornament of indistinct low radial ribs” – Williams et al. (2000, p167).

Kutorgina chengjiangensis: Unornamented.

Lingulellotretra malongensis: Very faint costellae in some specimens but coded absent.

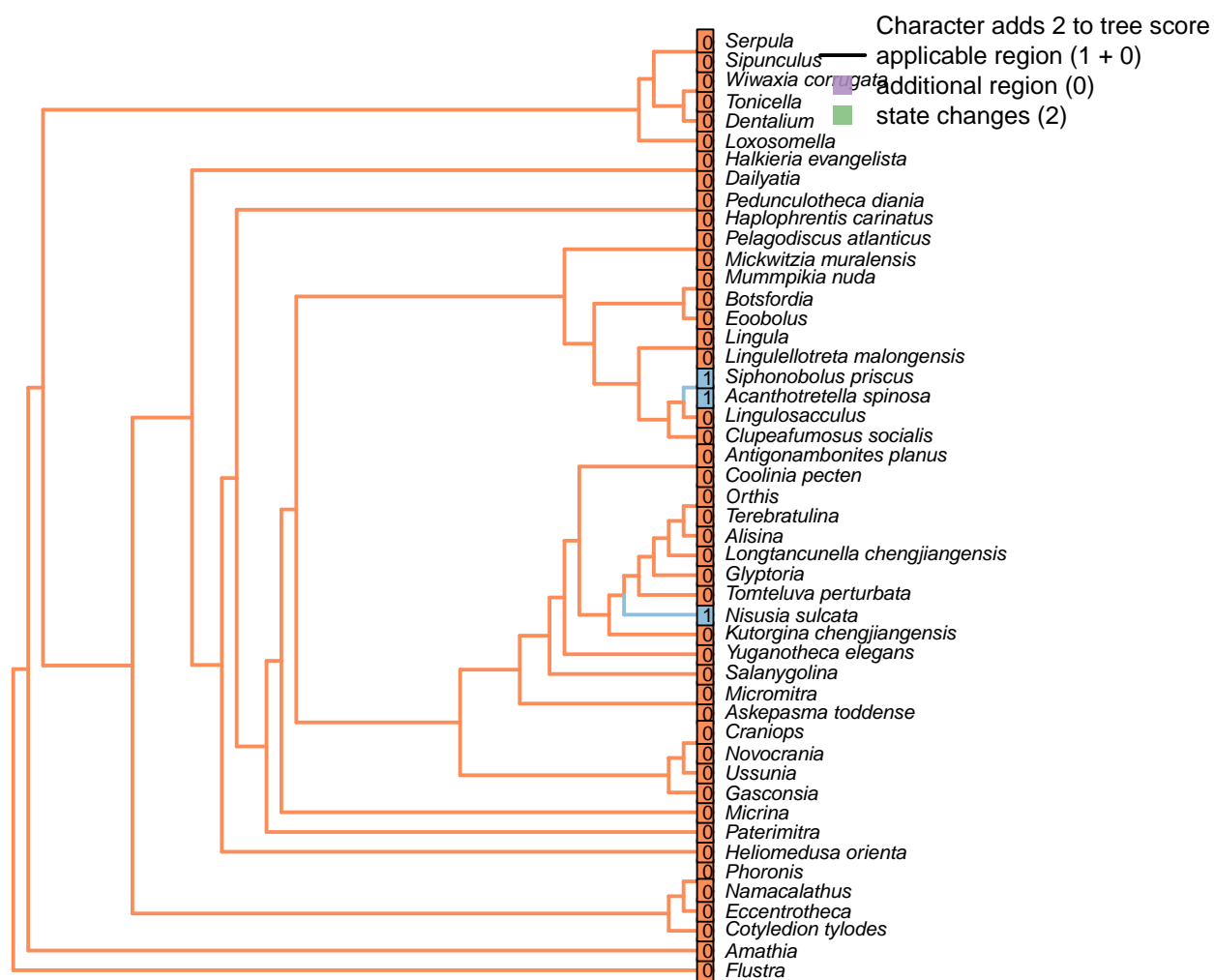
Longtancunella chengjiangensis: “Coarsely costate” – Williams et al. (2000, p710).

Micrina: See fig. 1715 in Williams et al. (2007).

Novocrania: “Ornament of irregularly developed, concentric growth lamellae; microornament of irregularly arranged, polygonal pits” – Williams et al. (2000), p153; figs on p.155.

NA: “Indistinct radial ribs accentuated by radial rows of tubercles” – Popov et al. (2009).

[121] Shell-penetrating spines



CI = 0.5; Fitch CI = 0.5; Fitch RI = 0.5

0: Absent
1: Present

Character 121: Sclerites: Ornament: Shell-penetrating spines

0: Absent

1: Present

Neomorphic character.

Mineralized or partly mineralized spines are observed in *Heliomedusa* and *Acanthotretella*.

Acanthotretella spinosa: Aesthete canals penetrate the main valves of certain chitons, but are not equivalent to the shell-penetrating spines of brachiopods.

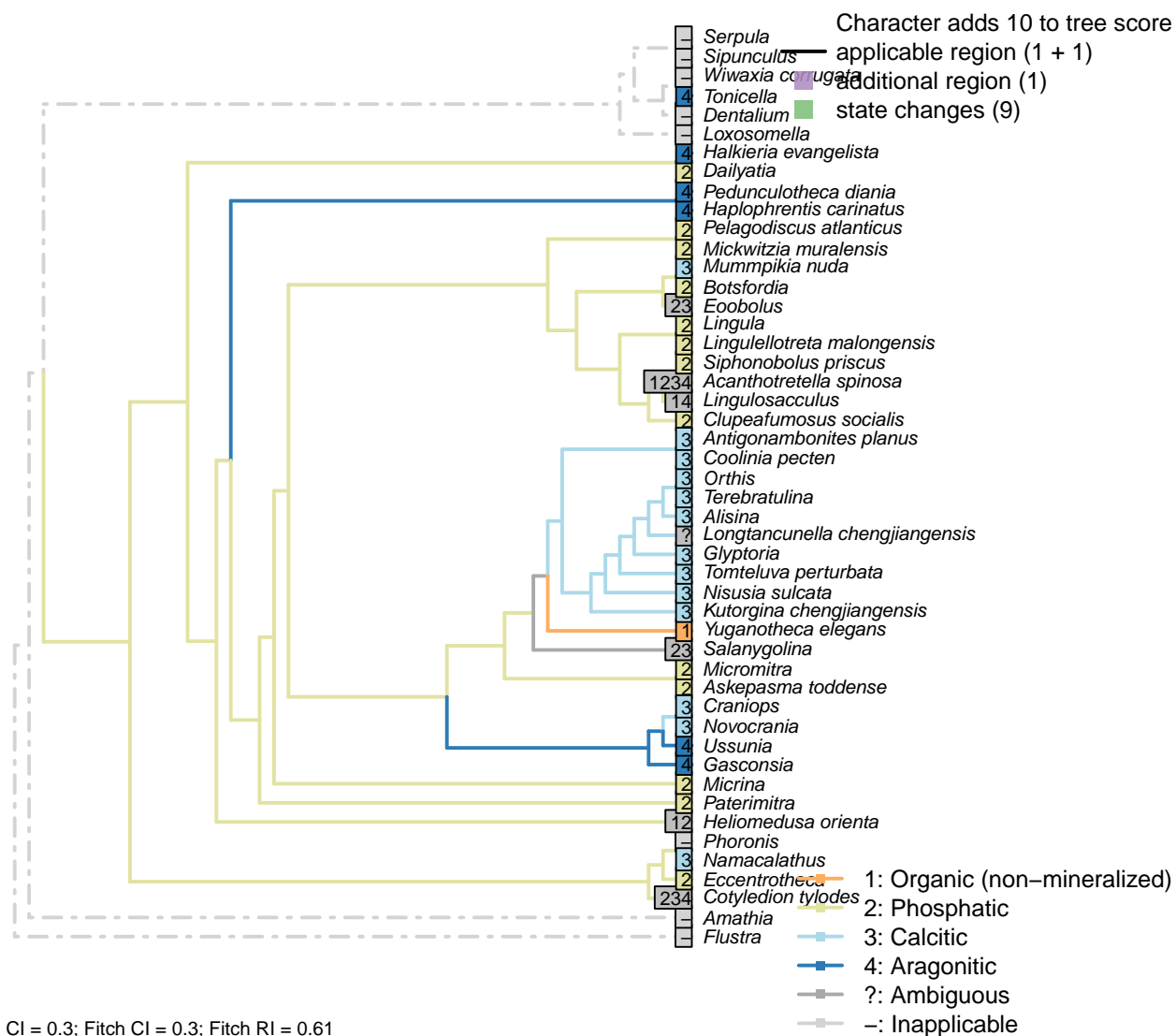
Longtancunella chengjiangensis: Neither evident nor reported in Williams *et al.* (2000).

Micrina: The ‘spines’ reported by Chen *et al.* (2007) are pyritized spinelike setae – see pp. 2580–2590 in Williams *et al.* (2007).

Tomteluva perturbata: Bears numerous small, hollow spines (Williams *et al.*, 2000).

3.23 Sclerites: Composition

[122] Mineralogy



Character 122: Sclerites: Composition: Mineralogy

- 1: Organic (non-mineralized)
 - 2: Phosphatic
 - 3: Calcitic
 - 4: Aragonitic
- Transformational character.

Clupeafumosus socialis: Holmer & Caron (2006) note the absence of brittle breakage, interpreted as indicating the absence of a material mineralized component to the shells. The preservation is strikingly different from that of other Burgess Shale brachiopods, ruling out a primarily calcitic or phosphatic composition. The two-dimensional nature of the preservation also differs from that of co-occurring aragonitic taxa (hyoliths; Holmer and Caron, 2006, p. 273), indicating that any mineralization was minor at best.

Holmer & Caron (2006, p. 286) suggest that it is more likely that a (minor) mineral component was present

than that it was not, though without providing an uncontested rationale. To be as conservative as possible, we therefore code this taxon as ambiguous.

Eoobolus: Ventral valve uncalcified in extant forms or sometimes thin (Williams et al., 2000), but coded as calcitic as calcite-mineralizing pathways are present.

Glyptoria: Shell calcitic.

Heliomedusa orientalis: Confirmed in Trimerella by Balthasar et al. (2011).

Kutorgina chengjiangensis: Trimerellids were probably aragonitic (Williams et al., 2000).

Lingulellotreta malongensis: “the original shell of *Eoobolus* contained small calcareous grains that were incorporated into organic-rich layers alongside apatite” (Balthasar, 2007).

Mickwitzia muralensis: The absence of relief in *Lingulosacculus* rules out a phosphatic or calcitic composition, but co-occurring (and presumably aragonitic) hyolithids are preserved in the same fashion. Its constitution was thus either organic or aragonitic (Balthasar and Butterfield, 2009).

Micrina: “Shell originally organophosphatic, but may generally have been poorly mineralized” – Williams et al. (2007) – cf. *ibid.*, p. 2889, “These strong similarities to discinoids in soft-part anatomy imply that the *Heliomedusa* shell was chitinous or chitinophosphatic, not calcareous.”

Mummpikia nuda: Coded as phosphatic by Zhang et al. (2014), but with no explanation.

Cracks within shells of Chengjiang specimens (e.g. Zhang et al., 2007a, fig. 3) demonstrate that the shells were originally mineralized, but not the identity of the original biomineral. This said, phosphatized material from Kazakhstan (Holmer et al., 1997) is attributed to the same species; presuming this phosphate to be original and the material to be conspecific, *L. malongensis* is coded as having phosphatic shells.

Nisusia sulcata: “The original composition of the shell cannot be determined with certainty”, though it was “most probably entirely soft and organic” – Zhang et al. (2011a).

Salanygolina: Calcite and silica deemed diagenetic by Balthasar (2004).

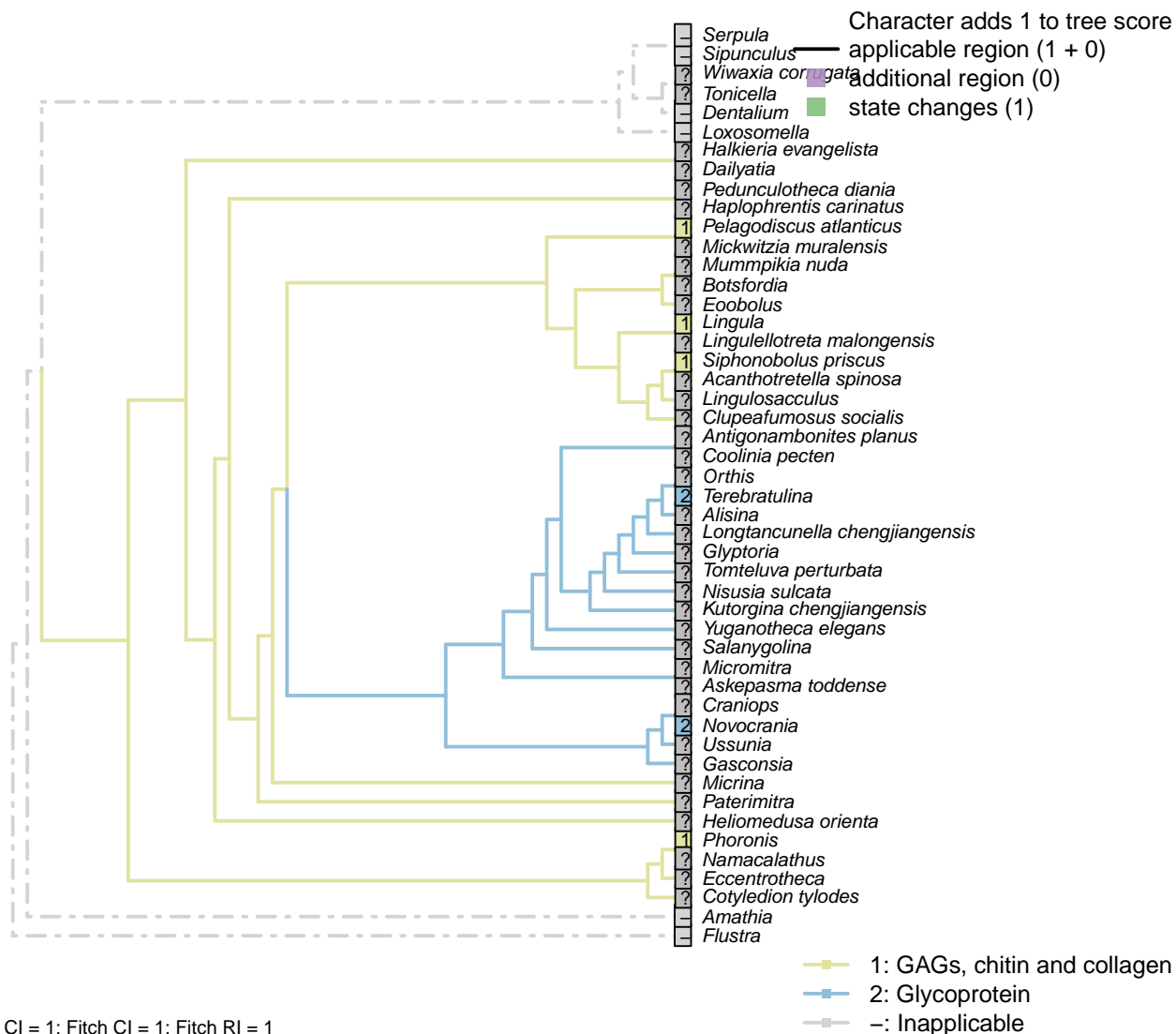
Siphonobolus priscus: Identified as calcareous by preservational criteria, and description “primary calcitic shells of *M. nuda*” (Balthasar, 2008).

Terebratulina: The extensive relief and association with pyrite framboids indicates original mineralization, but the identity of the biomineral remains uncertain (Zhang et al., 2013).

Ussunia: Phosphatic – hence the conventional placement within Linguliformea.

NA: Original mineralogy unknown, but known to be mineralised and anticipated to be phosphatic (Holmer et al., 2009).

[123] Cuticle or organic matrix

**Character 123: Sclerites: Composition: Cuticle or organic matrix**

1: GAGs, chitin and collagen

2: Glycoprotein

Transformational character.

Williams *et al.* (1996) identify glycoprotein-based organic scaffolds as distinct from those comprising glycosaminoglycans (GAGs), chitin and collagen. This character can only be scored for extant taxa.

Dentalium: Coded as GAGs, chitin and collagen in lingulids by Williams *et al.* (1996).

Eoobolus: Coded as glycoprotein for craniids by Williams *et al.* (1996).

Serpula: Coded as GAGs, chitin and collagen in discinids by Williams *et al.* (1996).

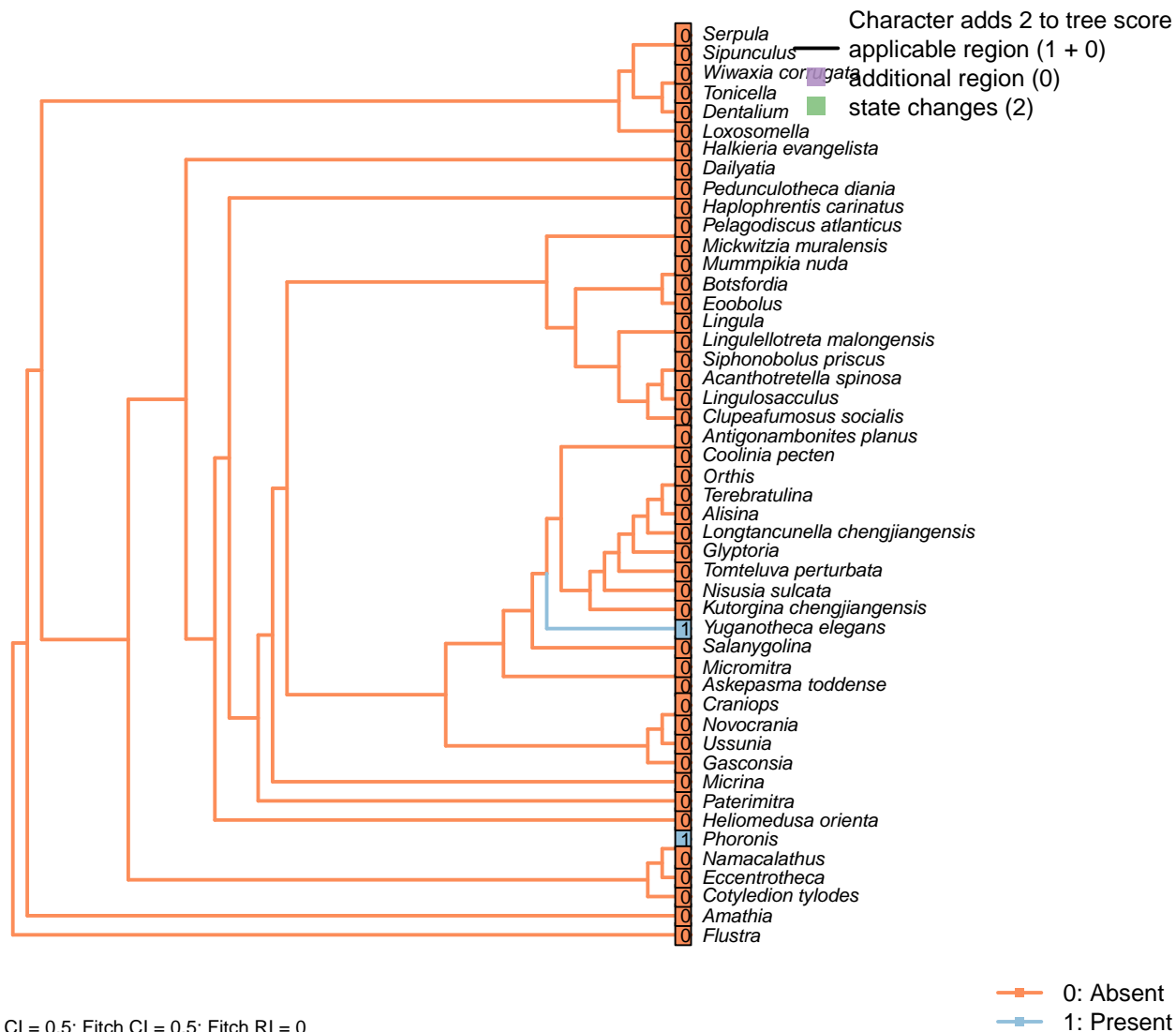
Tonicella: Coded as glycoprotein for terebratulids by Williams *et al.* (1996).

Wiwaxia corrugata: “The presence of sulphated glycosaminoglycans (GAGs) in the chitinous cuticle of *Phoronis* (Herrmann, 1997, p. 215) would suggest a link with linguliforms, as GAGs are unknown in rhynchonelli-

form shells (Fig. 1891, 1896)” – Williams et al. (2007), p. 2830.

NA: Lenticular chambers in siphonotretid shells interpreted as degraded GAG residue (Williams et al., 2004).

[124] Incorporation of sedimentary particles



Character 124: Sclerites: Composition: Incorporation of sedimentary particles

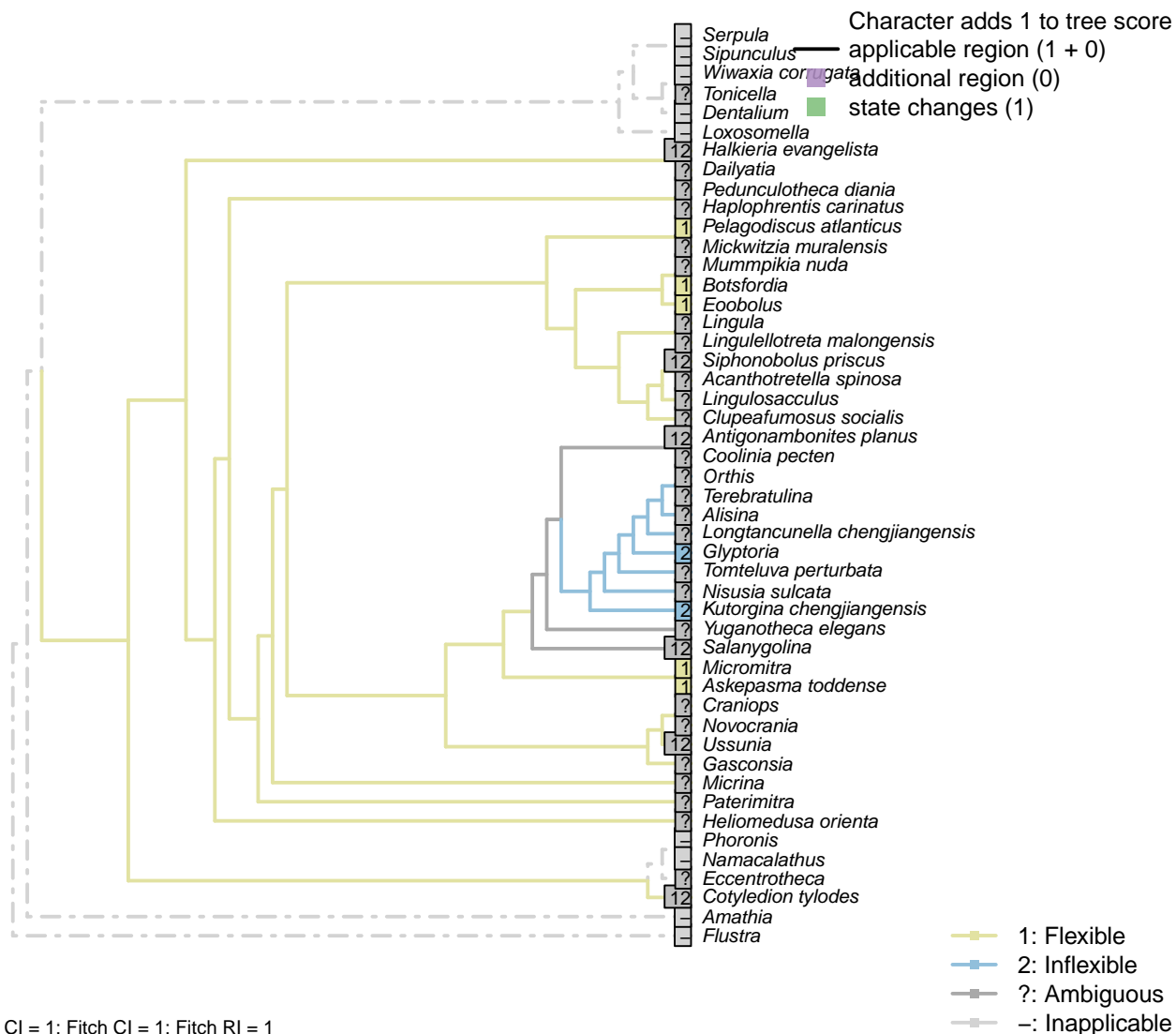
0: Absent

1: Present

Neomorphic character.

Phoronids and *Yuganotheca* agglutinate particles into their sclerites.

[125] Periostracum: Flexibility

**Character 125: Sclerites: Composition: Periostracum: Flexibility**

1: Flexible

2: Inflexible

Transformational character.

Following character 9 in Williams *et al.* (1998); see their p228–230 for a discussion of how this might be inferred from fossil material.

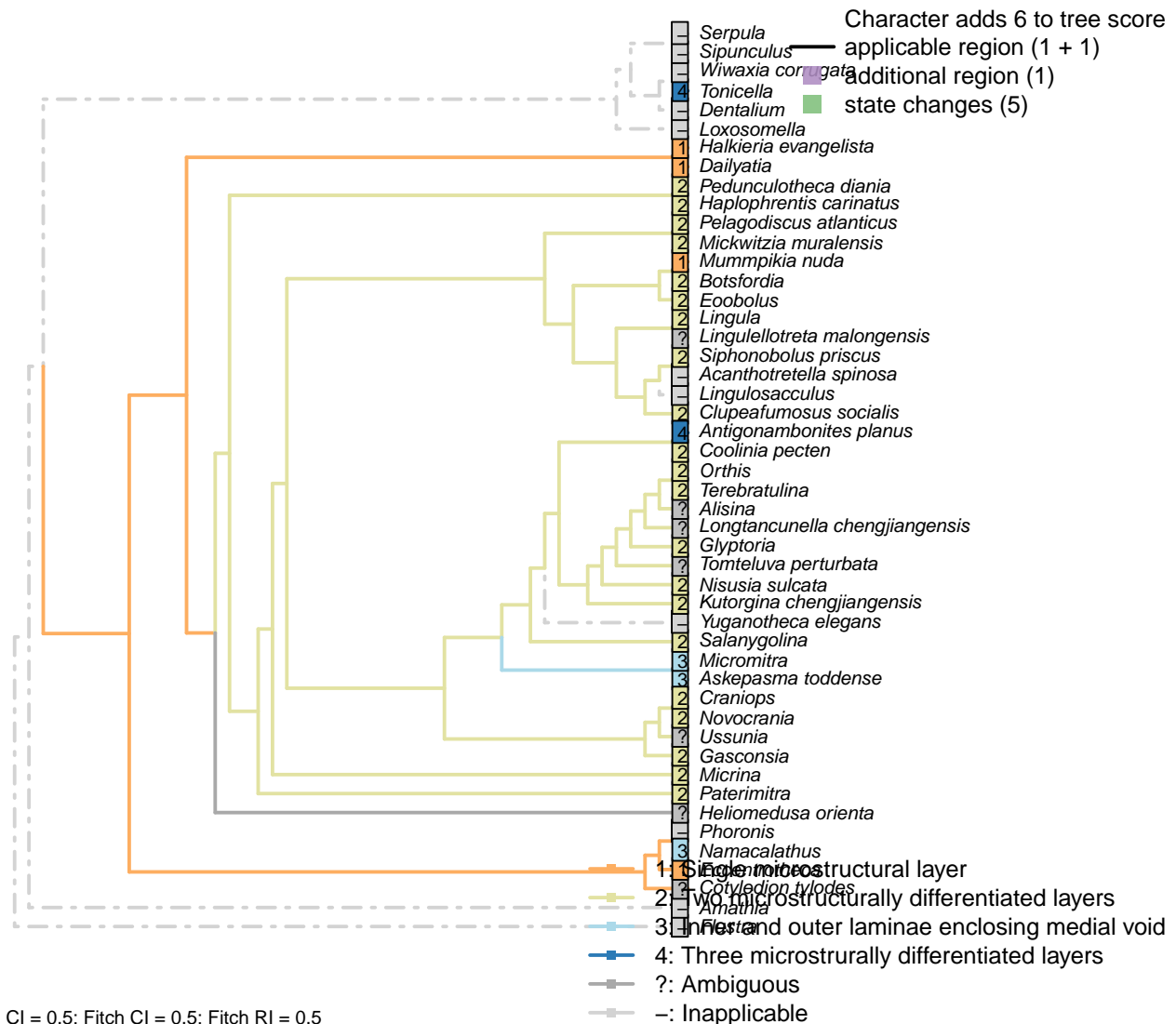
Gasconsia, *Lingulellotretra malongensis*: Coded as flexible in Williams *et al.* (1998), Appendix 2.

Longtancunella chengjiangensis, *Micromitra*, *Novocrania*, *Paterimitra*: Following appendix 2 in Williams *et al.* (1998).

Serpula: Flexible (Williams *et al.*, 1998).

NA: Coded as uncertain in appendix 2 in Williams *et al.* (1998).

[126] Microstructure: Layers

**Character 126: Sclerites: Composition: Microstructure: Layers**

- 1: Single microstructural layer
 - 2: Two microstructurally differentiated layers
 - 3: Inner and outer laminae enclosing medial void
 - 4: Three microstructurally differentiated layers
- Transformational character.

Hyolith conchs comprise two mineralized layers of fibrous bundles. Bundles are measure 5–15 μm across; their constituent fibres are each 0.1–1.0 μm wide. In the inner layer, the fibres are transverse; in the outer layer, the bundles are inclined towards the umbo, becoming longitudinal on the outermost margin.

Obolellids comprise a single laminated mineralogical layer (Balthasar, 2008). Shell-penetrating canals are not considered as contributing to the mineralogical microstructure and are coded separately.

Coded as non-additive as there is no clear necessity to pass through the brachiopod-like construction: the three layers could arise by the addition of a void to a single pre-existing layer, for example.

Inapplicable in taxa with a non-mineralized shell.

Acanthotretella spinosa: From periostracum inwards, Chiton bears three microstructural layers: fine-grained, nacreous, and regular crossed lamellar.

Amathia: Assumed to be equivalent to the hyoliths described by Kouchinsky (2000).

Antigonambonites planus: Single layer of fibrous aragonite (Porter, 2008).

Gasconsia: “Composed of a thin primary layer and a laminate secondary shell exhibiting baculate shell structure” – Skovsted & Holmer (2005), with reference to Skovsted and Holmer (2003).

Lingulellotreta malongensis: “*Eoobolus* shells exhibit the general characteristics of modern linguliform shells, i.e. they were composed of alternating sets of organic and apatite-rich layers that were separated by thin sheets of recalcitrant organic layers.” – Balthasar (2007).

Namacalathus: *Namacalathus* exhibits three layers, none of which have any obvious correspondence with those of brachiopods.

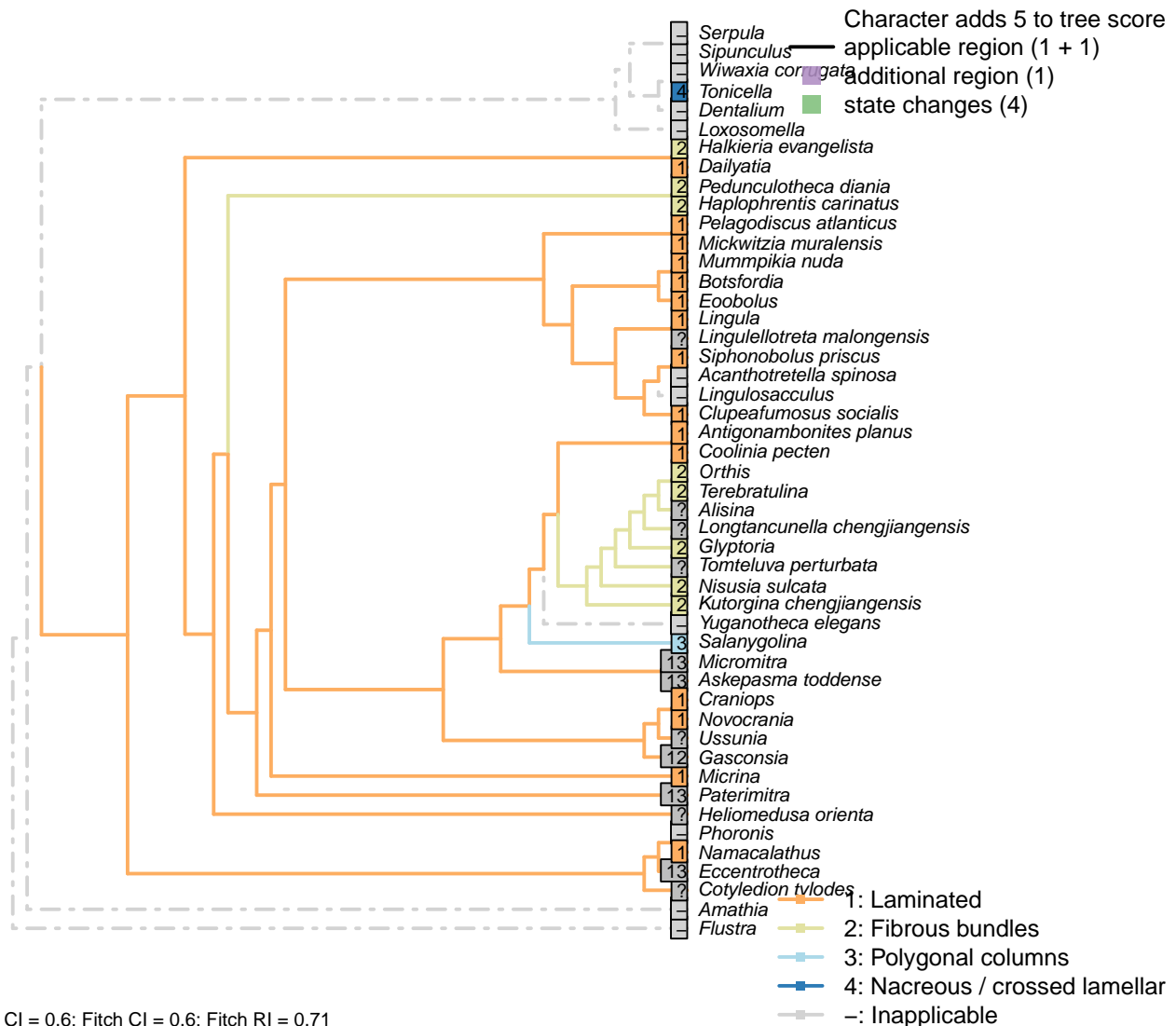
Orthis: Identical to *Mickwitzia* and more derived linguliforms (Holmer et al., 2011).

Salanygolina: “the shell structure of *Mickwitzia* [...] is closely similar to the columnar shell of linguliform acrotretoid brachiopods as well as to the linguloid *Lingulellotreta*, in that it has slender columns in the laminar succession” – Williams et al. (2007).

Ussunia: General acrotretid structure taken from Zhang *et al.* (2016).

NA: “Orthodoxly secreted primary and secondary layers” – Williams et al. (2004).

[127] Microstructure: Crystal format

**Character 127: Sclerites: Composition: Microstructure: Crystal format**

- 1: Laminated
 - 2: Fibrous bundles
 - 3: Polygonal columns
 - 4: Nacreous / crossed lamellar
- Transformational character.

Hyolith conchs comprise two mineralized layers of fibrous bundles. Bundles measure 5–15 μm across; their constituent fibres are each 0.1–1.0 μm wide. In the inner layer, the fibres are transverse; in the outer layer, the bundles are inclined towards the umbo, becoming longitudinal on the outermost margin.

Obolellids comprise a single laminated mineralogical layer (Balthasar, 2008). Shell-penetrating canals are not considered as contributing to the mineralogical microstructure and are coded separately.

The pervasive (not just superficial) polygonal structures in *Paterimitra* are distinct, and characterize *Askepasma*, *Salanygolina*, *Eccentrotheca* and *Paterimitra* (Larsson et al., 2014)

Williams *et al.* (2000) identify cross-bladed laminae as diagnostic of Strophomenata, with the exception of

some older groups that contain fibres or laminar laths.

Amathia: Inferred from other hyolithids (e.g. Moore and Porter, 2018).

Craniops: Shell structure of this taxon is laminated, rather than fibrous as previously considered.

Gasconsia: “Composed of a thin primary layer and a laminate secondary shell exhibiting baculate shell structure” – Skovsted & Holmer (2005), with reference to Skovsted and Holmer (2003).

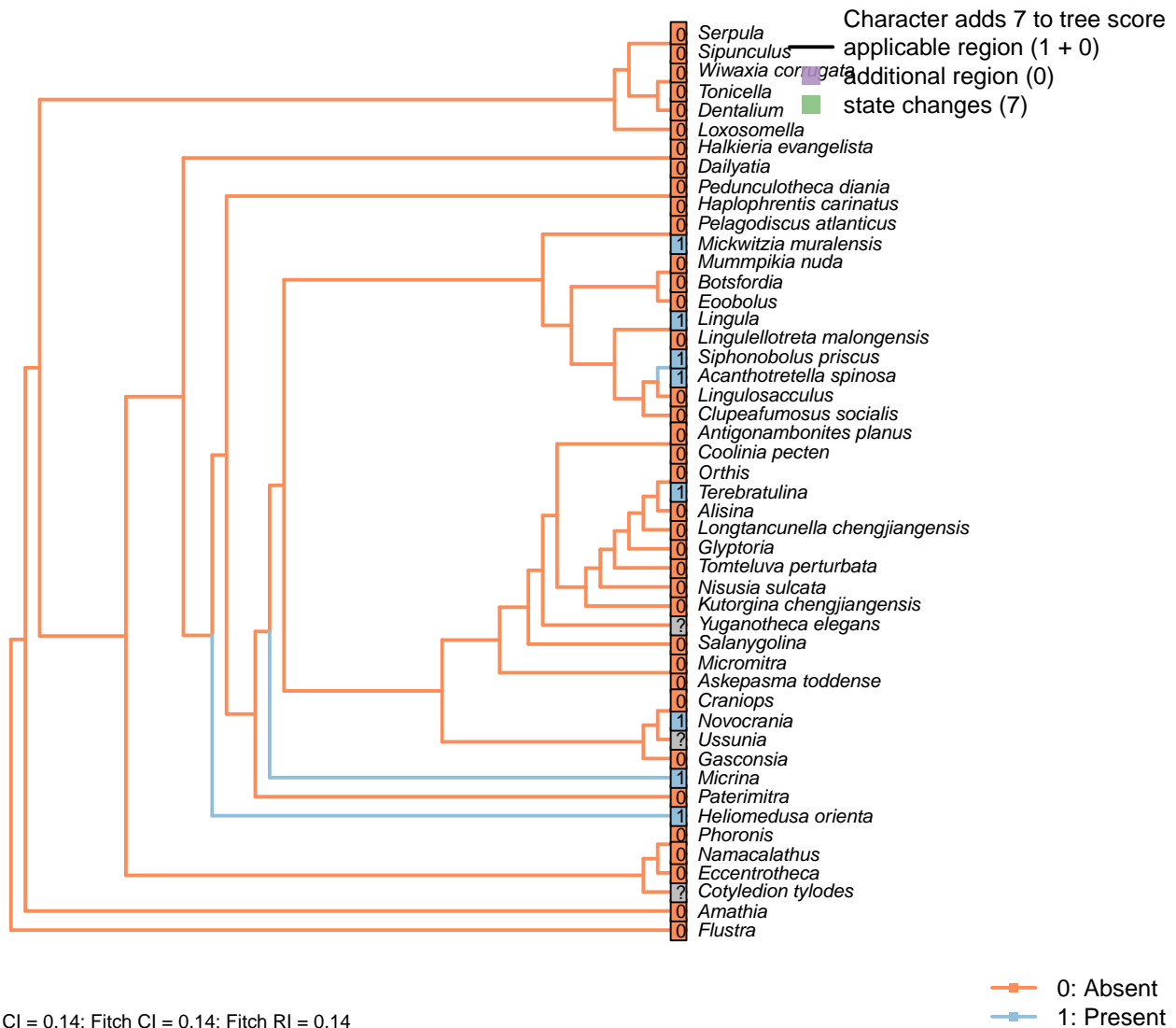
Glyptoria: “with calcitic or possibly aragonitic inarticulated shells with laminar (tabular) secondary layers” (Williams et al., 2000).

Namacalathus: The inner and outer layer are foliated. The columnar inflections lack canals, and as such we do not consider them to bear any obvious homology with the hollow pillars of tomotiids and certain brachiopods, their superficial similarity to strophomenid pseudopunctae notwithstanding.

Pelagodiscus atlanticus: Assumed to be fibrous by analogy with the allothecomorph orthothecid described by Kouchinsky (2000).

NA: Prominent laminations; see Williams *et al.* (2004).

[128] Microstructure: Punctae



Punctae are 10–20 μm wide canals created by multicellular extensions of the outer epithelium. They penetrate the full depth of the shell.

Balthasar (2008) writes:

“Vertical shell penetrating structures, such as punctae, pseudopunctae, extropunctae and canals, are common in many groups of brachiopods and are distinguished based on their geometry and size (Williams et al., 1997). Punctae are 10–20 μm wide and represent multicellular extensions of the outer epithelium (Owen and Williams, 1969). Pseudopunctae and extropunctae are similar in diameter but, instead of canals, are vertical stacks of conical deflections of individual shell layers (Williams and Brunton, 1993). None of these three types of vertical shell structure, all of which are confined to calcitic-shelled brachiopods, compares with the much smaller canals (< 1 μm in diameter) of *M. nuda*. The only type of vertical structure that fits the

size and nature of the canals of the Mural obolellids are the canals of linguliform brachiopods, which range in width from 180 to 740 nm and are occupied by proteinaceous strands in extant taxa (Williams et al., 1992, 1994, 1997). In contrast to obolellid canals, however, linguliform canals are not known to penetrate the entire shell but terminate in organic-rich layers (Williams et al., 1997). Based on these considerations it would, therefore, be misleading to call obolellid shells punctate (they are as much "punctate" as acrotretids or other linguliforms); rather their shell structure should be called canaliculate (Williams et al., 1997)."

Amathia: The tubules within the centre of the bundles of hyolith shells (Kouchinsky, 2000) are c. 10 μm wide, making them an order of magnitude larger than the canals that characterize lingulid valves, and a similar scale to punctae. This said, they have only been reported in a putative allatheid, so the presence of equivalent structures in hyolithids has never been demonstrated.

Glyptoria: "impunctate".

Micrina: 'Identical' to those in *Mickwitzia* – see Williams et al. (2007).

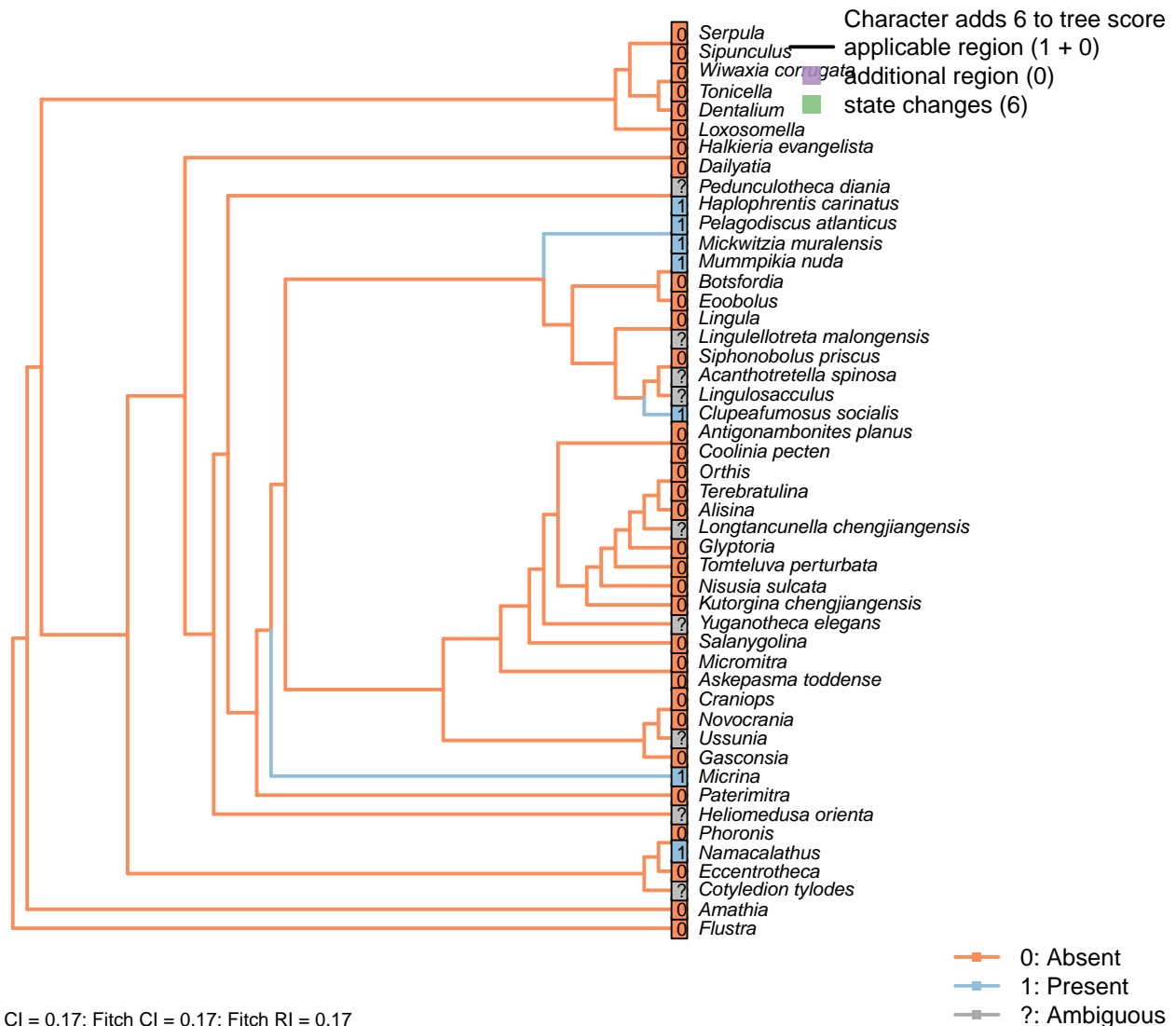
Salanygolina: Coded as present to reflect that the chambers contained setae; following Carlson in Williams et al. (2007), the punctae may or may not be homologous as punctae, but are likely homologous as shell perforations; both these perforations and those of *Micrina* were associated with setae, even if their equivalence may be with juvenile vs adult setal structures in modern brachiopods (Balthasar, 2004, p. 397).

Siphonobolus priscus: "Vertical shell penetrating structures, such as punctae, pseudopunctae, extropunctae and canals, are common in many groups of brachiopods and are distinguished based on their geometry and size (Williams et al., 1997). Punctae are 10–20 μm wide and represent multicellular extensions of the outer epithelium (Owen and Williams, 1969). [...] None of these three types of vertical shell structure, all of which are confined to calcitic-shelled brachiopods, compares with the much smaller canals ($< 1 \mu\text{m}$ in diameter) of *M. nuda*. The only type of vertical structure that fits the size and nature of the canals of the Mural obolellids are the canals of linguliform brachiopods, which range in width from 180 to 740 nm and are occupied by proteinaceous strands in extant taxa (Williams et al., 1992, 1994; Williams et al., 1997)." – Balthasar (2008).

Tonicella: Endopunctae are relatively large canals, diameter vary greatly from 5–20 μm .

NA: The 'canals' through the shell have a diameter of c. 20 μm (Williams et al., 2004, text-fig. 2a), falling within the definition of punctae used herein.

[129] Microstructure: Canals

**Character 129: Sclerites: Composition: Microstructure: Canals**

0: Absent

1: Present

Neomorphic character.

A caniculate microstructure occurs in lingulids; canals are narrower ($< 1 \mu\text{m}$) than punctae, may branch, and do not fully penetrate the shell, terminating just within the boundaries of a microstructural layer. See Williams et al. (1997), p303ff, and Balthasar (2008), p273, for discussion.

Tubules described in hyoliths by Kouchinsky (2000) measure around $10 \mu\text{m}$ in diameter, making them an order of magnitude wider than lingulid canals.

This said, Balthasar (2008) considers the tubules within the columnar shell microstructure of *Mickwitzia* cf. *occidens* ($1\text{--}3 \mu\text{m}$ wide, Skovsted and Holmer, 2003), acrotretids ($1 \mu\text{m}$ wide, see Holmer, 1989, Zhang et al. (2016)) and lingulellotretids (100 nm wide, Cusack et al., 1999) as equivalent to lingulid canals.

Micrina exhibits both punctae and canals (Harper et al., 2017), challenging Carlson's contention (in Williams

et al., 2007) that the structures are potentially homologous as shell perforations.

Acanthotretella spinosa: Aesthete canals do not fall within the definition of this character.

Amathia: Zhang *et al.* (2018) have reported um-scale canals, replicated in phosphate, within the shell of the hyolithid *Paramicrocornus*; as shell microstructure is not preserved in *Haplophrentis*, this latter taxon is taken as a model.

Antigonambonites planus: The chambers in halkieriid sclerites do not correspond in morphology or dimension to the brachiopod-like canals documented by this character.

Gasconsia: Not evident in section presented by Skovsted & Holmer (2003).

Namacalathus: Canal-like structures have been reported in *Namacalathus* (Zhuravlev et al., 2015), and interpreted as evidence for a Lophophorate affinity. Though the structures are not necessarily directly equivalent, the hypothesis of homology is followed here.

Nisusia sulcata: Preservational resolution not sufficient to evaluate.

Orthis: Acrotretid laminae bear characteristic columns (e.g. Zhang et al., 2016); a similar fabric has been reported, and assumed homologous, in *Micrina* (Butler et al., 2012).

A similar columnar shell microstructure also occurs in the closely related *Mickwitzia* (Balthasar, 2008).

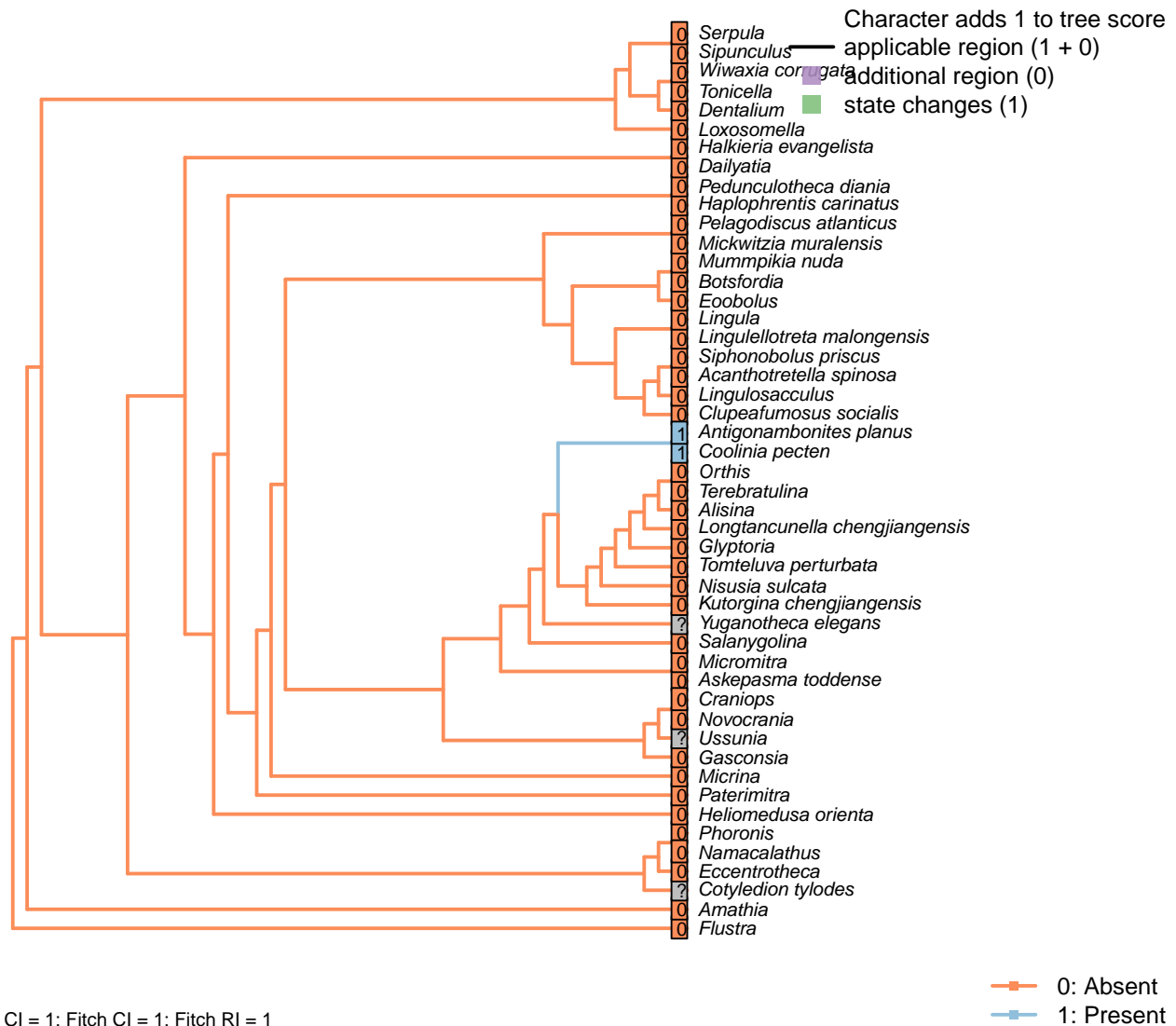
Salanygolina: Coded as present to reflect similarity of columnar microstructure remarked on by, among others, Balthasar (2008); Williams *et al.* (2007); Skovsted & Holmer (2003).

Ussunia: Acrotretid laminae bear characteristic columns (e.g. Zhang et al., 2016).

Balthasar (2008) considers these columns as homologous with tubules within the columnar shell microstructure *Mummpikia*, *Mickwitzia* and lingulellotretids.

NA: The ‘canals’ through the shell have a diameter of c. 20 μm (Williams et al., 2004, text-fig. 2a), falling within the definition of punctae (rather than canals) used herein.

[130] Microstructure: Pseudopunctae

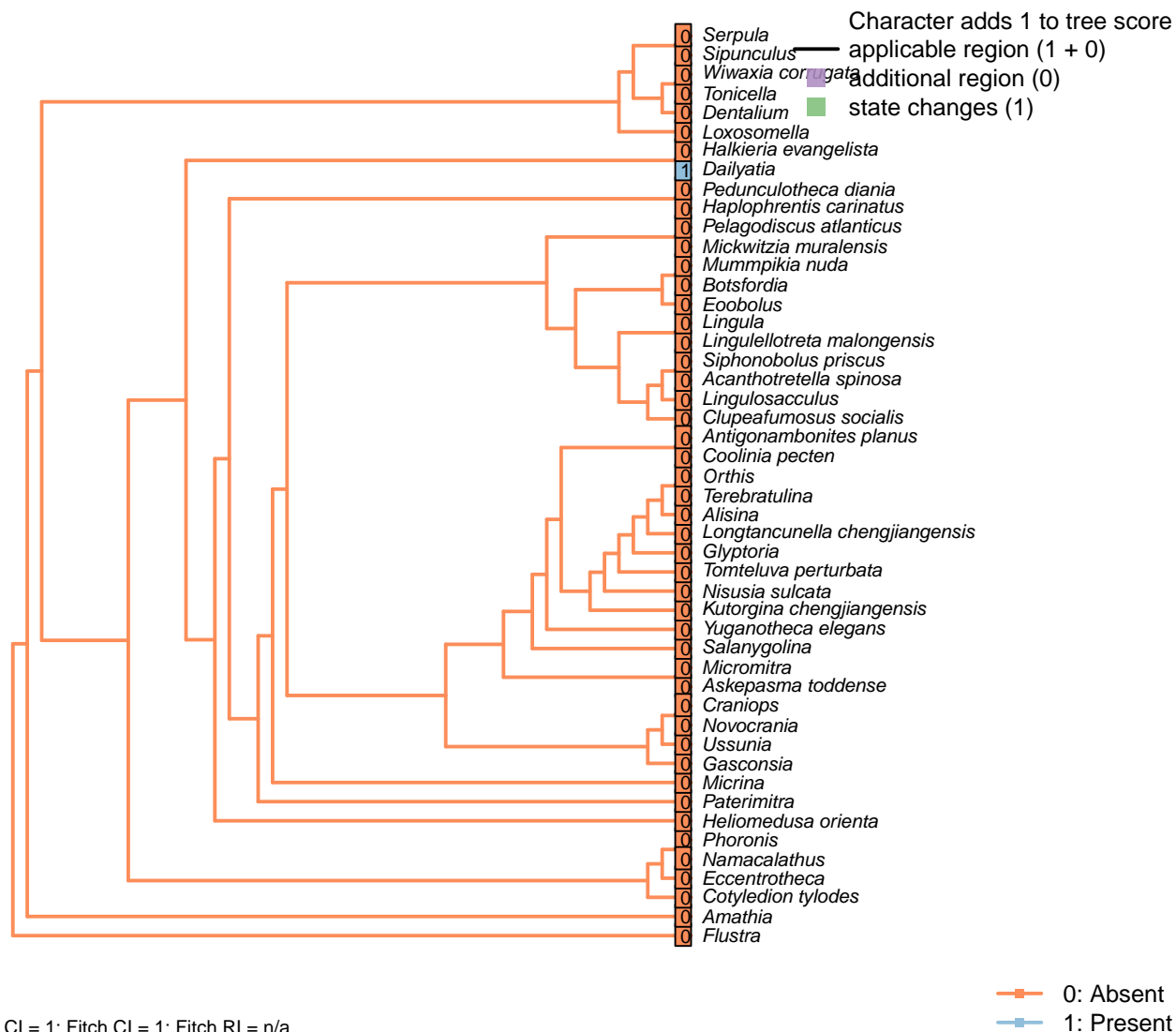


Pseudopunctae are not punctae, but deflections of shell laminae. They characterise Strophomenata in particular.

Craniops, *Longtancunella chengjiangensis*, *Tomteluva perturbata*: Scored absent in data matrix of Benedetto (2009).

Yuganotheca elegans: Scored absent (in *Eoorthis*) in data matrix of Benedetto (2009).

[131] Microstructure: External polygonal ornament

**Character 131: Sclerites: Composition: Microstructure: External polygonal ornament**

0: Absent

1: Present

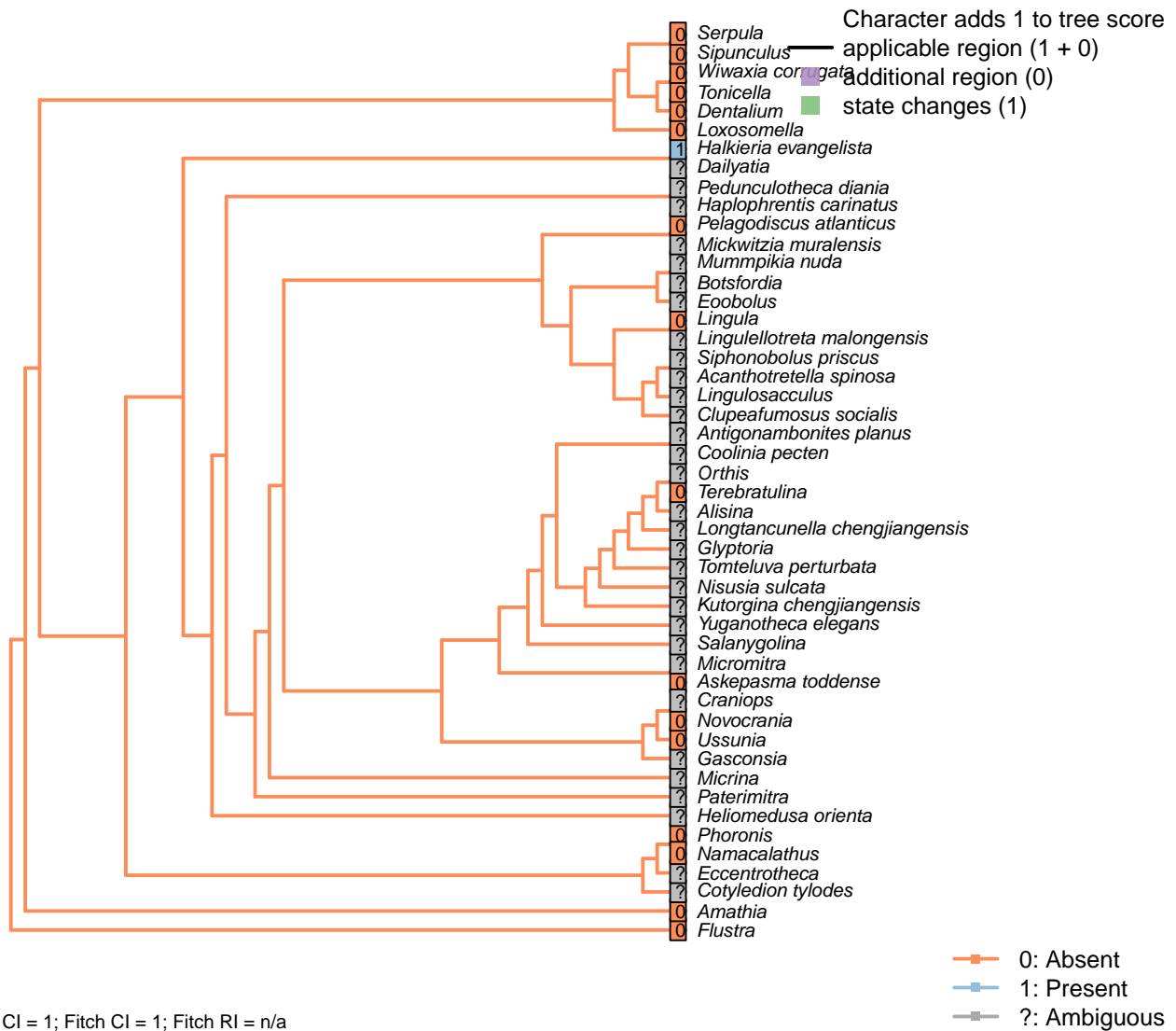
Neomorphic character.

Regular polygonal compartments, around 10 µm in diameter, characterise *Paterimitra*. Walls between compartments have the cross-section of an anvil. An external polygonal structure (possible imprints of epithelial tissue) occurs in *Daliyatia*, but it is a surface pattern, which is different from the polygonal prisms in the body wall of other paterinid-like groups.

Ussunia: The polygonal ornament reported in acrotretids by Zhang *et al.* (2016) is on the internal surface of the shell.

3.24 Sclerites

[132] Periodically shed and replaced



Character 132: Sclerites: Periodically shed and replaced

0: Absent

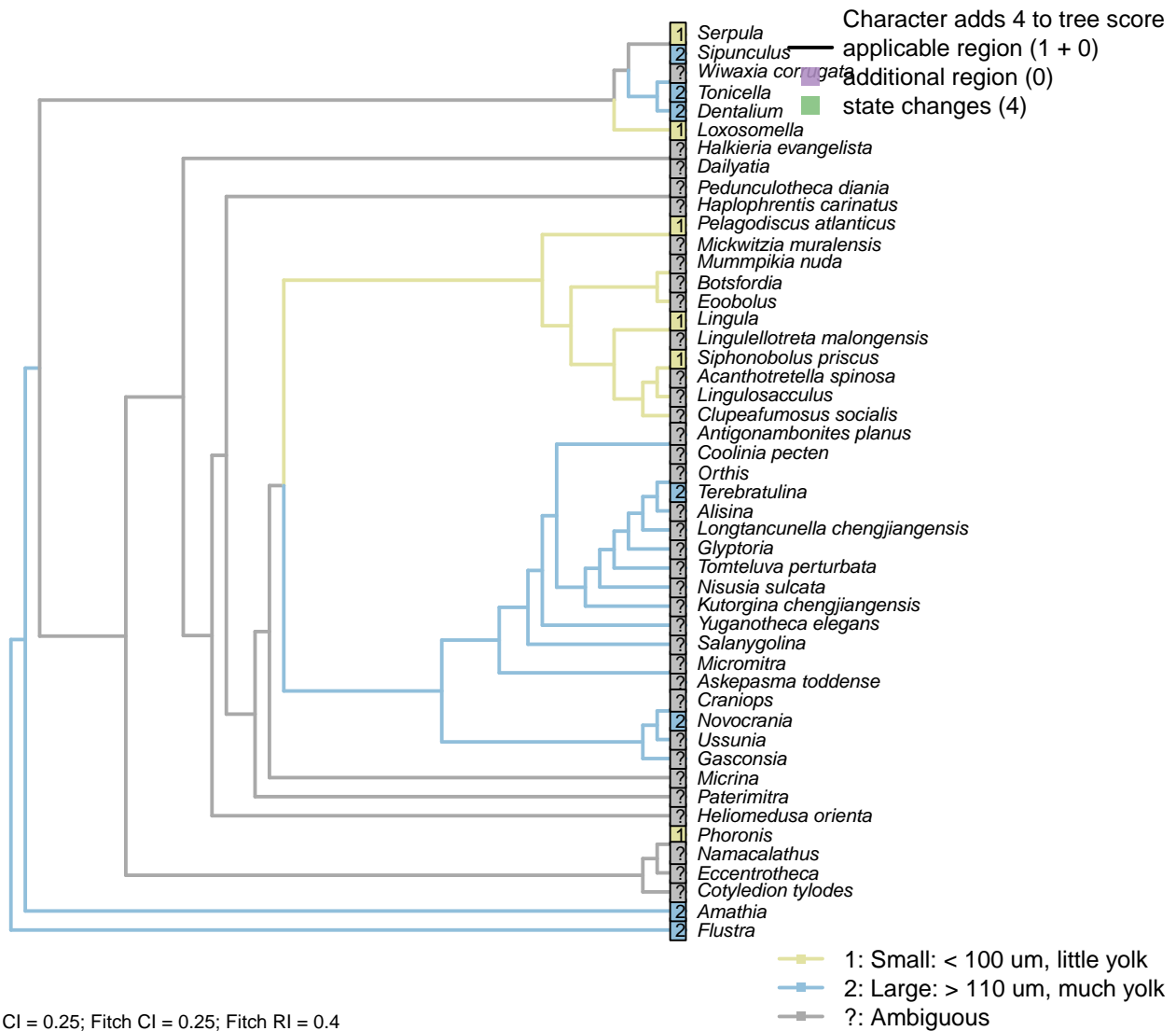
1: Present

Neomorphic character.

Certain taxa periodically slough and replace some of their individual sclerites during growth.

3.25 Gametes

[133] Egg size



Character 133: Gametes: Egg size

- 1: Small: < 100 um, little yolk
 - 2: Large: > 110 um, much yolk
- Transformational character.

Following Carlson (1995), character 7. This character is only possible to code in extant taxa. It is not considered independent of Carlson's character 11, number of gametes released per spawning, as it is possible to produce more small eggs than large eggs – thus this latter character is not reproduced in the present study. The same goes for Carlson's character 12, gamete dispersal mode; brooders will tend to brood large eggs.

Acanthotretella spinosa: Buckland-Nicks et al. (1988).

Alisina: Egg size can vary from 60–200 µm in scaphopods, but in *Dentalium* the eggs are large (Dufresne-

Dube et al., 1983).

Dailyatia: c. 50 μm in *Hydroides* (Miles et al., 2007).

Dentalium, *Eoobolus*, *Serpula*, *Tonicella*: Following coding for class in Carlson (1995) appendix 1, character 7.

Halkieria evangelista: c. 200 μm in diameter (Rice, 1988).

Lingula: Tiny (Nielsen, 1966).

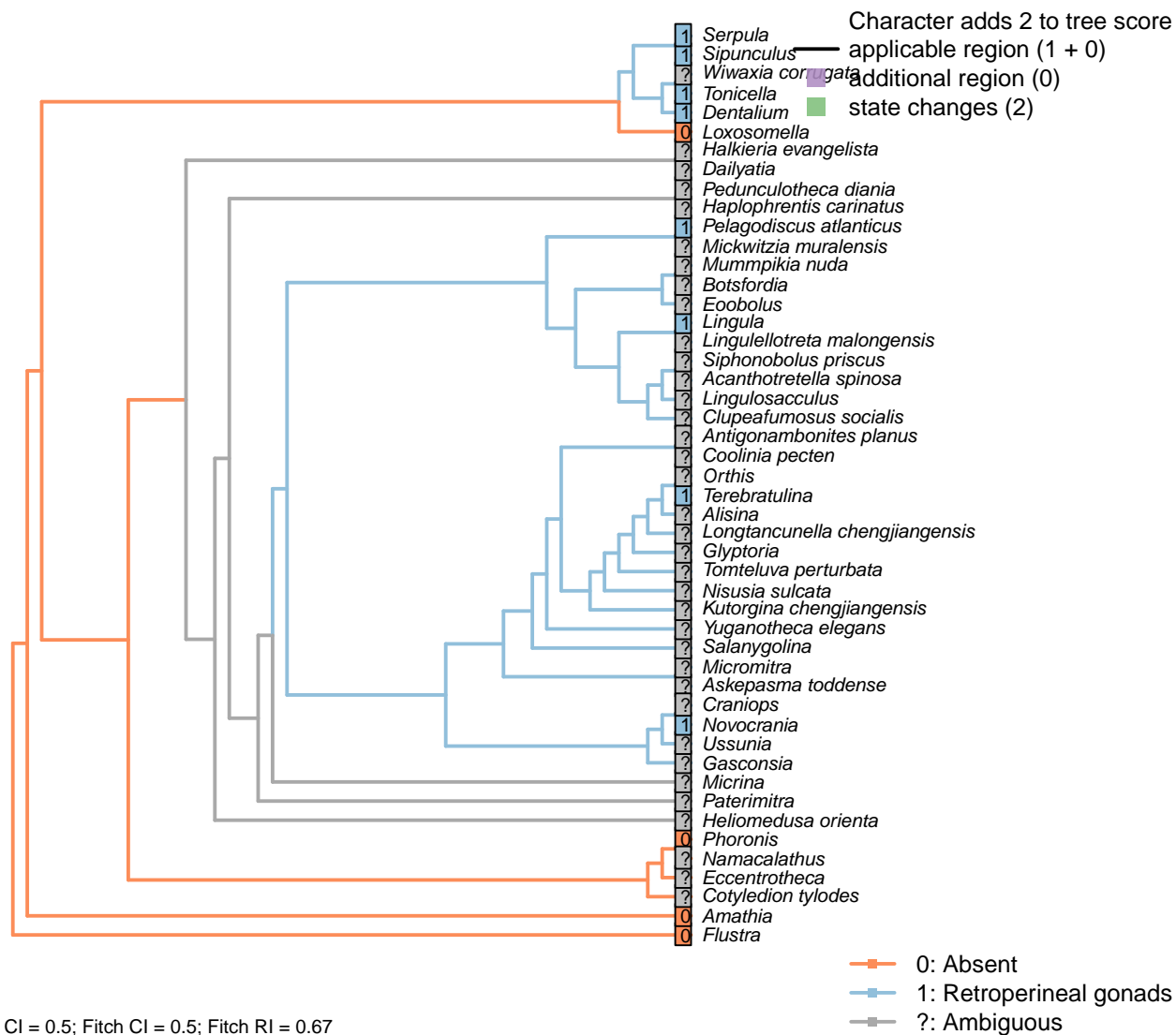
Phoronis: “Mature eggs commonly measure about 200 μm in diameter” – Franzén (1977).

Sipunculus: “Mature eggs commonly measure about 200 μm in diameter” (Franzén, 1977); the larva is a similar size (Reed and Cloney, 1982).

Wiwaxia corrugata: *Phoronis* has planktotrophic larvae. indicating a small egg size (Ruppert et al., 2004). Carlson (1995) codes phoronids as polymorphic, as some members of the phylum have eggs of each size.

NA: “the ventral brephic valve [was] 50 μm across, [which] is close to the known lower limit of the brachiopod egg size” – Popov et al. (2009).

[134] Gonocoel

**Character 134: Gametes: Gonocoel**

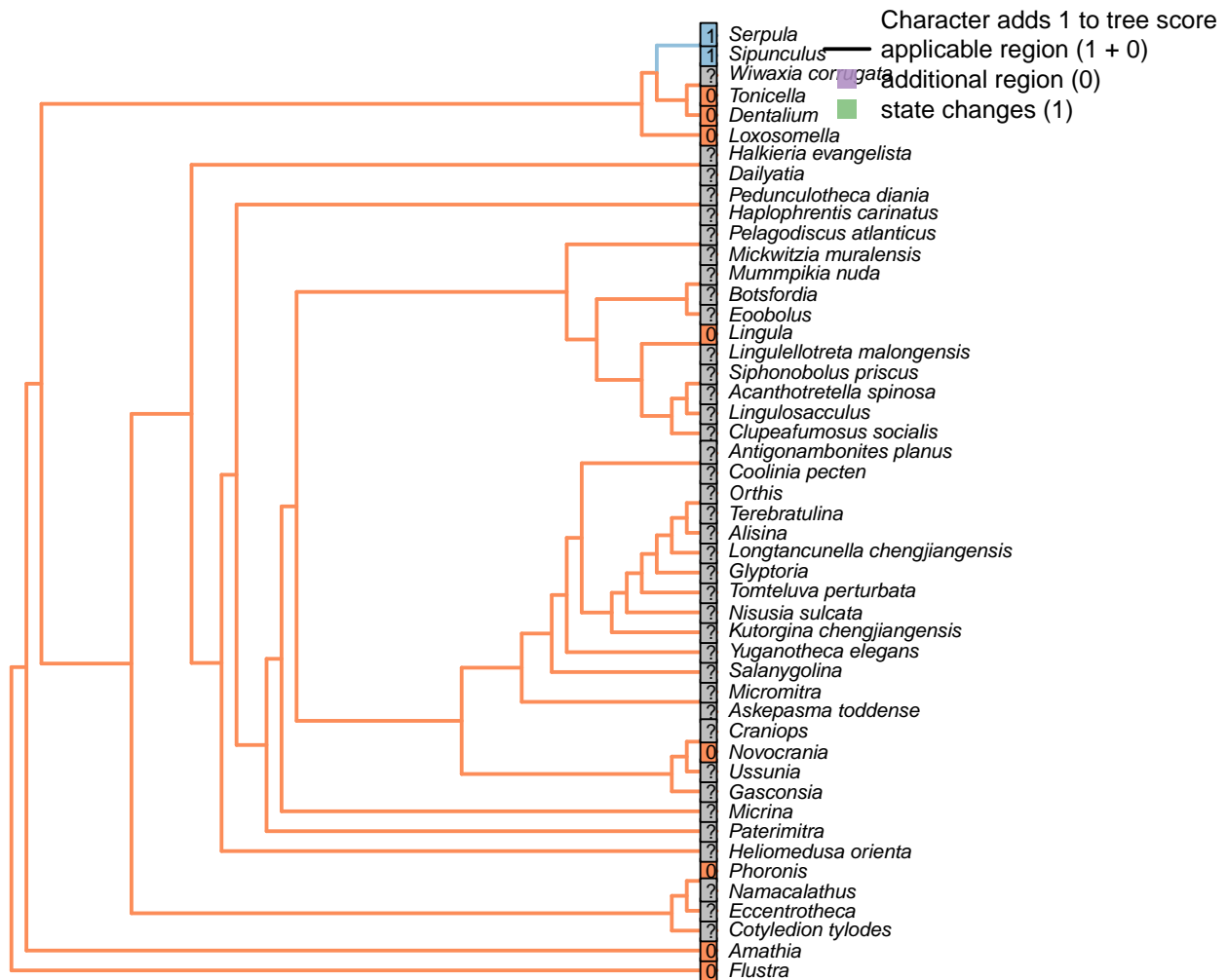
0: Absent

1: Retroperineal gonads

Neomorphic character.

Character 27 in Haszprunar (1996).

[135] Ovary wall saccular



CI = 1; Fitch CI = 1; Fitch RI = 1

Character 135: Gametes: Ovary wall saccular

0: Plain

1: Saccular

Neomorphic character.

After character 31 in Haszprunar (1996).

[136] Testis wall saccular

Character 136: Gametes: Testis wall saccular

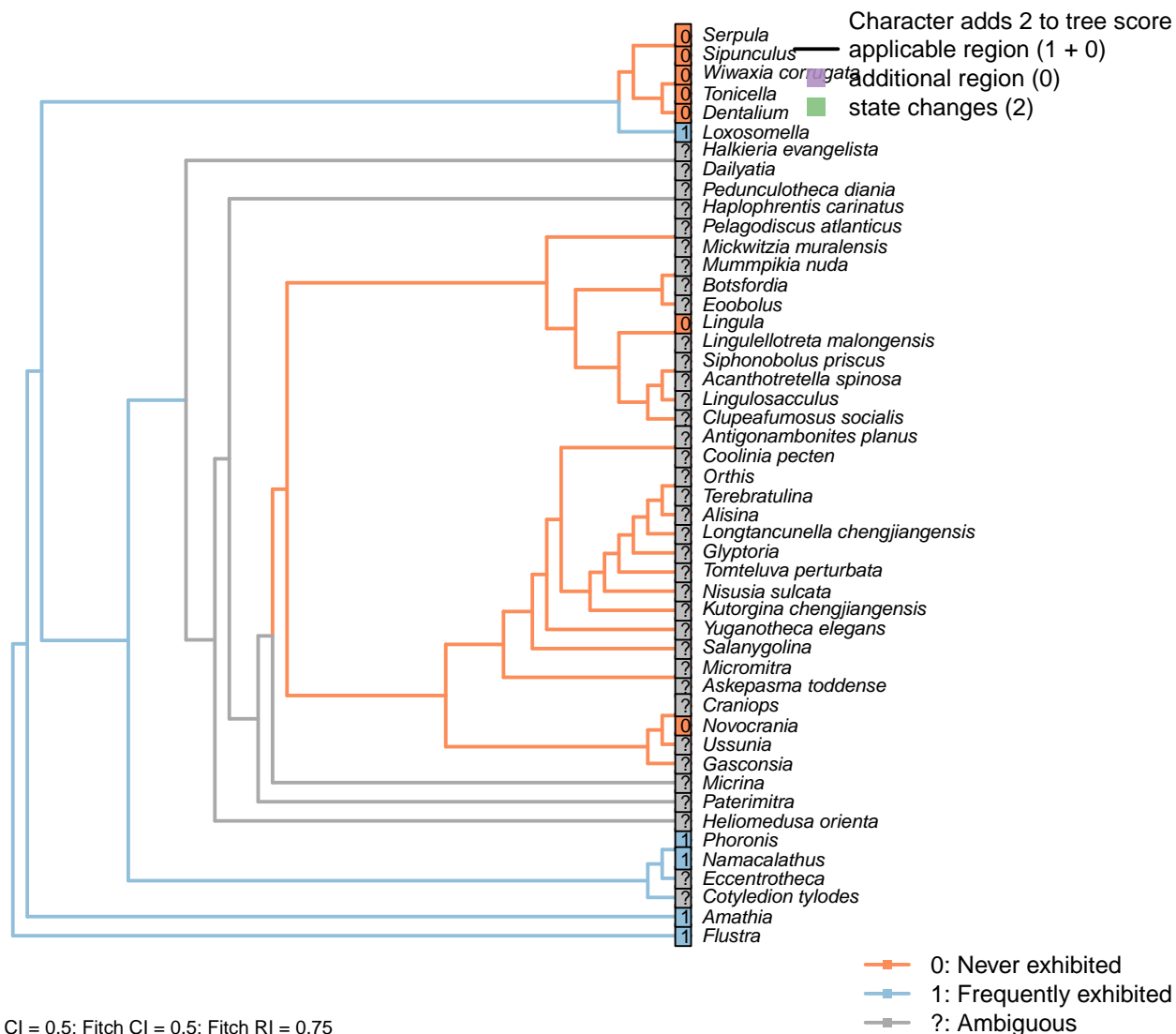
0: Plain

1: Saccular

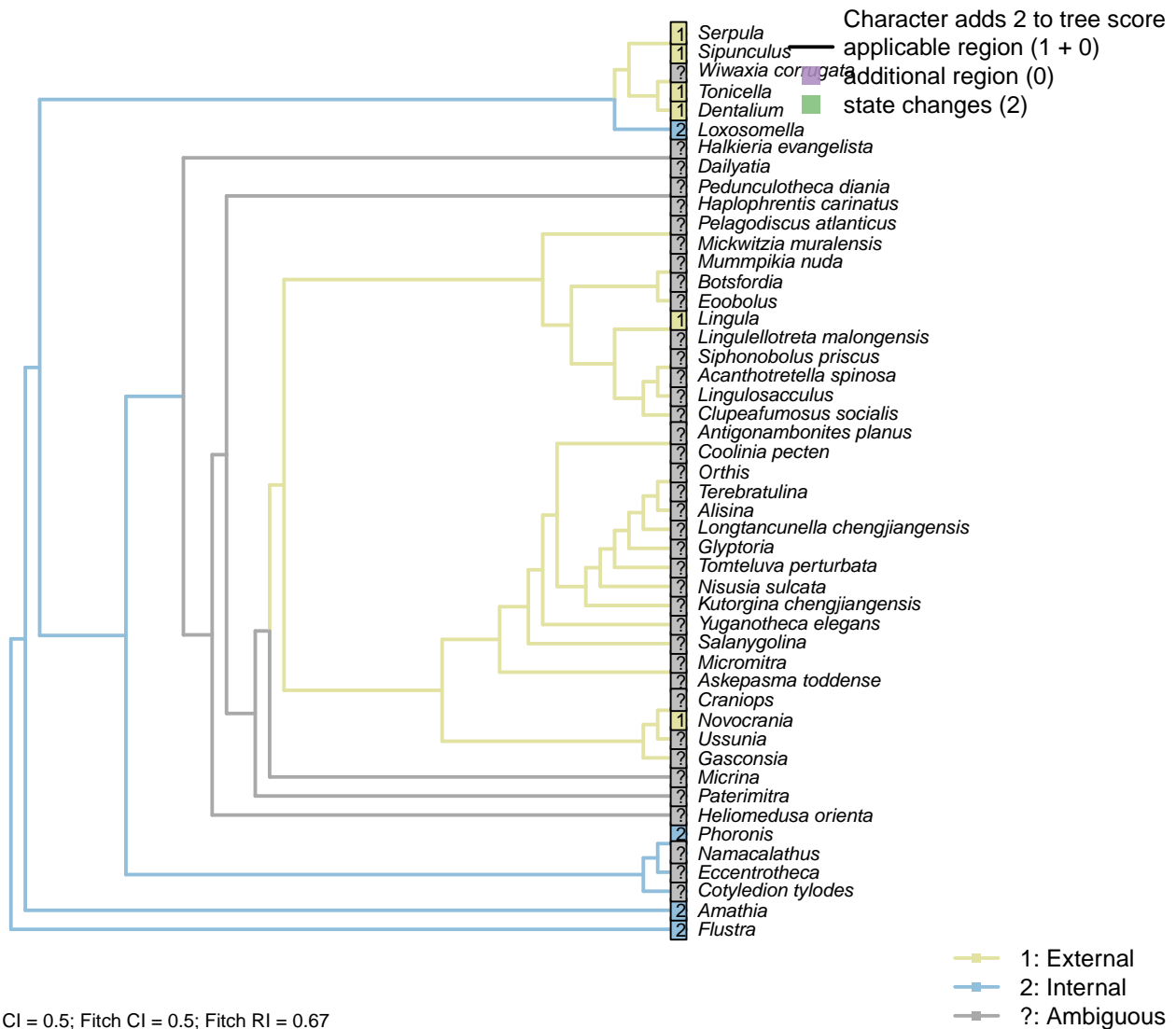
Neomorphic character.

After character 31 in Haszprunar (1996).

[137] Asexual reproduction



[138] Fertilization

**Character 138: Gametes: Fertilization**

1: External

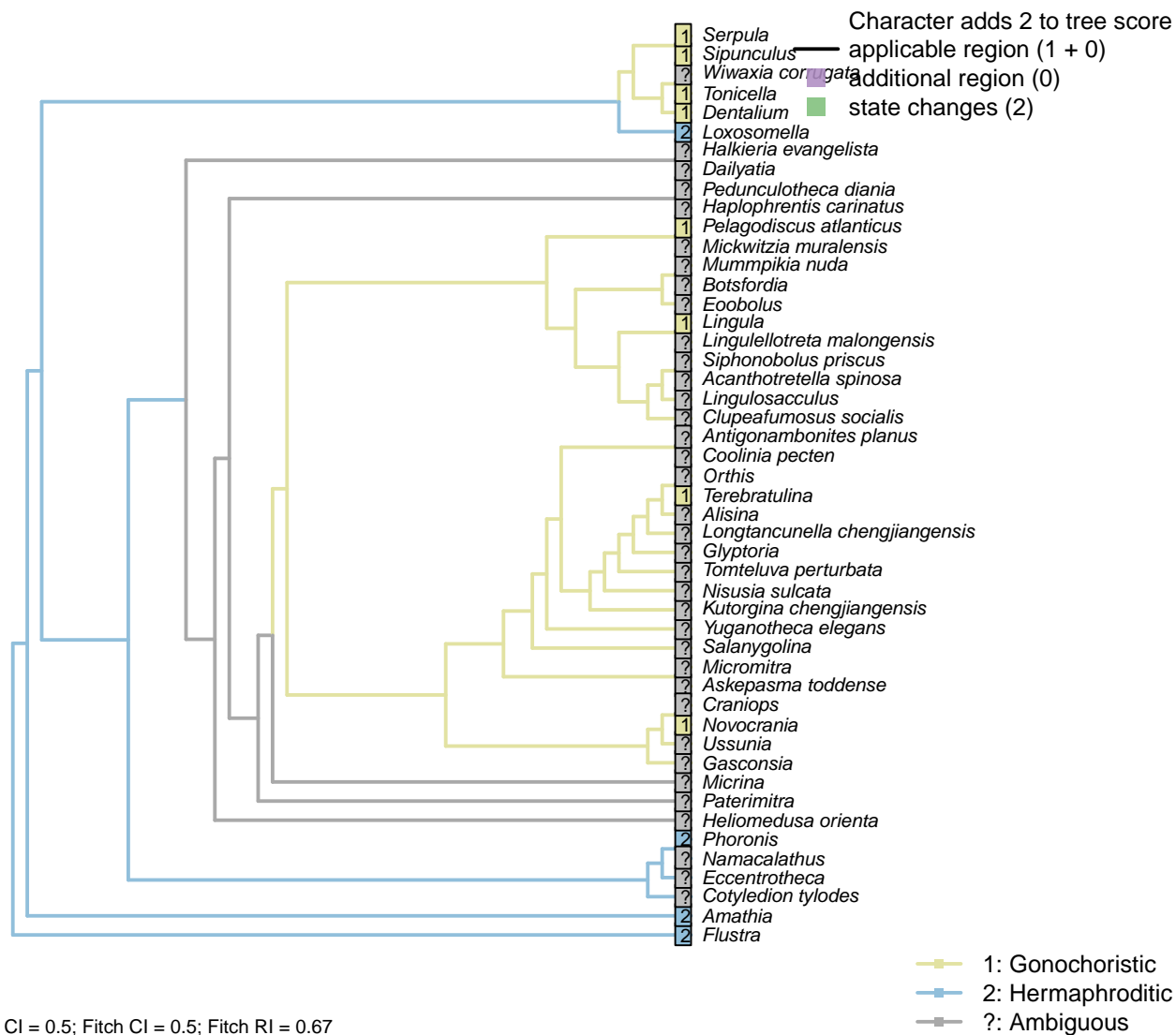
2: Internal

Transformational character.

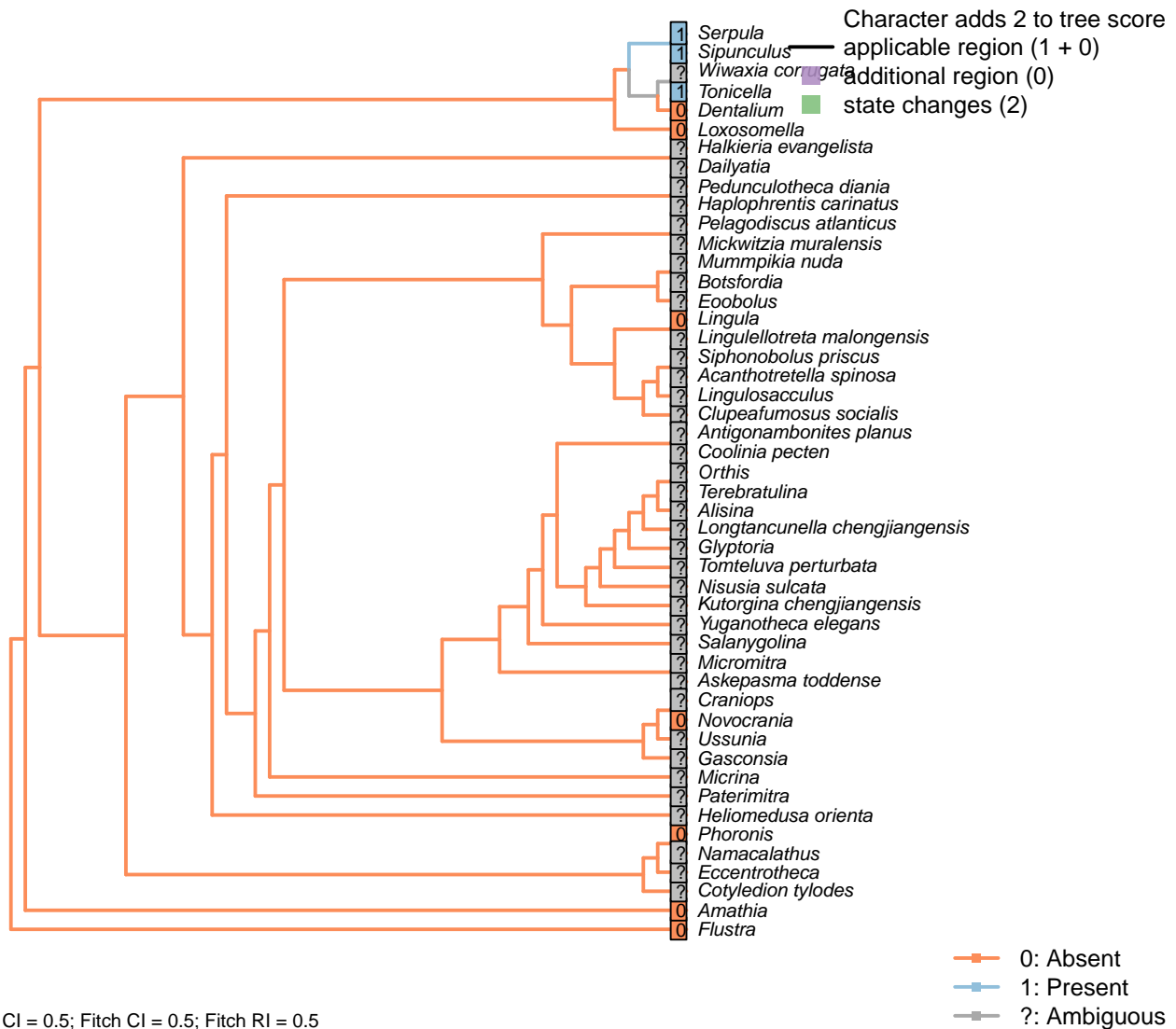
After character 62 in Haszprunar (2000).

Sipunculus: Brood pouches in abandoned lophophore.

[139] Sexes



[140] Protective membrane

**Character 140: Gametes: Egg: Protective membrane**

0: Absent

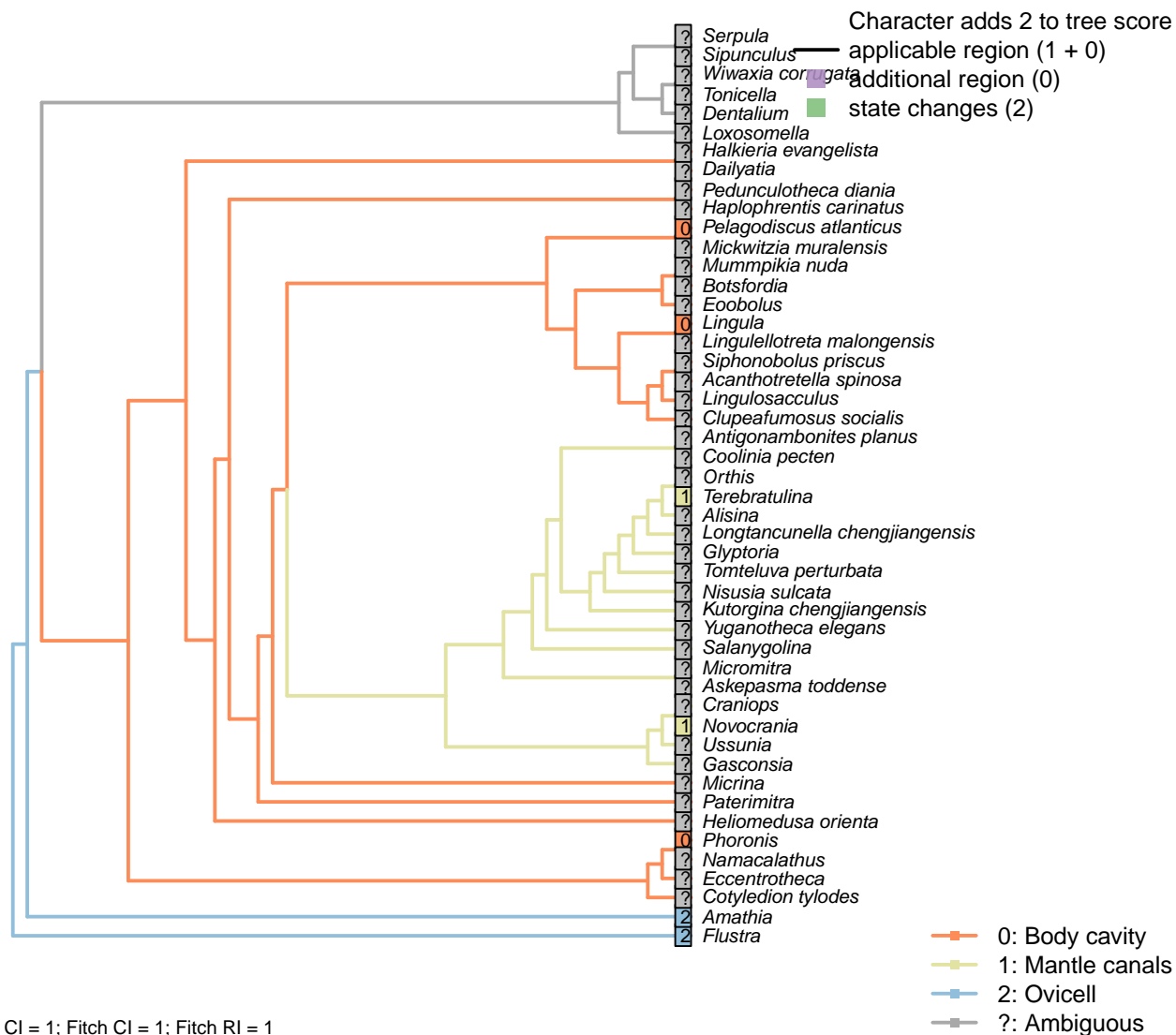
1: Present

Neomorphic character.

After character 4.69 in von Salvini-Plawen and Steiner (1996).

Phoronis, *Sipunculus*: “Eggs have a loose consistency and are capable of changing form” (Franzén, 1977).*Wiwaxia corrugata*: Eggs “are surrounded by a delicate fertilization membrane” (Pennerstorfer and Scholtz, 2012).

3.26 Gametes: Site of maturation [141]



Character 141: Gametes: Site of maturation

0: Body cavity

1: Mantle canals

2: Ovicell

Neomorphic character.

After Carlson (1995), character 9. Only possible to code in extant taxa. Mantle canals is considered the derived state, as it represents a migration from the body cavity, where gametes are produced.

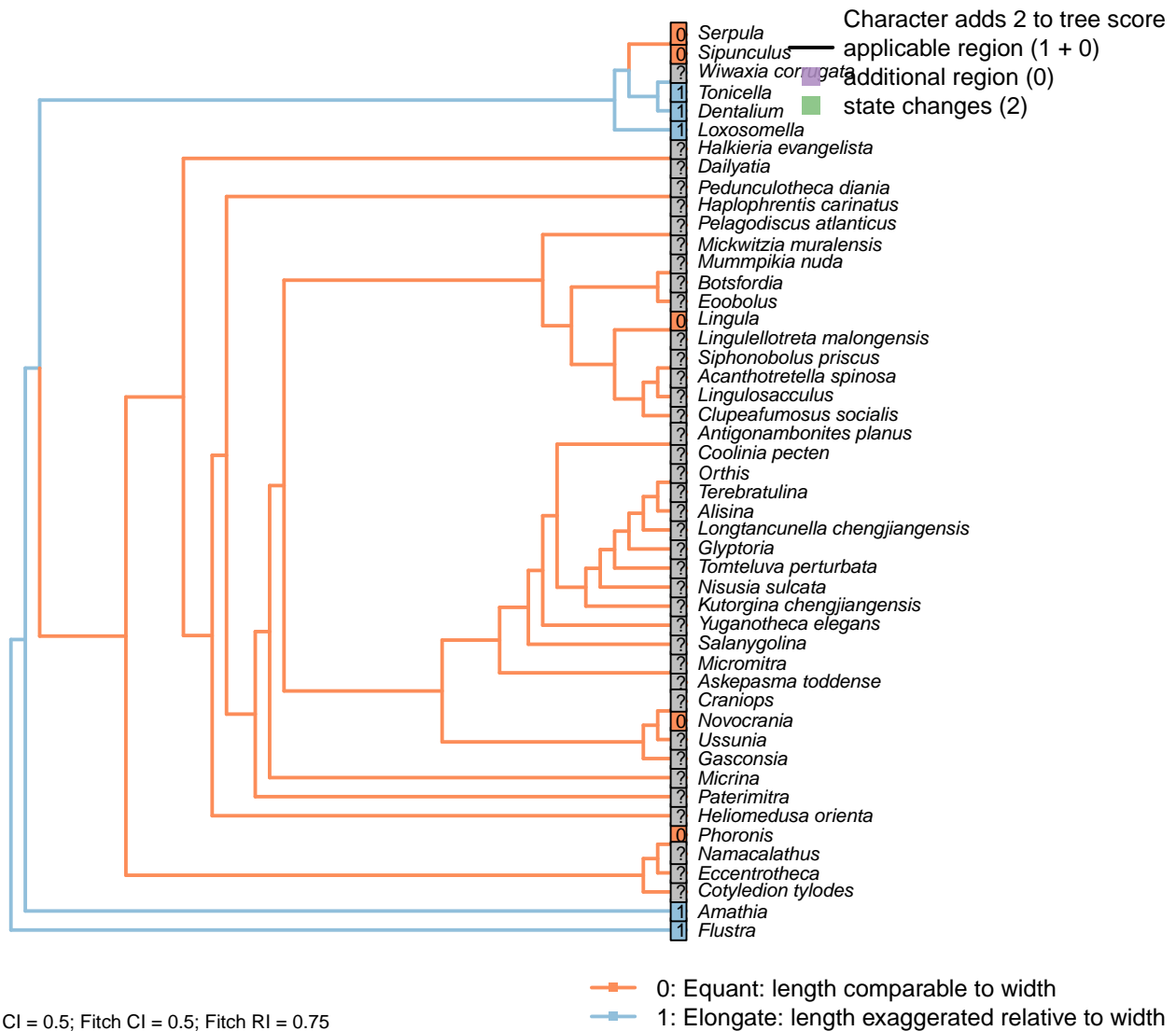
Dentalium, *Eoobolus*, *Serpula*, *Tonicella*: Following Hodgson & Reunov (1994).

Phoronis, *Sipunculus*: Ovicell (Franzén, 1977).

Wiwaxia corrugata: Following coding for class in Carlson (1995) Appendix 1, character 9.

3.27 Gametes: Spermatozoa

[142] Nucleus: Shape



Character 142: Gametes: Spermatozoa: Nucleus: Shape

0: Equant: length comparable to width

1: Elongate: length exaggerated relative to width

Neomorphic character.

After character 41 in Ponder and Lindberg (1997).

Acanthotretella spinosa: Profoundly elongated nucleus (Buckland-Nicks et al., 1988).

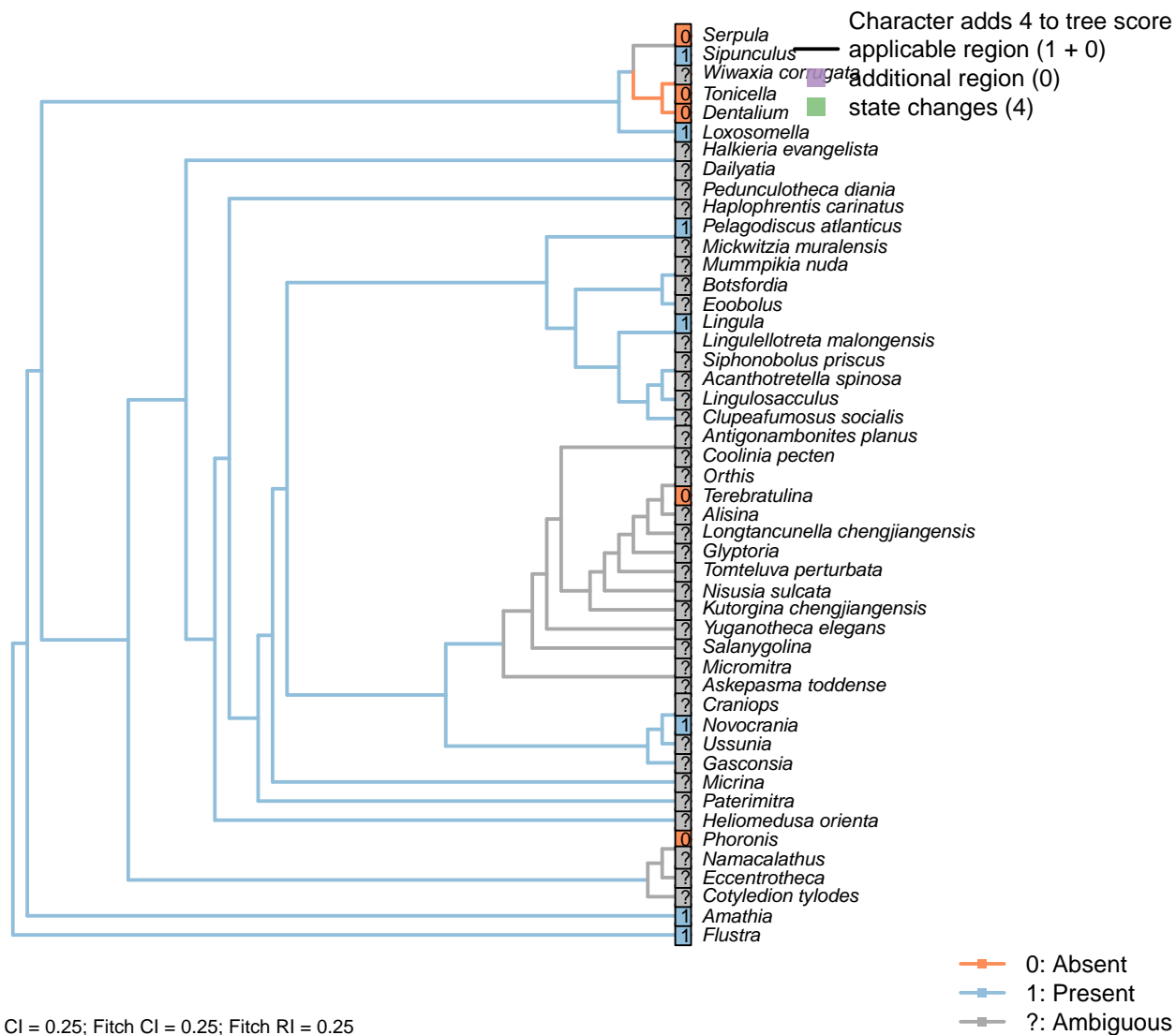
Alisina: Elongate nucleus, 4–6 times longer than wide (Dufresne-Dube et al., 1983).

Dailyatia: Gherardi et al. (2011).

Lingula: Elongate in *Loxosoma* [Franzen 2000].

Phoronis, *Sipunculus*: Elongate (Franzén, 1981).

[143] Anterior nuclear fossa



or impression.

Acanthotretella spinosa: Buckland-Nicks et al. (1988).

Alisina: Dufresne-Dube et al. (1983).

Dailyatia: Absent: subacrosomal space does not impinge on nuclear envelope (Gherardi et al., 2011).

Halkieria evangelista: Prominent in *Phascolion* (Rice, 1993).

Lingula: Present in *Loxosoma* [Franzen 2000].

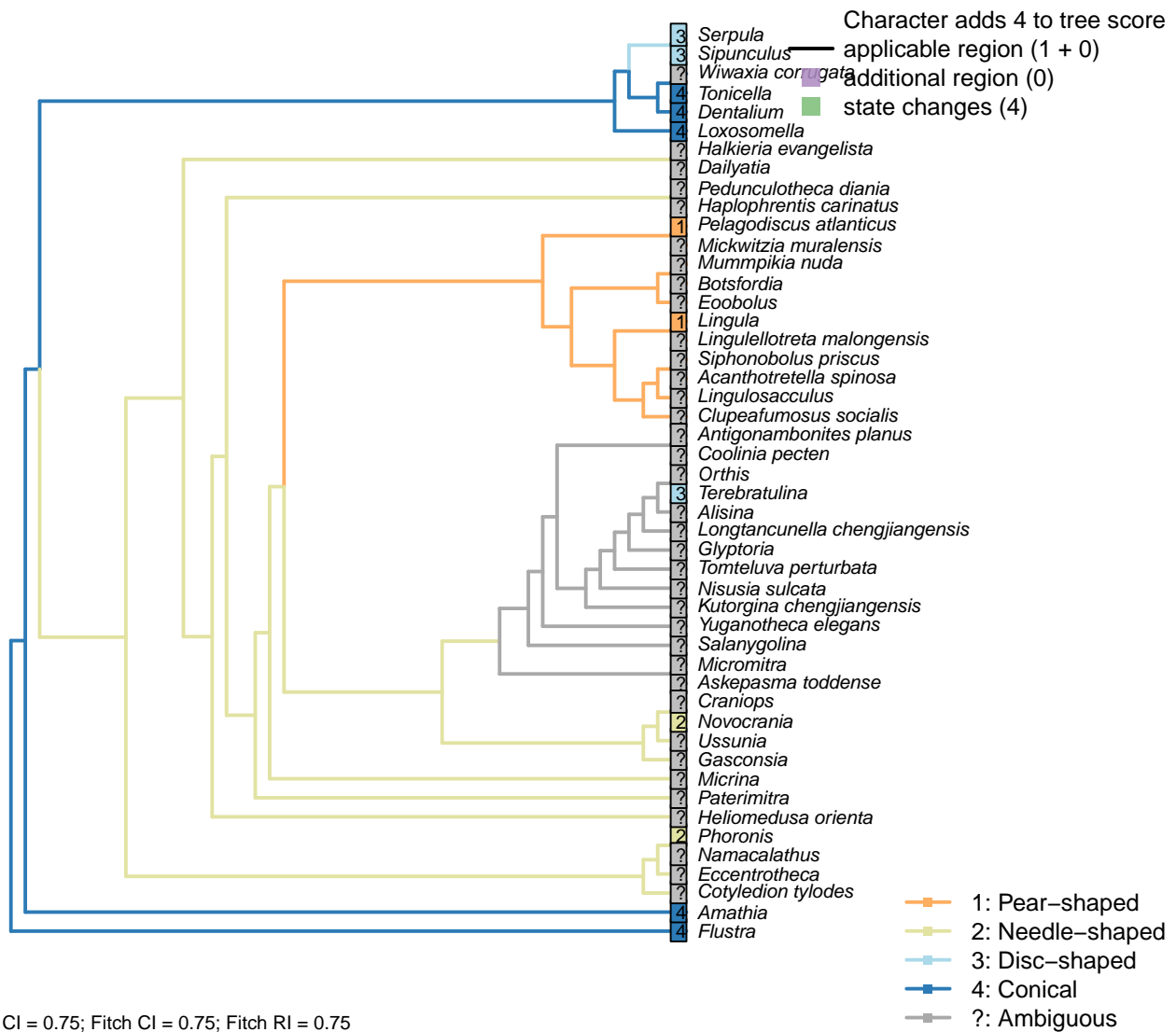
Phoronis, *Sipunculus*: Present (in *Tubulipora*; Franzén, 1984).

Serpula: Present in *Discinisca tenuis* (Hodgson and Reunov, 1994).

Tonicella: No anterior invagination (Hodgson and Reunov, 1994).

Wiwaxia corrugata: Nucleus “almost round” (Reunov and Klepal, 2004).

[144] Acrosome: Shape



Character 144: Gametes: Spermatozoa: Acrosome: Shape

- 1: Pear-shaped
- 2: Needle-shaped
- 3: Disc-shaped
- 4: Conical

Transformational character.

Acanthotretella spinosa: Elongate: cylindrical to conical (Buckland-Nicks et al., 1988).

Alisina: Low conical aspect (Dufresne-Dube et al., 1983).

Dailyatia: Gherardi et al. (2011).

Dentalium: Pear-shaped (Fukumoto, 2003).

Eoobolus: Needle-shaped (Afzelius and Ferraguti, 1978).

Halkieria evangelista: A peaked disc in *Phascolion* (Rice, 1993).

Lingula: Conical/cylindrical acrosome-like extension in *Loxosoma* [Franzen 2000].

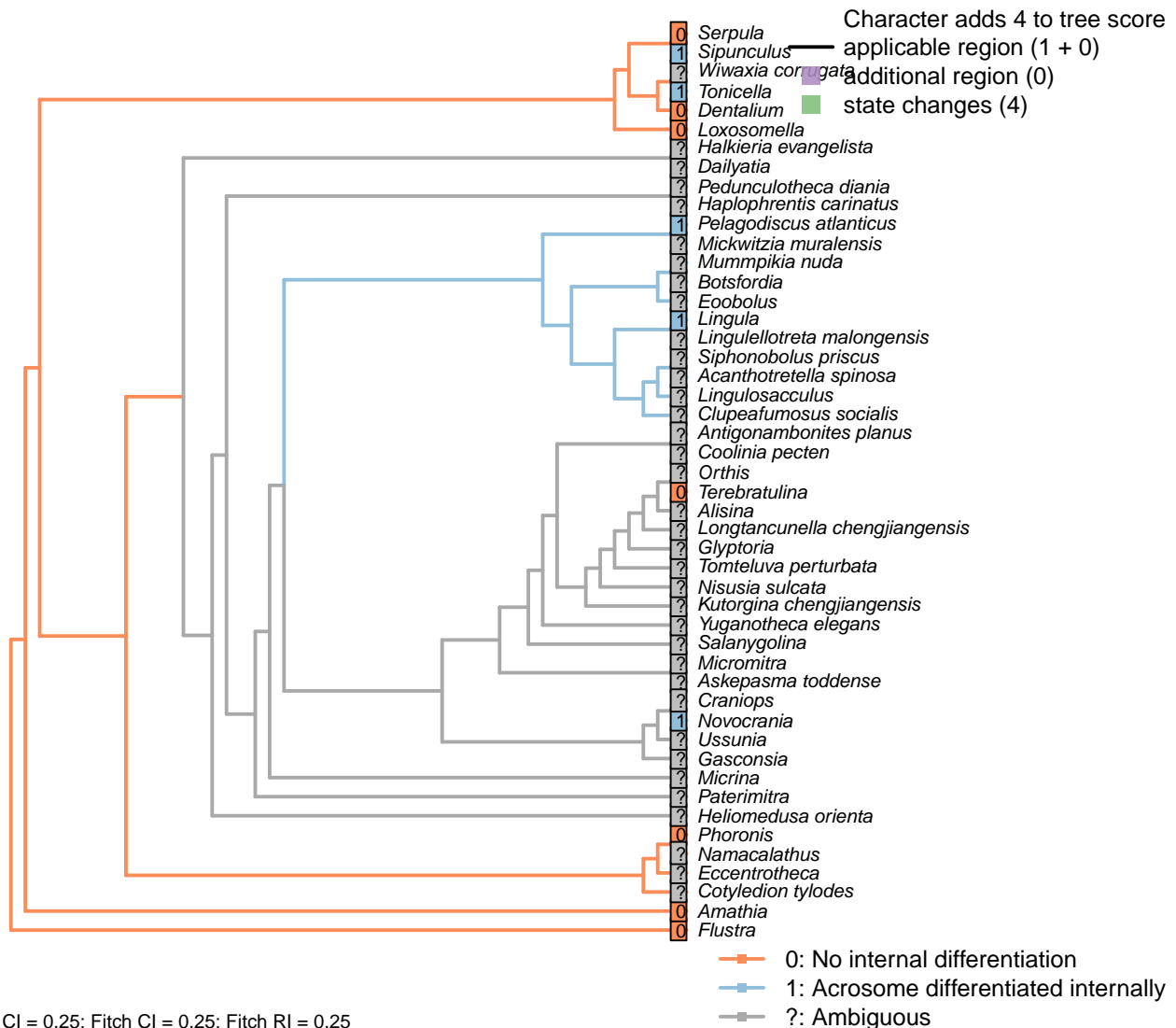
Phoronis, *Sipunculus*: Conical (in *Tubulipora*; Franzén, 1984).

Serpula: Pear-shaped (Hodgson and Reunov, 1994).

Tonicella: Disc-shaped (in *Kraussina*) (Hodgson and Reunov, 1994).

Wiwaxia corrugata: Needle-shaped (Reunov and Klepal, 2004).

[145] Acrosome: Differentiated internally

**Character 145: Gametes: Spermatozoa: Acrosome: Differentiated internally**

0: No internal differentiation

1: Acrosome differentiated internally

Neomorphic character.

Hodgson and Reunov (1994) describe the *Discinisca* acrosome as having “an electron-lucent centre and an electron-dense outer region”, and state that this trait is characteristic of inarticulate brachiopods.

Acanthotretella spinosa: “One can distinguish two components in the acrosome, an apical and a basal granule” – Buckland-Nicks et al. (1988).

Alisina: Differentiated membrane only (Dufresne-Dube et al., 1983).

Dailiyatia: Gherardi et al. (2011).

Dentalium: Clear differentiation of marginal area (Fukumoto, 2003).

Eoobolus: “Along the inner and outer margins there are periodically banded layers, and between them there

is a less dense layer” – Afzelius and Ferraguti (1978).

Halkieria evangelista: No differentiation within acrosomal vesicle (Rice, 1993).

Lingula: Not evident in *Loxosoma* [©Franzen 2000].

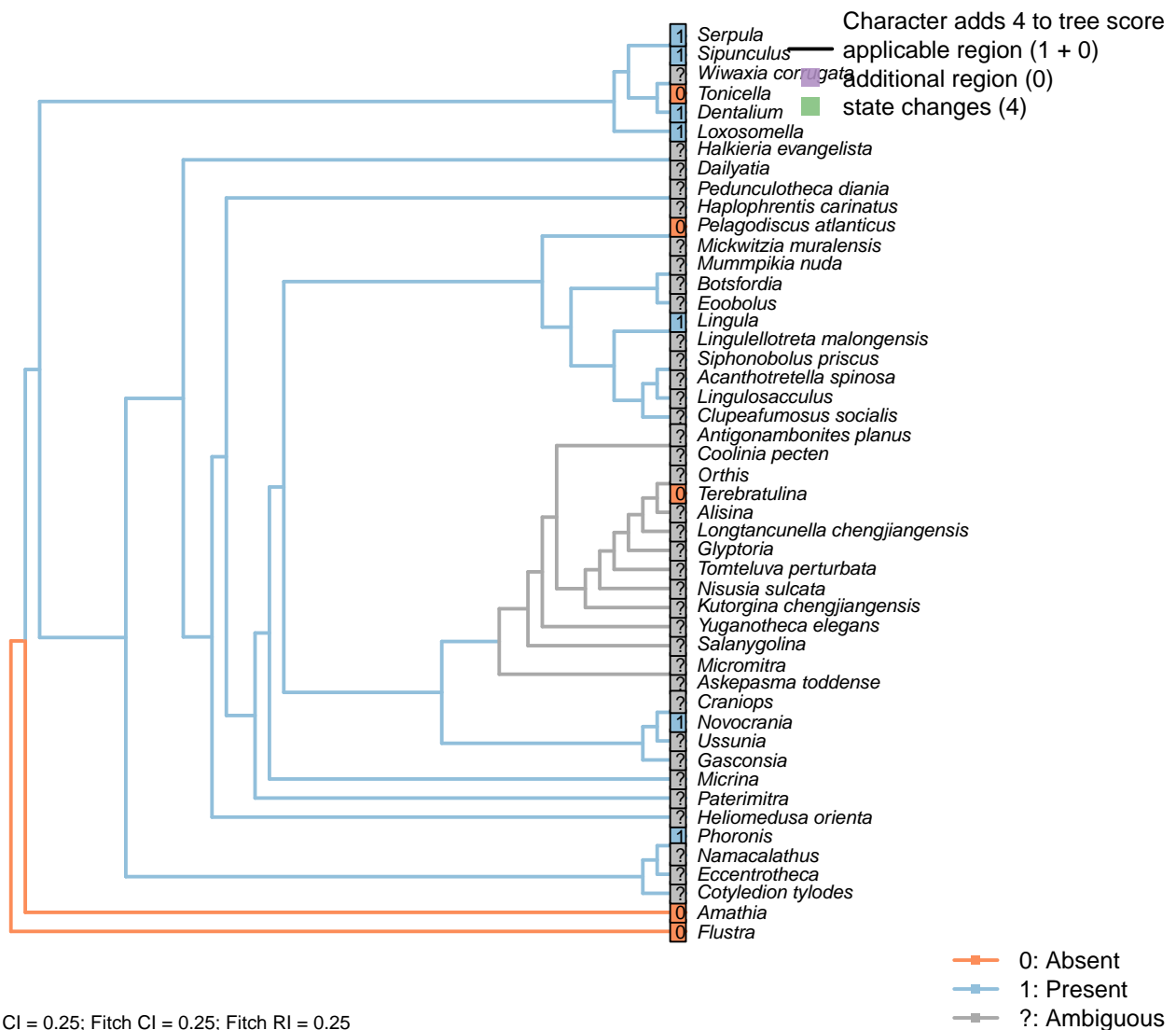
Phoronis, *Sipunculus*: No evidence of internal differentiation (in *Tubulipora*; Franzén, 1984).

Serpula: Following *Discinisca tenuis*, described in Hodgson & Reunov (1994).

Tonicella: Following Hodgson & Reunov (1994).

Wiwaxia corrugata: Acrosome-like structure; no internal division or surrounding membrane, with possibility that much of the acrosome is secondarily lost (Reunov and Klepal, 2004).

[146] Acrosome: Sub-acrosomal space



Character 146: Gametes: Spermatozoa: Acrosome: Sub-acrosomal space

0: Absent

1: Present

Neomorphic character.

Acanthotretella spinosa: Not evident (Buckland-Nicks et al., 1988).

Alisina: Dufresne-Dube et al. (1983).

Dailyatia: Gherardi et al. (2011).

Dentalium: Filled with sub-acrosomal substance (Fukumoto, 2003).

Eoobolus: Prominent (Afzelius and Ferraguti, 1978).

Halkieria evangelista: Rice (1993).

Lingula: Present in *Loxosoma* [Franzen 2000].

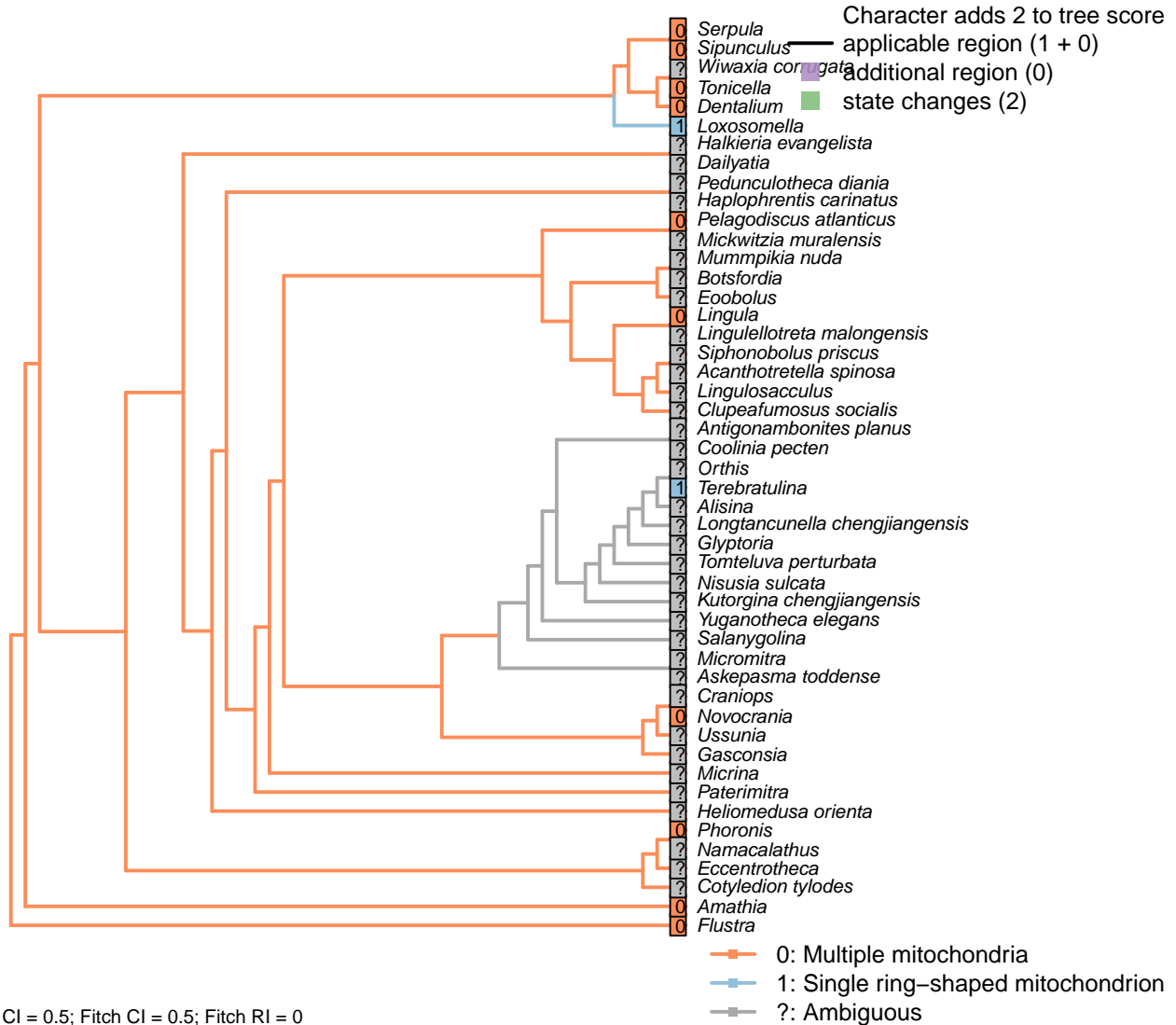
Phoronis, *Sipunculus*: No distinct space (in *Tubulipora*; Franzén, 1984).

Serpula: Subacrosomal material (in *Discinisca*) but no subacrosomal space (Hodgson and Reunov, 1994).

Tonicella: No subacrosomal material, let alone a subacrosomal space (e.g. Hodgson and Reunov, 1994).

Wiwaxia corrugata: The filament-like acrosome continues backwards as a tube-like structure (Franzén and Ahlfors, 1980, summarized in Jamieson (1991)).

[147] Mid-piece



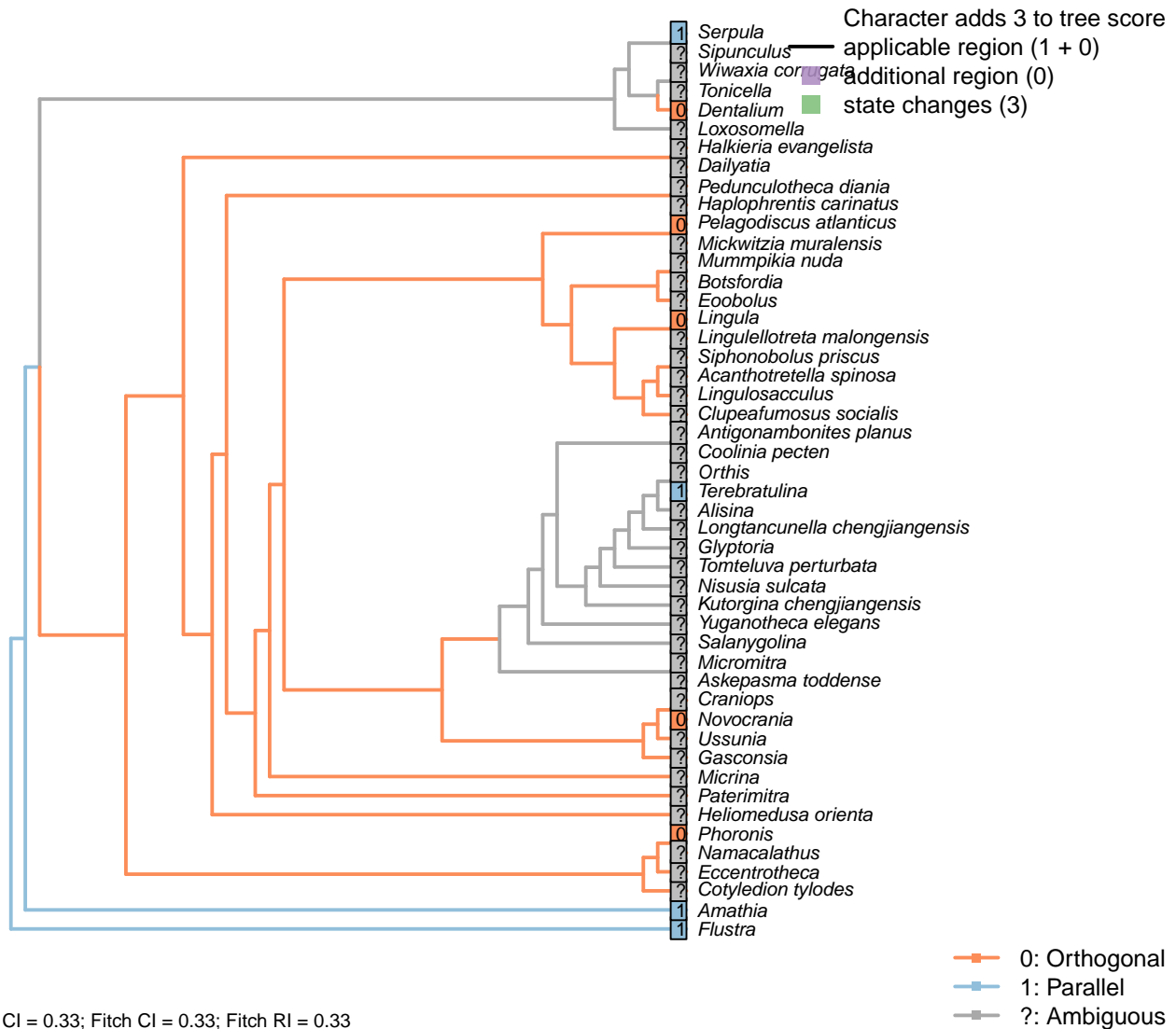
central rod of electron-dense material.

Phoronis, *Sipunculus*: Two mitochondrial derivatives in *Flustra* (Franzén, 1981, 1977); four in *Tubulipora* (Franzén, 1984).

Serpula: Following *Discinisca tenuis*, described in Hodgson & Reunov (1994).

Wiwaxia corrugata: The mitochondria fuse in the middle stage of spermiogenesis to become a pair of mitochondria (Reunov and Klepal, 2004).

[148] Centrioles: Orientation



Character 148: Gametes: Spermatozoa: Centrioles: Orientation

0: Orthogonal

1: Parallel

Neomorphic character.

Following Hodgson and Reunov (1994).

Alisina: Dufresne-Dube et al. (1983).

Dailyatia: The proximal centriole is parallel to the flagellum (Gherardi et al., 2011).

Dentalium, *Tonicella*: Following Hodgson & Reunov (1994).

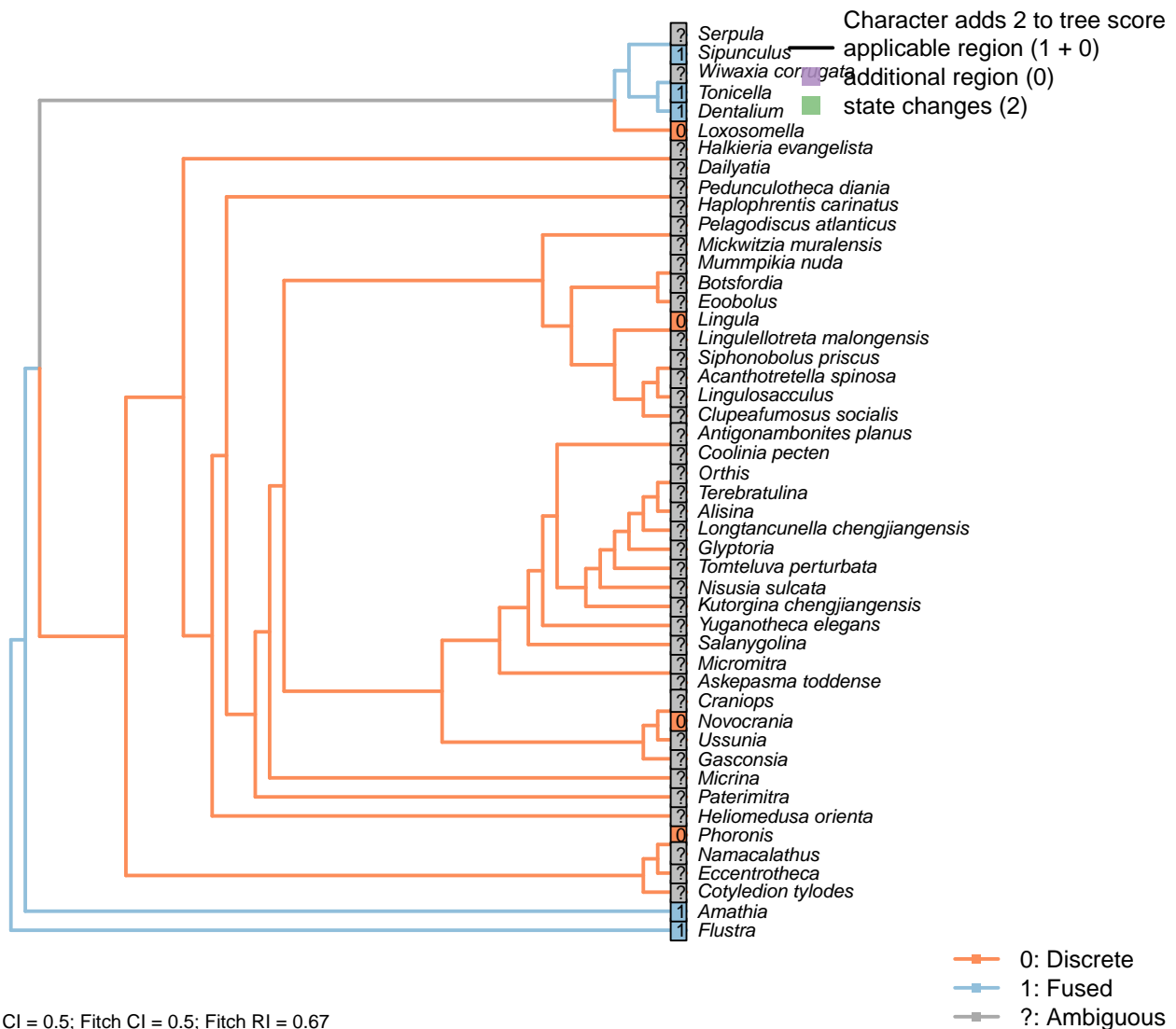
Eoobolus: Two orthogonal centrioles (Afzelius and Ferraguti, 1978).

Phoronis, *Sipunculus*: (Franzén, 1981).

Serpula: Following *Discinisca tenuis*, described in Hodgson & Reunov (1994).

Wiwaxia corrugata: Only one centriole in spermatzoon (Reunov and Klepal, 2004, p. 7), but centrioles are perpendicularly oriented in spermatogonia (ibid., p. 2).

[149] Centrioles: Fusion



0: Discrete

1: Fused

Neomorphic character.

Following Smith (2012a); see Buckland-Nicks (2008).

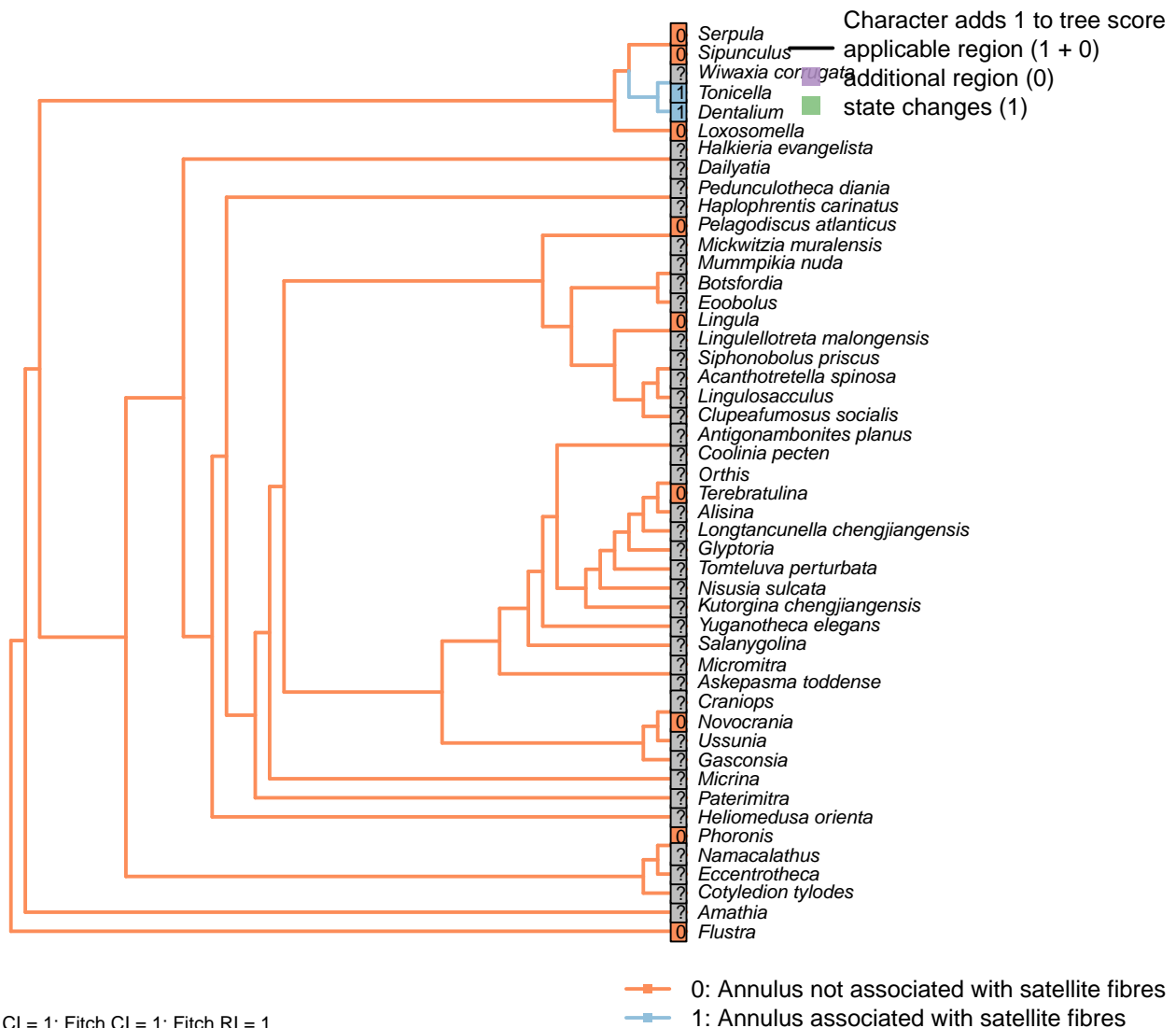
Acanthotretella spinosa: Proximal centriole fused lateral to distal centriole and offset.

Alisina: Proximal centriole fused anterior to distal centriole (Dufresne-Dube et al., 1983).

Dentalium, *Eoobolus*, *Lingula*, *Wiwaxia corrugata*: Basal body in deep nuclear fossa.

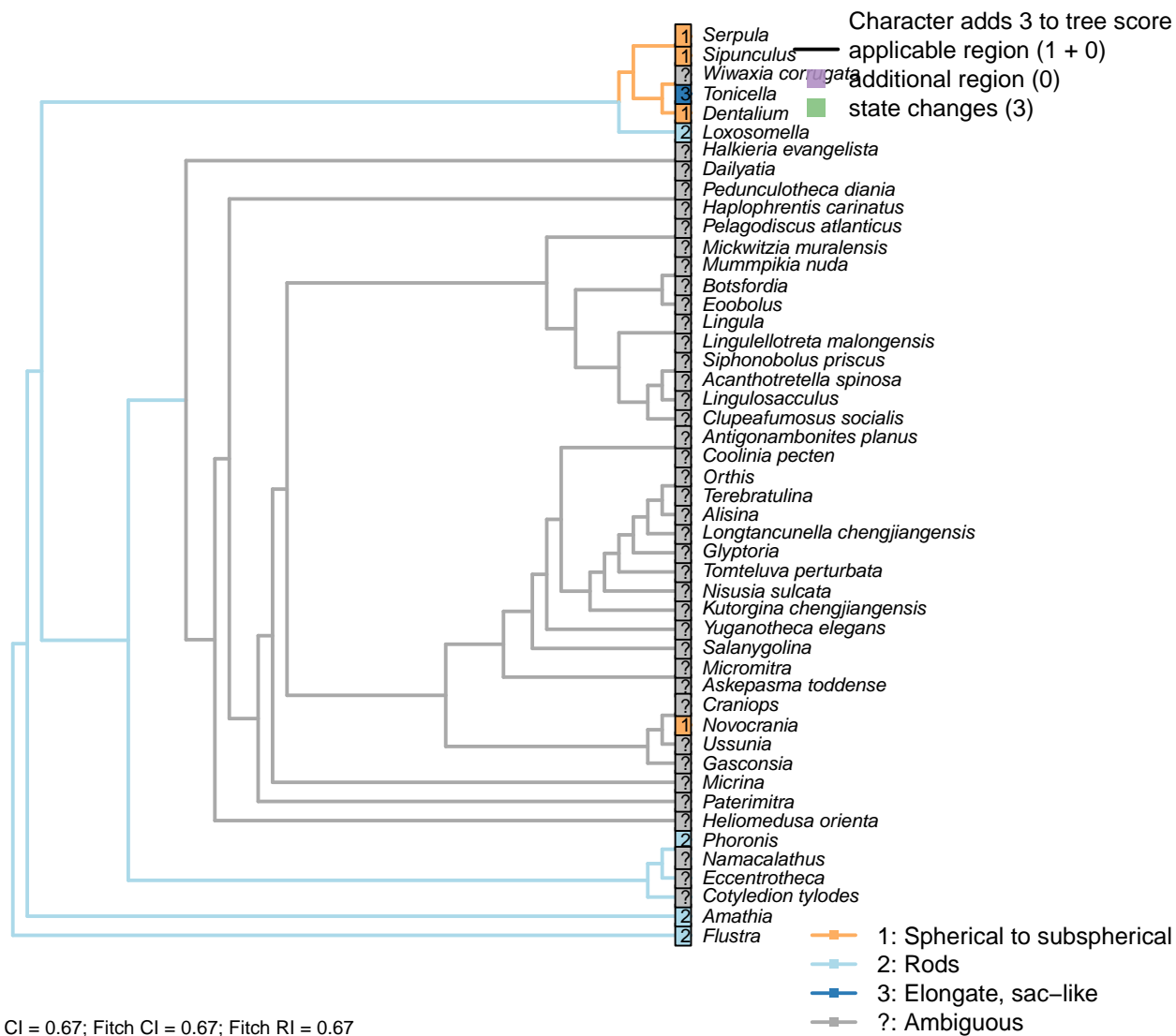
Halkieria evangelista, *Phoronis*, *Sipunculus*: Proximal centriole fused anterior to distal centriole.

[150] Satellite fibre complex



Following Smith (2012a), after character 48 in Ponder and Lindberg (1997).

[151] Mitochondria: Shape



Character 151: Gametes: Spermatozoa: Mitochondria: Shape

- 1: Spherical to subspherical
- 2: Rods
- 3: Elongate, sac-like
- Transformational character.

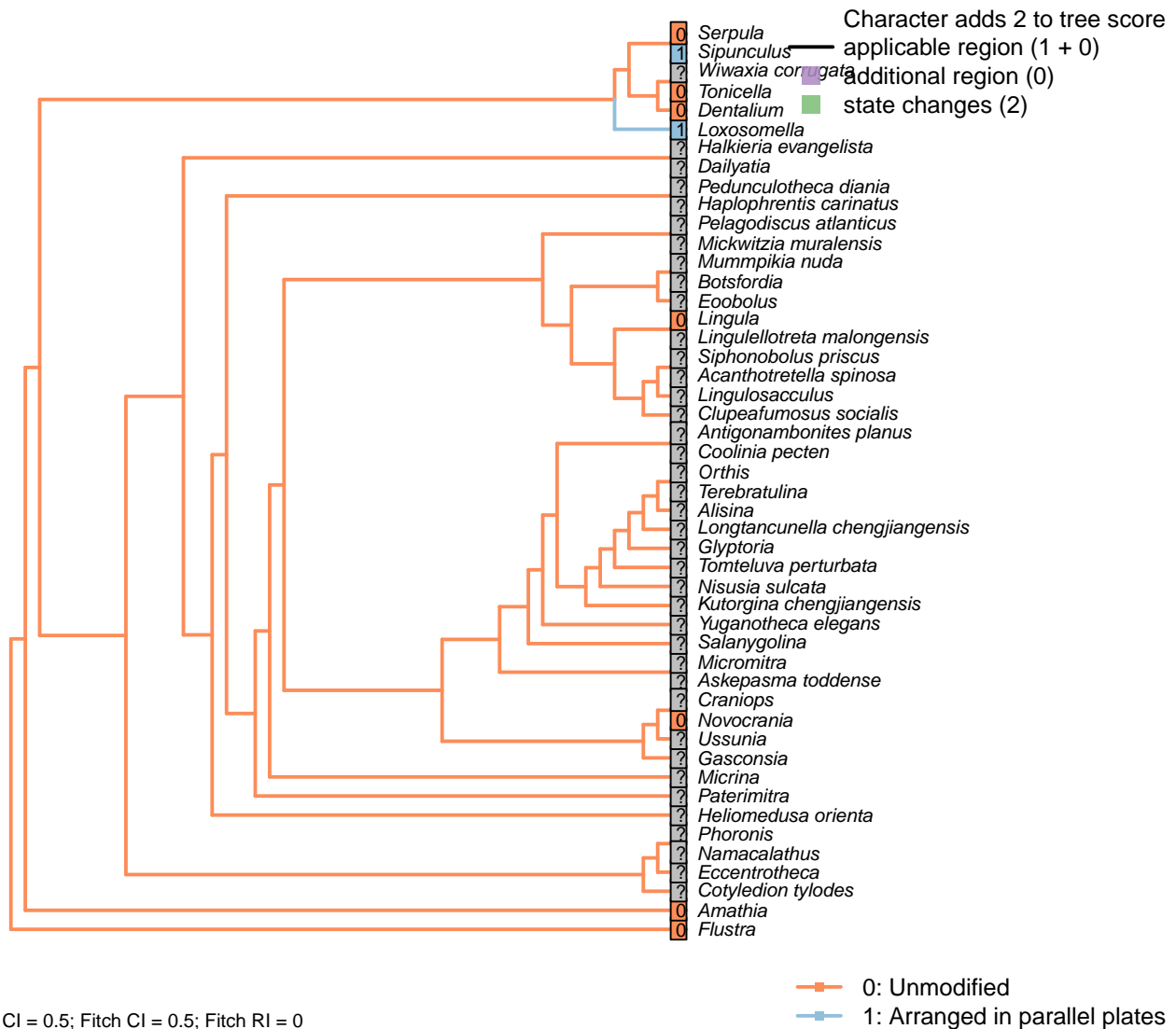
After character 5 in Buckland-Nicks (2008); see also character 43 in Ponder and Lindberg (1997).

Acanthotretella spinosa: See Buckland-Nicks et al. (1988).

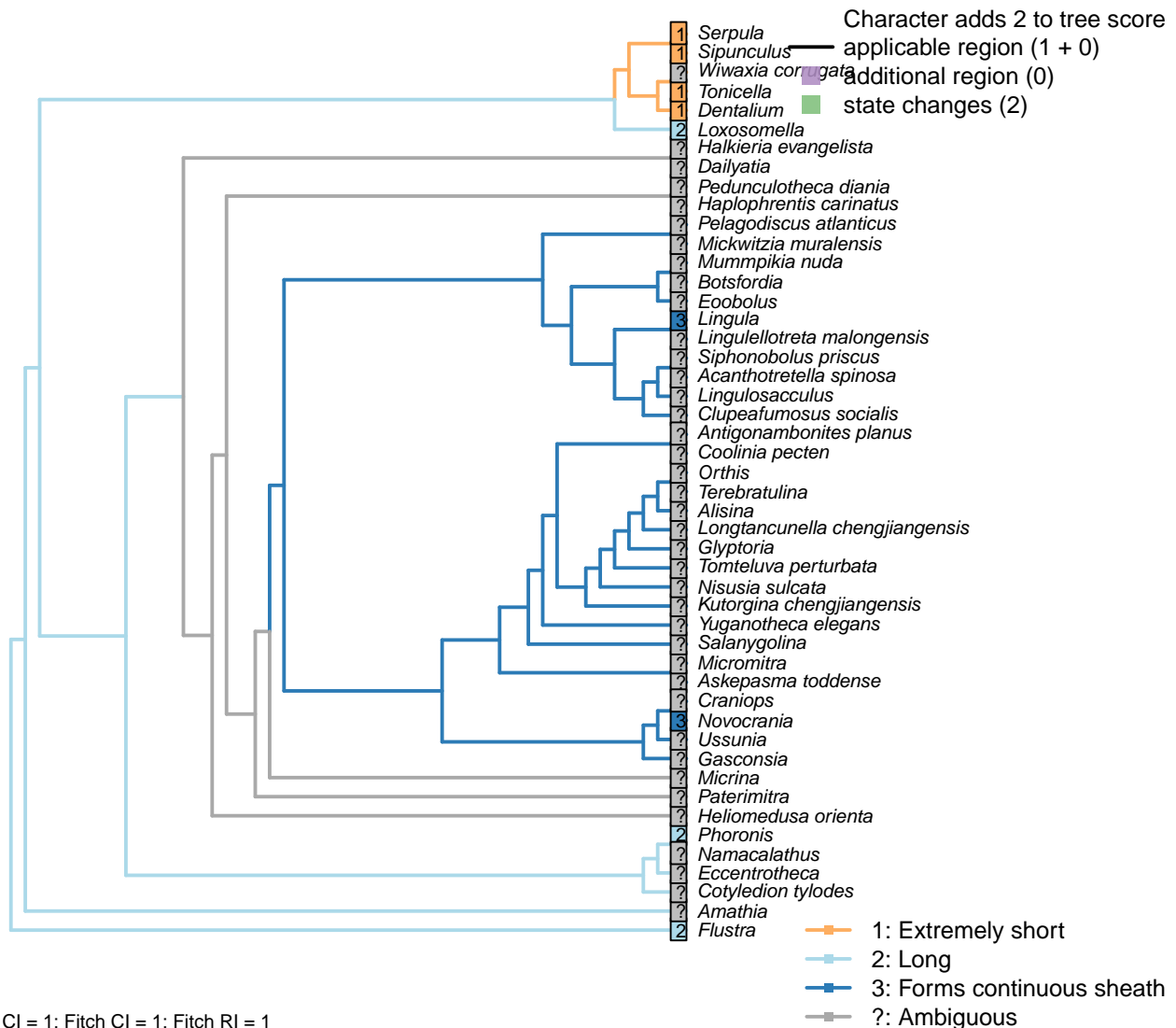
Lingula: Elongate rods in *Loxosoma* (Franzén, 2000).

Phoronis, *Sipunculus*: Rods (Franzén, 1981).

[152] Mitochondria: Cristae: Configuration



[153] Mitochondria: Midpiece

**Character 153: Gametes: Spermatozoa: Mitochondria: Midpiece**

- 1: Extremely short
 - 2: Long
 - 3: Forms continuous sheath
- Transformational character.

After Smith (2012a); see also character 43 in Ponder and Lindberg (1997); character 164 in Giribet and Wheeler (2002).

Dailyatia: Five mitochondria surround the base of the flagellum in short midpiece, comparable to that of *Sipunculus* and *Dentalium* (Gherardi et al., 2011).

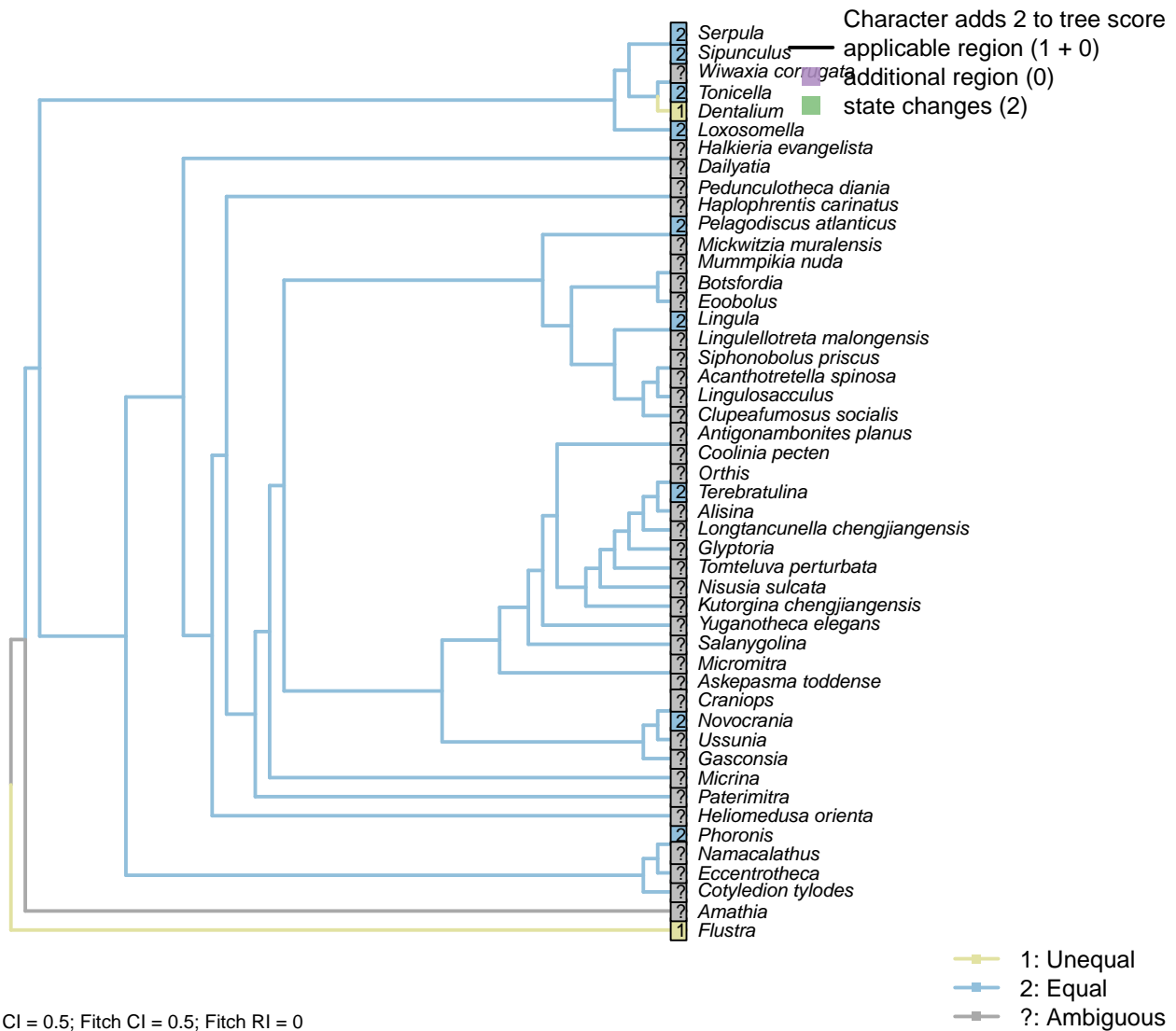
Halkieria evangelista: Short ring of five mitochondria around the central centriole (Rice, 1993).

Lingula: As long as the flagellum in *Loxosoma* (Franzén, 2000).

Phoronis, *Sipunculus*: Long (Franzén, 1981).

3.28 Embryo: Cleavage

[154] Equal



CI = 0.5; Fitch CI = 0.5; Fitch RI = 0

Character 154: Embryo: Cleavage: Equal

1: Unequal

2: Equal

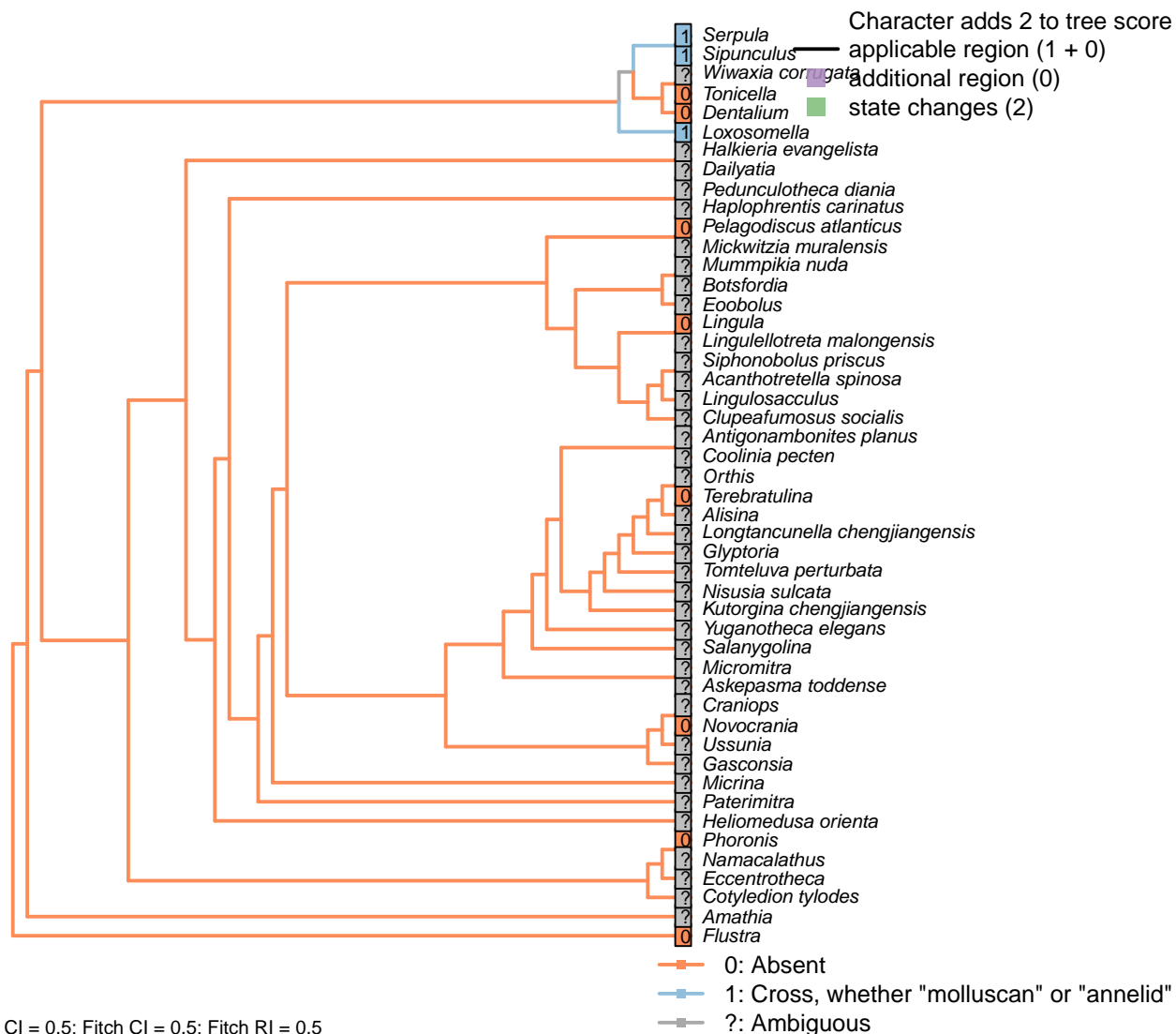
Transformational character.

Following character 170 in Giribet and Wheeler (2002).

Dentalium, *Eoobolus*, *Serpula*, *Tonicella*: Equal, in all brachiopods (Williams et al., 1997).

Wiwaxia corrugata: “Cleavage is holoblastic and results in approximately equal sized, or adequal, blastomeres.” – Pennerstorfer and Scholtz (2012).

[155] Cross pattern

**Character 155: Embryo: Cleavage: Cross pattern**

0: Absent

1: Cross, whether "molluscan" or "annelid"

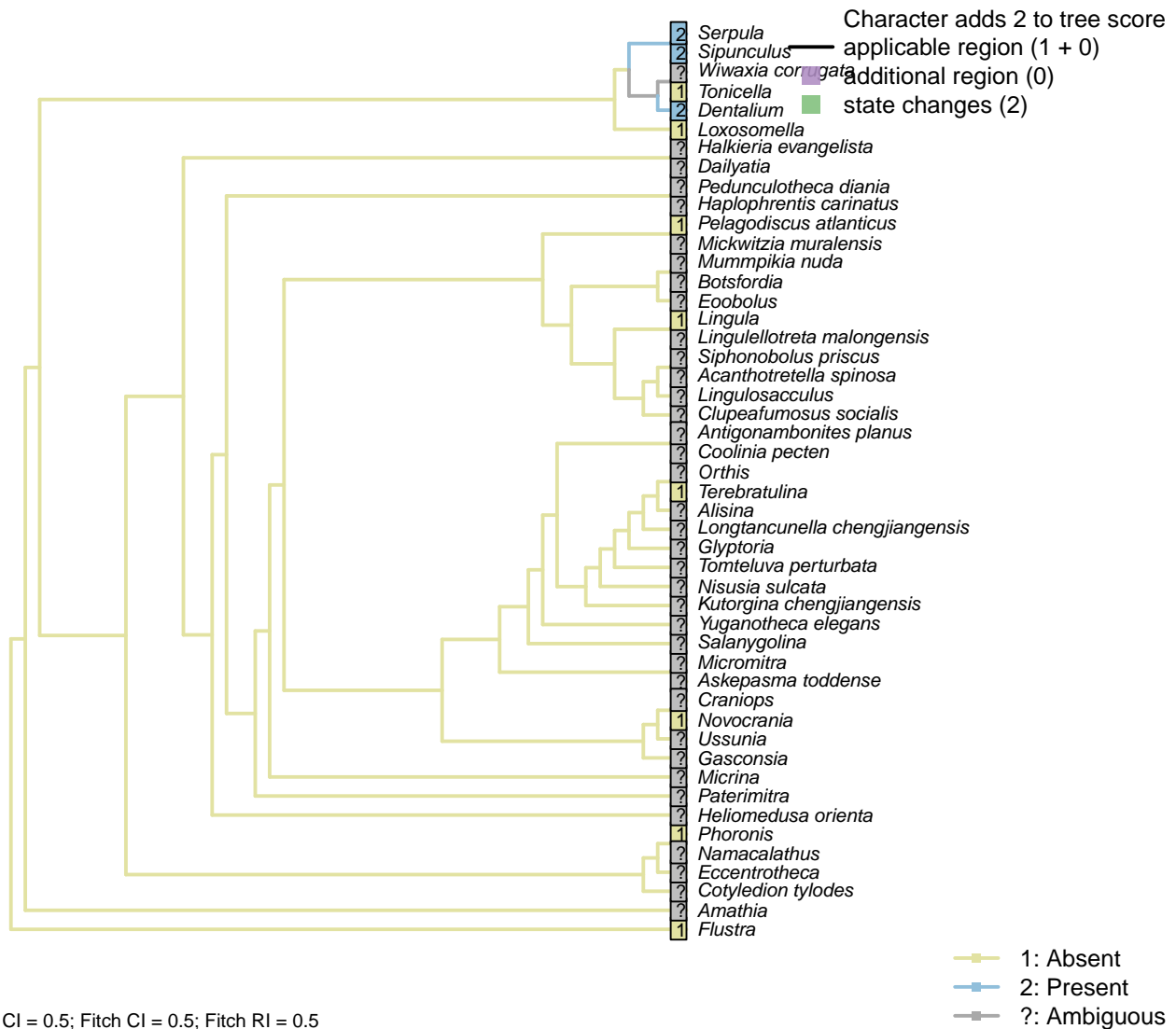
Neomorphic character.

The "molluscan cross" and "annelid cross" cannot be systematically discriminated from one another, so are treated as a single state.

See characters 127 & 128 in Rouse (1999); 1.49 in von Salvini-Plawen and Steiner (1996);

character 34 in Haszprunar (1996); 35 in Haszprunar (2000); 172 in Giribet and Wheeler (2002).

[156] Polar lobe formation

**Character 156: Embryo: Cleavage: Polar lobe formation**

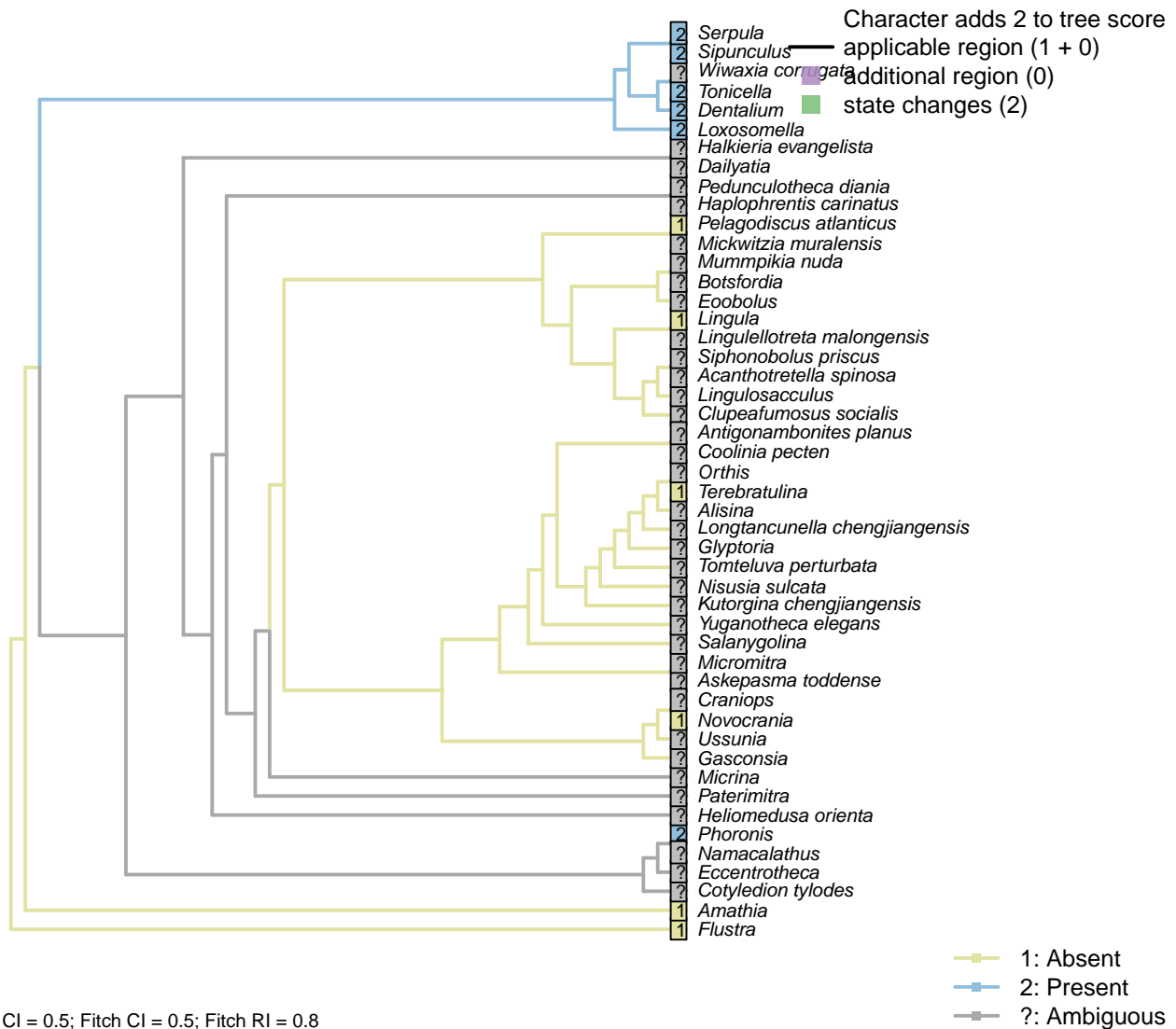
1: Absent

2: Present

Transformational character.

Following character 171 in Giribet and Wheeler (2002).

[157] Spiral

**Character 157: Embryo: Cleavage: Spiral**

1: Absent

2: Present

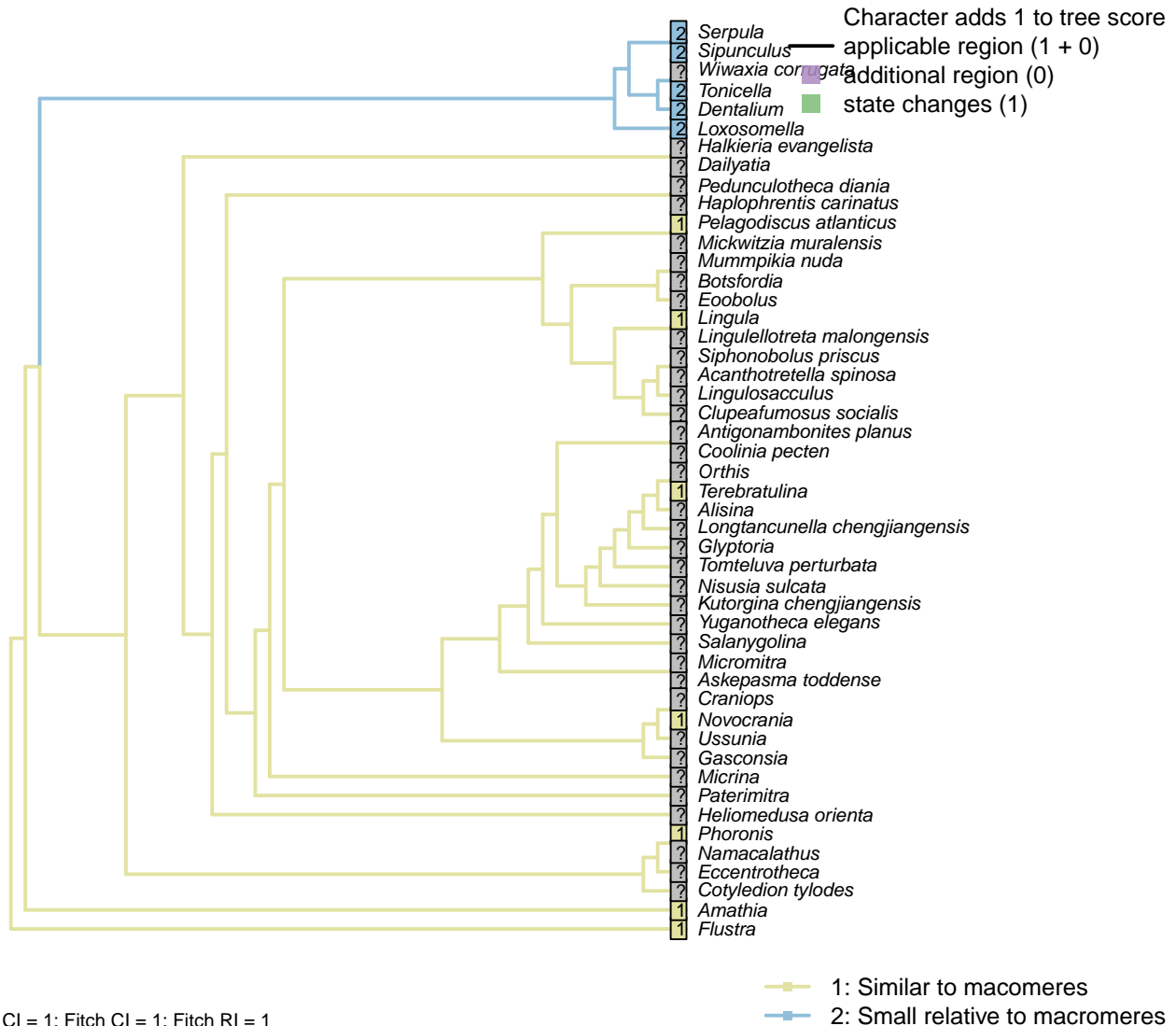
Transformational character.

See characters 32–33 in Haszprunar (1996); character 1.48 in von Salvini-Plawen and Steiner (1996); character 29 in Glenner et al. (2004).

Phoronis, *Sipunculus*: “While entoprocts are spiral cleavers, ectoprocts show a radial cleavage pattern” – Fuchs and Wanninger (2008).

Wiwaxia corrugata: “The observed cleavage displays several characters consistent with the pattern of spiral cleavage” (Pennerstorfer and Scholtz, 2012).

3.29 Embryo: Micromere size [158]

**Character 158: Embryo: Micromere size**

- 1: Similar to macomeres
 - 2: Small relative to macomeres
- Transformational character.

Following Hejnol (2010). Blastomeres may undergo significant size differentiation, generating macromeres and micromeres of prominently different sizes.

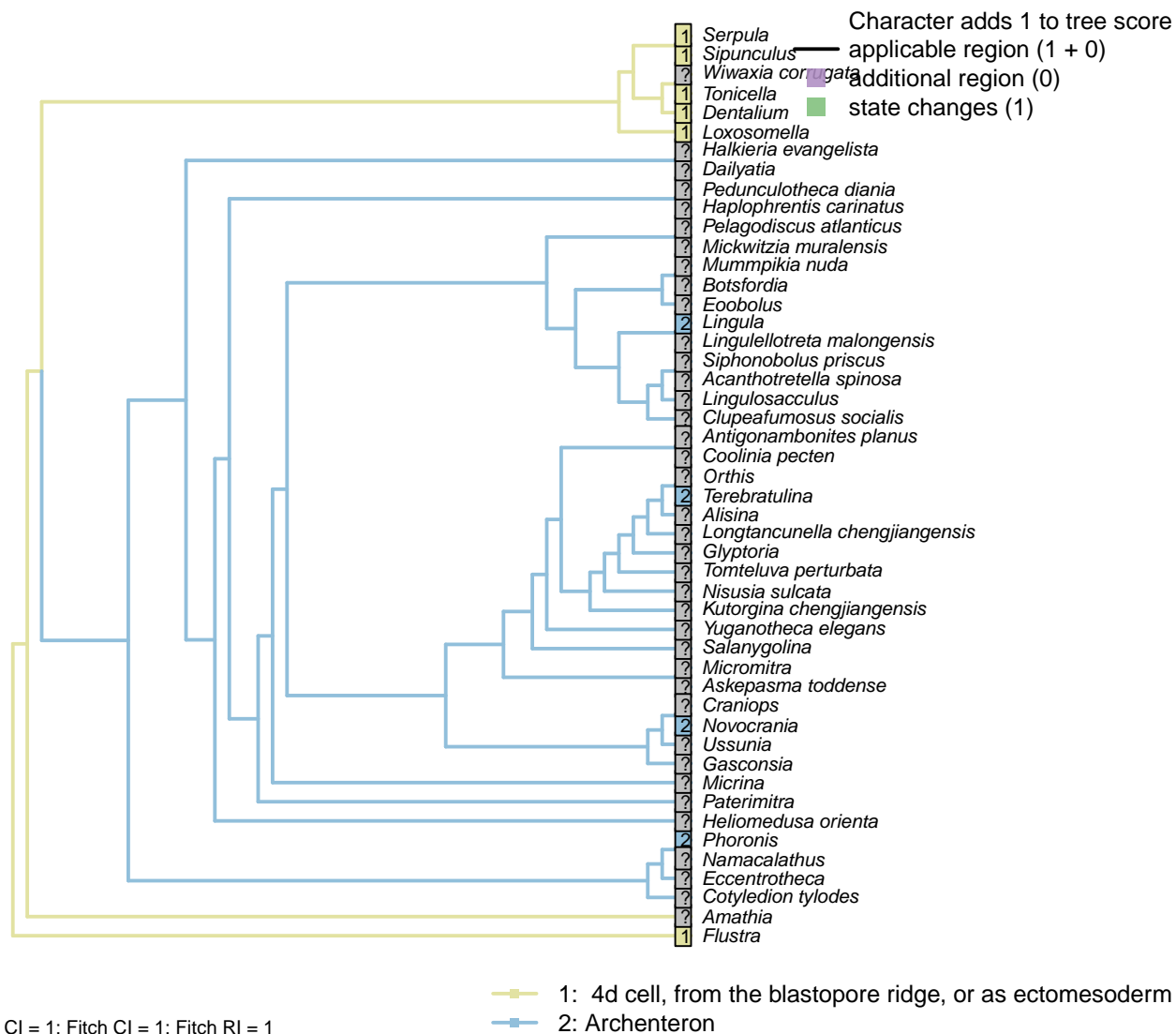
Dentalium, *Tonicella*: Williams et al. (1997).

Halkieria evangelista: Prominent differentiation in Phascolosoma (Adrianov et al., 2011).

Phoronis, *Sipunculus*: In *Membranipora*, “cleavage is slightly unequal resulting in little larger central blastomeres” (Gruhl, 2010b).

Wiwaxia corrugata: Uniform size (Pennerstorfer and Scholtz, 2012).

[159] Origin of mesoderm

**Character 159: Embryo: Origin of mesoderm**

1: 4d cell, from the blastopore ridge, or as ectomesoderm

2: Archenteron

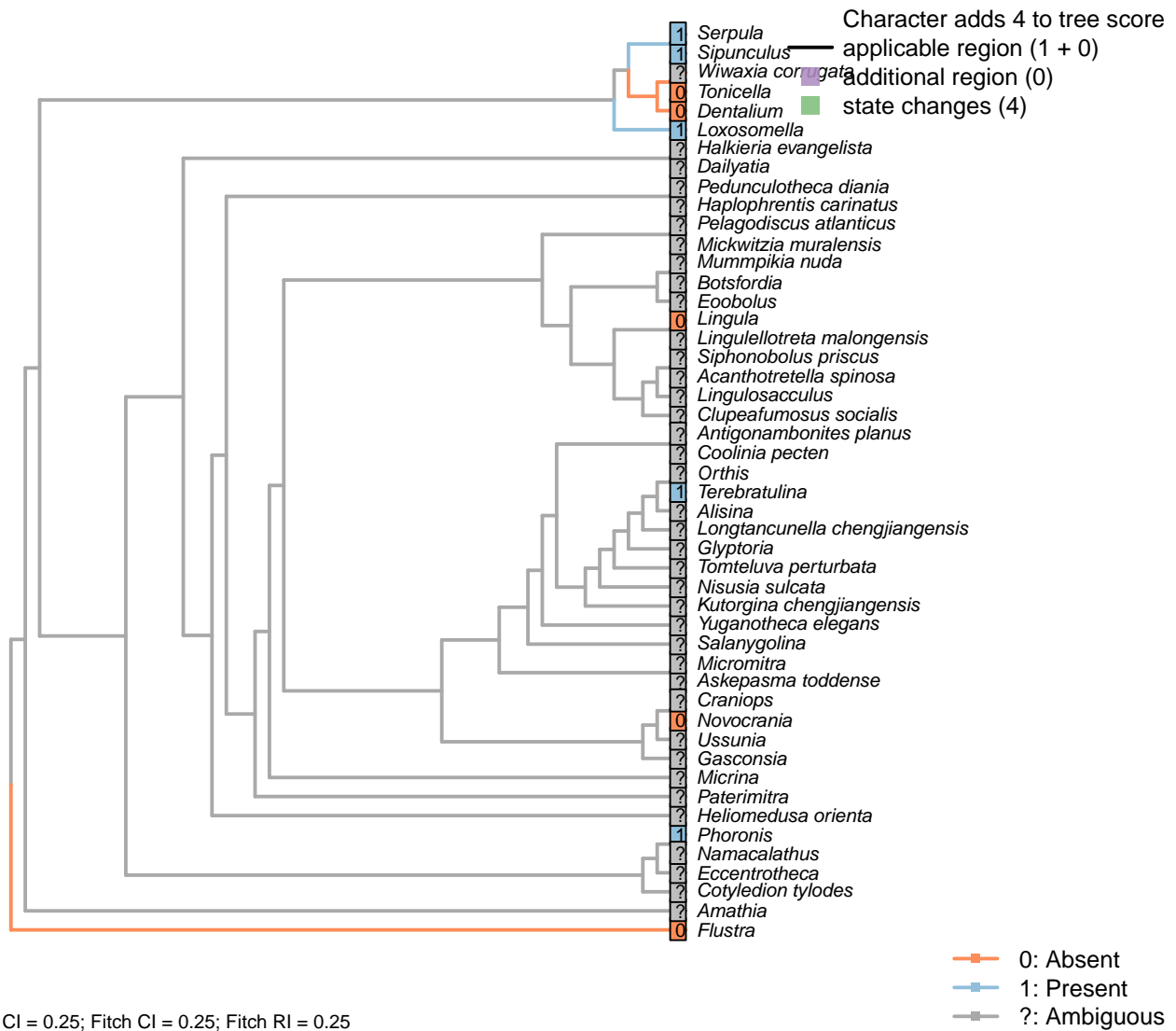
Transformational character.

After characters 32 in Grobe (2007) and 36–37 in Glenner et al. (2004).

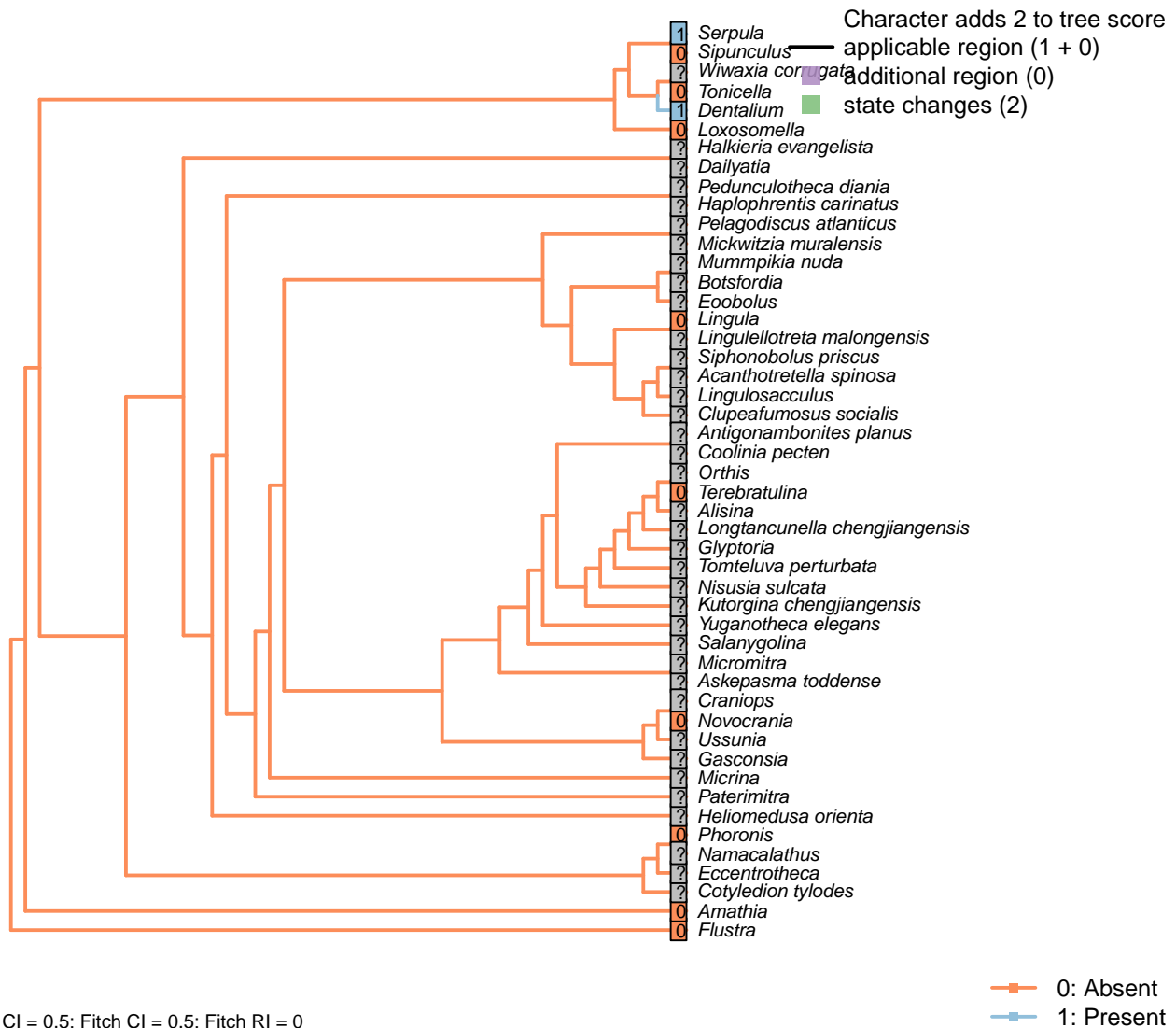
Tonicella: Williams et al. (1997).

3.30 Larva

[160] Metatroch



[161] Telotroch

**Character 161: Larva: Telotroch**

0: Absent

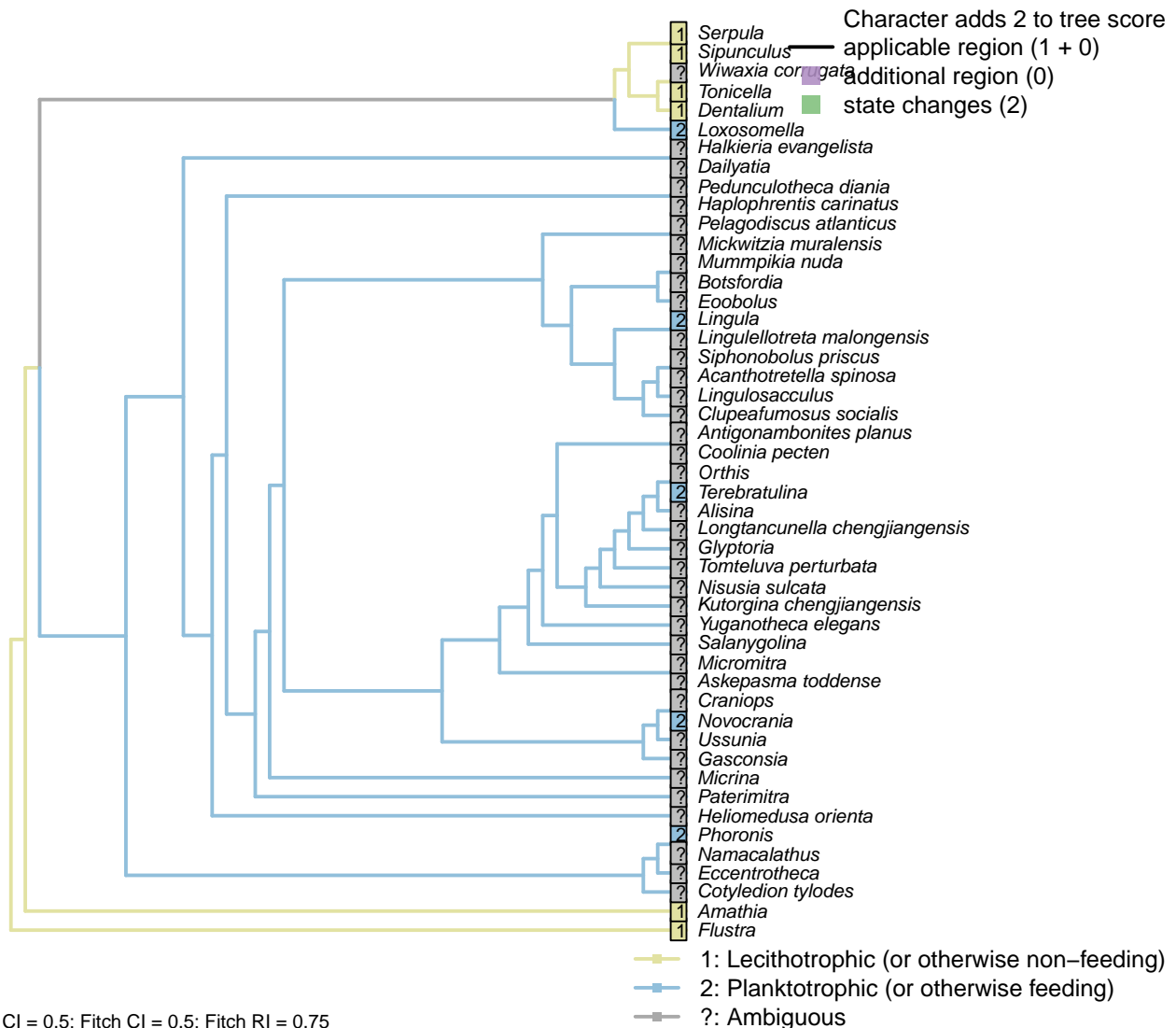
1: Present

Neomorphic character.

A posterior ciliary band. Character 136 in Rouse (1999).

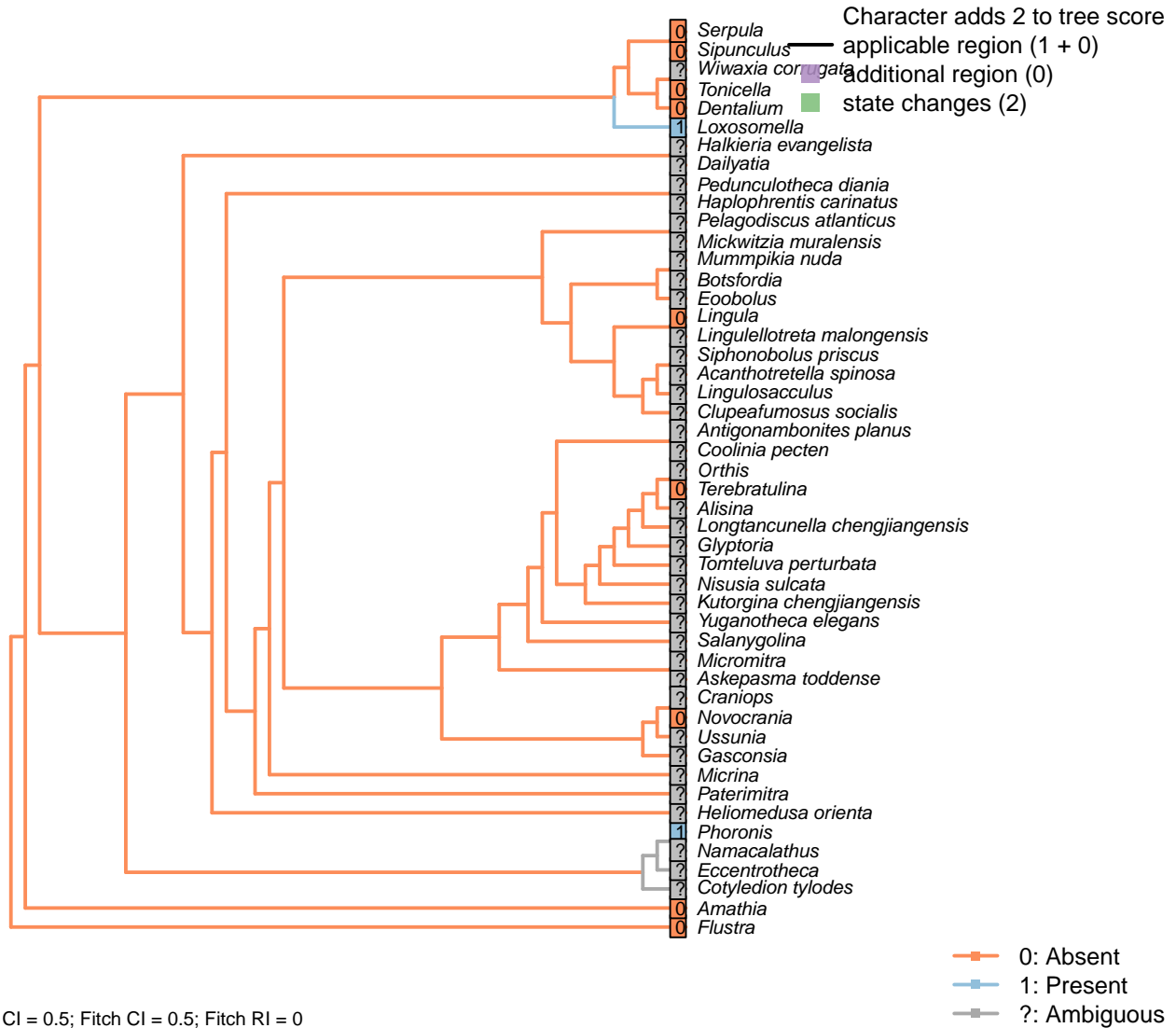
Phoronis: Absent (Zimmer and Woollacott, 2013).*Sipunculus*: Absent; single ciliary field lacks telotroch equivalent (Reed and Cloney, 1982).*Tonicella*: Williams et al. (1997).

[162] Feeding

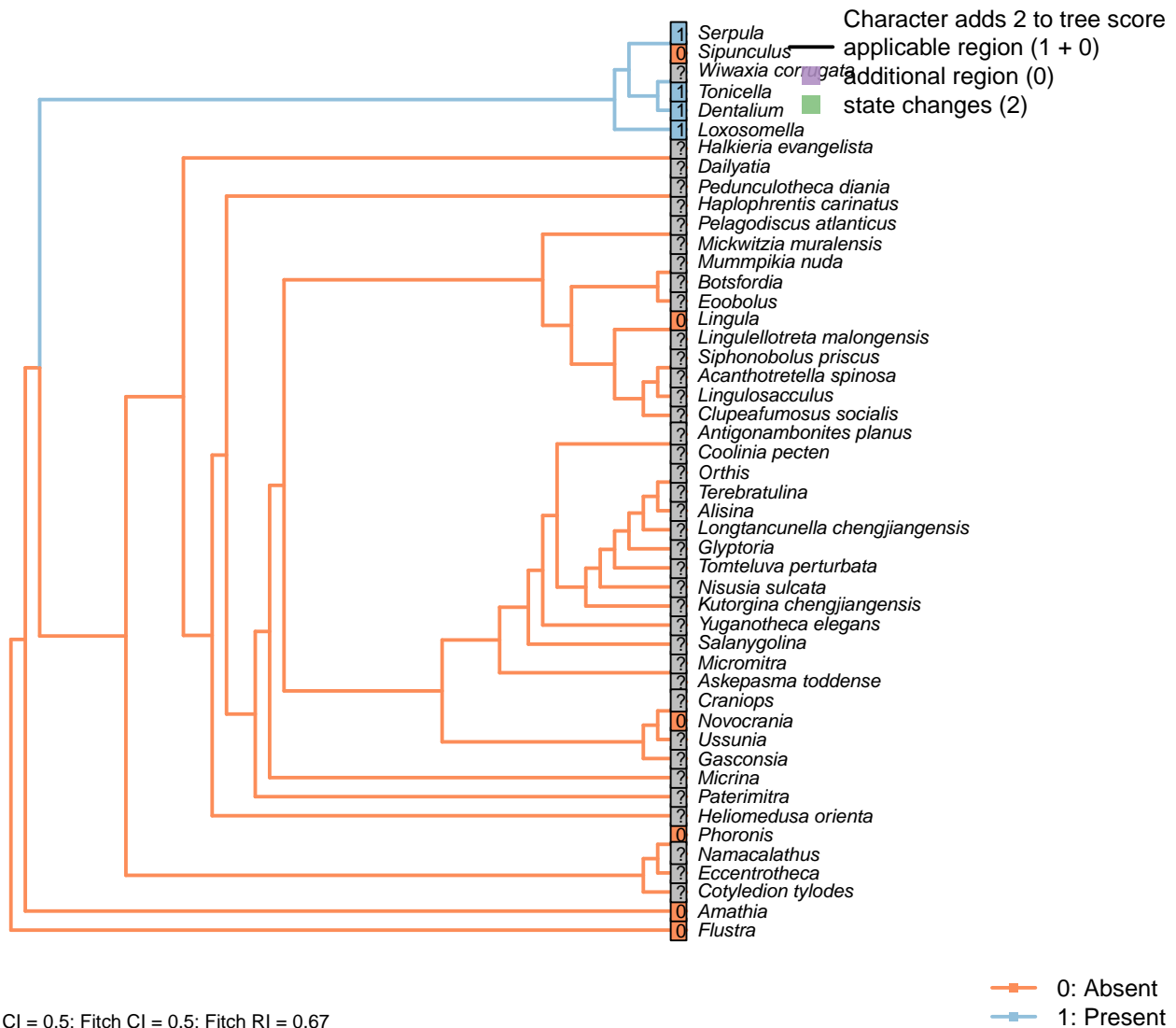


3.31 Larva: Cilia

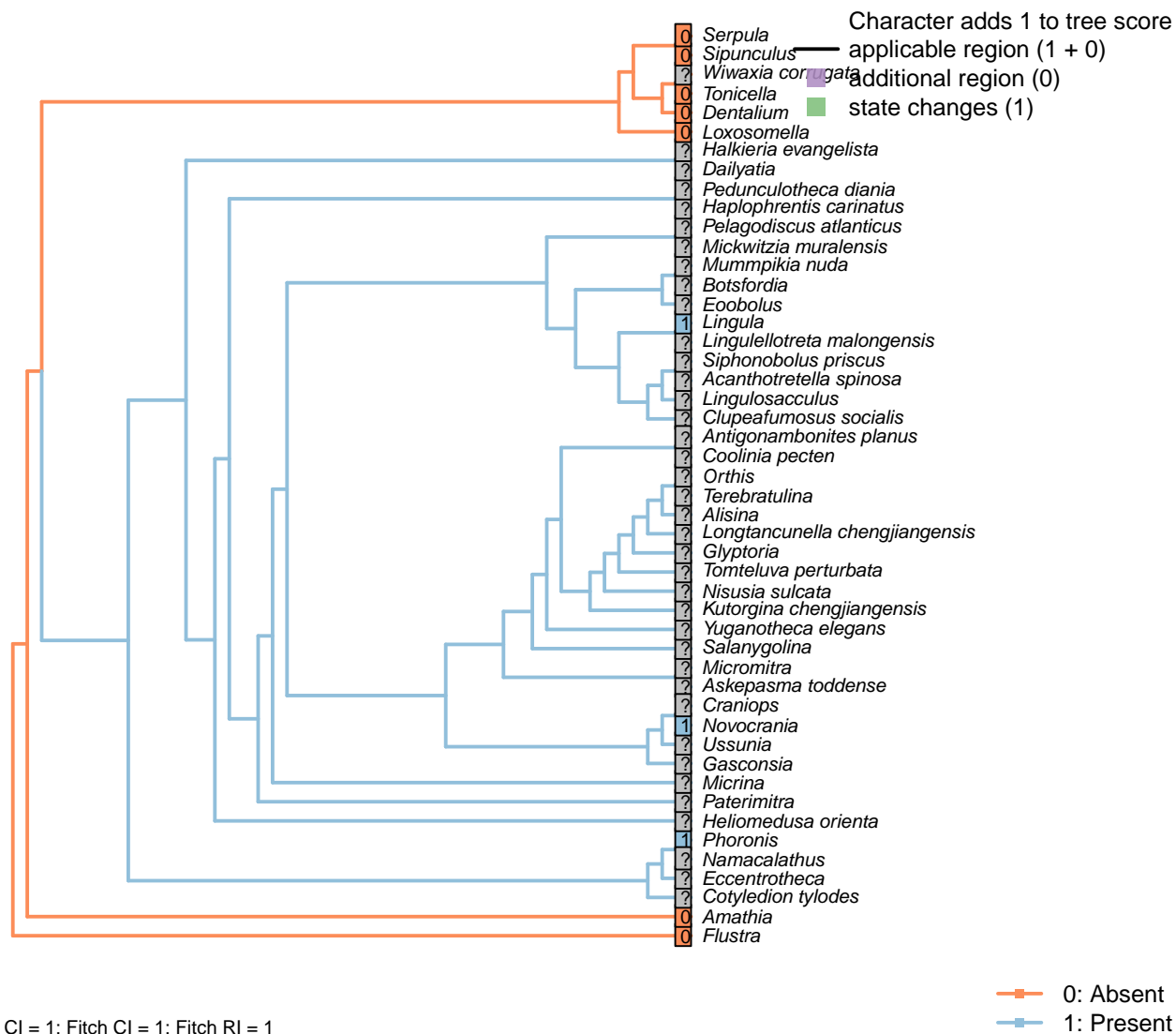
[163] Ciliated food groove



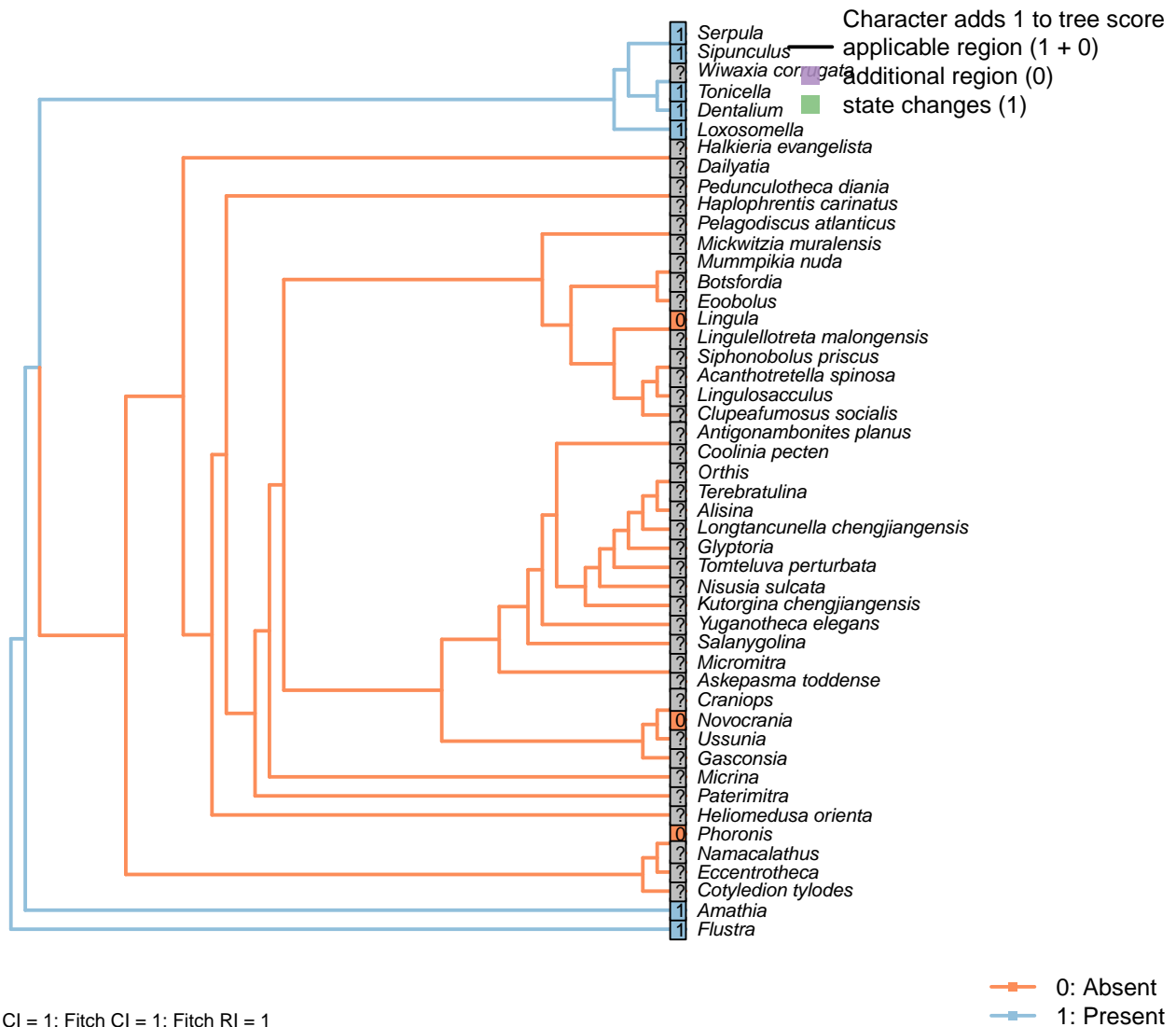
[164] Ciliary bands: Downstream



[165] Ciliary bands: Upstream



[166] Adoral ciliary band

**Character 166: Larva: Cilia: Adoral ciliary band**

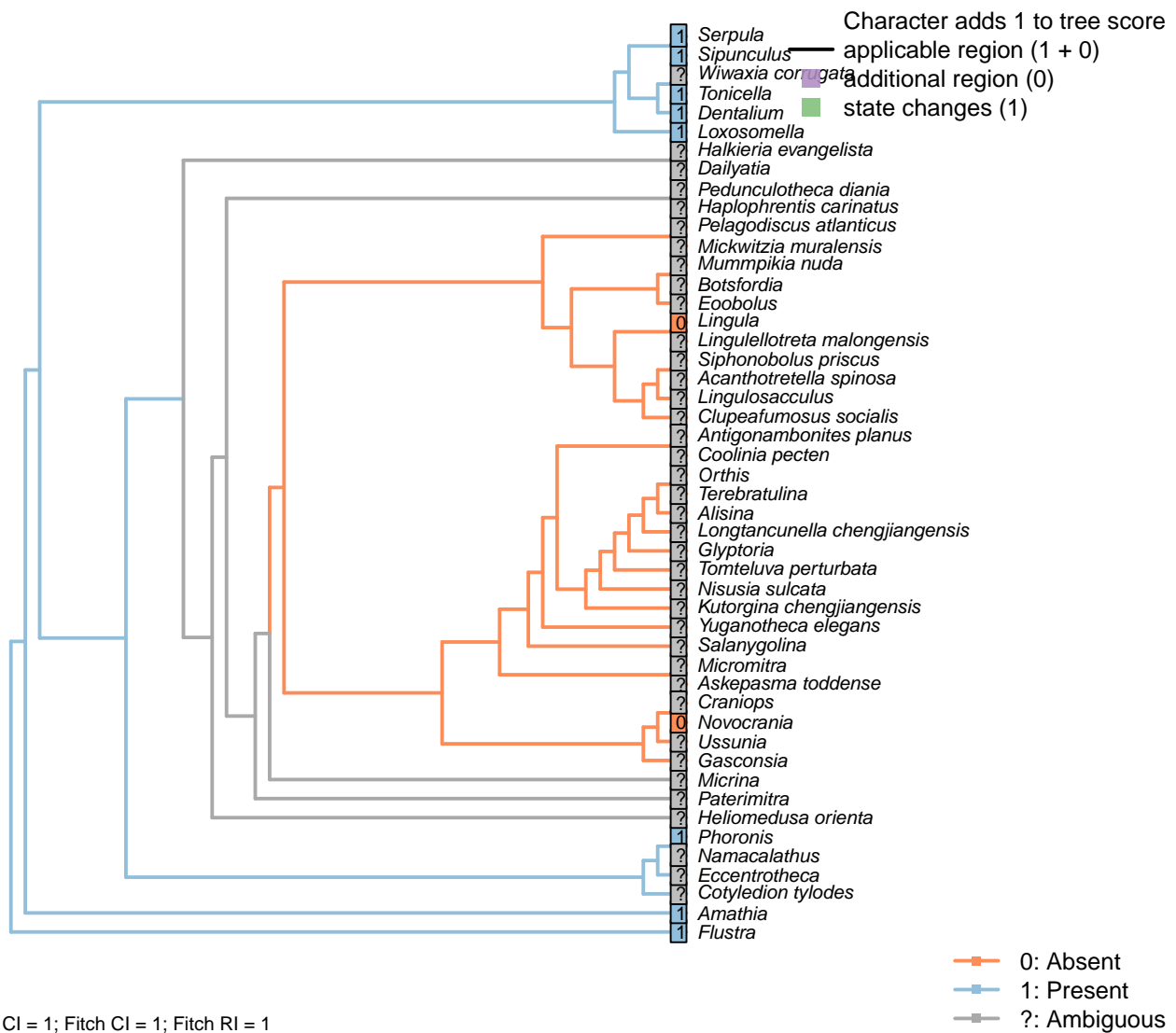
0: Absent

1: Present

Neomorphic character.

Characters 1.50, 2.66 and 4.68 in von Salvini-Plawen and Steiner (1996); 2 in Vinther et al. (2008). See also characters 39 in Haszprunar (1996) and 153 in Giribet and Wheeler (2002).

3.32 Larva: Nerve ring underlying ciliated larval swimming organ [167]



Character 167: Larva: Nerve ring underlying ciliated larval swimming organ

0: Absent

1: Present

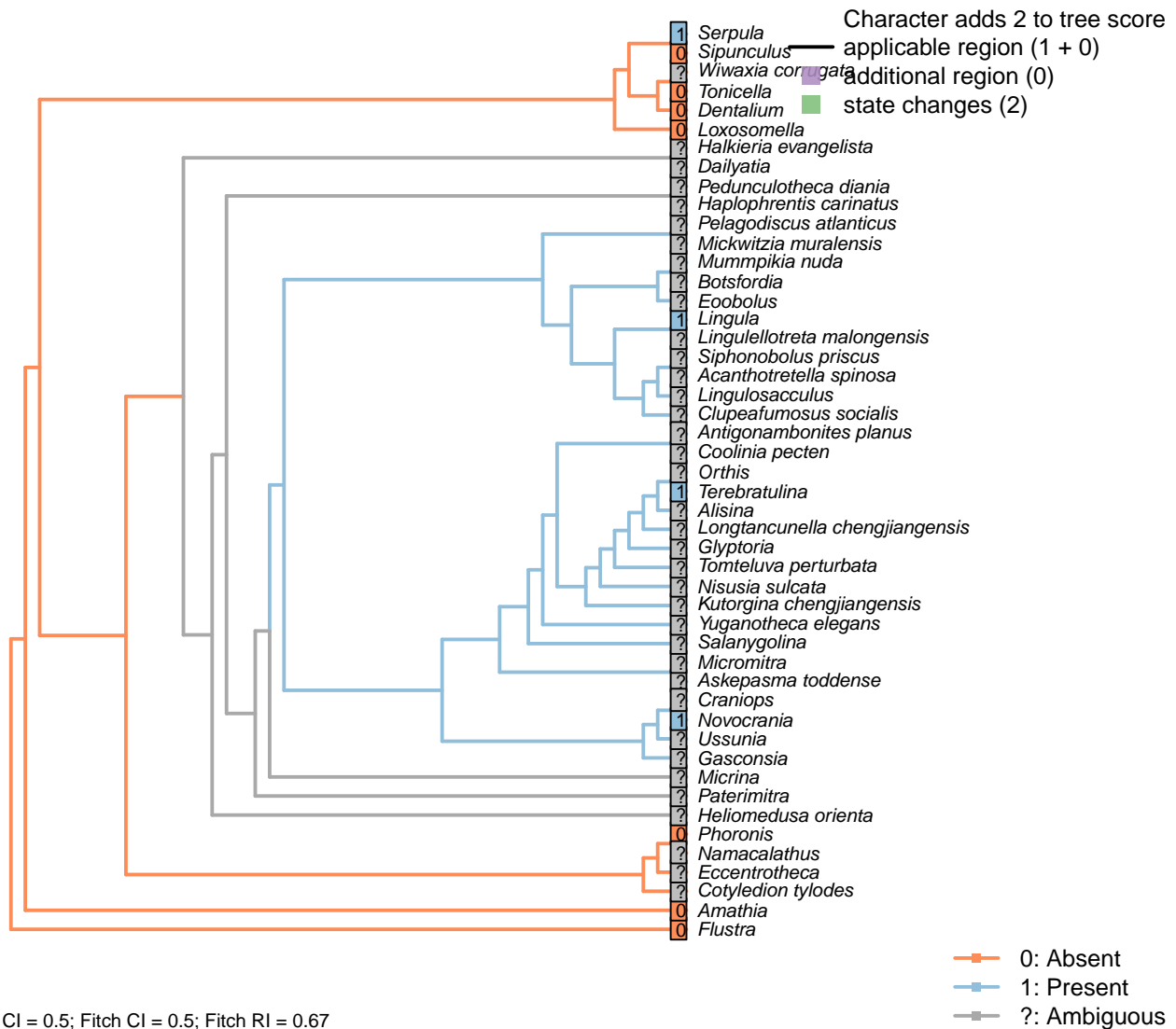
Neomorphic character.

Following Wanninger (2009).

Phoronis: Present, following schematic in Gruhl and Schwaha (2016).

Sipunculus: Nodular nerve ring underlies corona (Reed and Cloney, 1982).

[168] Paired dorsal setal bundles

**Character 168: Larva: Paired dorsal setal bundles**

0: Absent

1: Present

Neomorphic character.

Annelid chaetae are equivalent to the bundled setae expressed in certain brachiopod larvae. See character 12 in Vinther et al. (2008).

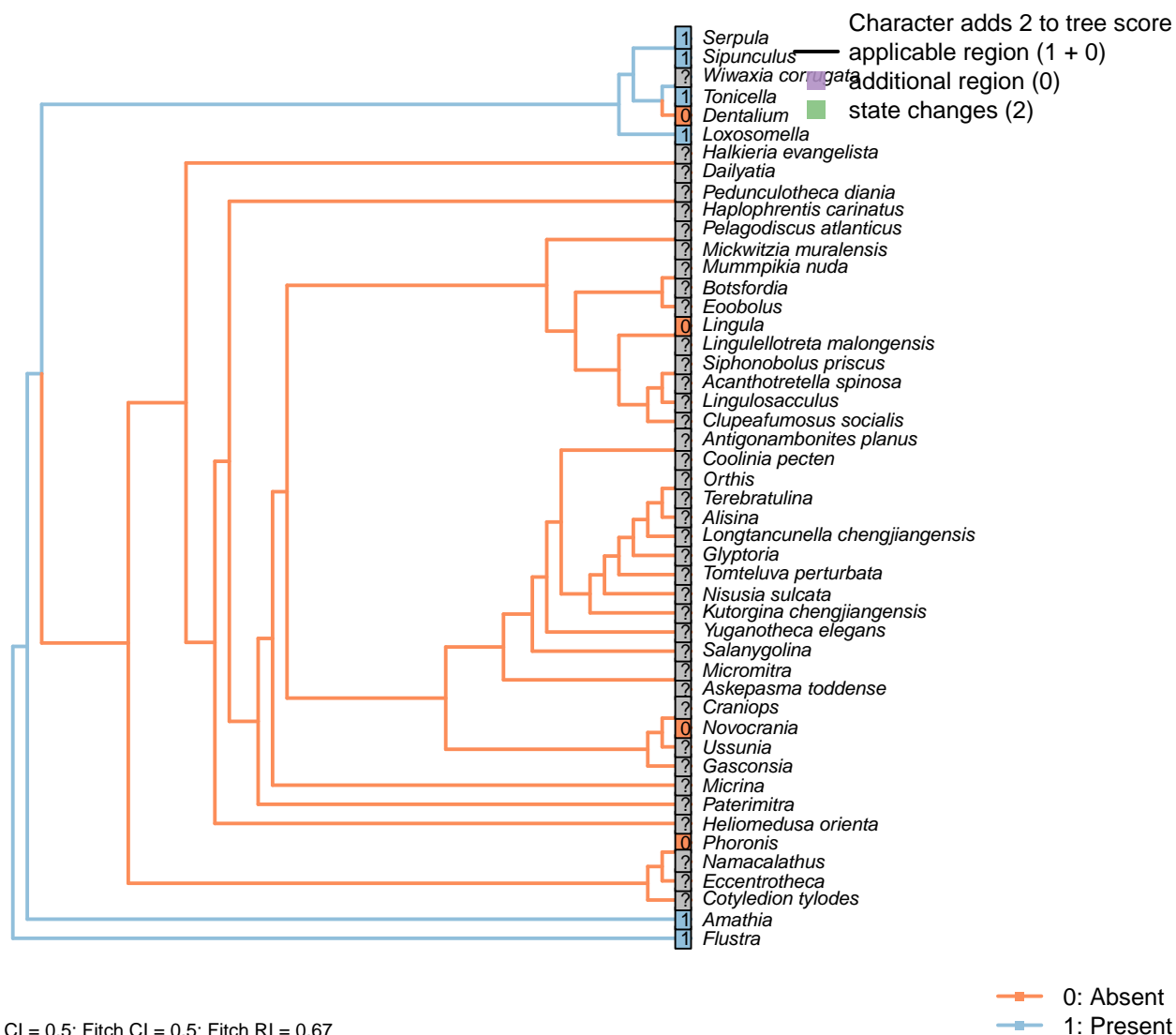
Phoronis: Absent (Zimmer and Woollacott, 2013).

Sipunculus: (Reed and Cloney, 1982).

Tonicella: Williams et al. (1997).

3.33 Larva: Apical organ

[169] Muscles extending to the hyposphere



Character 169: Larva: Apical organ: Muscles extending to the hyposphere

0: Absent

1: Present

Neomorphic character.

Character 8 in Vinther et al. (2008).

Alisina: Apical organ has disappeared before musculature is set in place (Wanninger and Haszprunar, 2002b).

Phoronis, *Sipunculus*: Median muscles extending from apical organ (Gruhl, 2008).

Wiwaxia corrugata: Not evident (Santagata, 2004, fig. 2C).

Character adds 4 to tree score
 applicable region (1 + 0)
 additional region (0)
 state changes (4)

CI = 0.5; Fitch CI = 0.5; Fitch RI = 0.5

3: Cluster of c. eight flask-shaped cells
 4: Aggregation of multiple cells of multiple types
 ? : Ambiguous

Phylogenetic tree showing relationships between various genera, including *Serpula*, *Sipunculus*, *Wiwaxia corrigata*, *Tonicella*, *Dentalium*, *Loxosomella*, *Halkieria evangelista*, *Dailyatia*, *Pedunculotheca diania*, *Haplophrentis carinatus*, *Pelagodiscus atlanticus*, *Mickwitzia muralensis*, *Mummpikia nuda*, *Botsfordia*, *Euobolus*, *Lingula*, *Lingulellothea malongensis*, *Siphonobolus priscus*, *Acanthotretella spinosa*, *Lingulosacculus*, *Clupeafumosus socialis*, *Antigonambonites planus*, *Coolinia pecten*, *Orthis*, *Terebratulina*, *Alisina*, *Longtancunella chengjiangensis*, *Glyptoria*, *Tomteluva perturbata*, *Nisusia sulcata*, *Kutorgina chengjiangensis*, *Yuganotheca elegans*, *Salanygolina*, *Micromitra*, *Askepasma toddense*, *Craniops*, *Novocrania*, *Ussunia*, *Gasconsia*, *Micrina*, *Paterimitra*, *Heliomedusa orientalis*, *Phoronis*, *Namacalathus*, *Eccentrotheca*, *Cotyledion tylodes*, *Amathia*, and *Fouriesia*.

- 1: Two flask-shaped cells
- 2: Four flask-shaped cells
- 3: Cluster of c. eight flask-shaped cells
- 4: Aggregation of multiple cells of multiple types

Transformational character.

Acanthotretella spinosa: Eight in *Ischnochiton* and *Mopalia* (Wanninger et al., 2007).

Eoobolus: Four flask-shaped cells (Altenburger and Wanninger, 2010).

Lingula: Six to eight apical cells; eight peripheral cells (Wanninger et al., 2007), indicating a probable

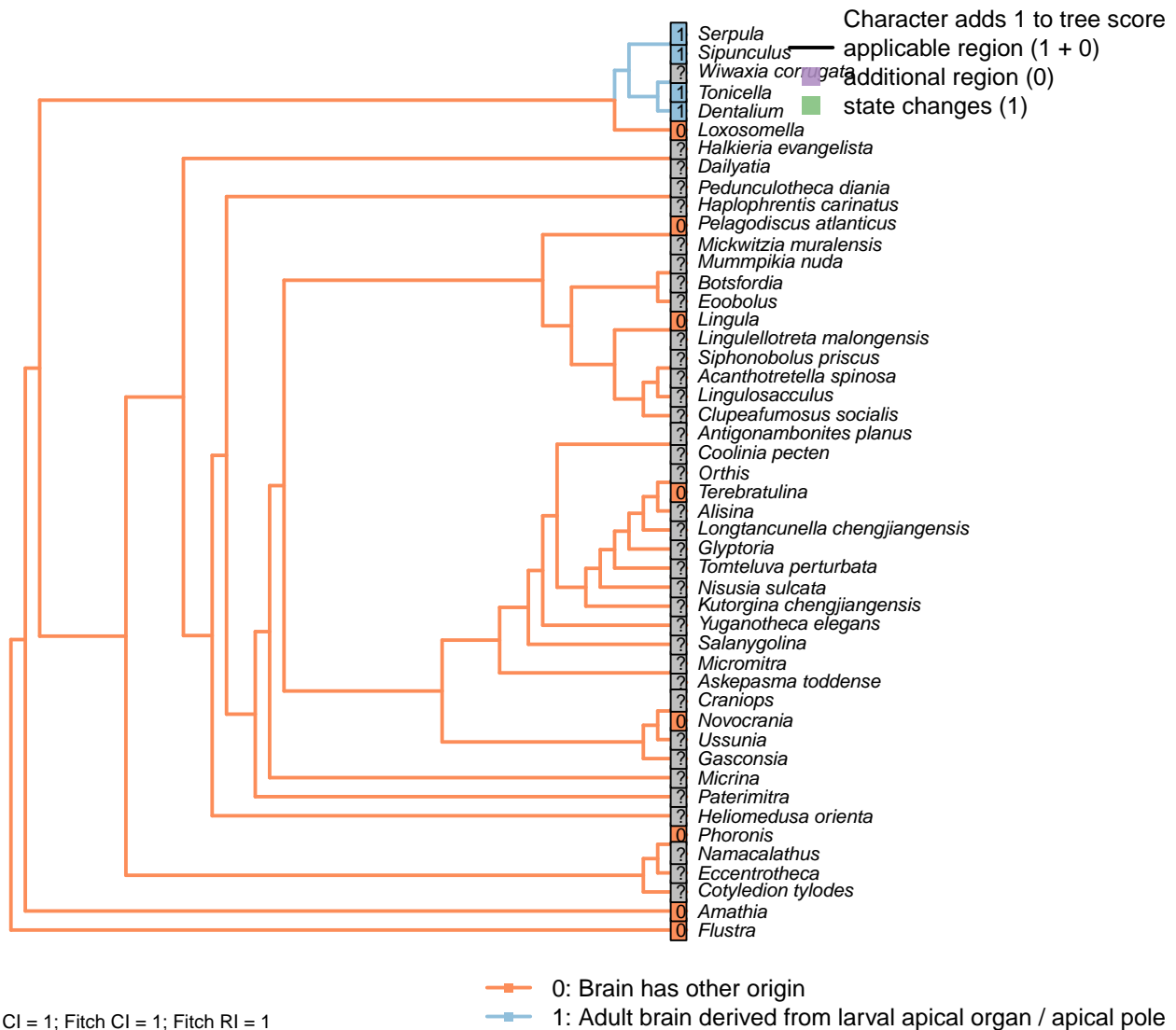
equivalence to polyplacophorans (Haszprunar and Wanninger, 2008).

Phoronis, *Sipunculus*: Concentration of 30–40 serotonergic perikarya (in *Fredericella*; Gruhl, 2010a).

Tonicella: Eight in *Terebratalia* (Lüter, 2016).

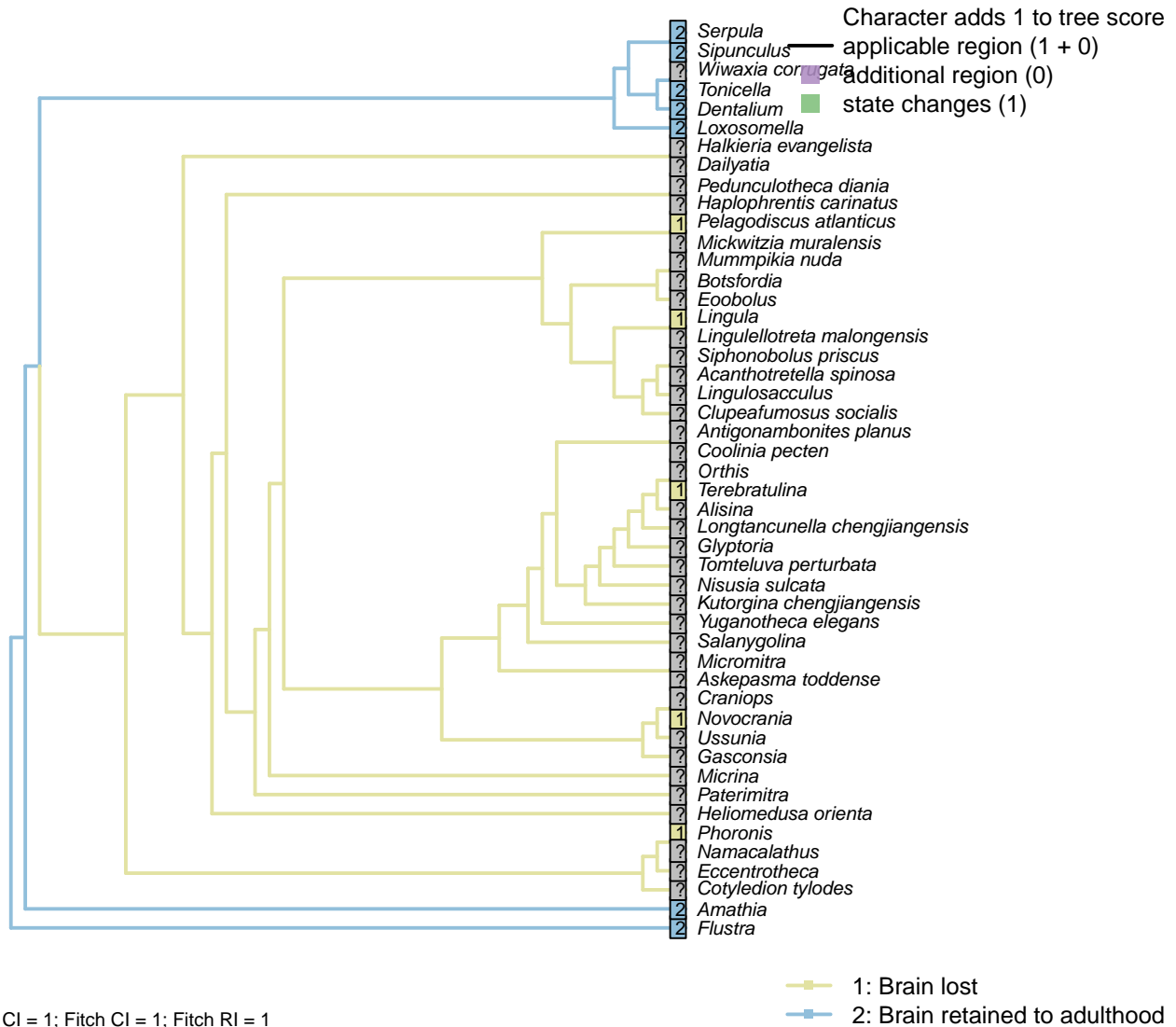
Wiwaxia corrugata: Multiple shapes of cells present (Santagata, 2002); resembles the linguliform arrangement (Altenburger and Wanninger, 2010).

[171] Develops into adult brain



the adult nervous system” (Hay-Schmidt, 1992), but not necessarily as the brain.

3.34 Larva: Brain persists into adulthood [172]

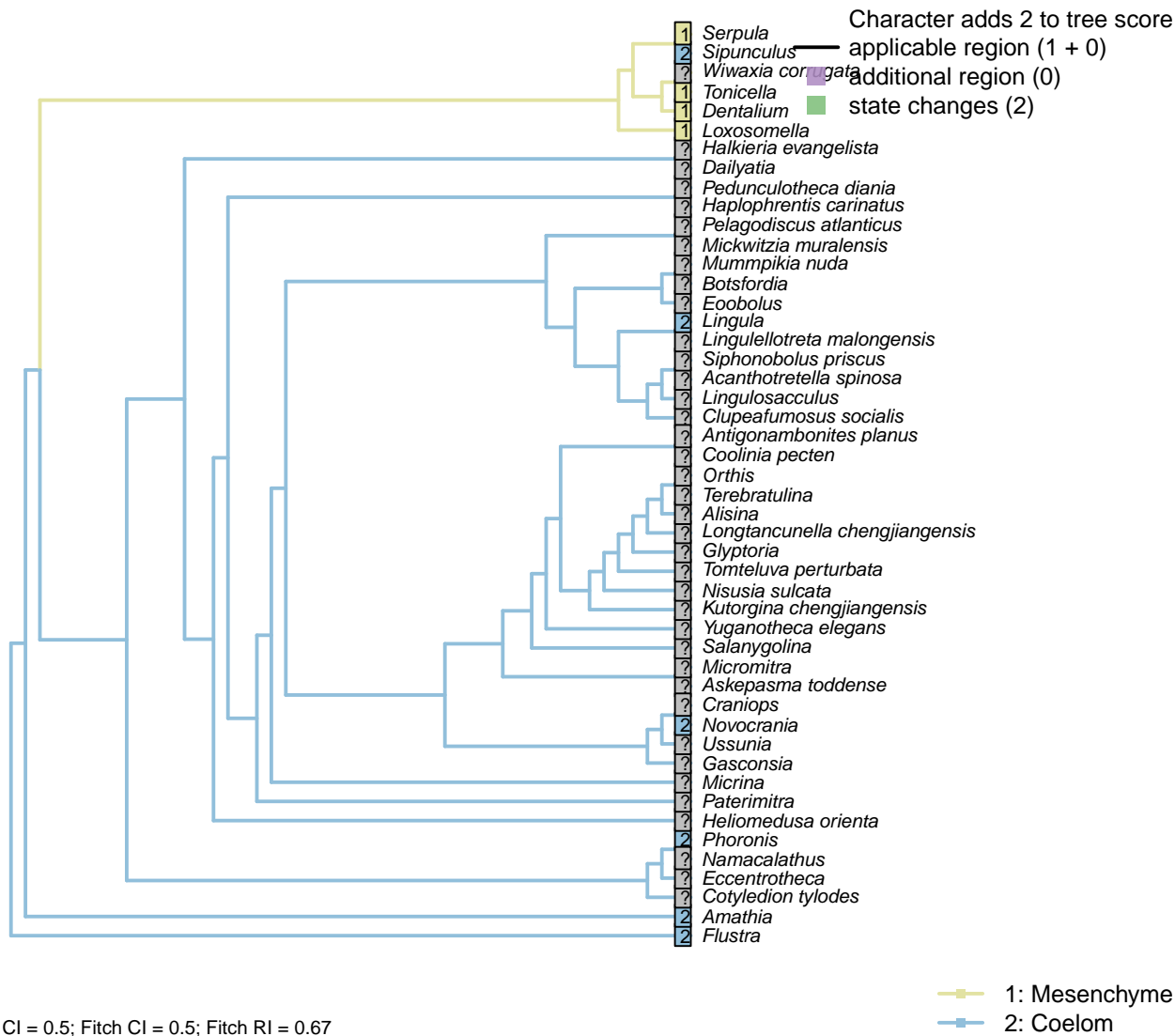


Character 172: Larva: Brain persists into adulthood

- 1: Brain lost
 - 2: Brain retained to adulthood
- Transformational character.

After character 3 in Richter et al. (2010).

[174] Origin of body cavity



Character 174: Larva: Origin of body cavity

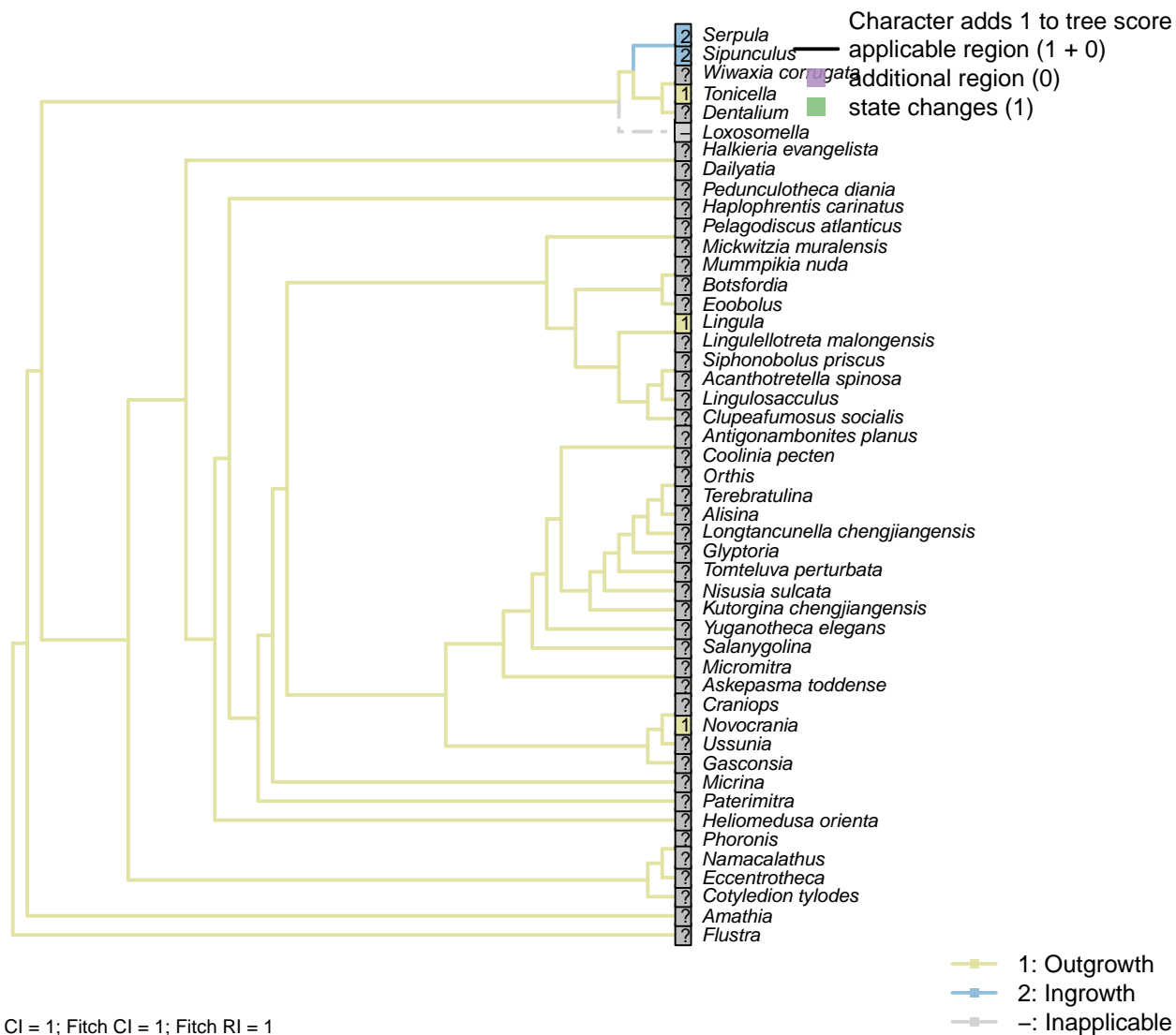
1: Mesenchyme

2: Coelom

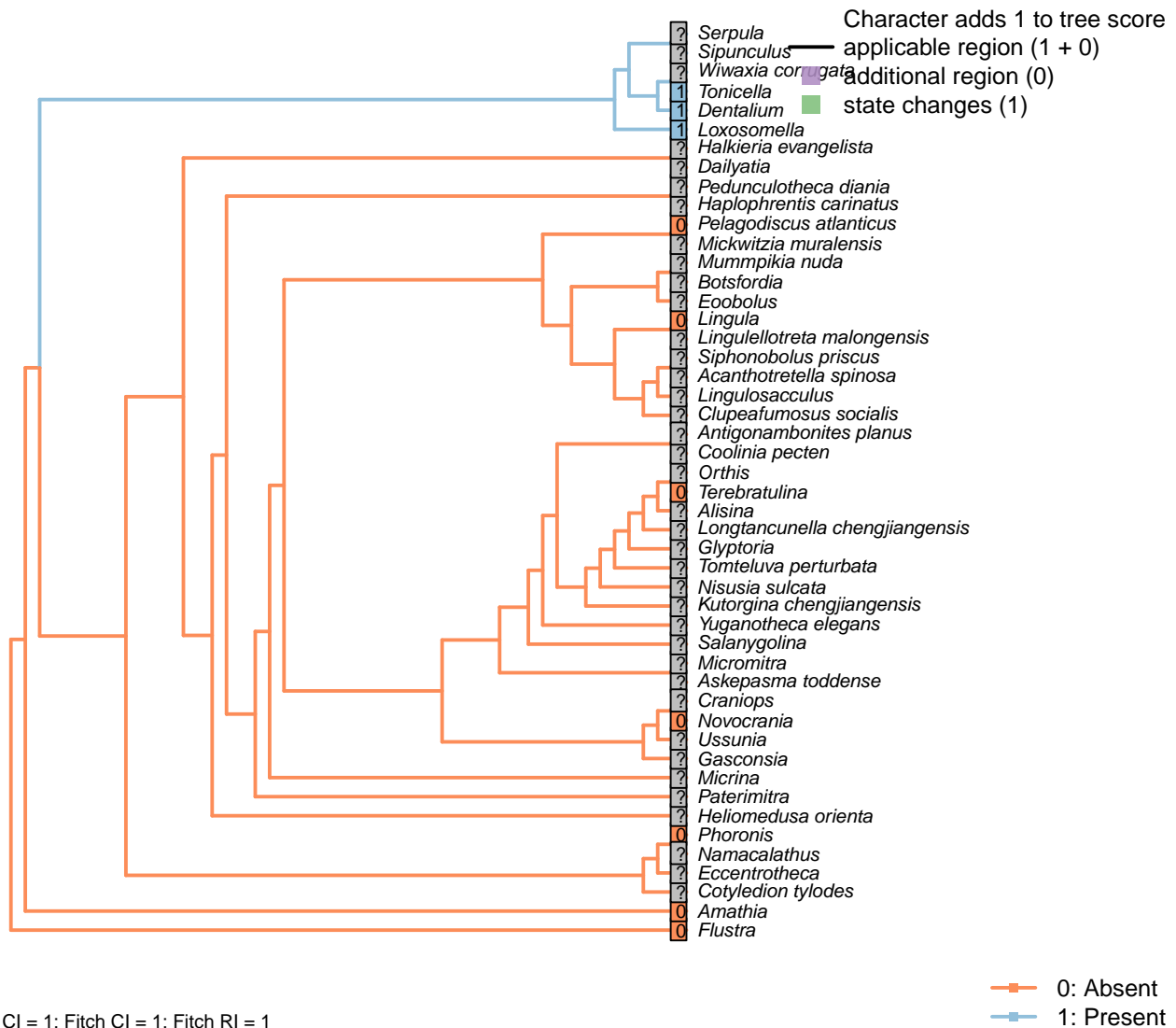
Transformational character.

Character 1.43 in@SPS1996.

[175] Formation of coelomoducts

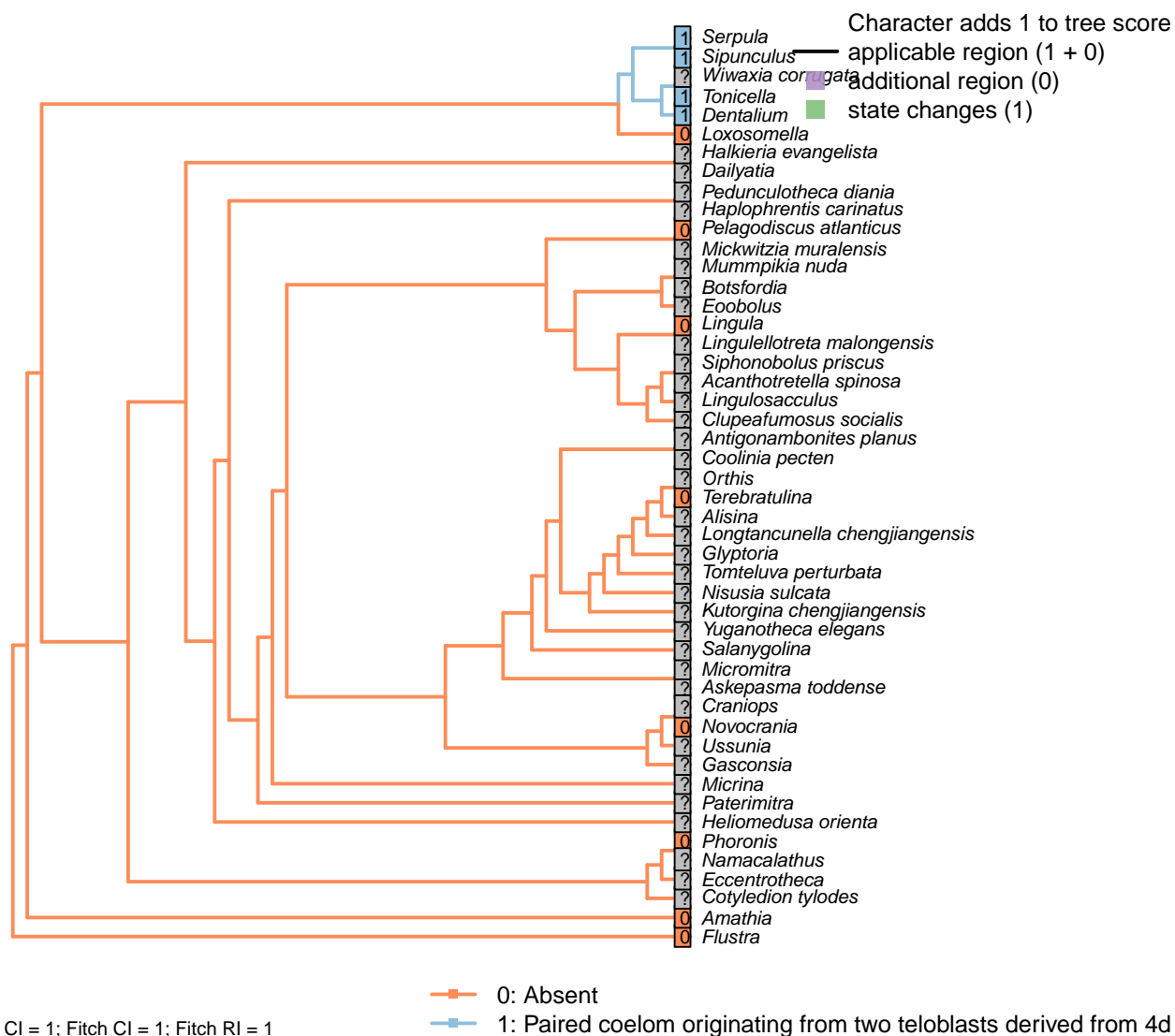


[176] Pedal gland

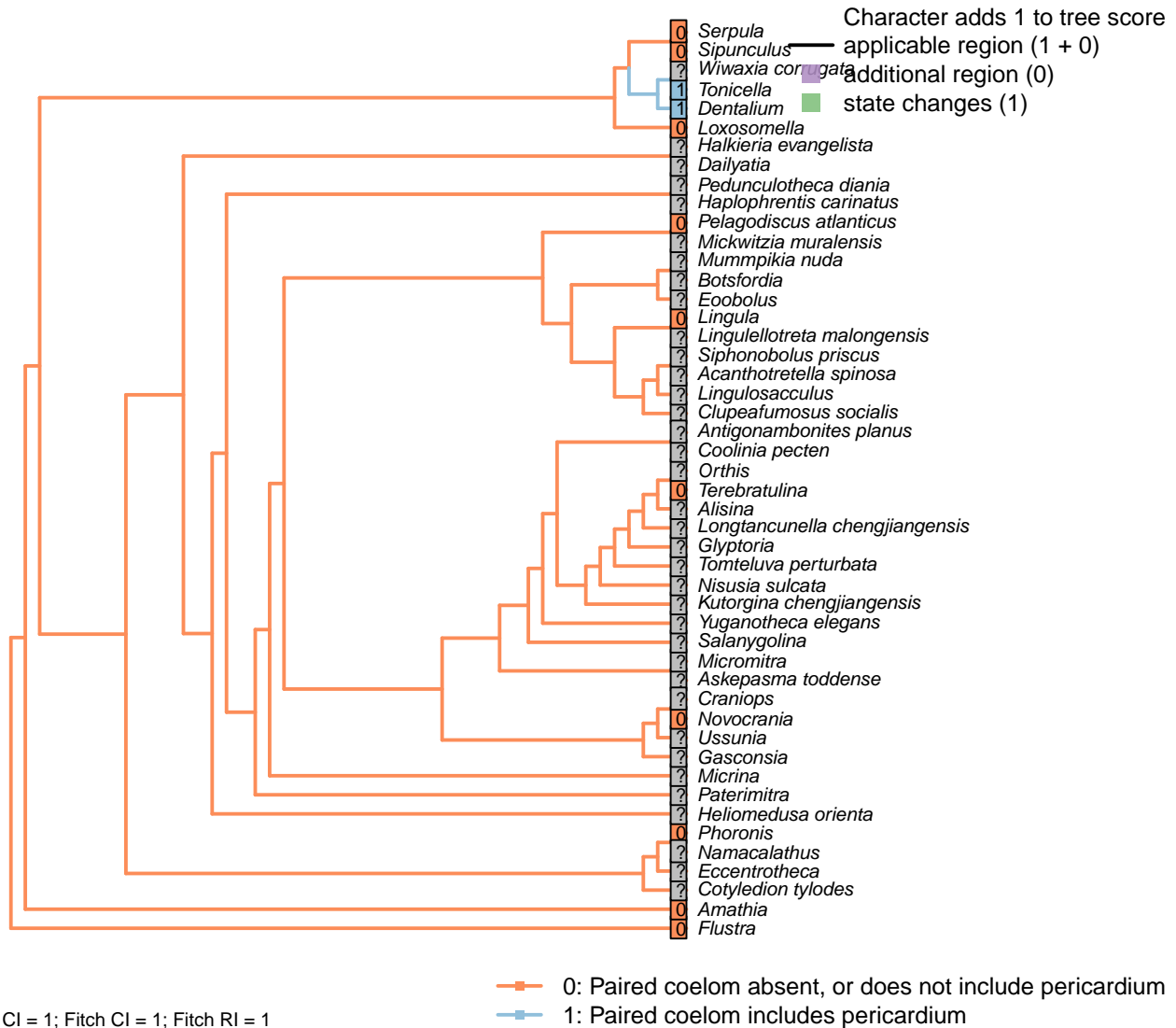


3.35 Larva: Coelom

[177] Paired



[178] Paried: Includes pericardium

**Character 178: Larva: Coelom: Paried: Includes pericardium**

0: Paired coelom absent, or does not include pericardium

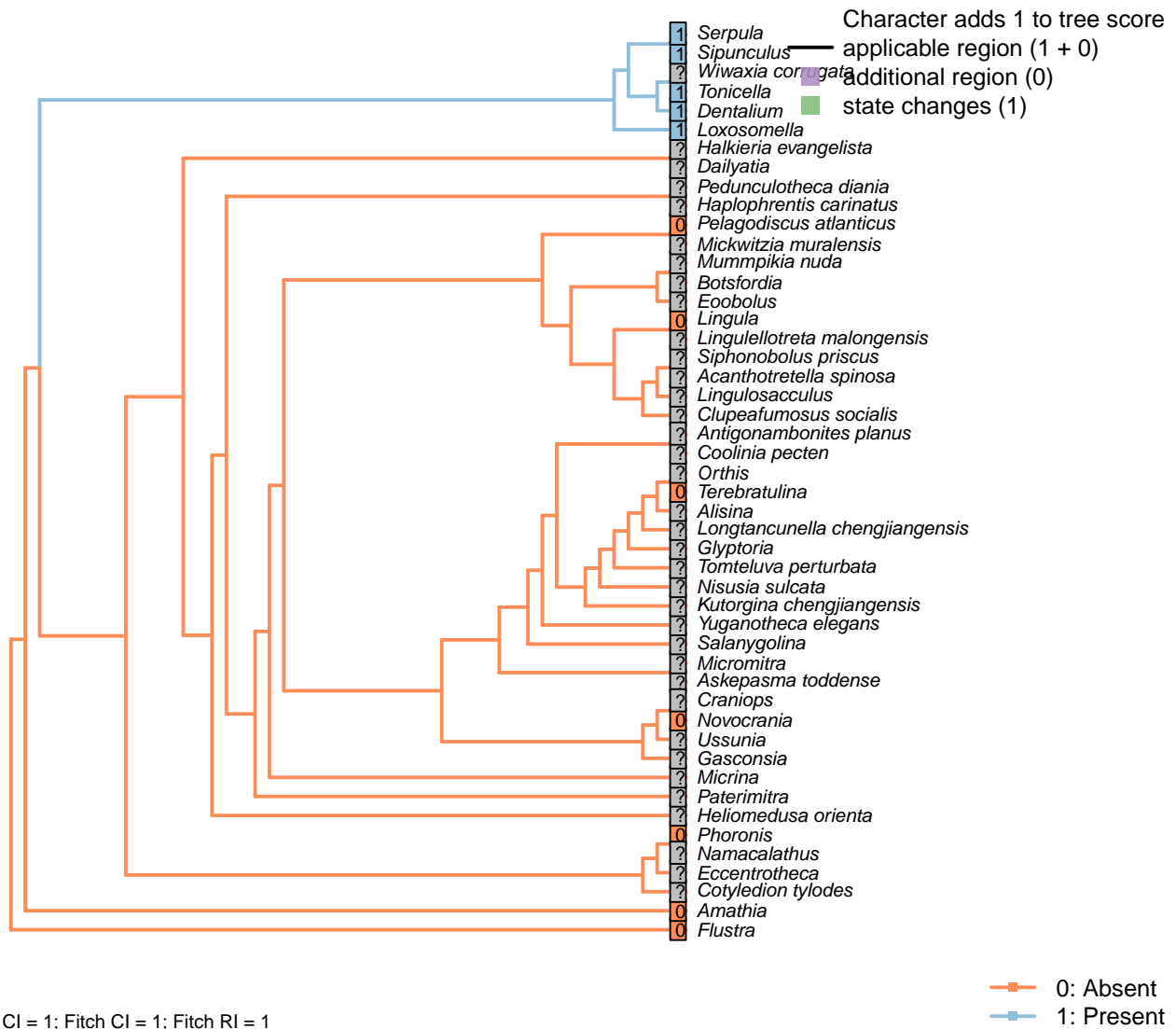
1: Paired coelom includes pericardium

Neomorphic character.

Character 1.03 in Scheltema (1993).

3.36 Larva

[179] Foot



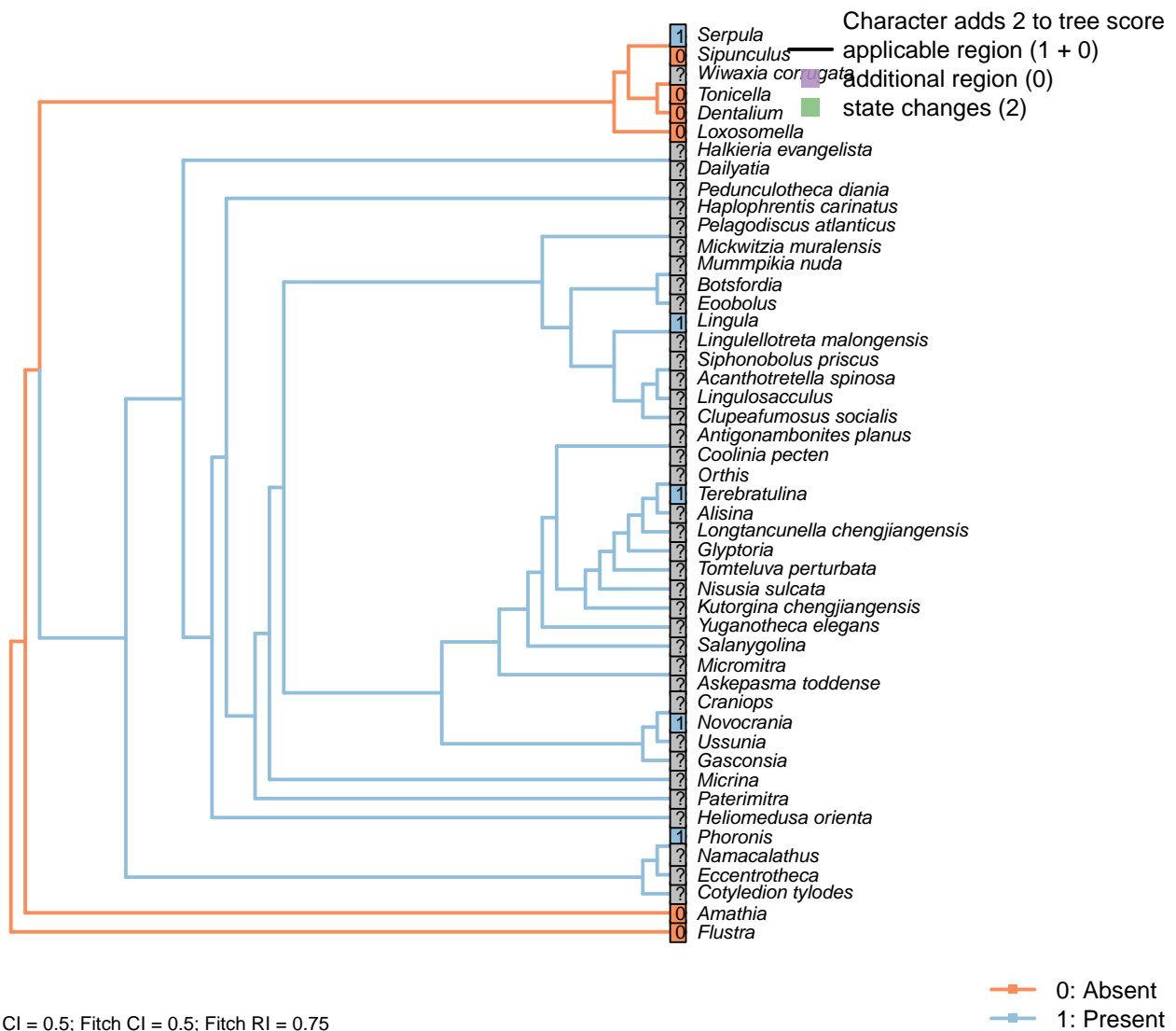
Foot or neurotroch present in larval stage, whether or not it is also present in mature individuals. Following Wingstrand (1985).

Dailyatia, *Halkieria evangelista*: Wingstrand (1985) considers the annelid neurotroch to be potentially homologous with the molluscan and entoproct foot.

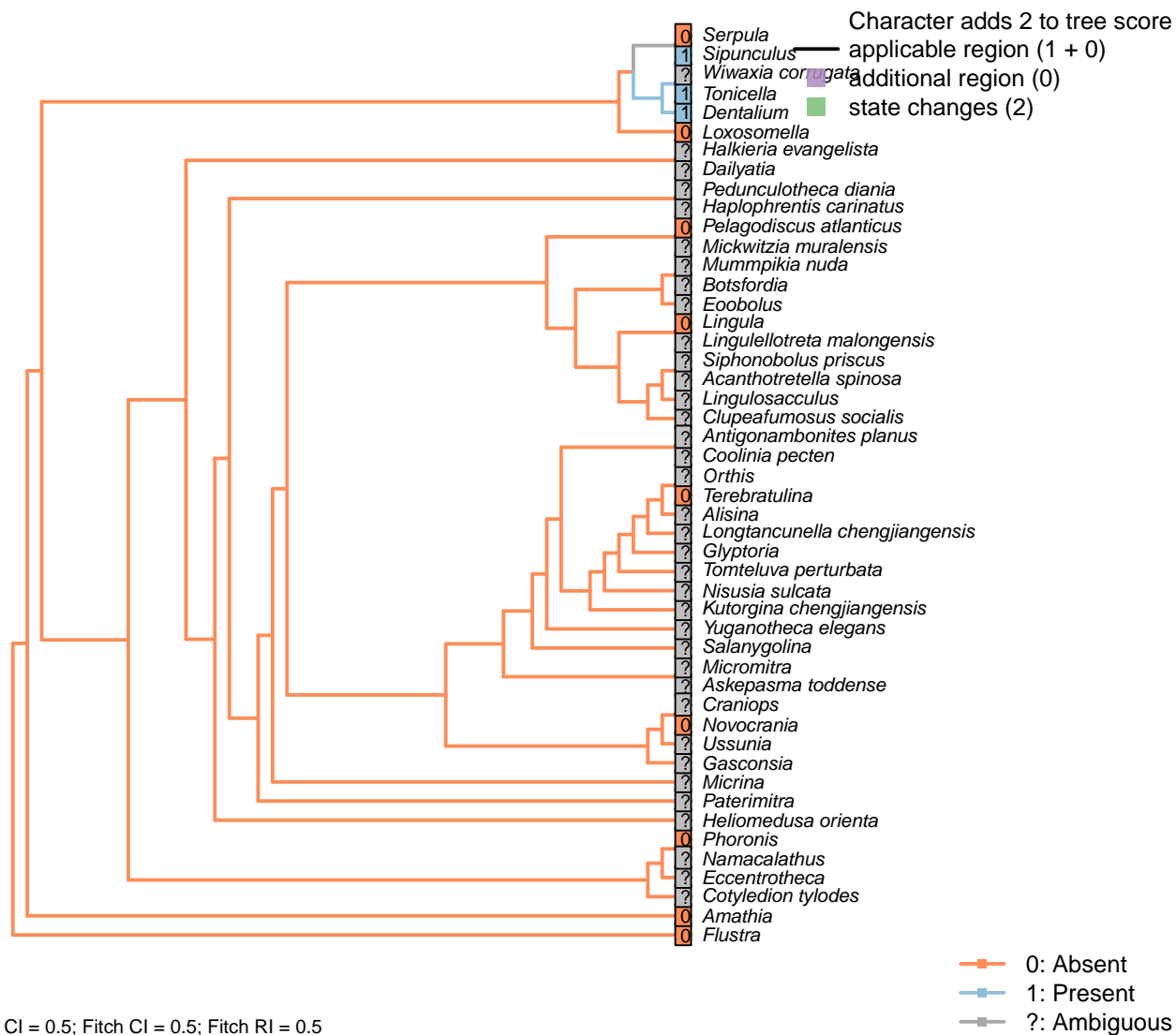
Lingula: A foot is present in the creeping-type larva of *Loxosomella murmanica*, though absent in *L. atkinsae* and the many other entoprocts that have swimming-type larvae (Fuchs and Wanninger, 2008).

3.37 Ciliary ultrastructure

[180] Accessory centriole



[181] Aggregation of granules below basal plate

**Character 181: Ciliary ultrastructure: Aggregation of granules below basal plate**

0: Absent

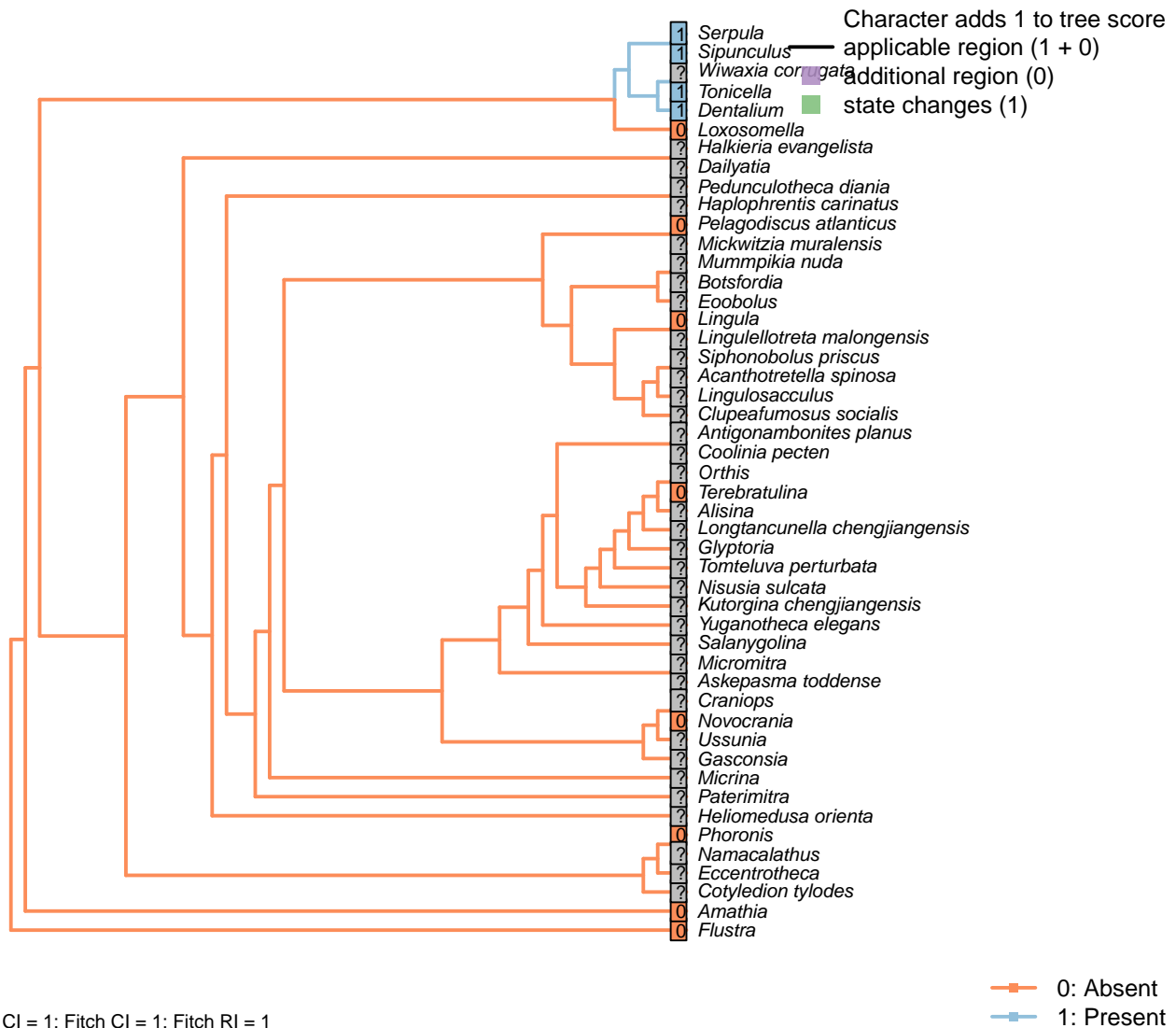
1: Present

Neomorphic character.

After Lundin et al. (2009).

Dailyatia: Following *Harmothoe* (Holborow et al., 1969).

[182] Radiating tubular fibres

**Character 182: Ciliary ultrastructure: Basal foot: Radiating tubular fibres**

0: Absent

1: Present

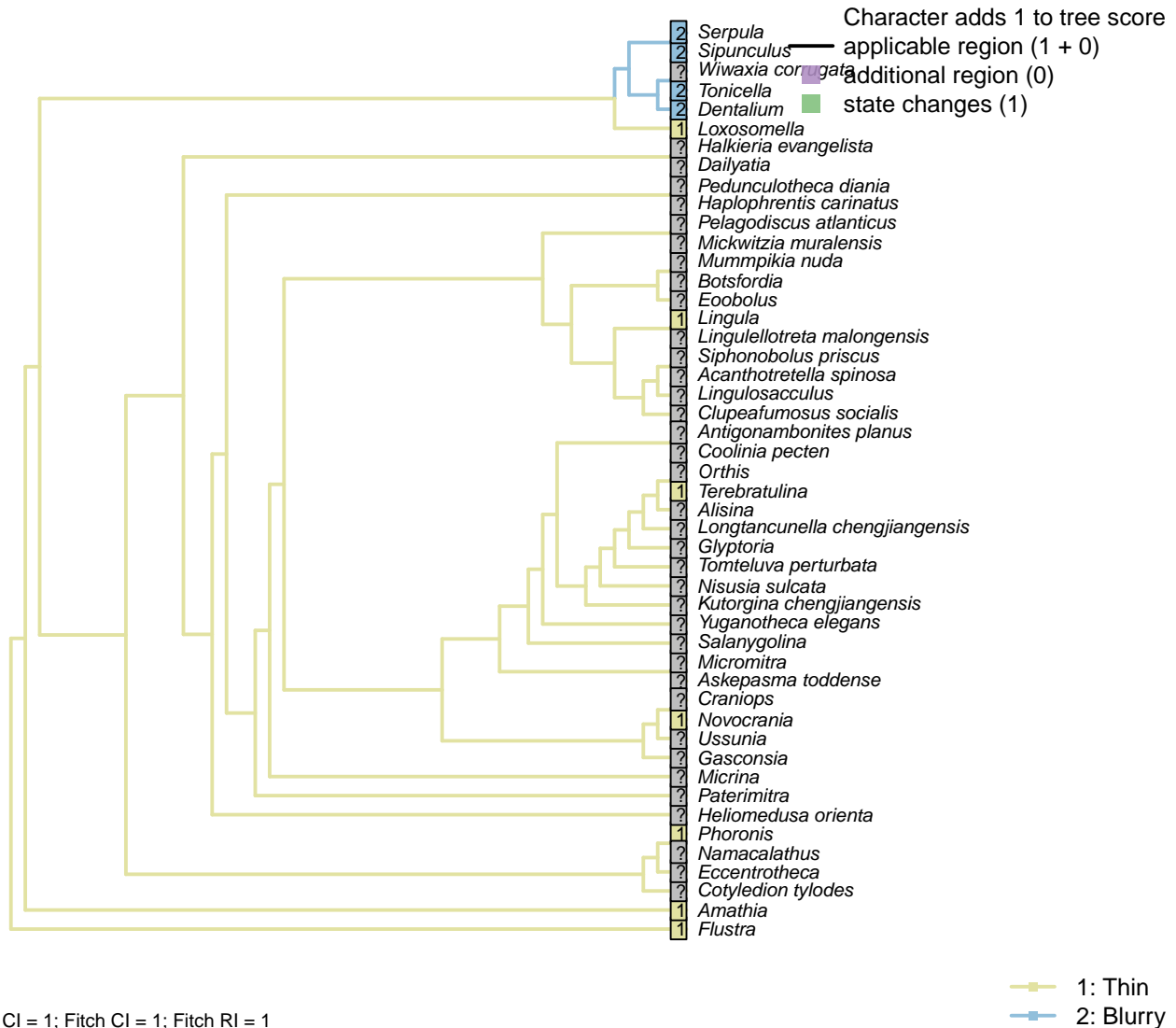
Neomorphic character.

After Lundin et al. (2009). Fibres radiate from the distal end of the basal foot of the cilia in certain taxa.

Dailyatia: Basal foot in *Magelona* is connected to cytoplasmic microtubules (Bartolomaeus, 1995).

Sipunculus: Reed and Cloney (1982).

3.38 Ciliary ultrastructure: Basal plate [183]



Character 183: Ciliary ultrastructure: Basal plate

1: Thin

2: Blurry

Transformational character.

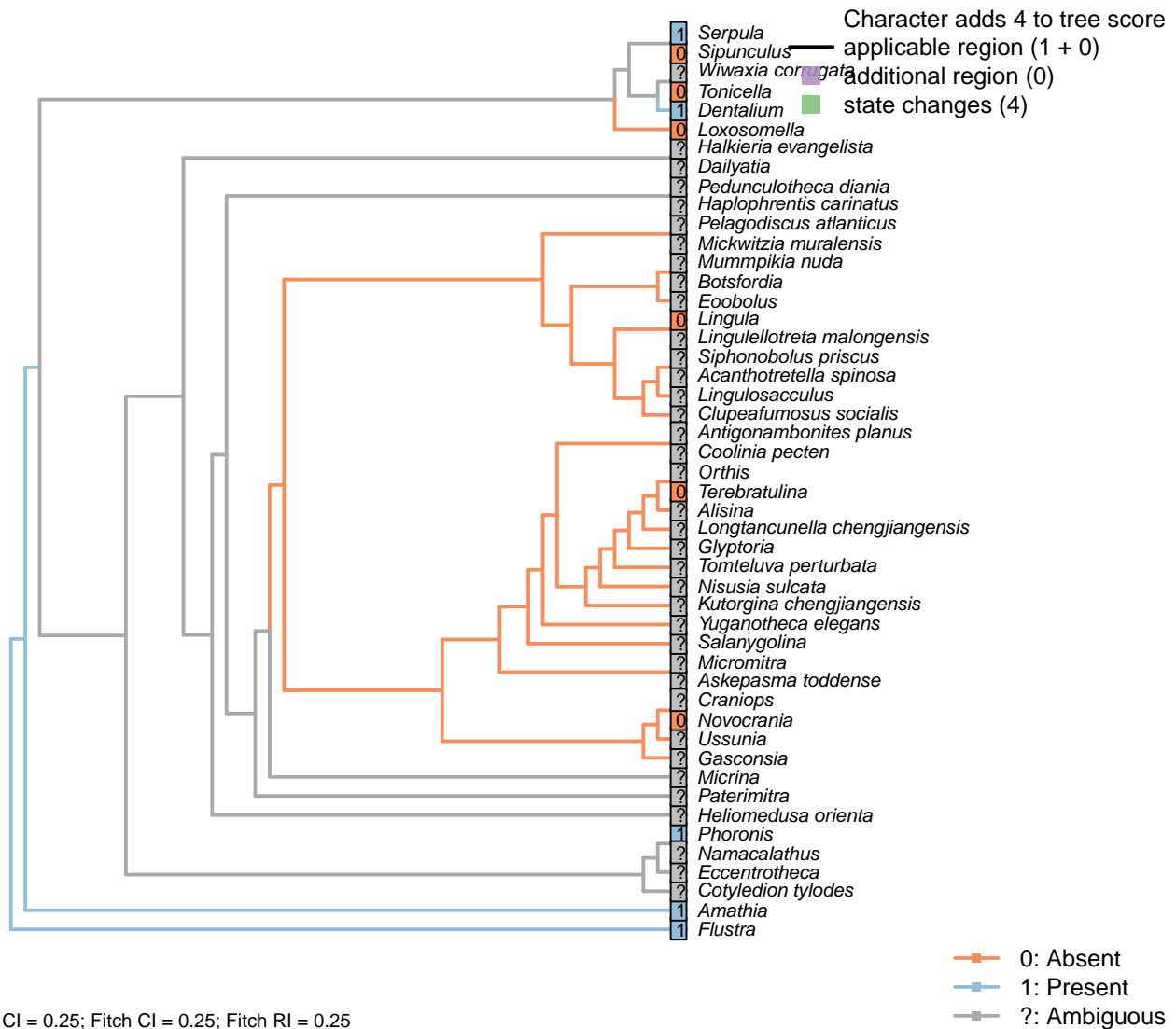
After Lundin et al. (2009). Also termed “dense plate”.

Dailyatia: Broad and ‘blurry’ in *Magelona* (Bartolomaeus, 1995).

Sipunculus: Reed and Cloney (1982).

Tonicella: Thin to thick, but not blurry (Lüter, 1995).

[184] Brushborder of microvilli

**Character 184: Ciliary ultrastructure: Brushborder of microvilli**

0: Absent

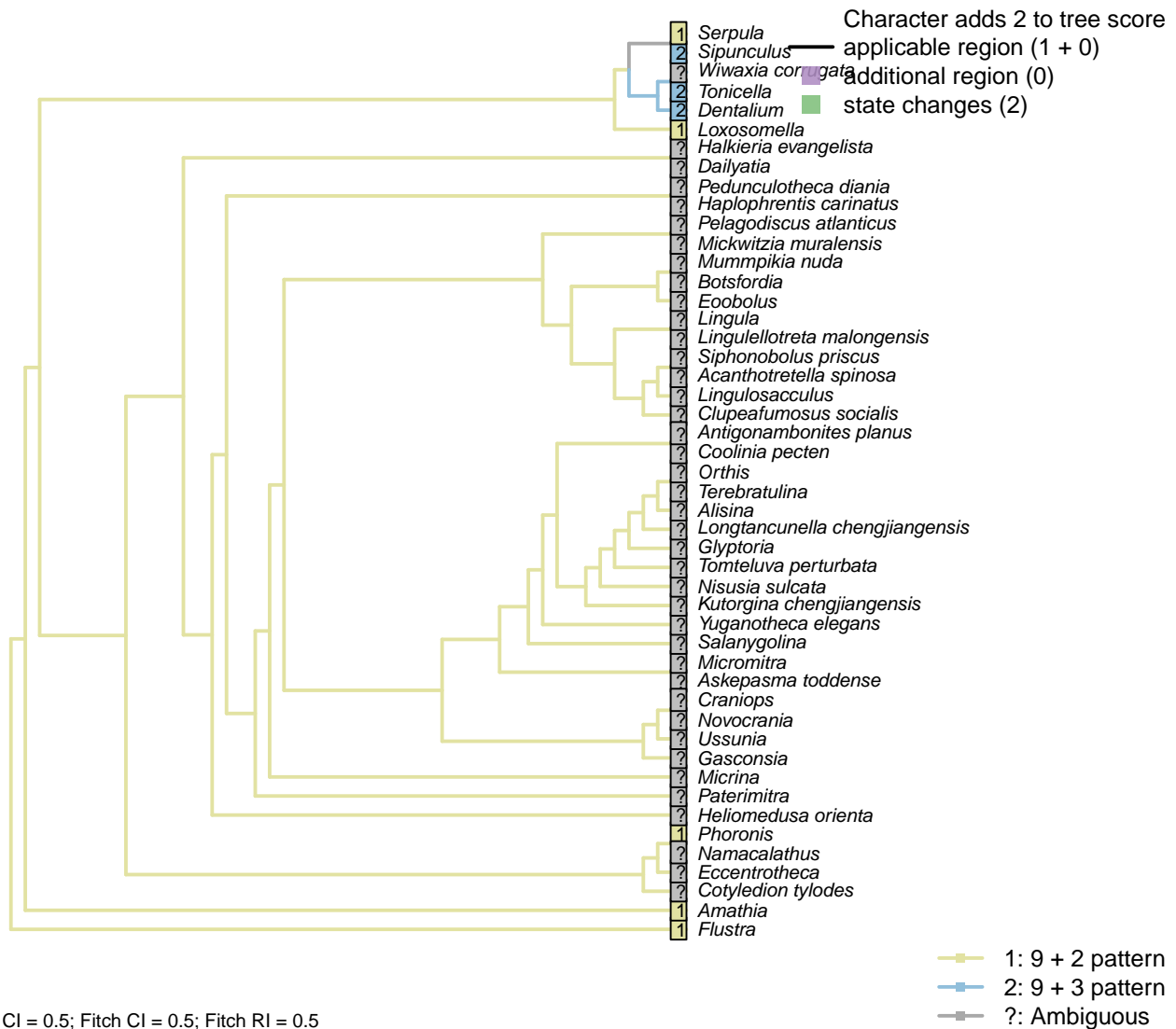
1: Present

Neomorphic character.

After Lundin et al. (2009); coded following Smith (2012a).

Sipunculus: Present (Reed and Cloney, 1982).*Tonicella*: Absent (Lüter, 1995).

[185] Centriolar triplet derivative in basal body

**Character 185: Ciliary ultrastructure: Centriolar triplet derivative in basal body**

1: 9 + 2 pattern

2: 9 + 3 pattern

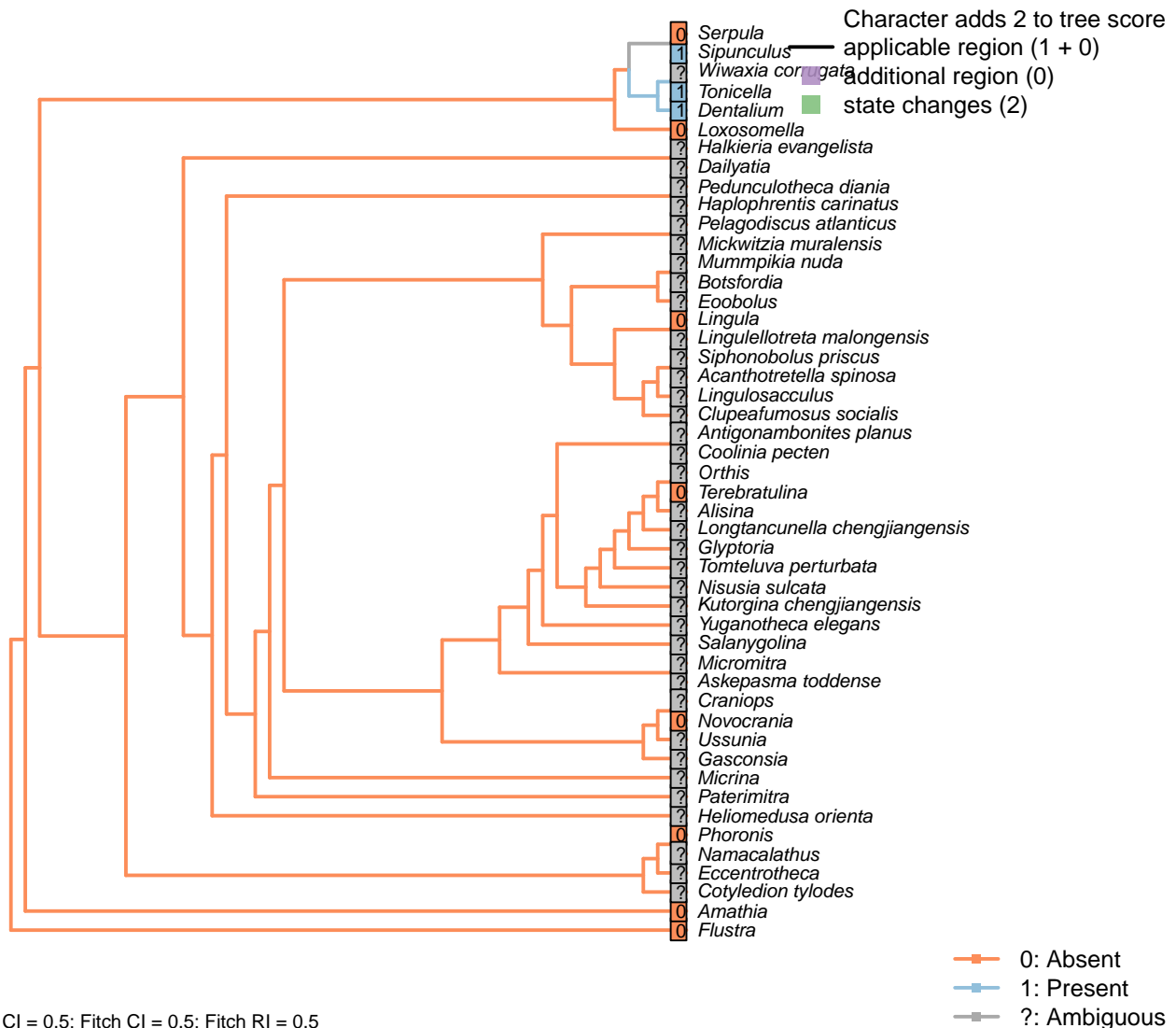
Transformational character.

After Lundin et al. (2009).

Dailyatia: Following *Enchytraeus* (Reger, 1967), *Magelona* (Bartolomaeus, 1995) and *Harmothoe* (Holborow et al., 1969).

Sipunculus: Reed and Cloney (1982).

[186] Ciliary necklace with connecting strands

**Character 186: Ciliary ultrastructure: Ciliary necklace with connecting strands**

0: Absent

1: Present

Neomorphic character.

After Lundin et al. (2009).

The ciliary necklace is defined by Gilula and Satir (1972) as “Well-defined rows or strands of membrane particles that encircle the ciliary shaft”. It occurs immediately below the basal plate, and comprises three beaded circles of on the circumference of the cilia membrane.

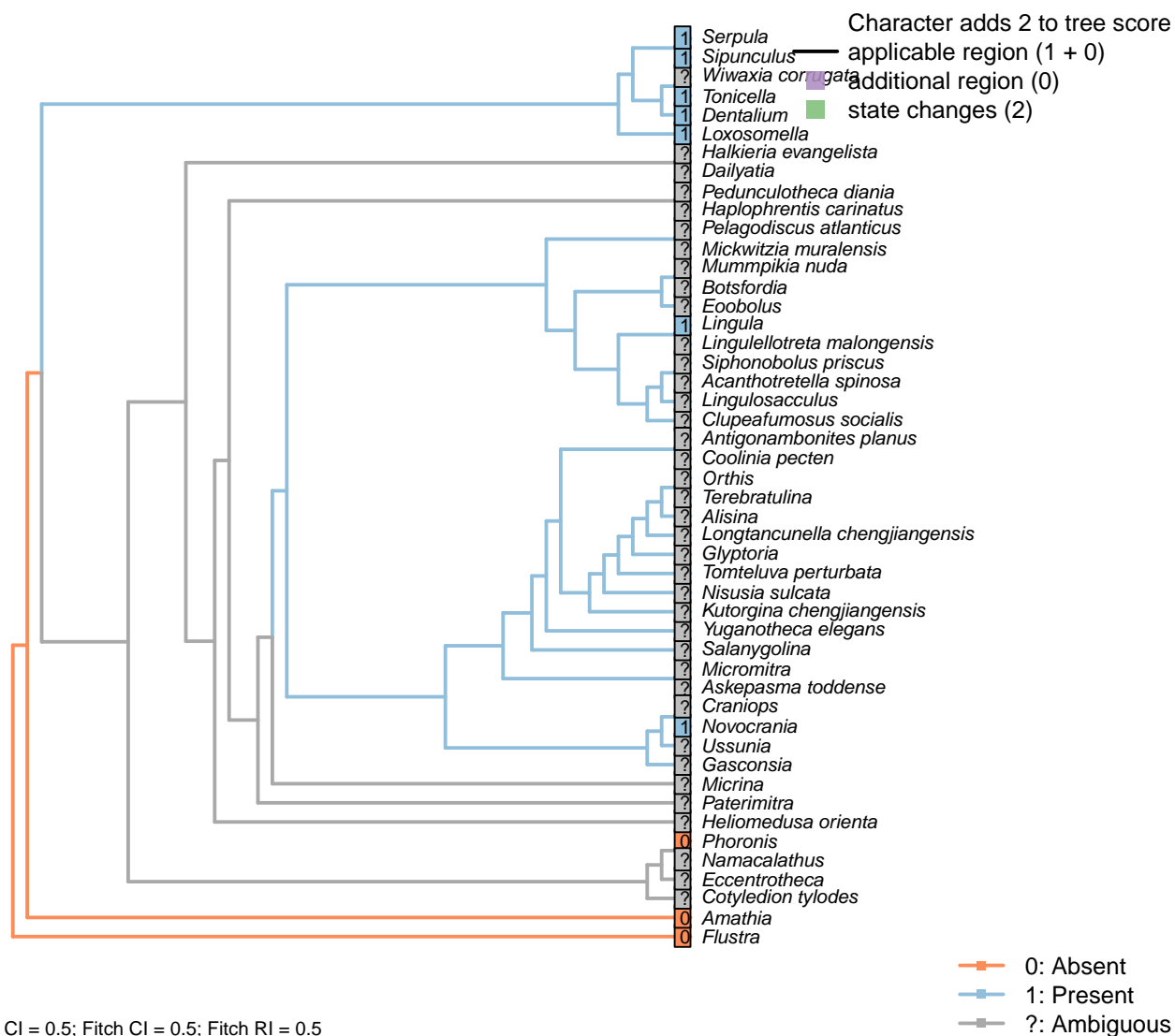
Daliyatia: Not evident in *Enchytraeus* (Reger, 1967), *Magelona* (Bartolomaeus, 1995) or *Harmothoe* (Holborow et al., 1969).

Sipunculus: Reed and Cloney (1982).

Tonicella: (Lüter, 1995).

3.39 Ciliary ultrastructure: Compound cilia

[187] Presence



Character 187: Ciliary ultrastructure: Compound cilia: Presence

0: Absent

1: Present

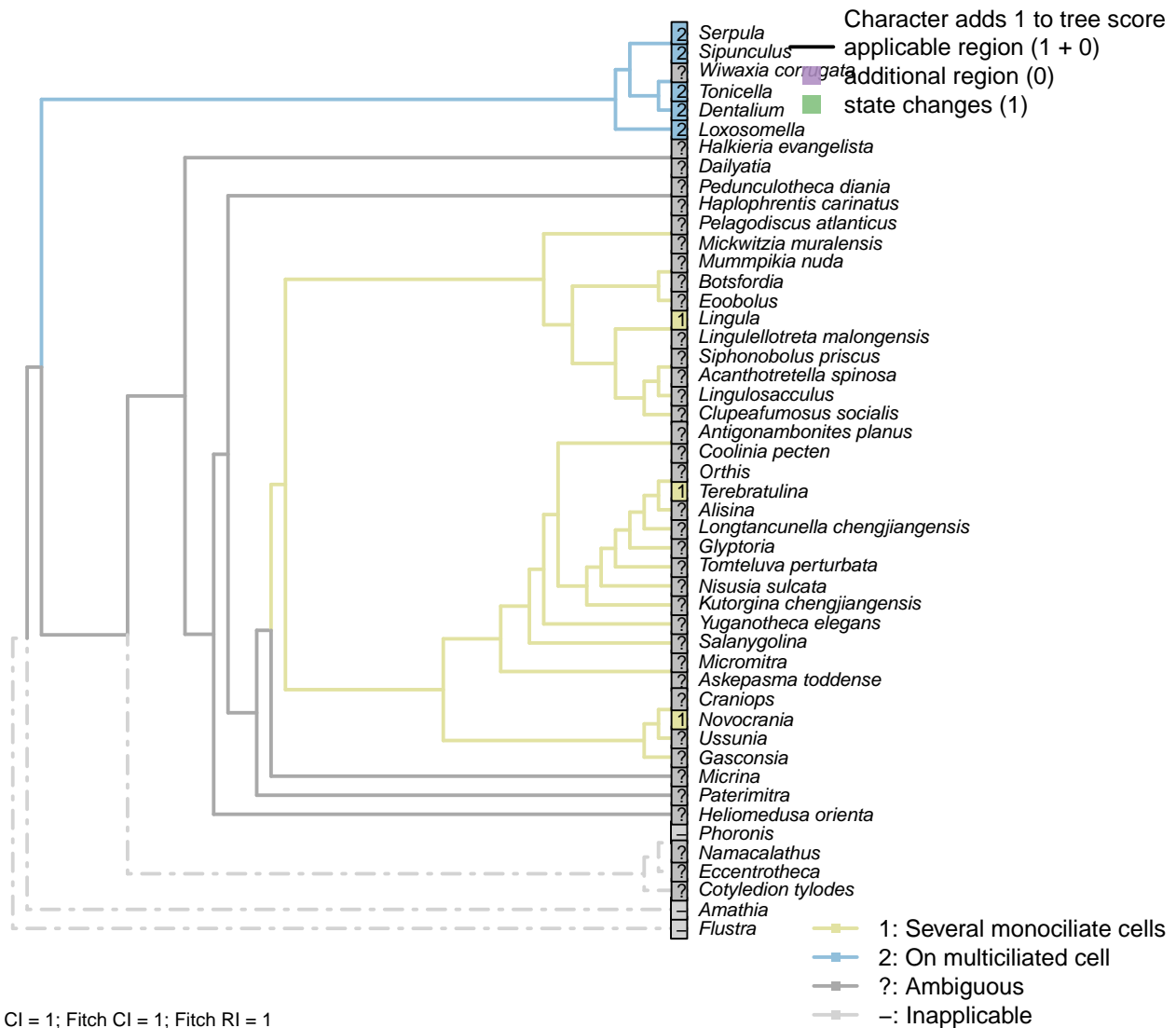
Neomorphic character.

After Lundin et al. (2009). Compound cilia are motile structures composed of 10–100 regular cilia used in locomotion or feeding.

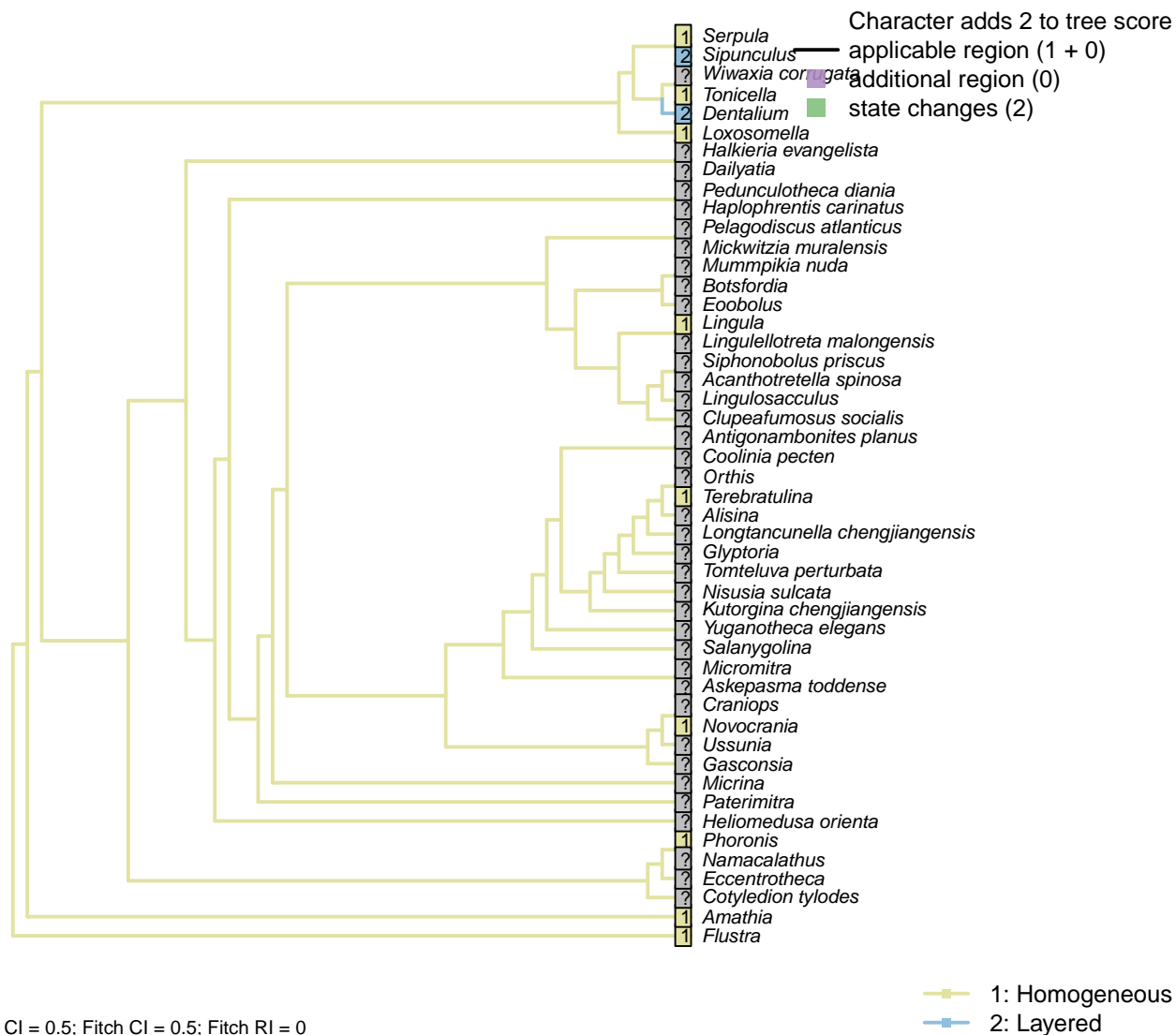
Dailiyatia: Nielsen (1987).

Sipunculus: Reed and Cloney (1982).

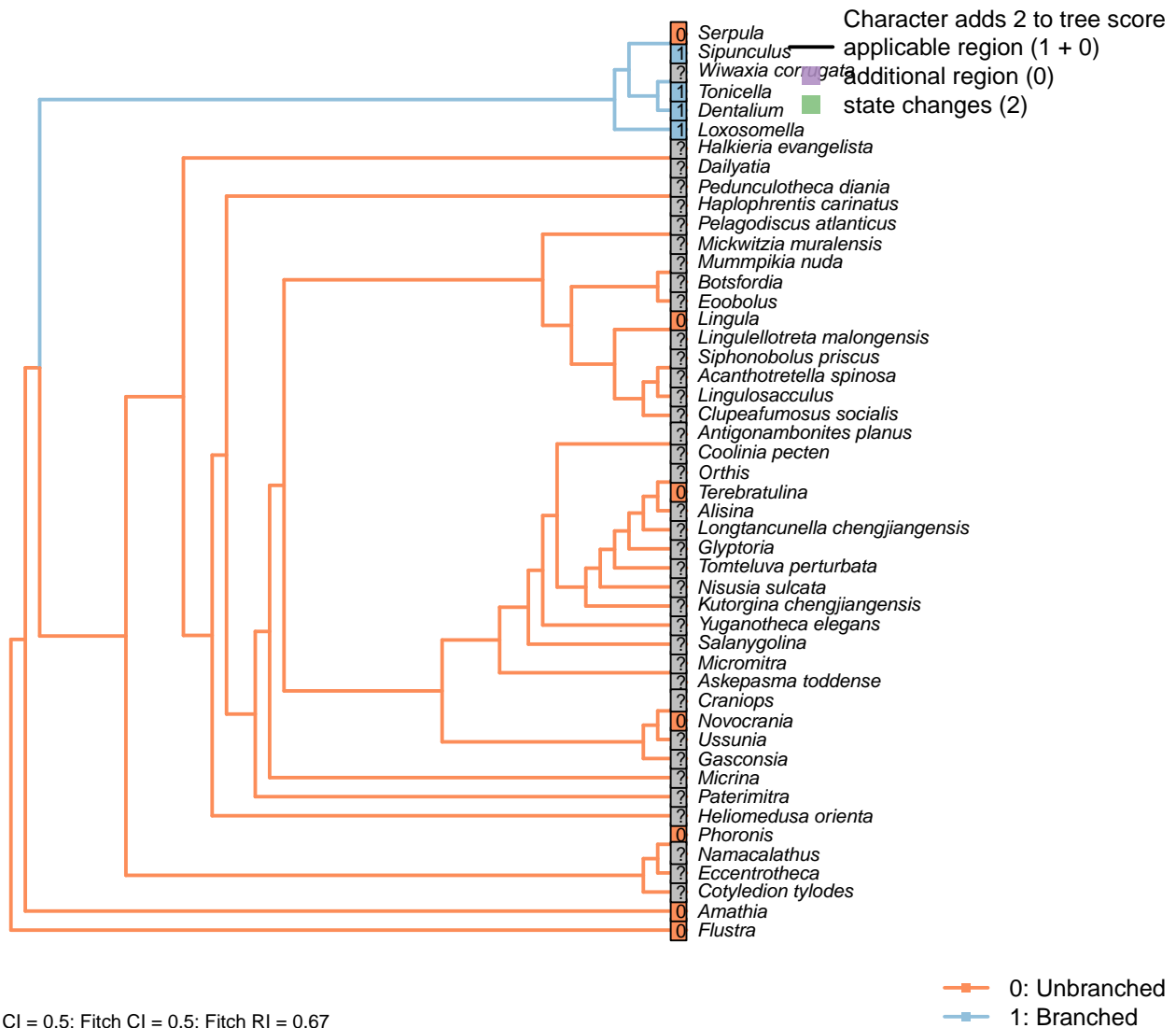
[188] Origin



3.40 Ciliary ultrastructure: Glycocalyx ultrastructure [189]

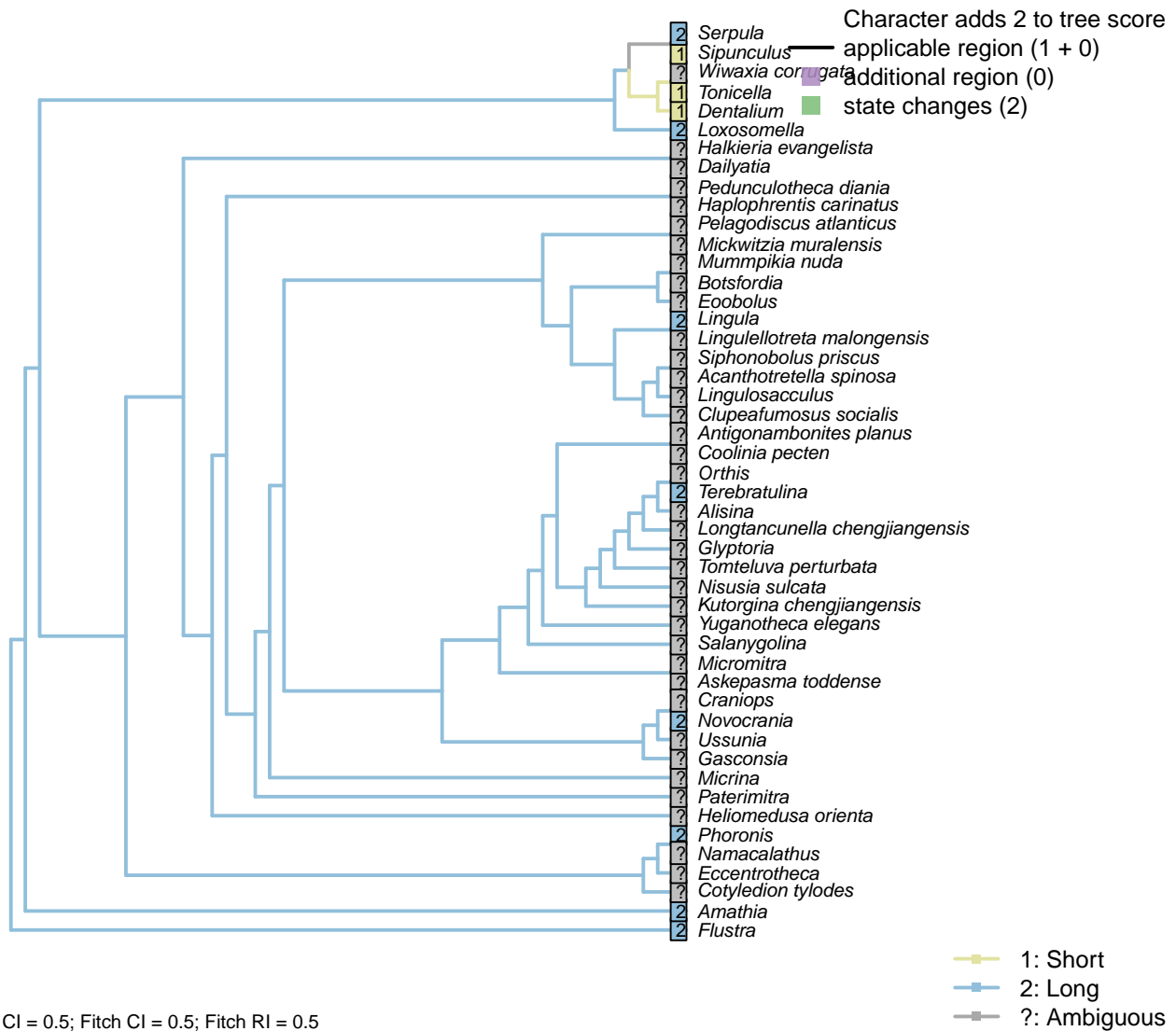


[190] Branched



3.41 Ciliary ultrastructure: Vertical ciliary rootlet

[191] Length



Character 191: Ciliary ultrastructure: Vertical ciliary rootlet: Length

1: Short

2: Long

Transformational character.

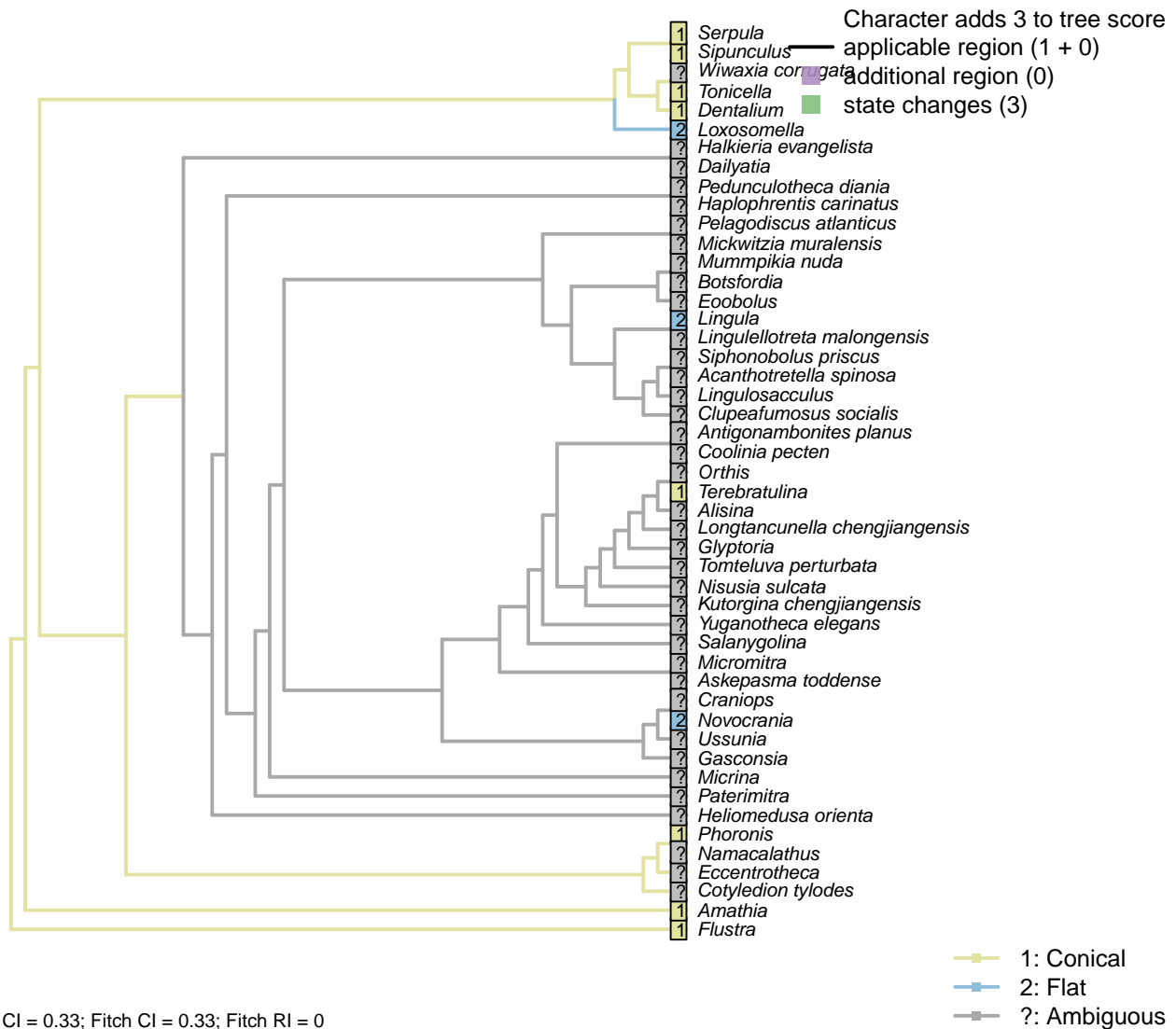
After Lundin et al. (2009). The vertical ciliary rootlet is also termed the posterior rootlet.

Lingula: Details of ciliary ultrastructure are illustrated in Nielsen and Rostgaard (1976).

Sipunculus: Reed and Cloney (1982).

Tonicella: Long (Lüter, 1995).

[192] Shape

**Character 192: Ciliary ultrastructure: Vertical ciliary rootlet: Shape**

1: Conical

2: Flat

Transformational character.

After Lundin et al. (2009). The vertical ciliary rootlet is also termed the posterior rootlet.

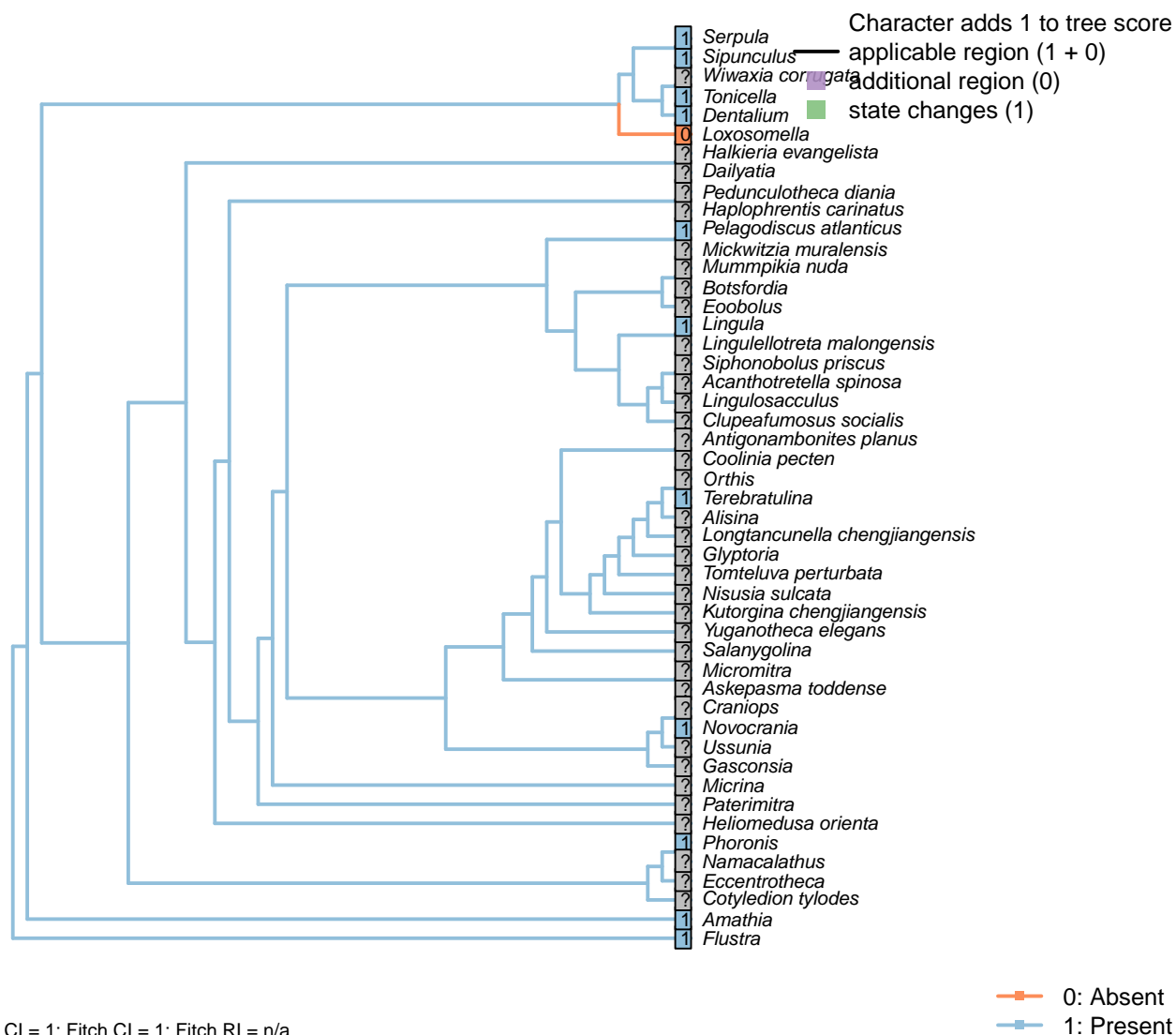
Dailyatia: Conical in *Enchytraeus* (Reger, 1967) and *Magelona* (Bartolomaeus, 1995).

Sipunculus: Reed and Cloney (1982).

Tonicella: Conical: tapering to a point (Lüter, 1995).

3.42 Ciliary ultrastructure: Secondary ciliary rootlet

[193] Presence



Character 193: Ciliary ultrastructure: Secondary ciliary rootlet: Presence

0: Absent

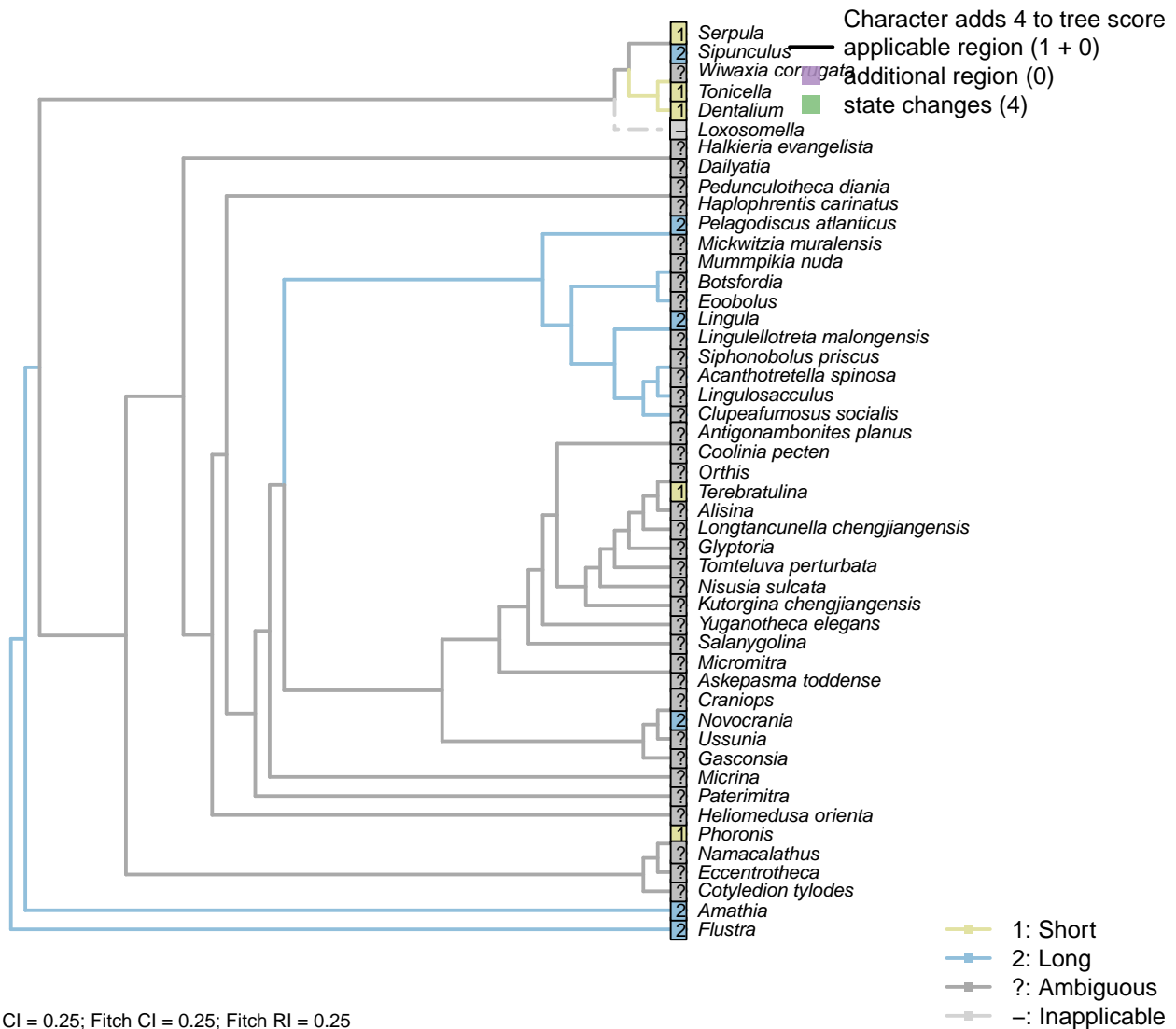
1: Present

Neomorphic character.

After Lundin et al. (2009). The secondary ciliary rootlet is also termed the anterior ciliary rootlet.

Sipunculus: Reed and Cloney (1982).

[194] Length

**Character 194: Ciliary ultrastructure: Secondary ciliary rootlet: Length**

1: Short

2: Long

Transformational character.

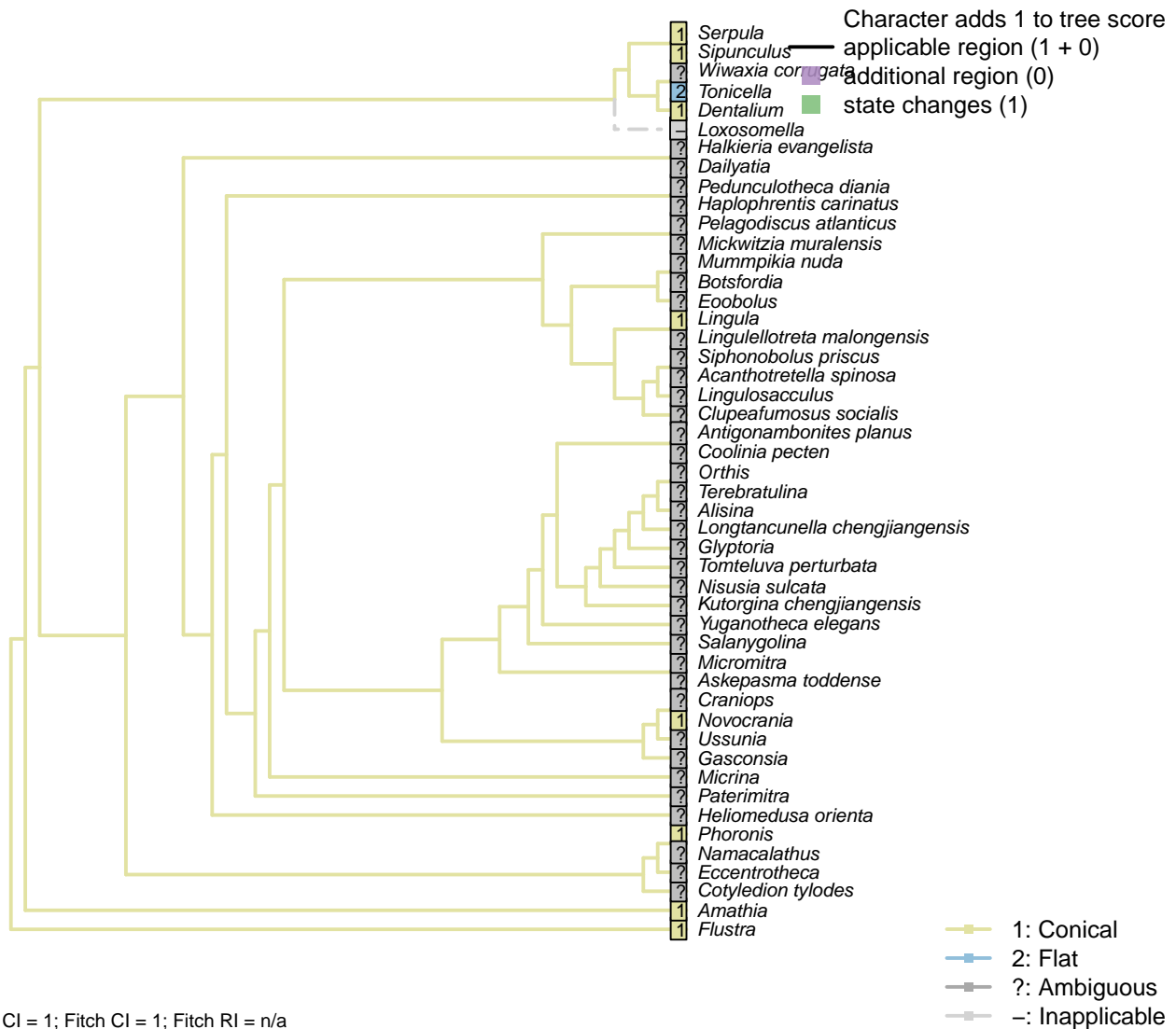
After Lundin et al. (2009). The secondary ciliary rootlet is also termed the anterior ciliary rootlet.

Dailyatia: Short in *Enchytraeus* (Reger, 1967), *Magelona* (Bartolomaeus, 1995) and *Harmothoe* (Holborow et al., 1969).

Sipunculus: Reed and Cloney (1982).

Tonicella: “Very small” – Lüter (1995).

[195] Shape

**Character 195: Ciliary ultrastructure: Secondary ciliary rootlet: Shape**

1: Conical

2: Flat

Transformational character.

After Lundin et al. (2009). The secondary ciliary rootlet is also termed the anterior ciliary rootlet.

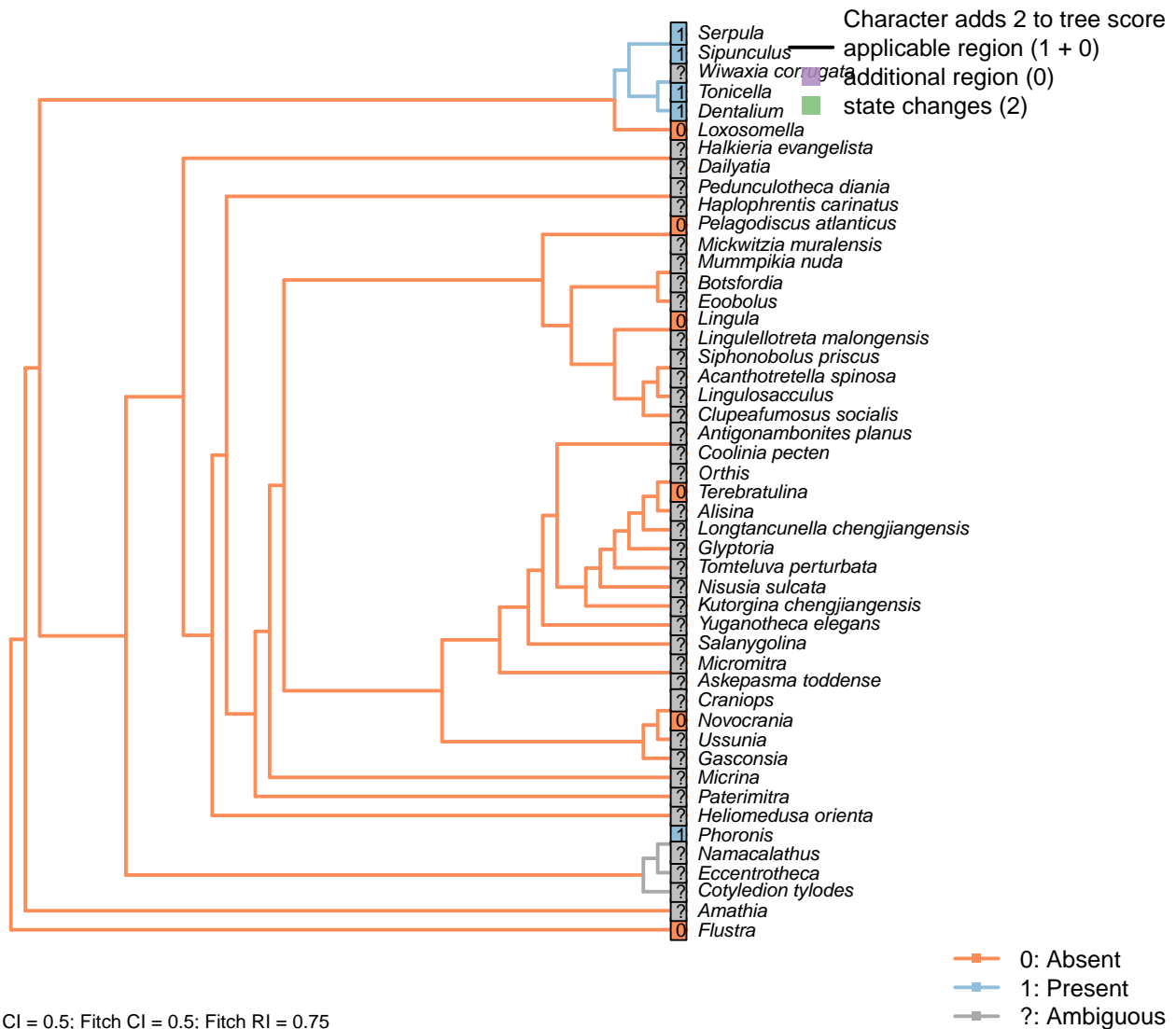
Dailyatia: Conical in *Magelona* (Bartolomaeus, 1995).

Sipunculus: Reed and Cloney (1982).

Tonicella: Too small to evaluate.

3.43 Nephridia

[196] Podocytes



Character 196: Nephridia: Podocytes

0: Absent

1: Present

Neomorphic character.

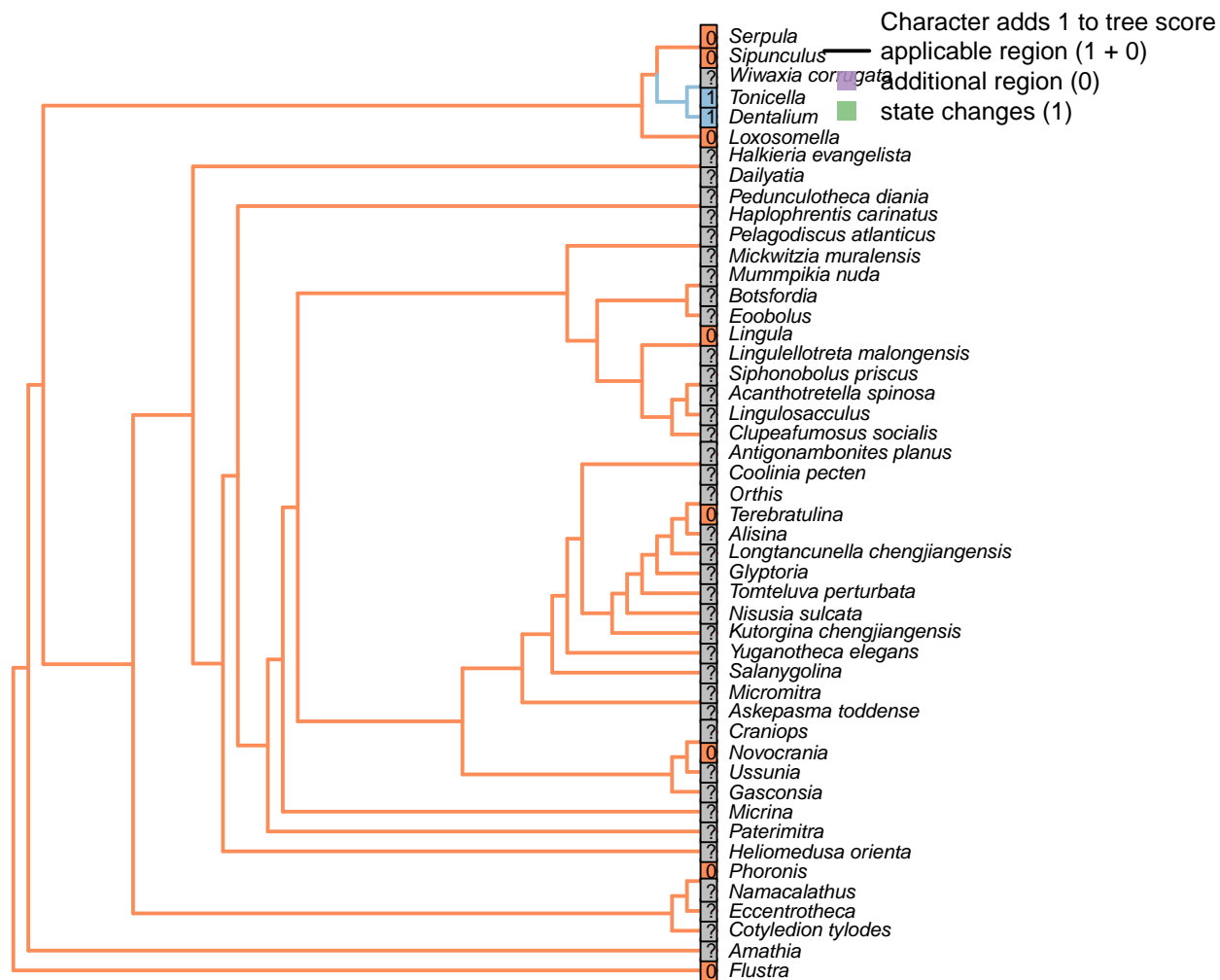
See characters 21 and 28 in Haszprunar (2000); 1.12 in Scheltema (1993).

Daliyatia: Present in serpulids (Bartolomaeus and Quast, 2005).

Dentalium, *Eoobolus*, *Serpula*, *Tonicella*: “In Brachiopoda, podocytes have never been observed” – Lüter (1995).

Wiwaxia corrugata: Present (Storch and Herrmann, 1978).

[197] Rhogocytes



CI = 1; Fitch CI = 1; Fitch RI = 1

Character 197: Nephridia: Rhogocytes

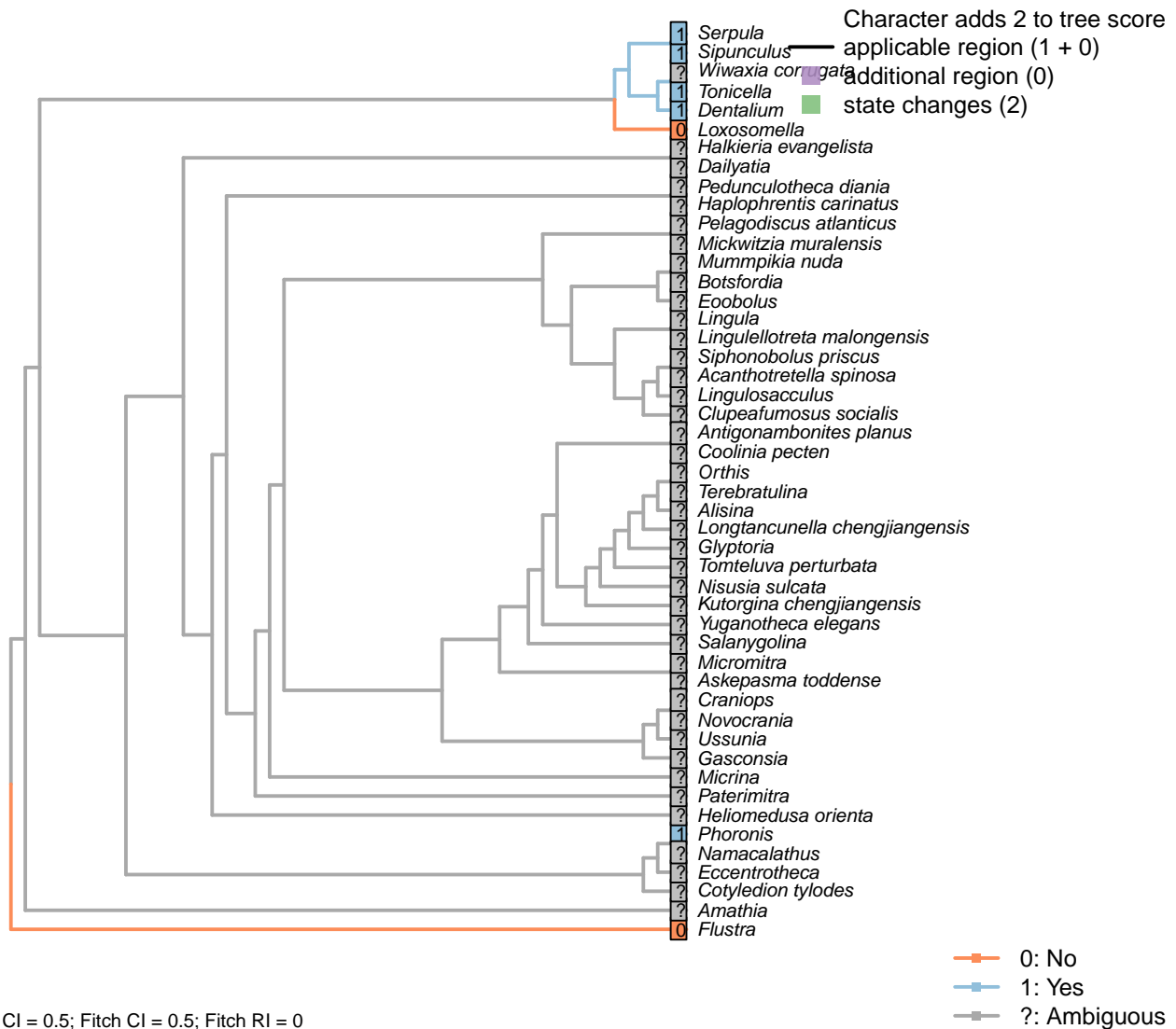
0: Absent

1: Present

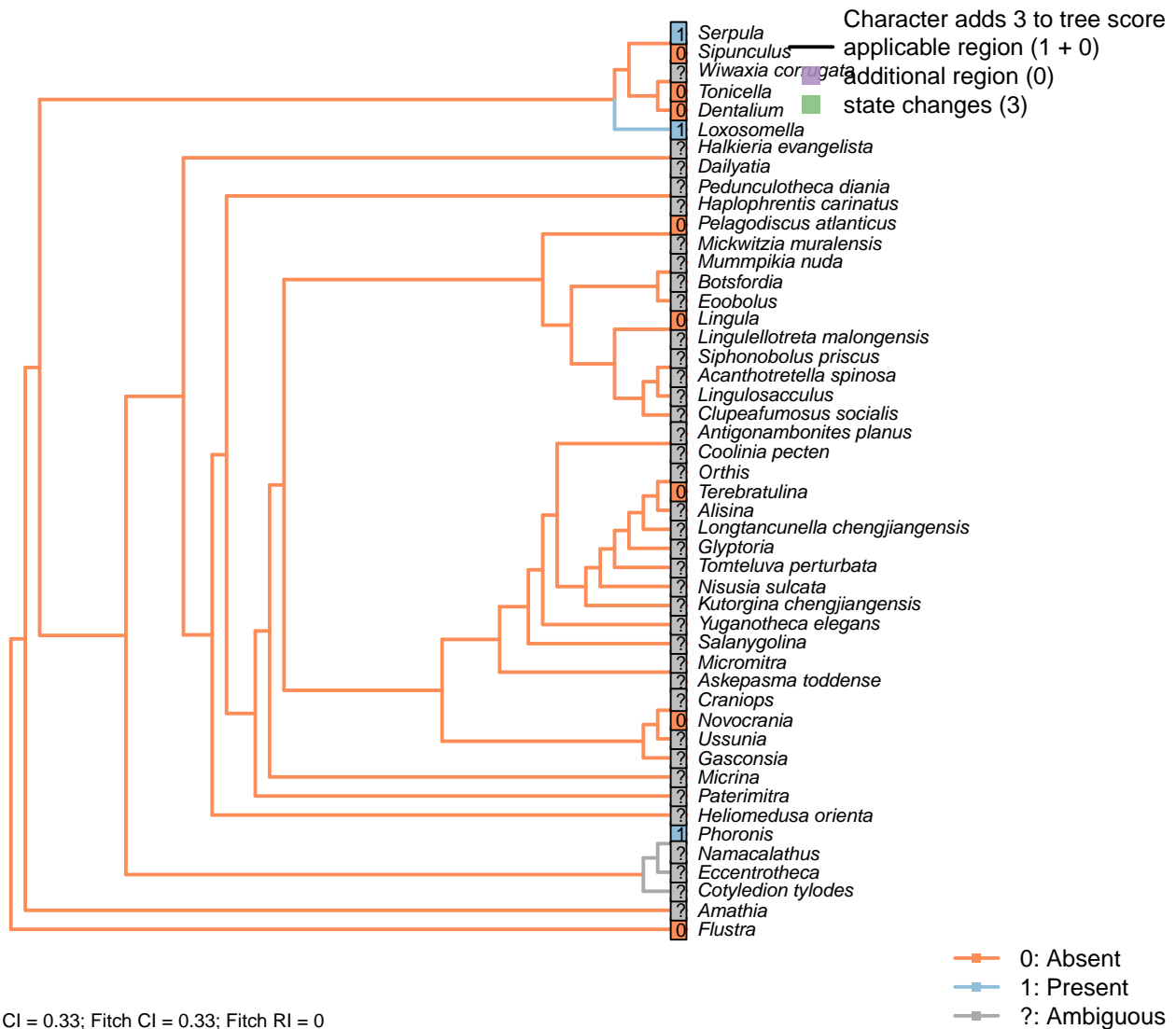
Neomorphic character.

Pore cells. Character 20 in Haszprunar (2000).

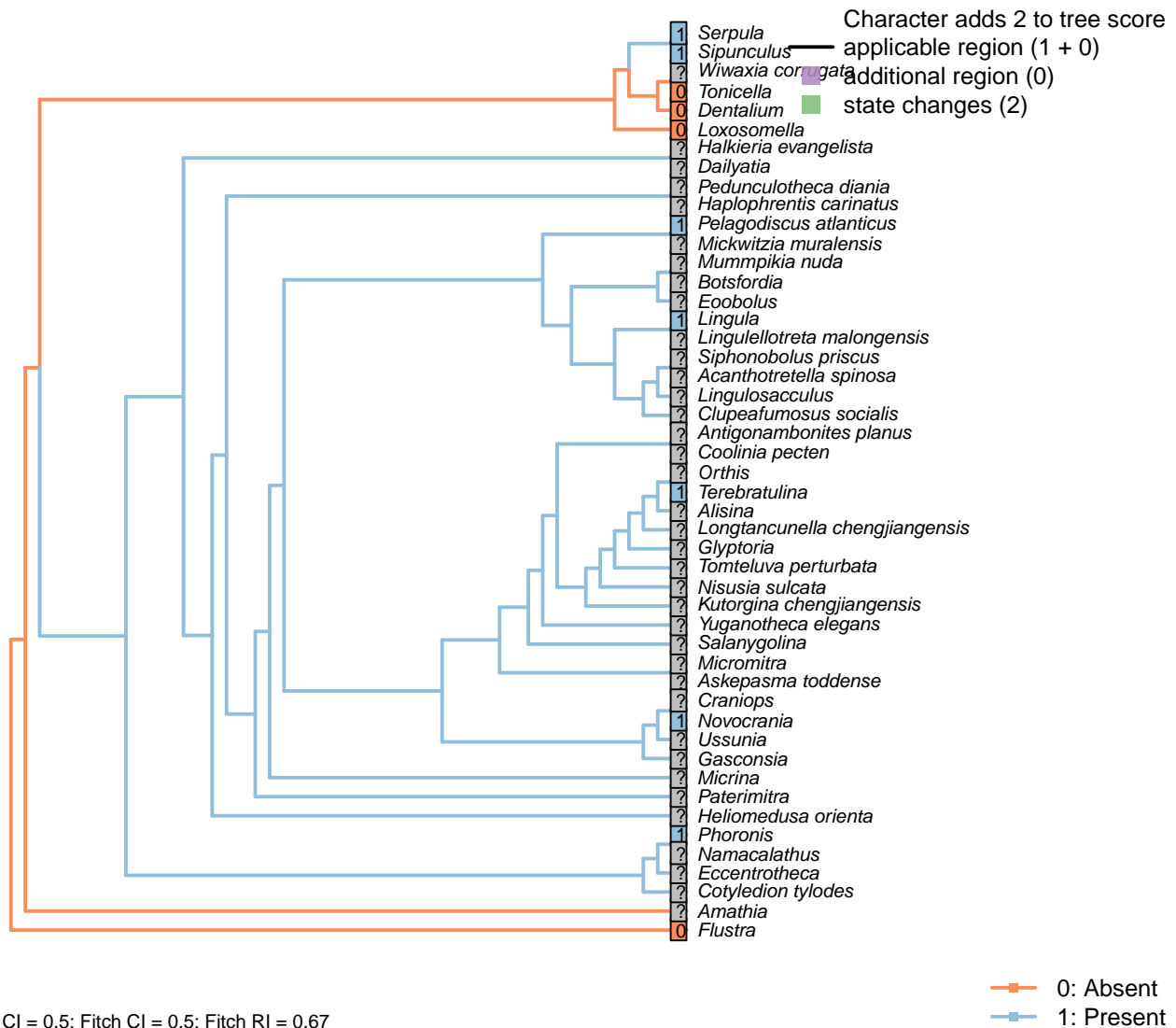
[198] Serve as excretory organs



[199] Protonephridia



[200] Metanephridia

**Character 200: Nephridia: Metanephridia**

0: Absent

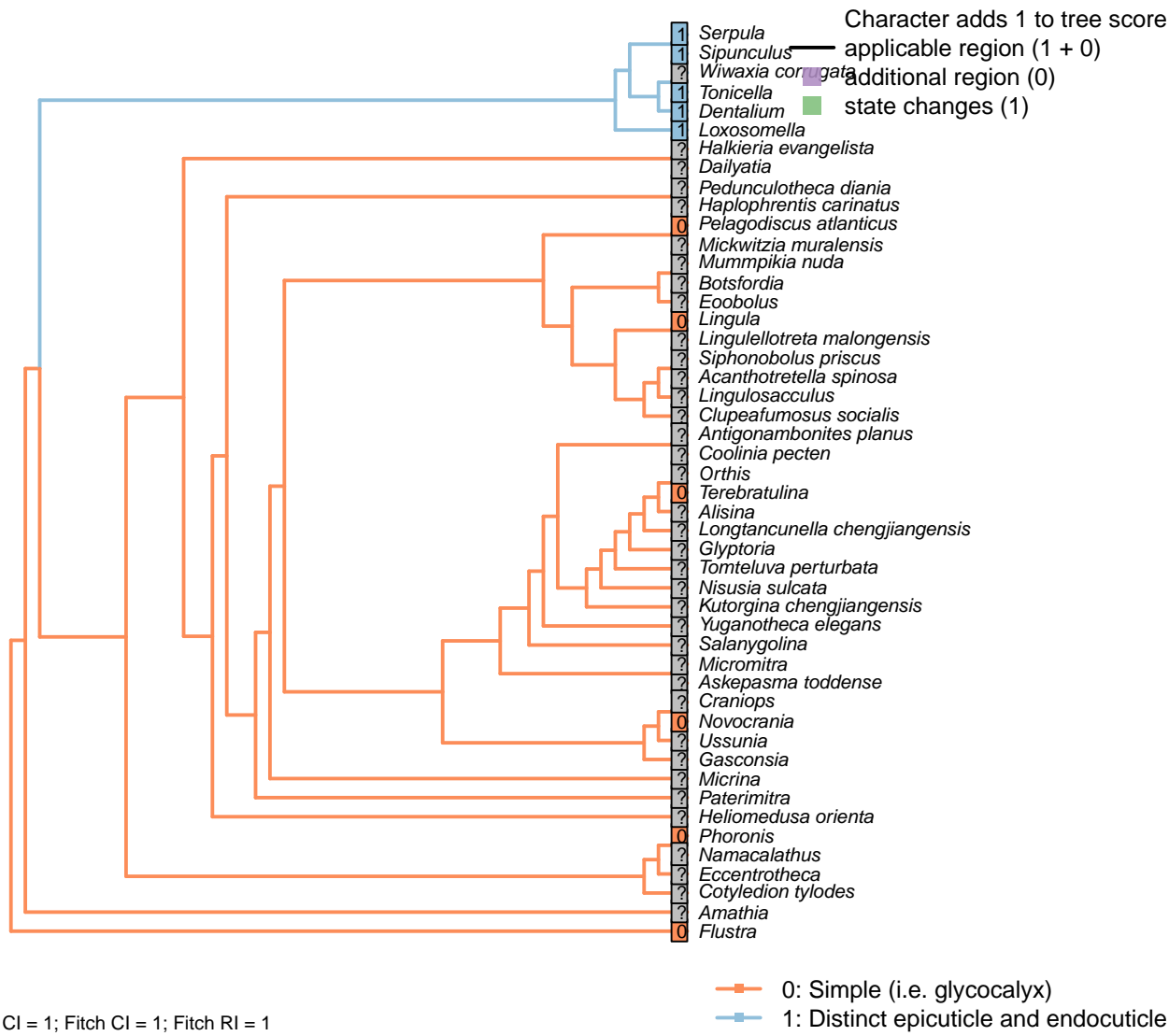
1: Present

Neomorphic character.

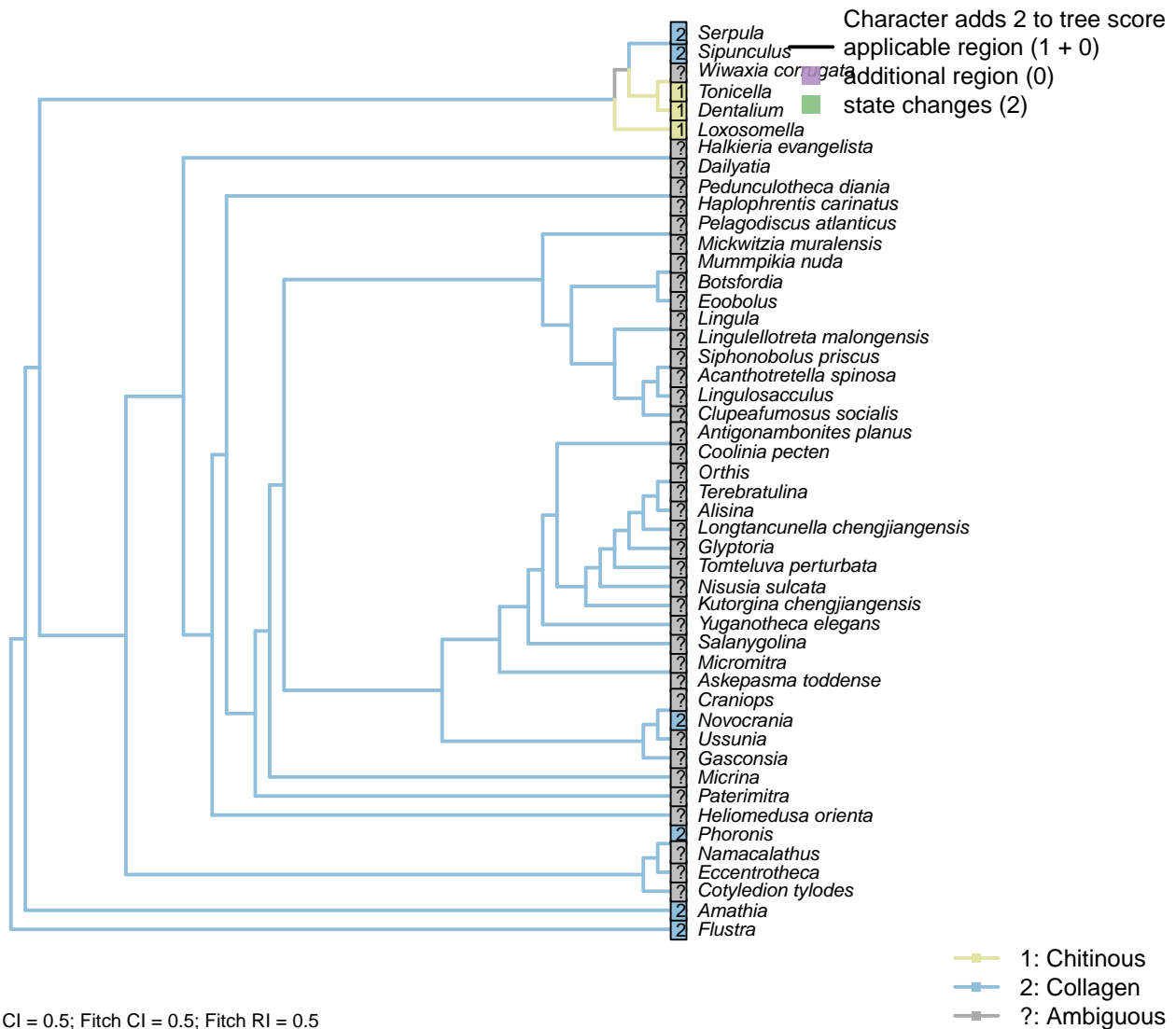
See characters 35 in Rouse (1999); 28 in Haszprunar (2000); 93 in Glenner et al. (2004); 1.47 in von Salvini-Plawen and Steiner (1996); 21 in Grobe (2007); 138 in Rouse (1999); 20 in Haszprunar (1996).

3.44 Cuticle

[201] Layers



[202] Composition

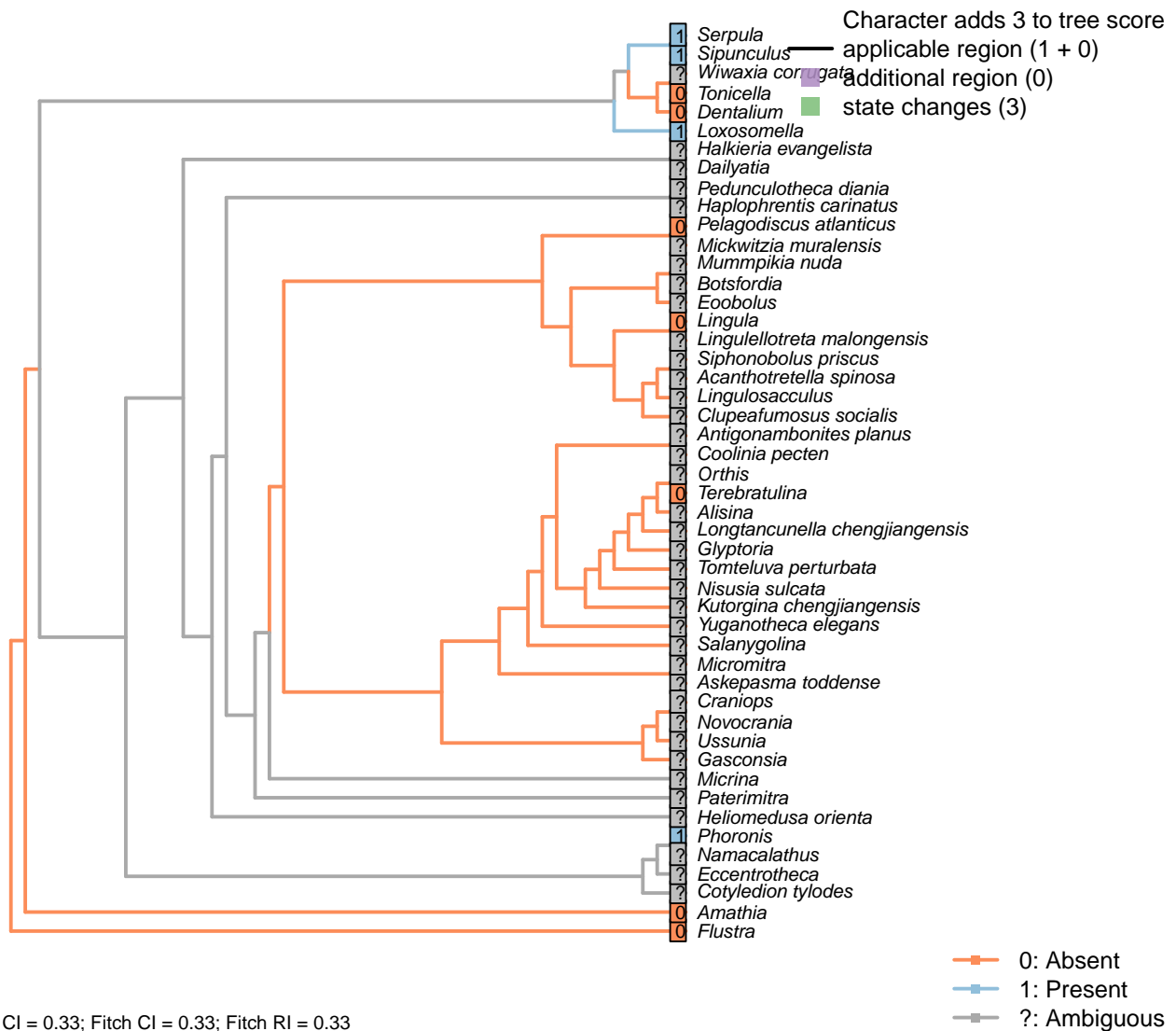


in regions where rigidity is necessary (Borisanova et al., 2015).

Phoronis, *Sipunculus*: Collagenous (Schopf and Manheim, 1967), though chitin is associated with the exoskeleton (Hunt, 1972).

Wiwaxia corrugata: Collagen fibres in tentacle cuticle (Bartolomaeus, 2001); chitin only present in tubes (Jeuniaux, 1971).

[203] Fibrous layer with thick fibrils



Character 203: Cuticle: Fibrous layer with thick fibrils

0: Absent

1: Present

Neomorphic character.

After Borisanova et al. (2015).

Acanthotretella spinosa, *Alisina*, *Daliyatia*, *Lingula*, *Phoronis*, *Sipunculus*: Following table 2 in Borisanova

et al. (2015).

Dentalium: Pedicle cuticle entirely homogeneous (Williams et al., 1997).

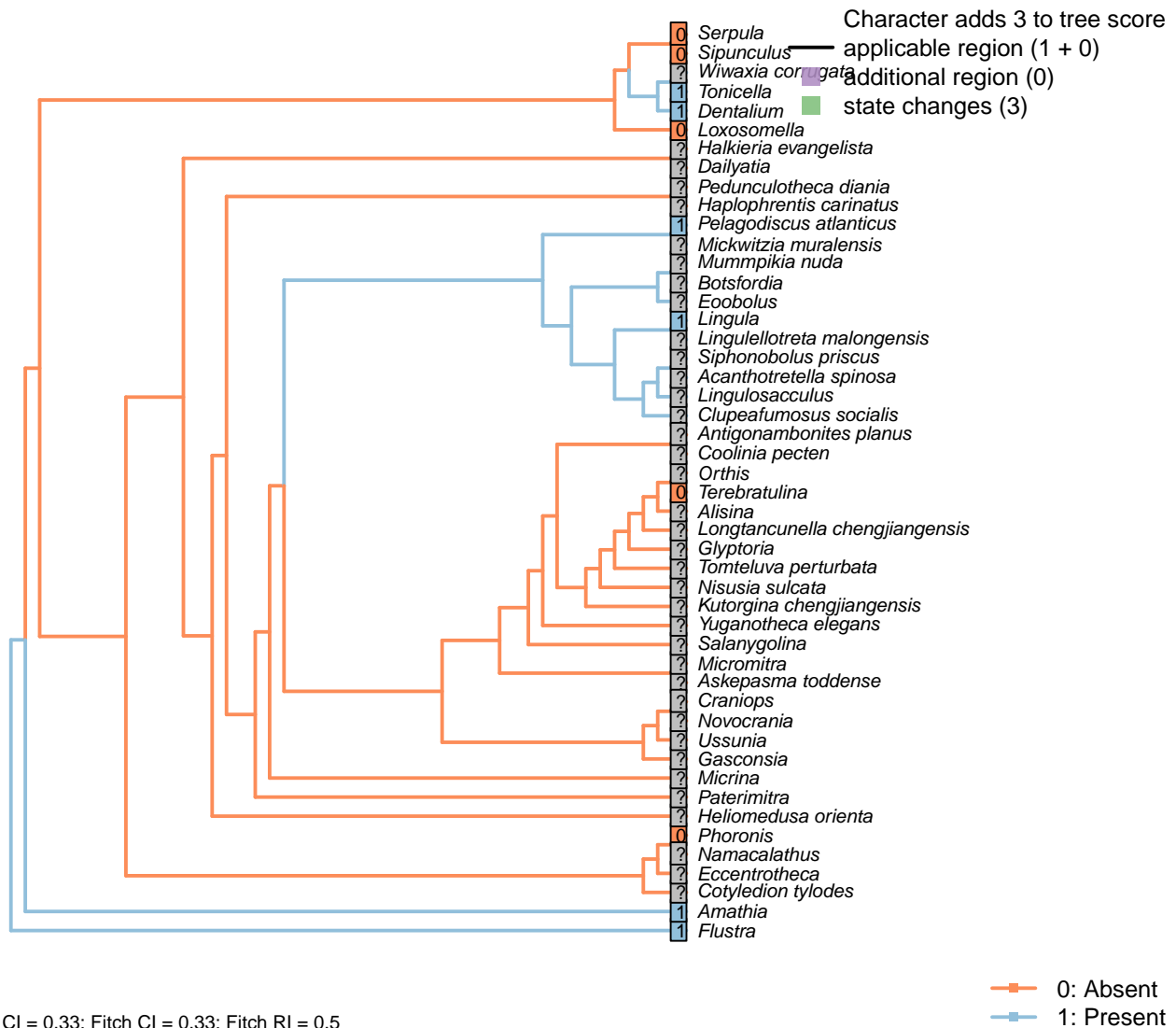
Halkieria evangelista: Fibrous collagen only (Bereiter-Hahn et al., 1984).

Serpula: Microvilli in otherwise homogeneous epidermis (Williams et al., 1997).

Tonicella: Not evident in *Notosaria* (Bereiter-Hahn et al., 1984; Williams et al., 1997).

Wiwaxia corrugata: Outer layer seemingly fibrous (Bereiter-Hahn et al., 1984).

[204] Homogeneous layer



After Borisanova et al. (2015).

Acanthotretella spinosa, *Alisina*, *Dailyatia*, *Lingula*, *Phoronis*, *Sipunculus*: Following table 2 in Borisanova et al. (2015).

Dentalium: Pedicle cuticle entirely homogeneous (Williams et al., 1997).

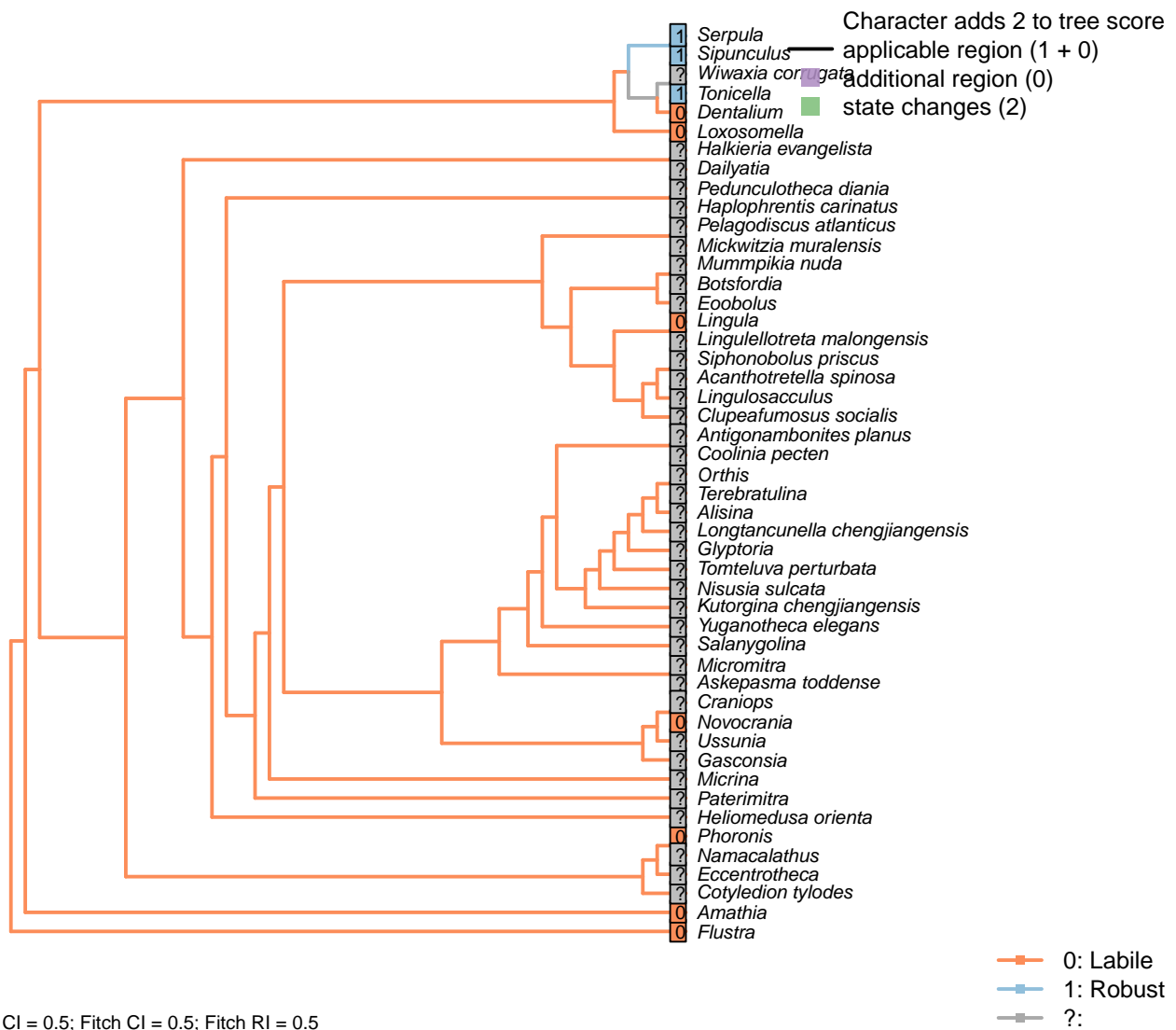
Halkieria evangelista: Fibrous collagen only (Bereiter-Hahn et al., 1984).

Serpula: Microvilli in otherwise homogeneous epidermis (Williams et al., 1997).

Tonicella: Cuticle is homogeneous in *Notosaria* (Bereiter-Hahn et al., 1984; Williams et al., 1997).

Wiwaxia corrugata: Not evident (Bereiter-Hahn et al., 1984).

[205] Resilience

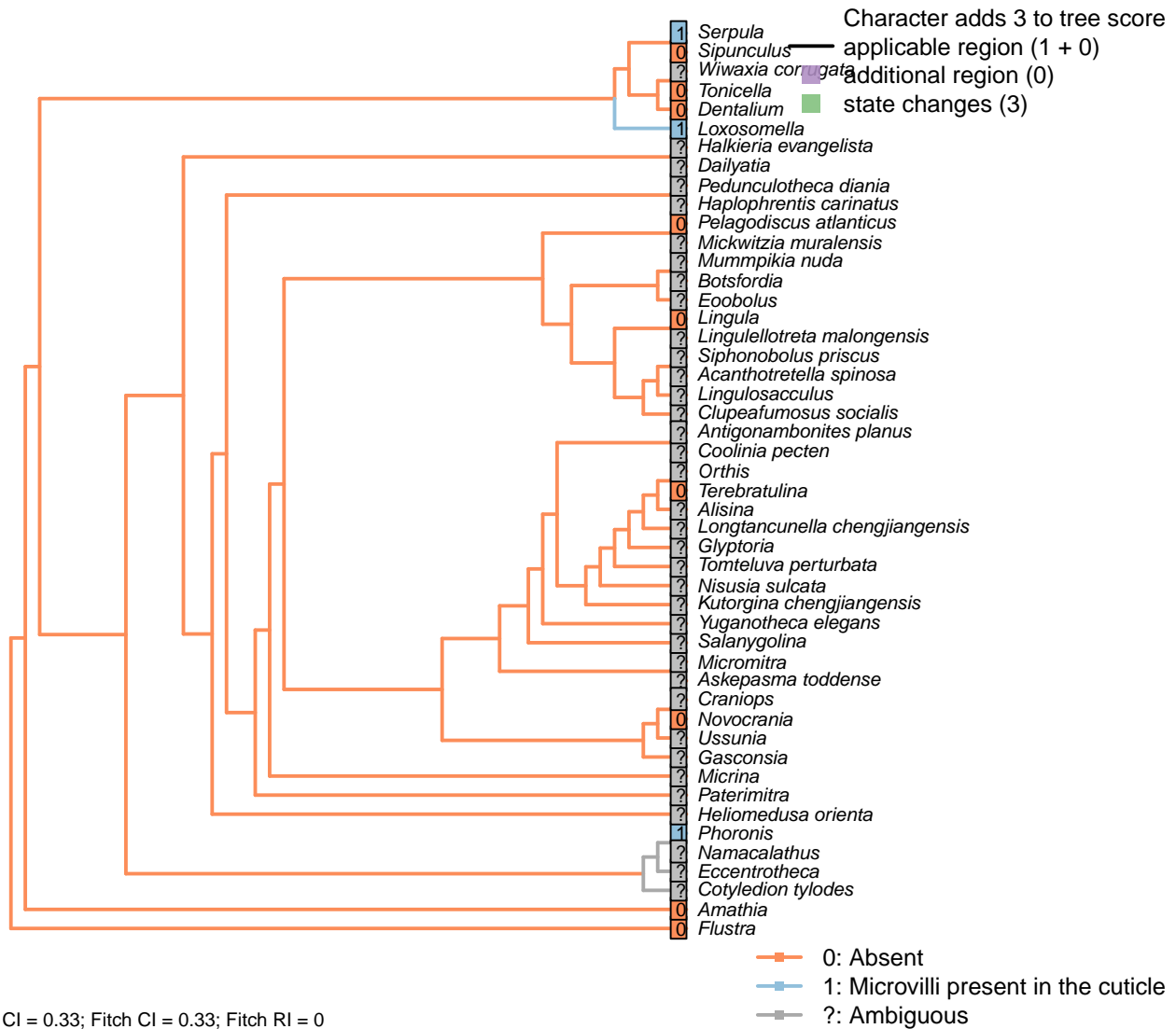


2:

Neomorphic character.

Character 1 in Haszprunar (2000).

[206] Microvilli

**Character 206: Cuticle: Microvilli**

0: Absent

1: Microvilli present in the cuticle

Neomorphic character.

After Borisanova et al. (2015).

Acanthotretella spinosa, *Alisina*, *Dailyatia*, *Lingula*, *Phoronis*, *Sipunculus*: Following table 2 in Borisanova

et al. (2015).

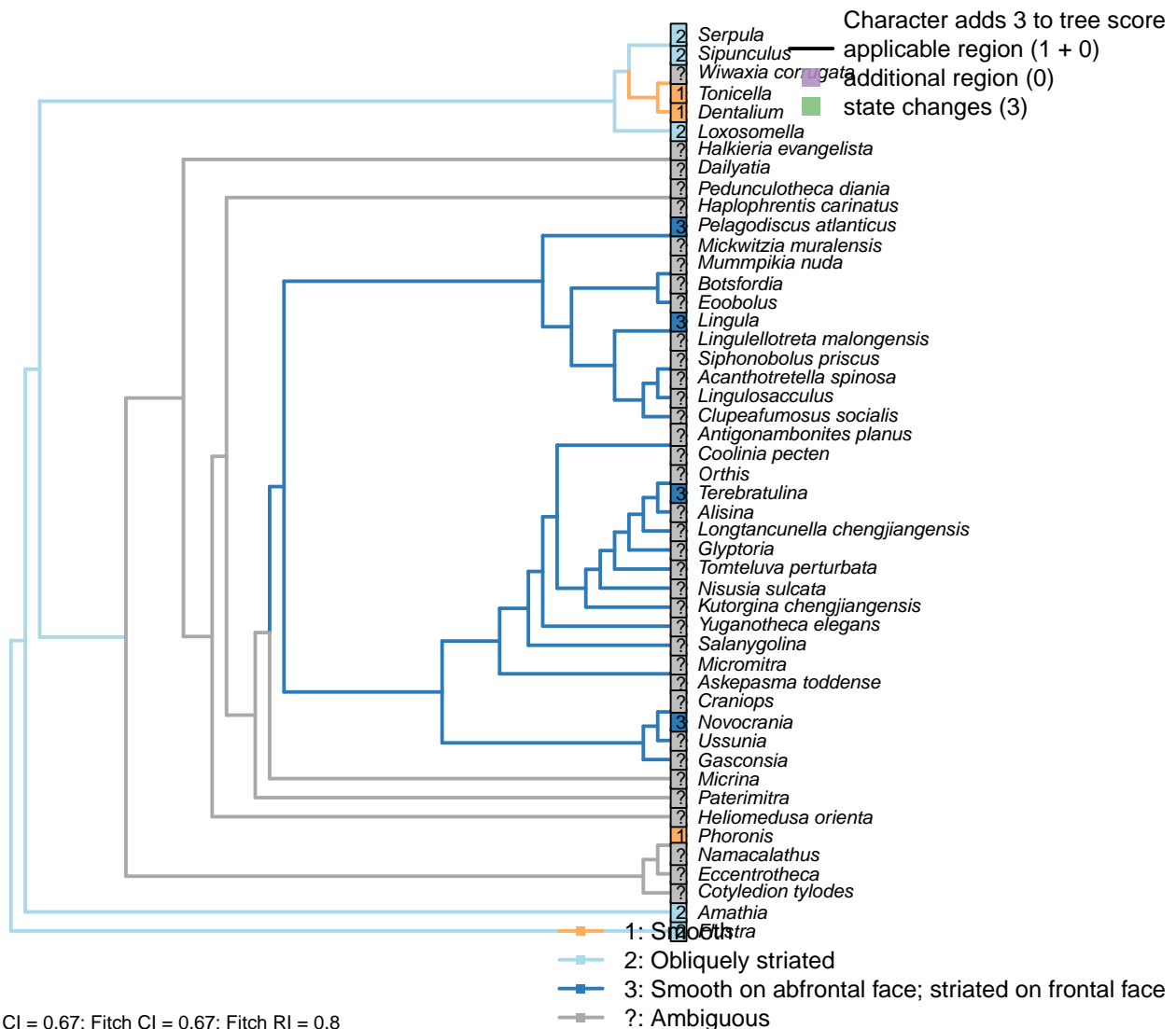
Halkieria evangelista: Fibrous collagen only (Bereiter-Hahn et al., 1984).

Serpula: Microvillios inner epithelium in *Discina* (Williams et al., 1997).

Wiwaxia corrugata: Present on outer epithelium (Bereiter-Hahn et al., 1984).

3.45 Muscles

[207] Cytology



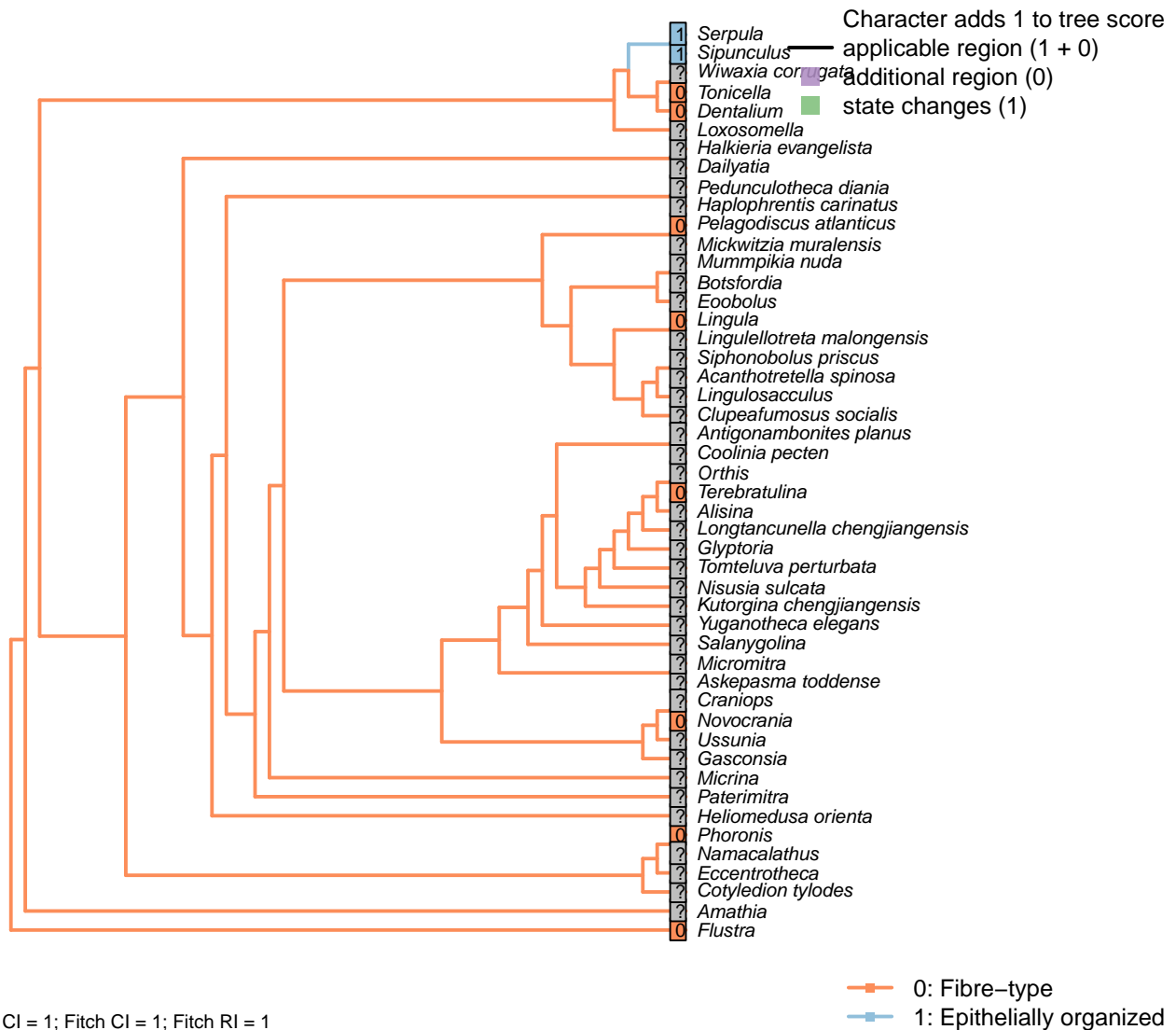
Character 19 in Haszprunar (1996); see also character 13 in Haszprunar (2000).

Dentalium, *Eoobolus*, *Serpula*, *Tonicella*: In brachiopods, myofibrils “are striated on the frontal face and smooth on the abfrontal face” (Pardos et al., 1991).

Phoronis, *Sipunculus*: In Bryozoa, myofibrils are “all striated” (Pardos et al., 1991).

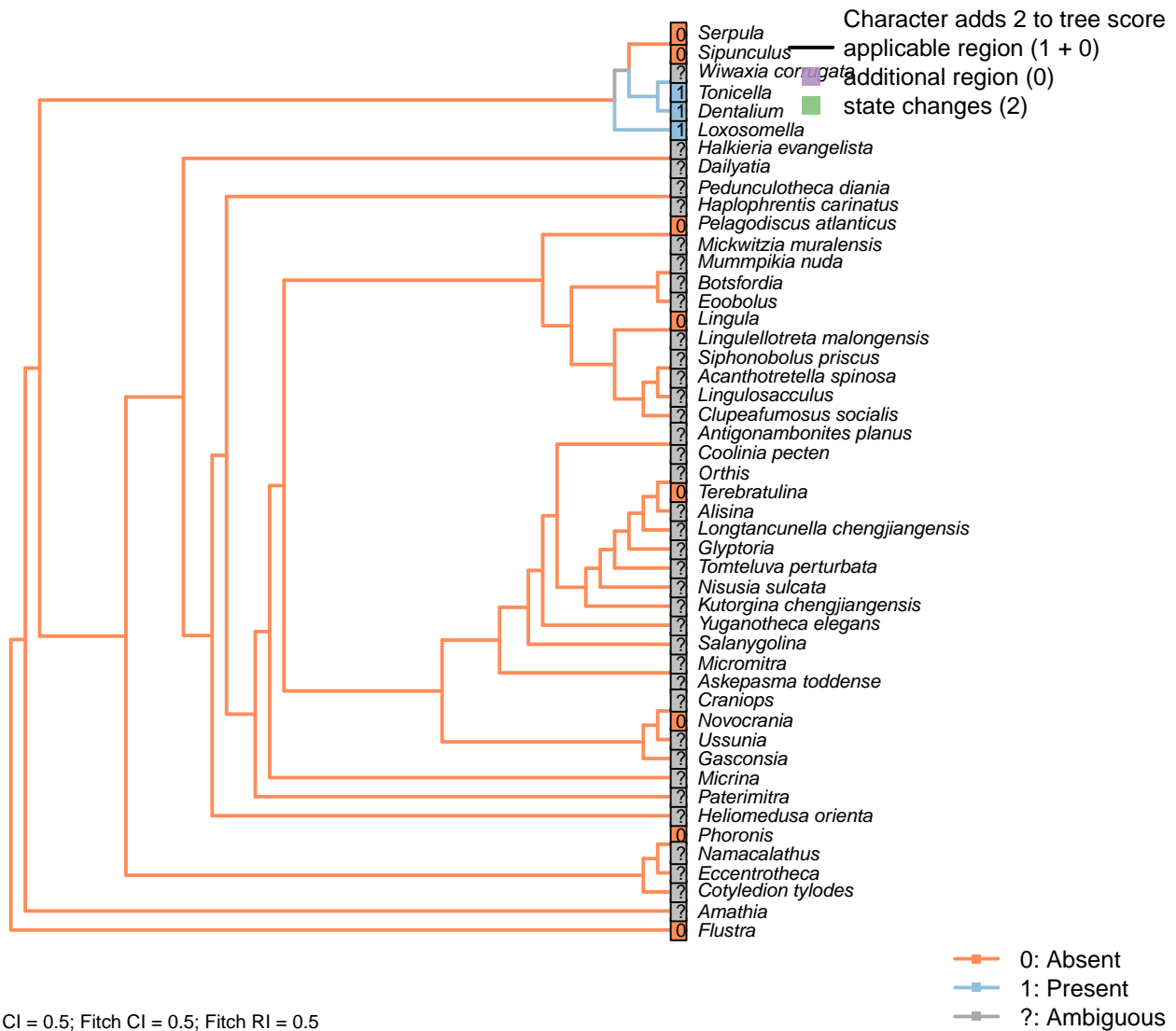
Wiwaxia corrugata: “In *P. australis* [...] all the myofibrils belong to the smooth type” – Pardos et al. (1991).

[208] Histology



3.46 Glands

[209] Pedal gland



Character 209: Glands: Pedal gland

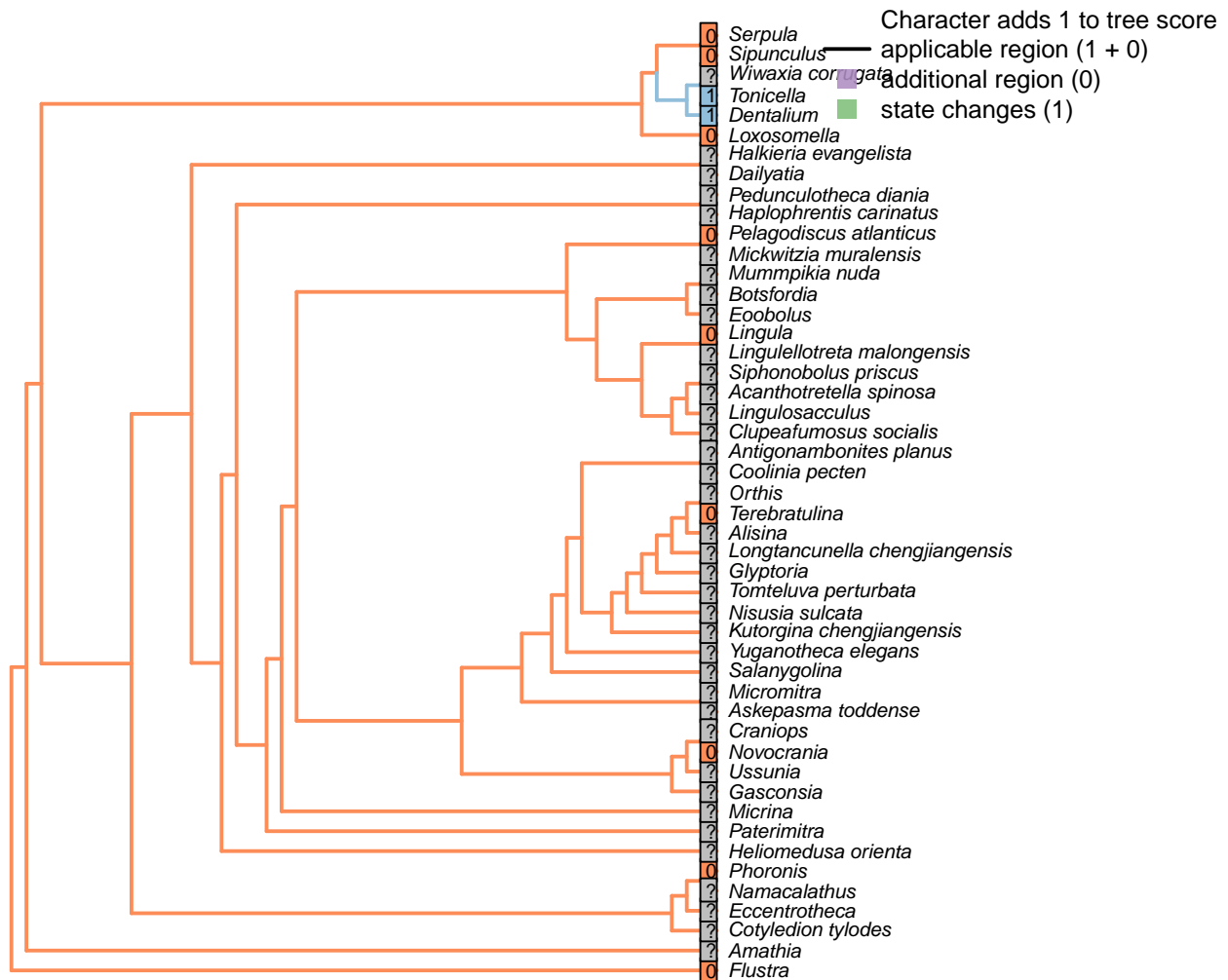
0: Absent

1: Present

Neomorphic character.

Characters 1.13, 1.40 & 2.08 in Scheltema (1993); 114 in Giribet and Wheeler (2002); 1.53 in von Salvini-Plawen and Steiner (1996); 9 in Haszprunar (1996).

[210] Paired pharyngeal diverticulae



CI = 1; Fitch CI = 1; Fitch RI = 1

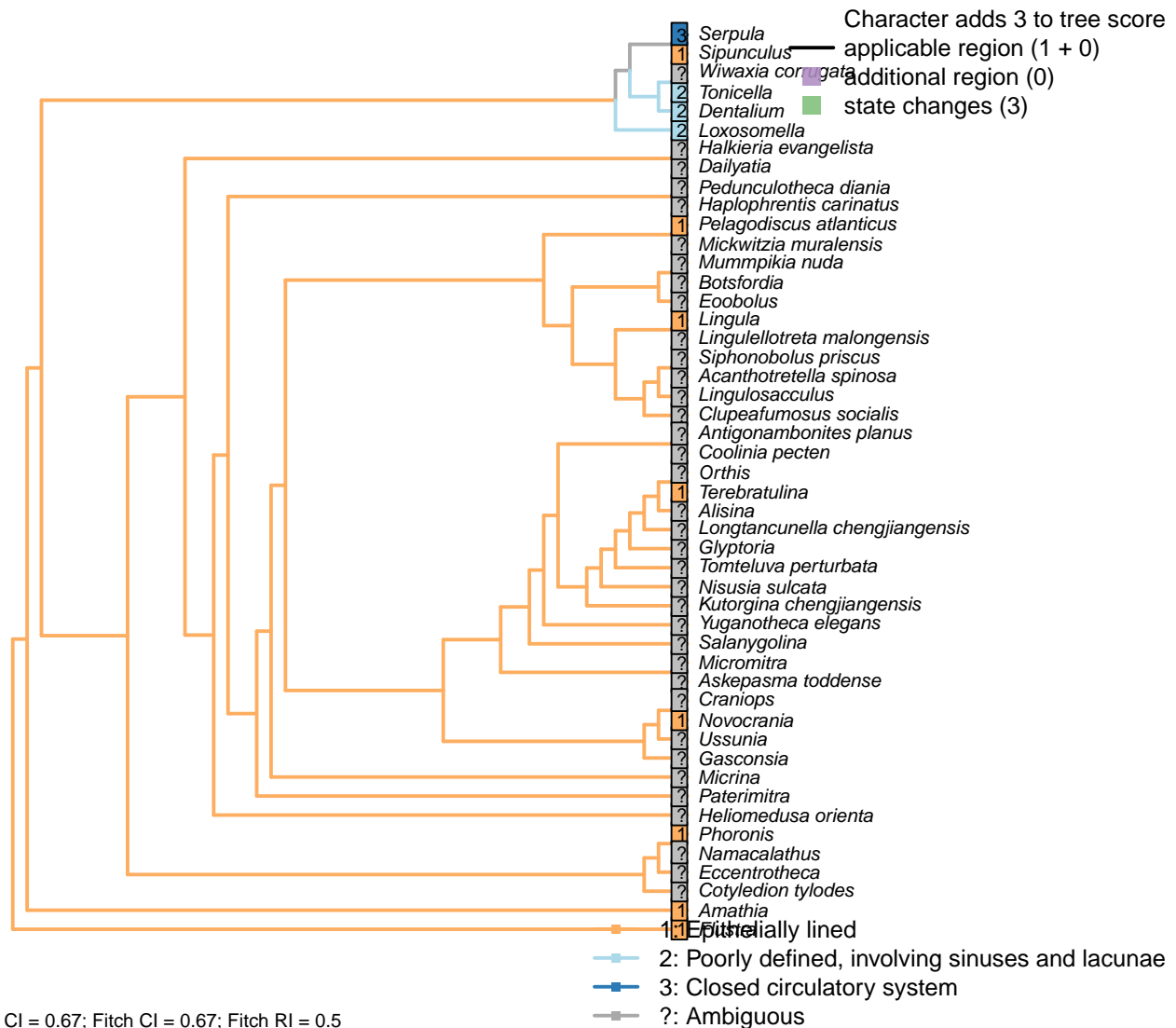
Character 210: Glands: Paired pharyngeal diverticulae

0: Absent

1: Present

Neomorphic character.

3.47 Body organization: Circulatory system [211]



After character 23 in Haszprunar (1996); 24 in Haszprunar (2000); 41 in Rouse (1999); 16 in Scheltema (1993); 16 in Vinther et al. (2008); 5 in Haszprunar and Wanninger (2008).

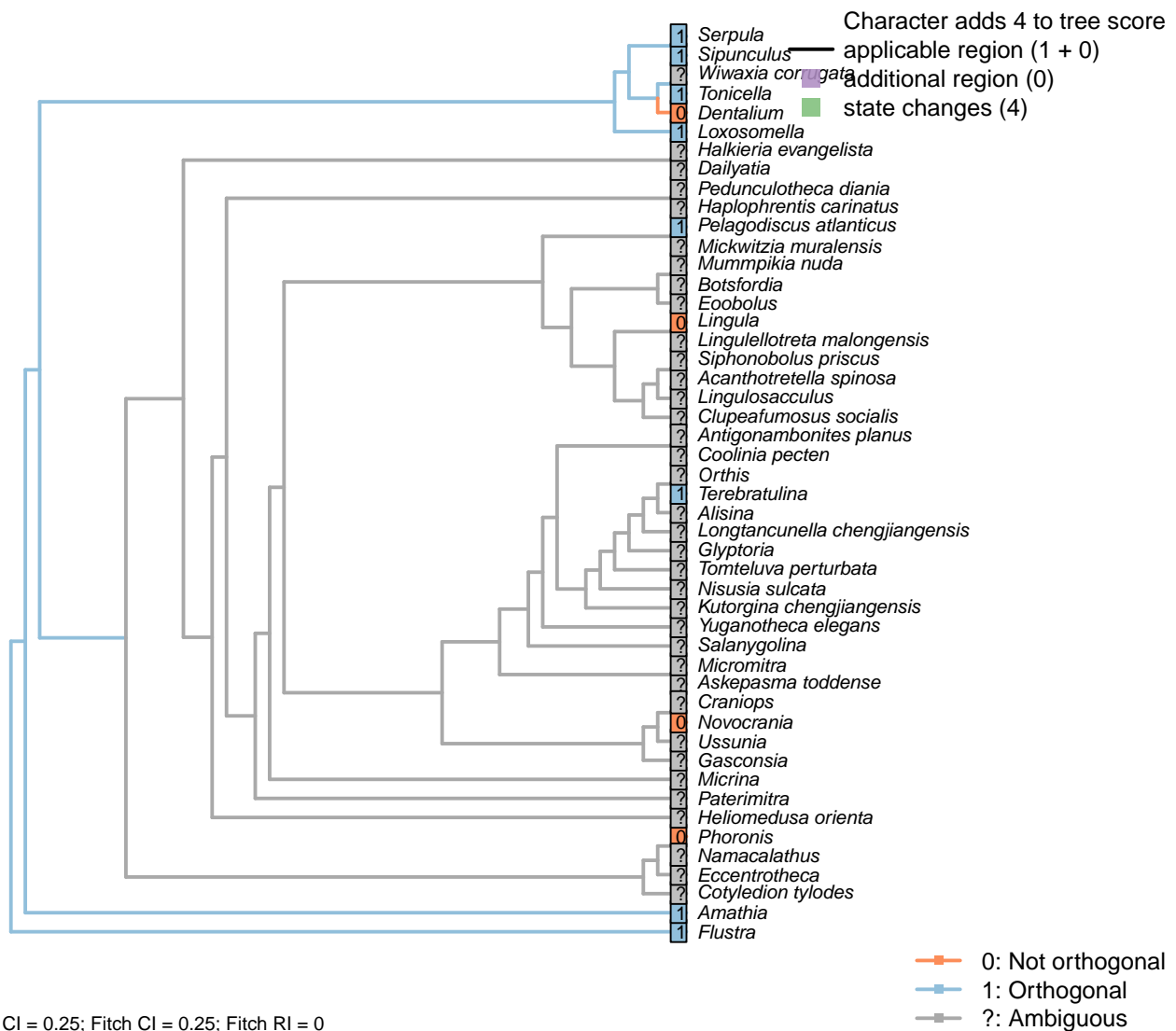
Acanthotretella spinosa, *Alisina*, *Lingula*: See Haszprunar and Wanninger (2008).

Halkieria evangelista: Open circulatory system.

Phoronis, *Sipunculus*: As Brachiopods, sipunculans and relatives (Ruppert and Carle, 1983).

3.48 Nervous system

[212] Orthogonal



Character 212: Nervous system: Orthogonal

0: Not orthogonal

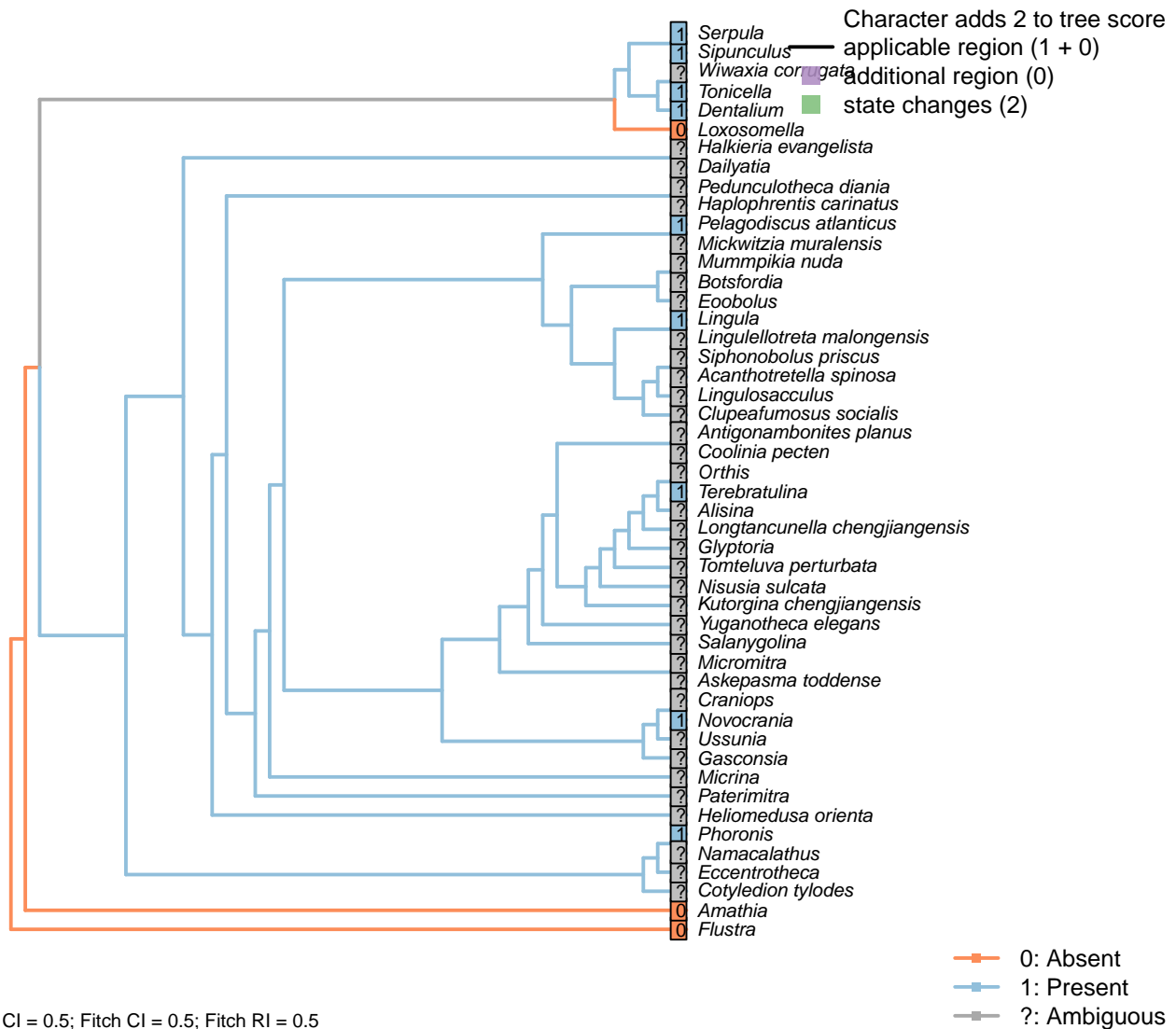
1: Orthogonal

Neomorphic character.

Character 14 in Haszprunar (1996). Paired longitudinal nerve cords regularly interconnected by transversal commissures to form a rectangular pattern.

Sipunculus: Temereva and Kosevich (2016).

[213] Glial system

**Character 213: Nervous system: Glial system**

0: Absent

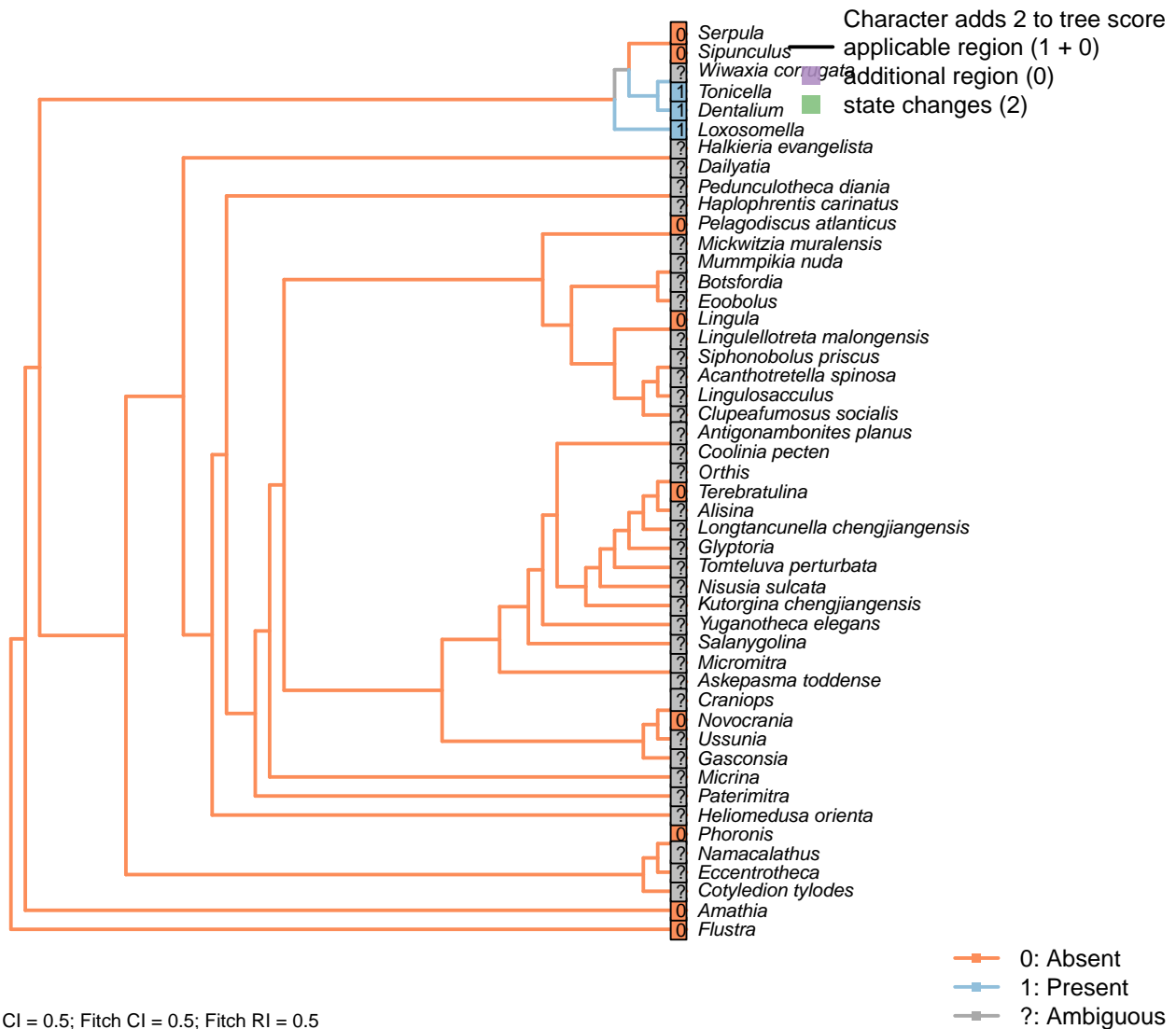
1: Present

Neomorphic character.

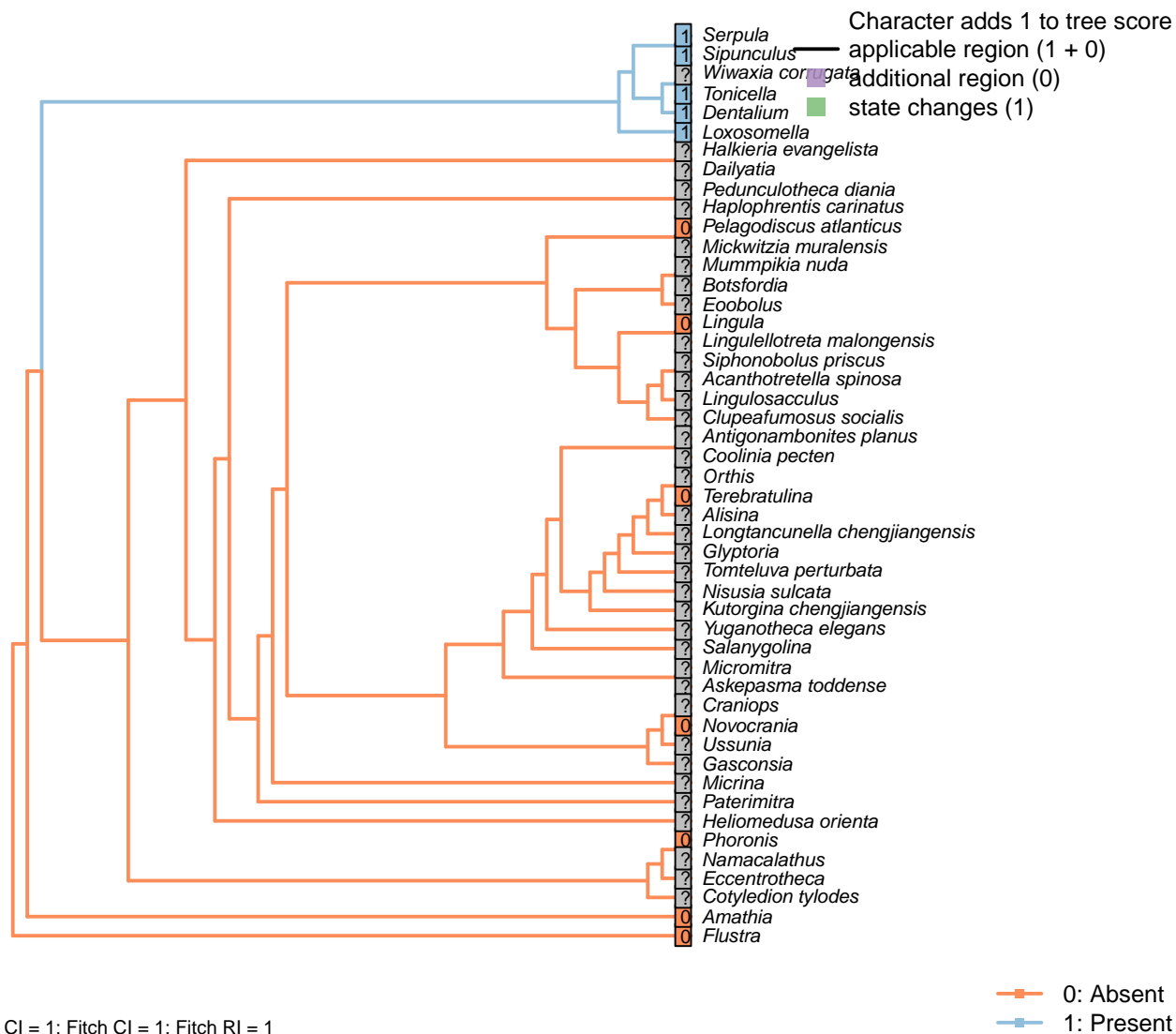
Character 16 in Haszprunar (1996). The Gliointerstitial system interconnects the nervous and muscle systems.

Wiwaxia corrugata: Glial cells are “abundant” (Temereva, 2016).

[214] Buccal nerve ring



[215] Anterior nerve loop

**Character 215: Nervous system: Anterior nerve loop**

0: Absent

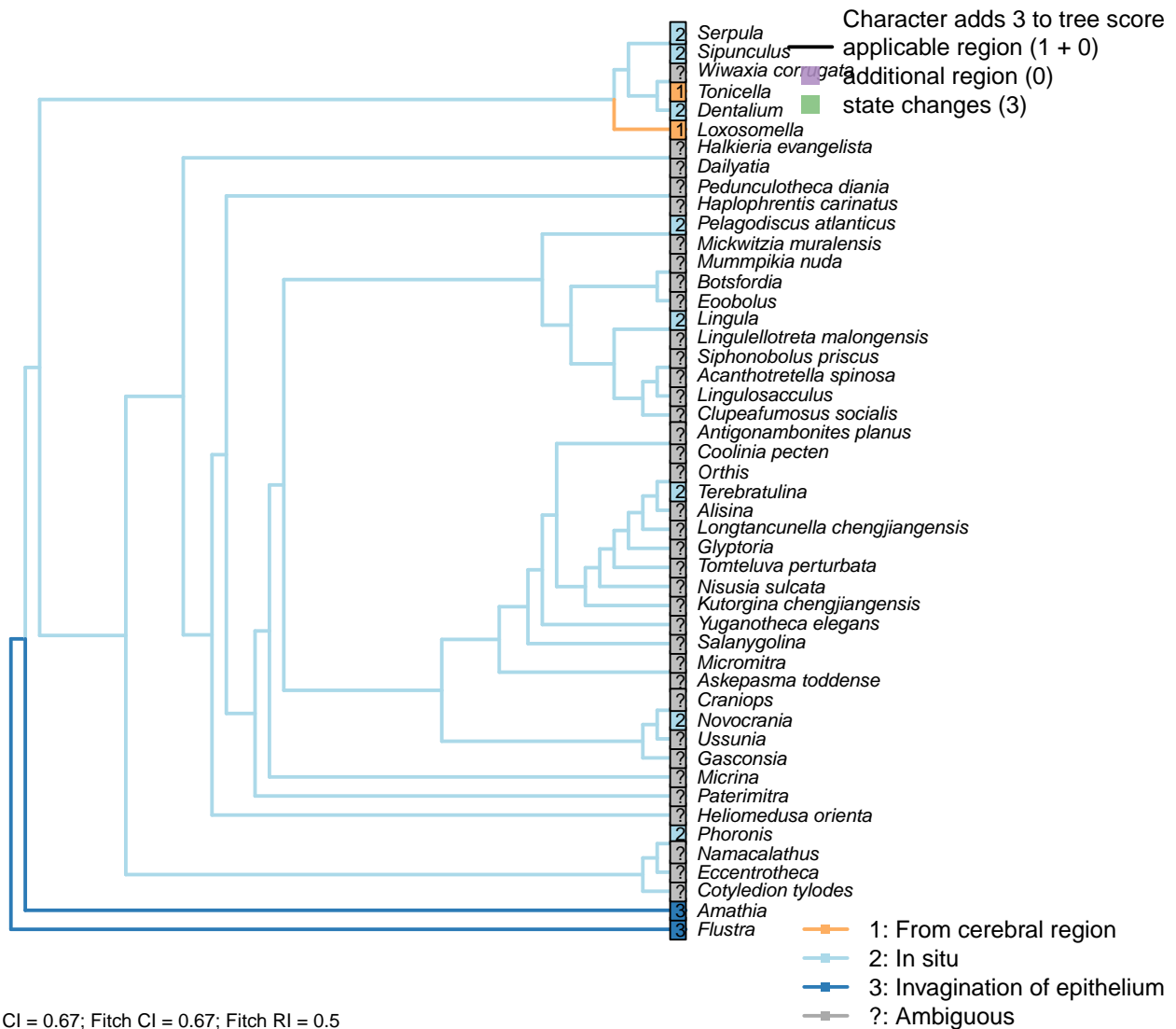
1: Present

Neomorphic character.

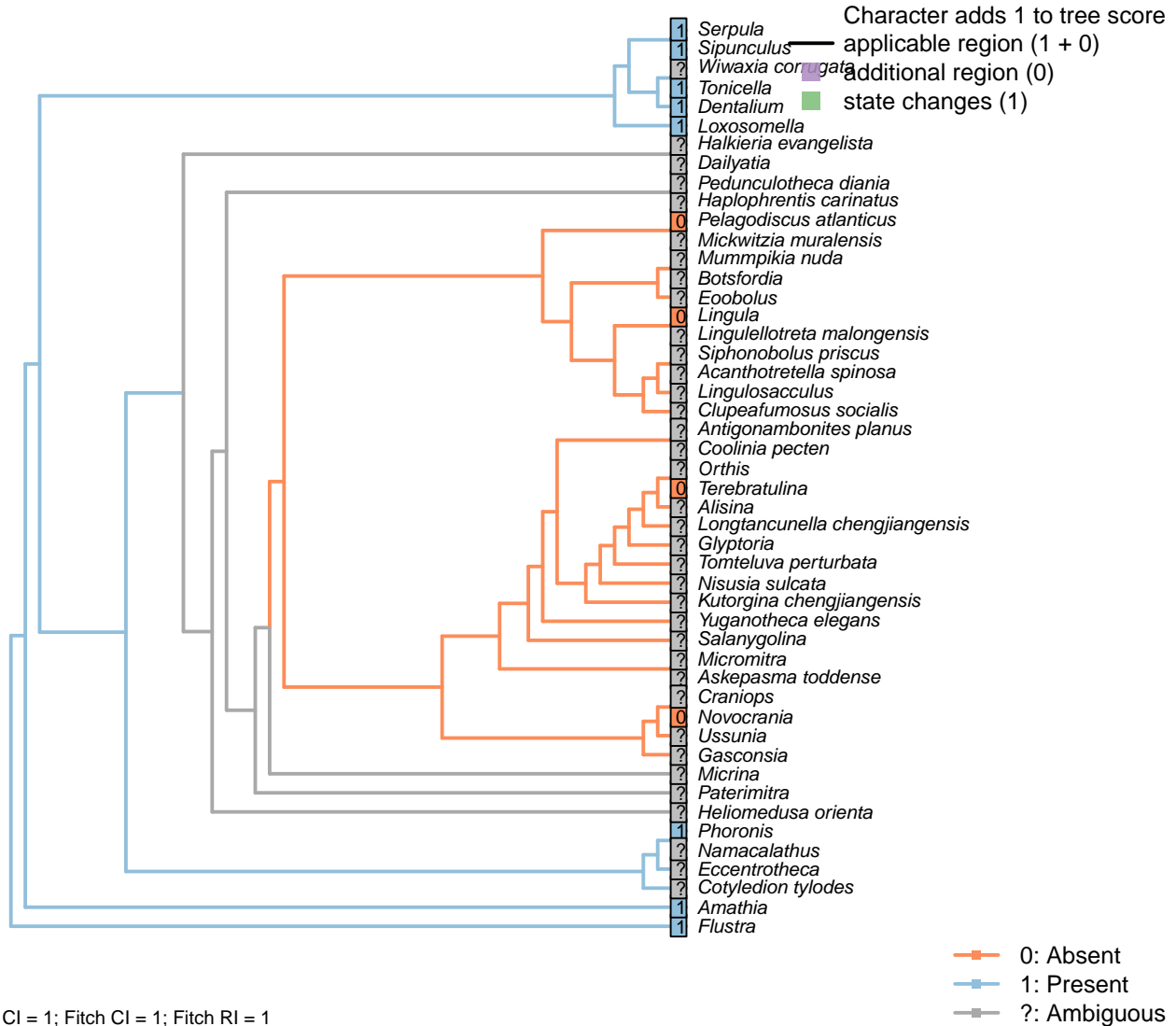
Character 7c in Haszprunar and Wanninger (2008). A pre-oral nerve loop is present in molluscs, *Loxosomella* and certain annelids (Wanninger et al., 2007).

Sipunculus: Temereva and Kosevich (2016).

[216] Formation of ganglia



[217] Presence

**Character 217: Nervous system: Cerebral ganglia: Presence**

0: Absent

1: Present

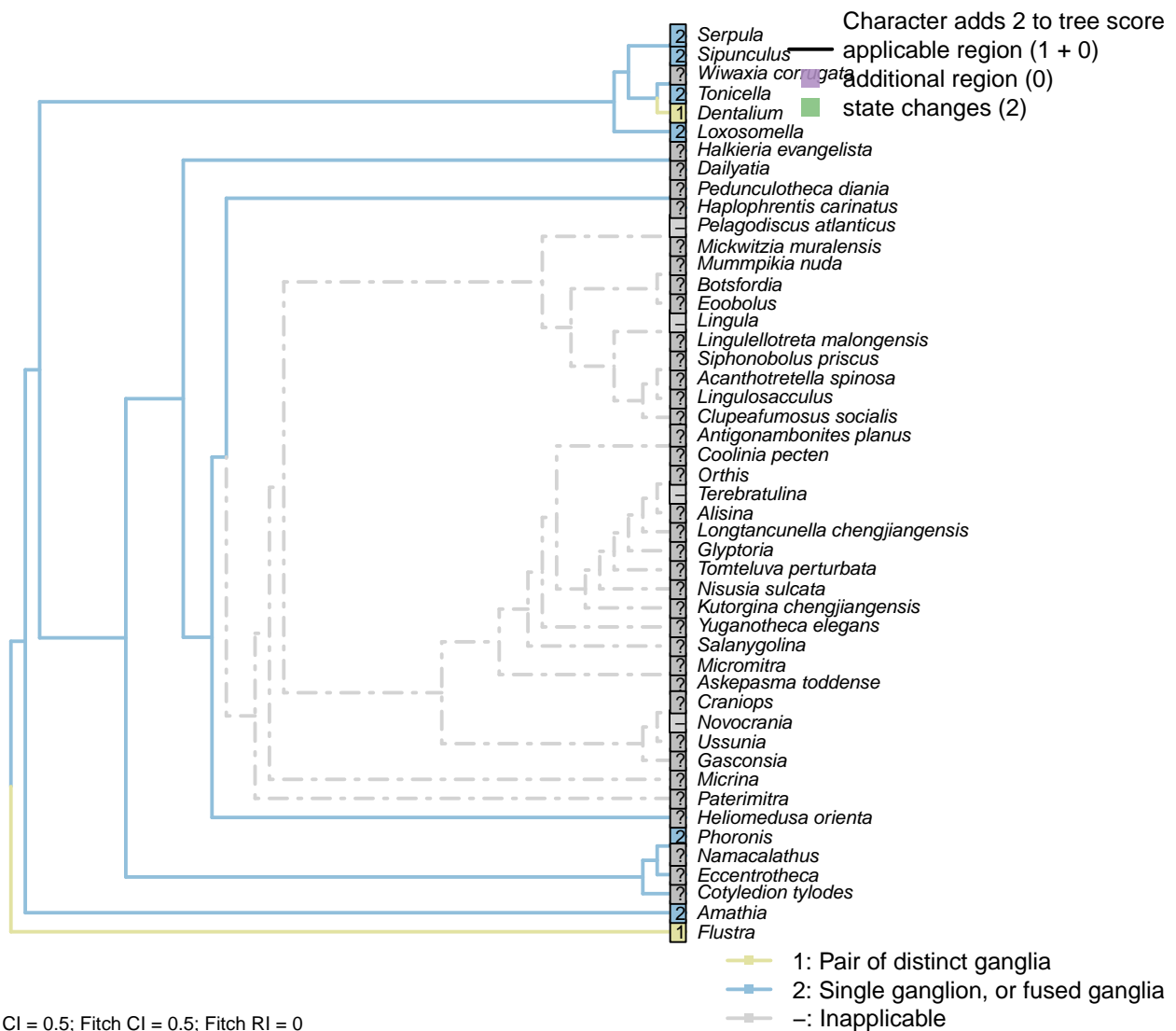
Neomorphic character.

After character 13 in Haszprunar (1996).

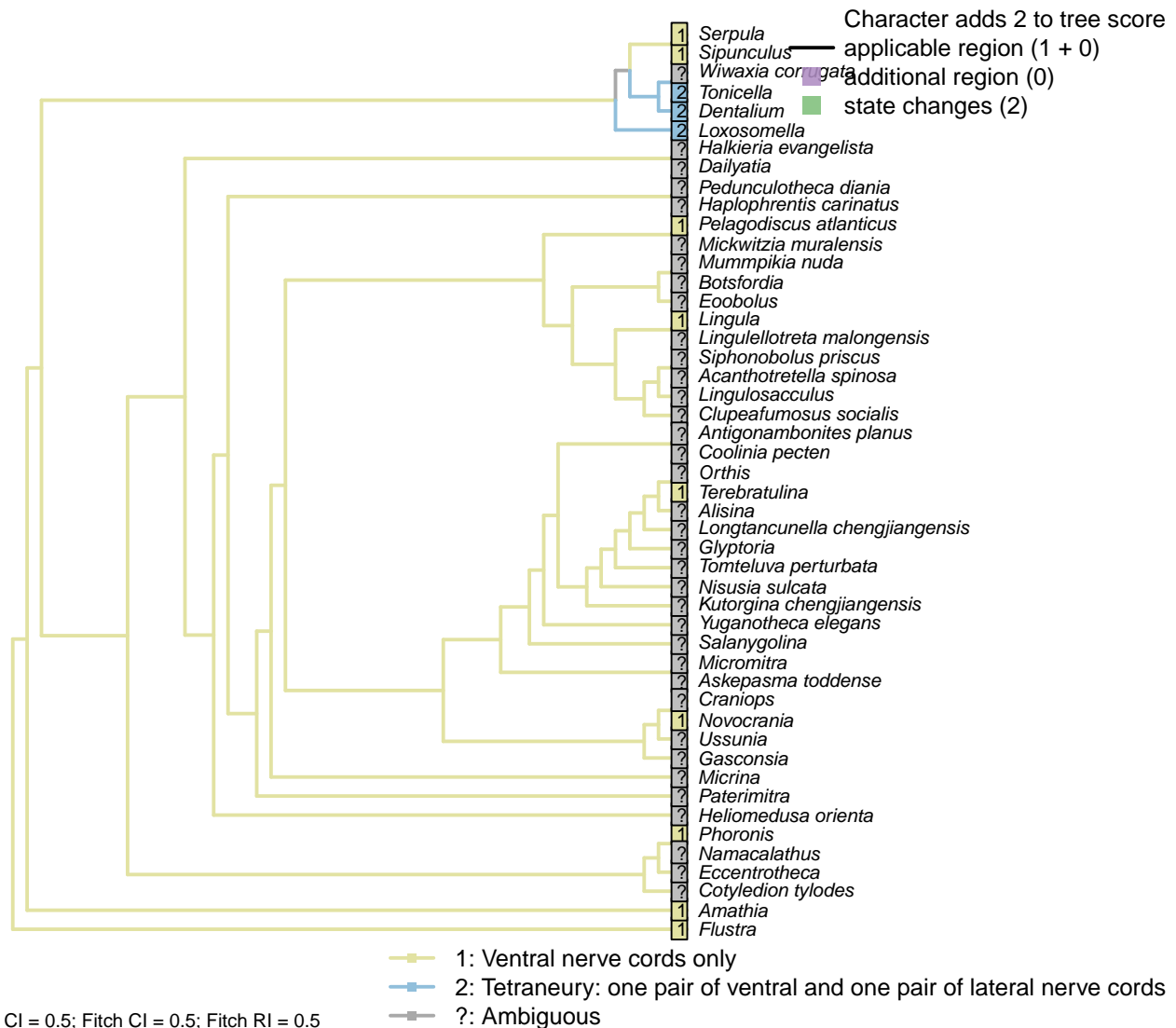
Sipunculus: Temereva and Kosevich (2016).*Wiwaxia corrugata*: We treat the dorsal ganglion, which is formed by two ends of the tentacular nerve ring (Temereva, 2016), as cerebral.

3.49 Nervous system

[218] Fused



3.50 Nervous system: Nerve cords [219]



Character 219: Nervous system: Nerve cords

1: Ventral nerve cords only

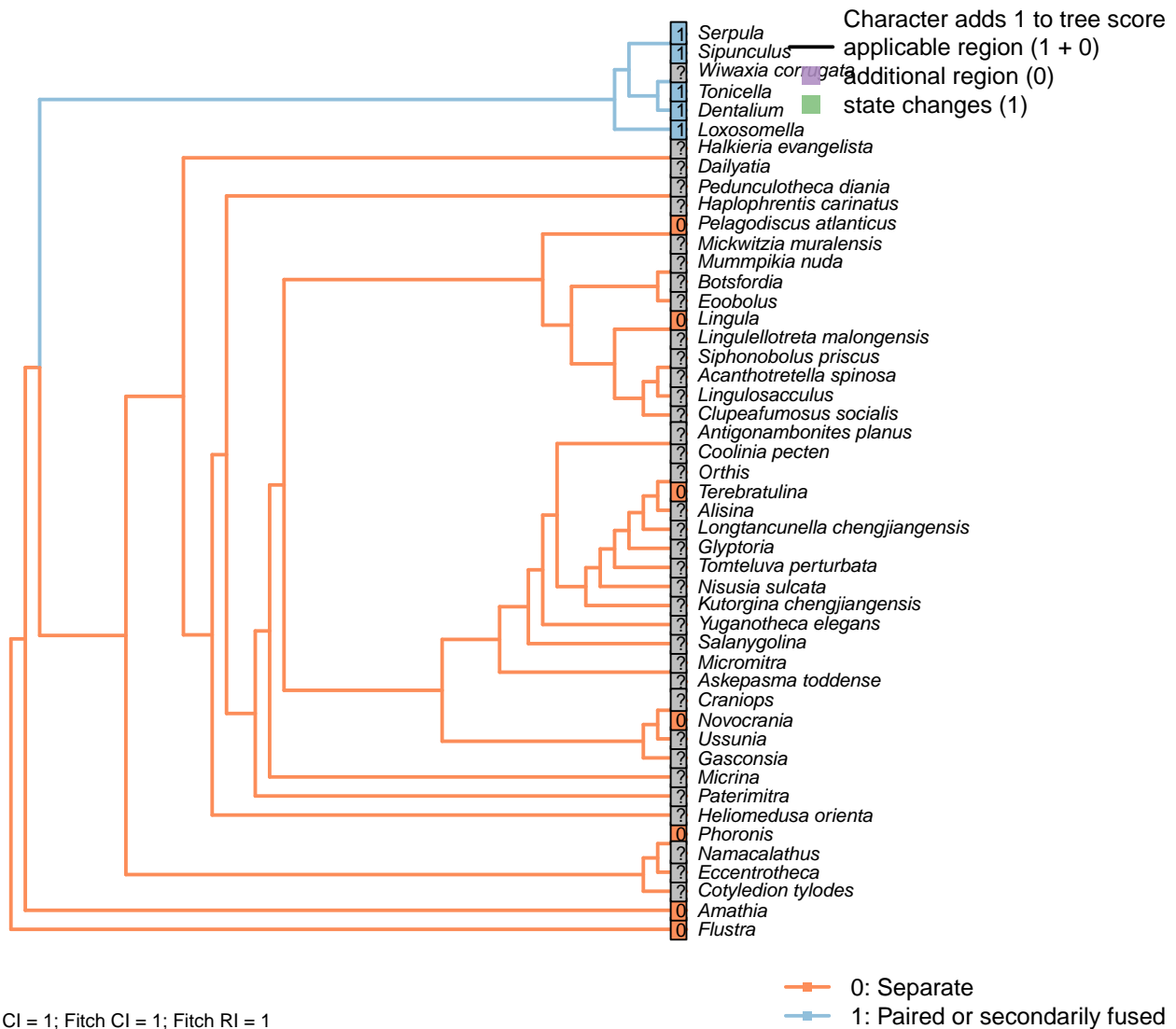
2: Tetraneury: one pair of ventral and one pair of lateral nerve cords

Transformational character.

See character 7 in Haszprunar and Wanninger (2008).

Sipunculus: Temereva and Kosevich (2016).

[220] Ventral longitudinal nerves



Chapter 4

Fitch parsimony

Parsimony search was conducted in TNT v1.5 (Goloboff and Catalano, 2016) using ratchet and tree drifting heuristics (Goloboff, 1999; Nixon, 1999), repeating the search until the optimal score had been hit by 1500 independent searches:

```
xmult:rat10 drift10 hits 1500 level 4 chklevel 5;
```

Searches were conducted under equal weights and results saved to file:

```
piwe-; xmult; /* Conduct search with equal weighting */  
tsav *TNT/ew.tre;sav;tsav/; /* Save results to file */  
keep 0; hold 10000; /* Clear trees from memory */
```

Further searches were conducted under extended implied weighting (Goloboff, 1997, 2014), under the concavity constants 2, 3, 4.5, 7, 10.5, 16 and 24:

```
xpiwe=; /* Enable extended implied weighting */  
piwe=2; xmult; /* Conduct analysis at k = 2 */  
tsav *TNT/xpiwe2.tre; sav; tsav/; /* Save results to file */  
keep 0; hold 10000; /* Clear trees from memory */  
piwe=3; xmult; /* Conduct analysis at k = 3 */  
tsav *TNT/xpiwe3.tre; sav ;tsav/; /* Save results to file */
```

We acknowledge the Willi Hennig Society for their sponsorship of the TNT software.

4.1 Results

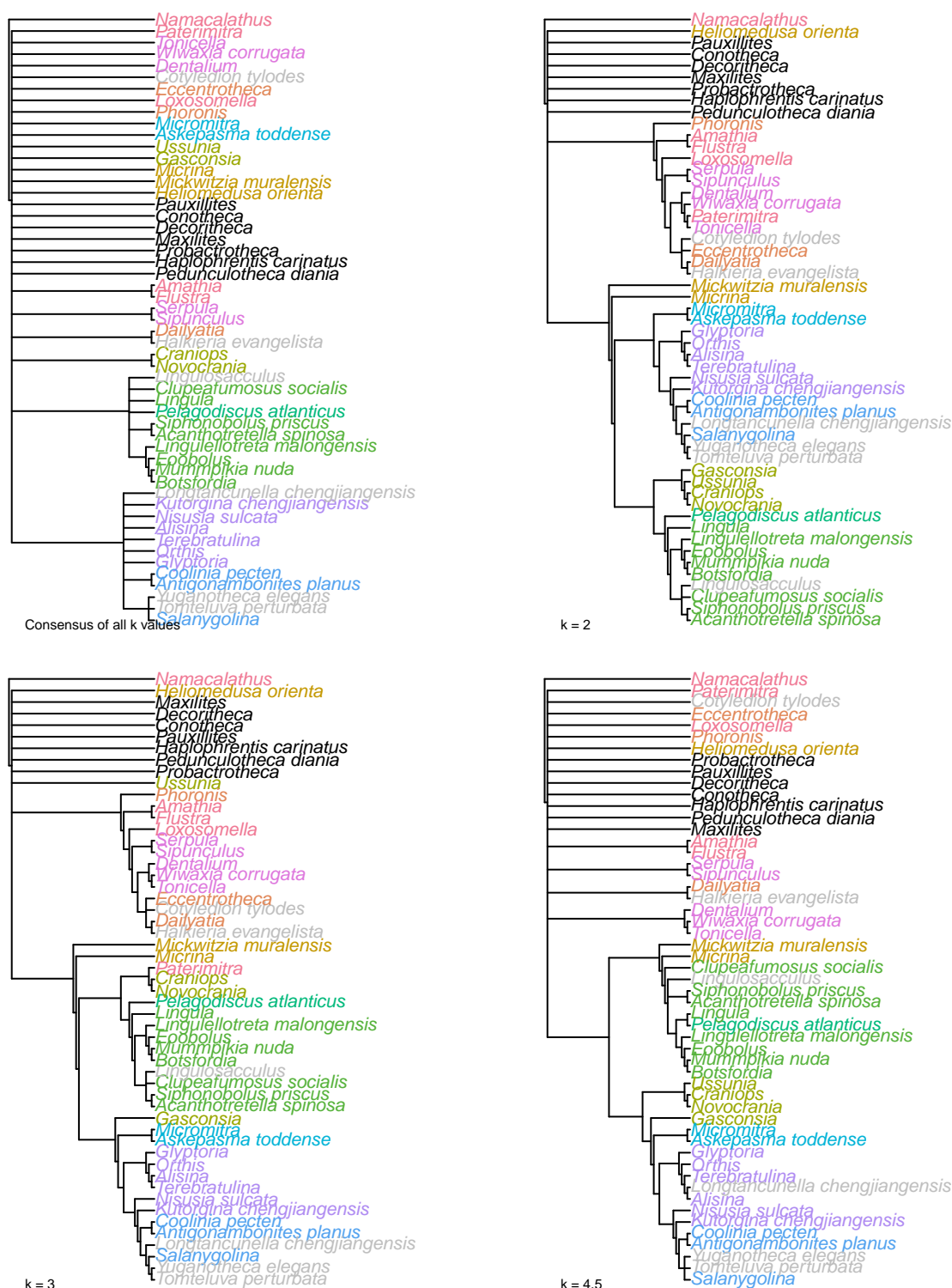


Figure 4.1: Strict consensus of all trees recovered by TNT using Fitch parsimony with implied weighting at all values of k , and at the individual values $k = 2, 3$ and 4.5 . The consensus of all implied weights runs is not very well resolved, largely due to a few wildcard taxa, particularly at $k = 4.5$, which obscures a consistent set of relationships between the remaining taxa.

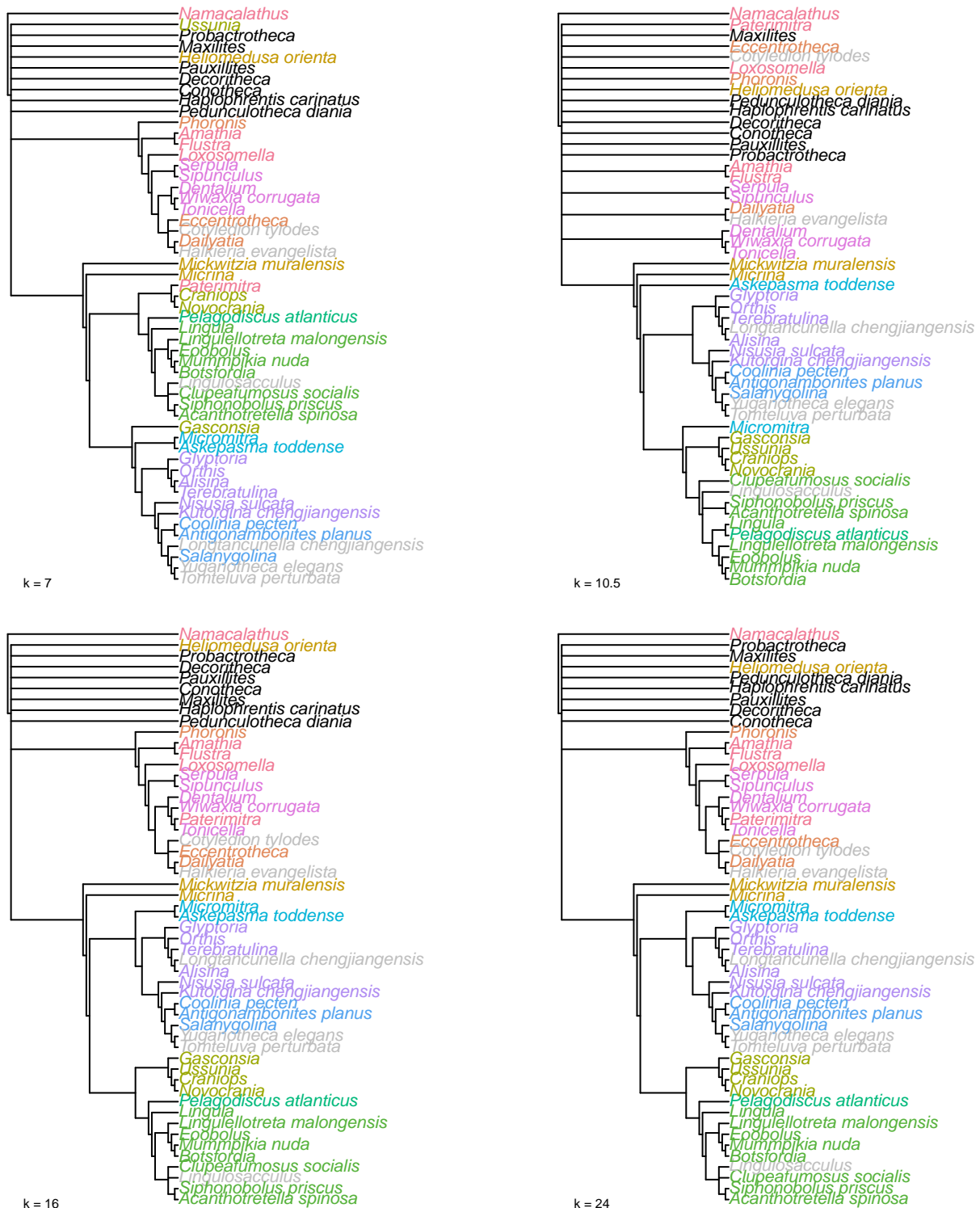


Figure 4.2: Strict consensus of all trees recovered by TNT using Fitch parsimony with implied weighting, at $k = 7, 10.5, 16$ and 24 .

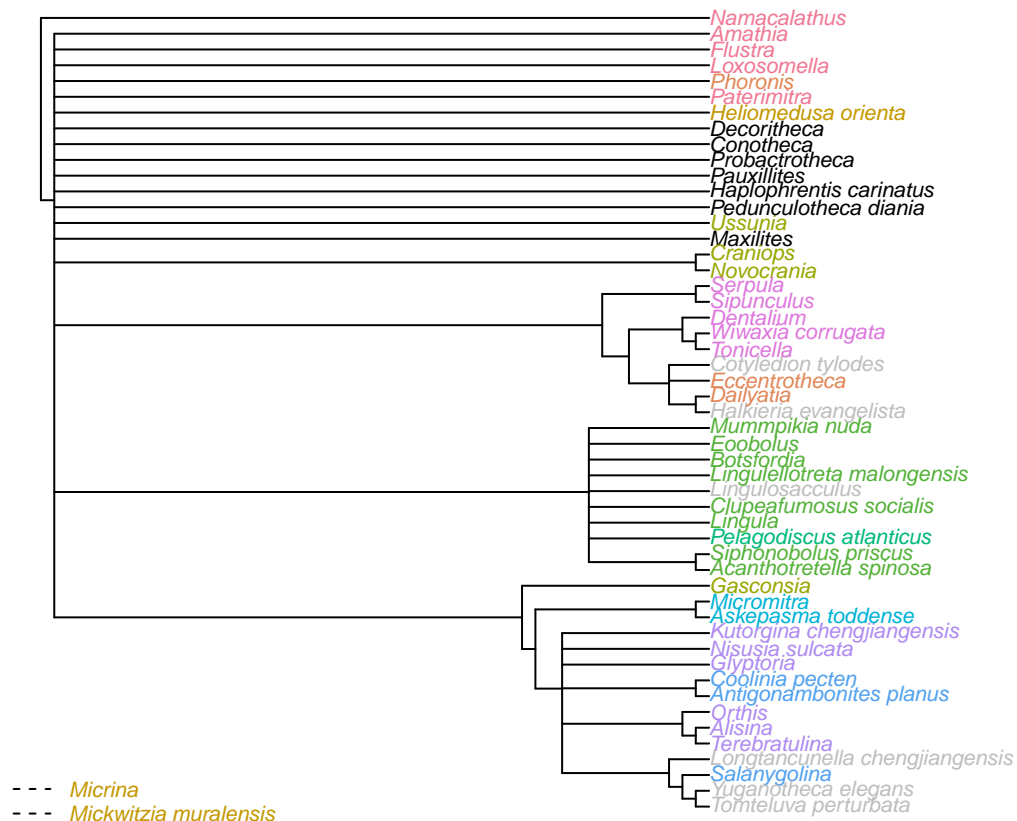


Figure 4.3: Consensus of all trees obtained using equally weighted Fitch parsimony in TNT. *Mickwitzia* and *Micrina* may equally parsimoniously be reconstructed in the basal region of the linguliform or rhynchonelliform lineages; as such, the inclusion of these taxa in the consensus tree reduces resolution. These taxa were still included in the analysis used to generate this tree, but were removed from each MPT before the consensus was calculated in order that the relationships that are present in each tree might be more easily observed.

Chapter 5

Bayesian analysis

Bayesian search was conducted in MrBayes v3.2.6 (Ronquist et al., 2012) using the Mk model (Lewis, 2001) with gamma-distributed rate variation across characters:

```
lset coding=variable rates=gamma;
```

Branch length was drawn from a dirichlet prior distribution, which is less informative than an exponential model (Rannala et al., 2012), but requires a prior mean tree length within about two orders of magnitude of the true value (Zhang et al., 2012). To satisfy this latter criterion, we specified the prior mean tree length to be equal to the length of the most parsimonious tree under equal weights, using a Dirichlet prior with $\alpha_T = 1$, $\beta_T = 1/(equal\ weights\ tree\ length/number\ of\ characters)$, $\alpha = c = 1$:

```
prset brlenspr = unconstrained: gammadir(1, 0.36, 1, 1);
```

Neomorphic and transformational characters (*sensu* Sereno, 2007) were allocated to two separate partitions whose proportion of invariant characters and gamma shape parameters were allowed to vary independently:

```
charset Neomorphic = 1 6 7 9 13 16 17 18 20 21 24 25 29 30 32 33 35 38 39 40 43 44 48 49 50 51  
52 53 54 55 56 60 61 63 64 66 68 69 70 71 73 75 78 79 80 82 83 85 86 87 88 91 92 93 94 95 96 97  
98 101 103 104 106 113 114 116 117 120 121 124 128 129 130 131 132 134 135 136 137 140 141  
142 143 145 146 147 148 149 150 152 155 160 161 163 164 165 166 167 168 169 171 176 177 178  
179 180 181 182 184 186 187 190 193 196 197 198 199 200 201 203 204 205 206 208 209 210 212  
213 214 215 217 220;
```

```
charset Transformational = 2 3 4 5 8 10 11 12 14 15 19 22 23 26 27 28 31 34 36 37 41 42 45 46  
47 57 58 59 62 65 67 72 74 76 77 81 84 89 90 99 100 102 105 107 108 109 110 111 112 115 118  
119 122 123 125 126 127 133 138 139 144 151 153 154 156 157 158 159 162 170 172 173 174 175  
183 185 188 189 191 192 194 195 202 207 211 216 218 219;
```

```
partition chartype = 2: Neomorphic, Transformational;
```

```
set partition = chartype;
```

```
unlink shape=(all) pinvar=(all);
```

Neomorphic characters were not assumed to have a symmetrical transition rate – that is, the probability of the absent \rightarrow present transition was allowed to differ from that of the present \rightarrow absent transition, being drawn from a uniform prior:

```
prset applyto=(1) symdirihyperpr=fixed(1.0);
```

The rate of variation in neomorphic characters was also allowed to vary from that of transformational characters:

```
prset applyto=(1) ratepr=variable;
```

Flustra was selected as an outgroup:

```
outgroup Flustra;
```

Four MrBayes runs were executed, each sampling eight chains for 5 000 000 generations, with samples taken every 500 generations. The first 10% of samples were discarded as burn-in.

```
mcmc ngen=5000000 samplefreq=500 nruns=4 nchains=8 burninfrac=0.1;
```

A posterior tree topology was derived from the combined posterior sample of all runs. Convergence was indicated by PSRF = 1.00 and an estimated sample size of > 200 for each parameter.

5.1 Parameter estimates

5.2 Results

Chapter 6

Taxonomic implications

This section briefly places key features of our results in the context of previous phylogenetic hypotheses.

Outgroup We advise caution in the interpretation of outgroup relationships. Outgroup taxa include single representatives of diverse and ancient phyla, and are thus prone to long branch error. The relationships of the lophotrochozoan phyla were not the primary object of this study, and have long resisted elucidation; this said, we have attempted to incorporate all morphological evidence that has been interpreted as informing relationships between these groups.

Brachiopod crown and stem group Crown- and stem-group terminology has great value in clarifying the early evolution of major lineages (Budd and Jensen, 2000; Carlson and Cohen, 2009). The crown group of a lineage is defined as the last common ancestor of all living members of a group, and all its descendants; the stem group as all taxa more closely related to the crown group than to any other extant taxon. In our analyses, the brachiopod crown group corresponds to the last common ancestor of *Terebratulina* and *Lingula*; the brachiopod stem group comprises anything between this node and the branching point of *Phoronis*.

Craniiforms Trimerellids are reconstructed as paraphyletic with respect to Craniiforms. This is consistent with the affinity commonly drawn between these groups (e.g. Williams et al., 2000), and helps to account for the stratigraphically late (Ordovician) appearance of Craniids in the fossil record. (Aragonite is underrepresented in early Palaeozoic strata due to taphonomic bias.)

The relationship of Craniiforms with respect to Linguliforms and Rhynchonelliforms remains unclear. Shell characters point to a relationship with the Rhynchonelliforms, which is countered by similarities between the spermatozoa of phoronids and terebratulids, which indicate a craniiform + linguliform clade.

It's worth noting that Bayesian and Fitch analyses place *Gasconsia* as the basalmost member of the Rhynchonellid lineage, upholding suggestions (Holmer et al., 2014) of a chileid rather than trimerellid affinity. This placement presumably represents an artefact resulting from the incorrect handling of inapplicable data. But if true, *Gasconsia* would be a close analogue for the common ancestor of Rhynchonelliforms + Craniiforms (+Linguliforms?).

Rhynchonelliforms The position of kutorginids within the rhynchonelliform stem lineage has been tricky to resolve (Holmer et al., 2018b); we resolve them as paraphyletic with respect to Rhynchonellata (which encompasses the obolellate *Alisina*), which is broadly in accord to previous proposals (Holmer et al., 2018a). Chileids form the adelphotaxon to this clade. *Longtancunella* (Zhang et al., 2011a) nests crownwards of the protorthid *Glyptoria*, but stemward of the obolellid *Alisina*.

Salanygolina has been interpreted as a stem-group rhynchonelliform based on its combination of paterinid and chileate features (Holmer et al., 2009). Our results position *Salanygolina* between paterinids and chileids, which directly corroborates this proposed phylogenetic position.

Basal rhynchonellids are characterized by a circular umbonal perforation in the ventral valve, associated with a colleplax. Partly on this basis, the aberrant taxa *Yuganotheca* and *Tomteluva* plot close to *Salanygolina*, the three often forming a clade – though the reliability of this grouping is perhaps liable to change as additional data comes to light. Nevertheless, an interpretation of *Yuganotheca* as a stem-group brachiopod (Zhang et al., 2014) is difficult to reconcile with the increasingly well-constrained nature of the early brachiopod body plan.

Linguliforms The reconstruction of Linguloformea comprising Linguloidea as sister to Discinoidea is as expected, though it is notable that Acrotretids and Siphonotretids plot more closely to Linguloidea than Discinoidea does.

Lingulellotretids also sit within this lingulid grouping; a position in the phoronid stem lineage (advocated by Balthasar and Butterfield, 2009) is not upheld.

More novel is the reconstruction of the calcitic obolellid *Mummpikia* in the linguliform total group: a rhynchonelliform affinity has been assumed based on its calcitic mineralogy. This said, Balthasar (2008) has highlighted the similarities between obolellids and linguliform brachiopods, including sub-vertical canals and the detailed configuration of the posterior shell margin. Our analysis upholds the case for a linguliform affinity for *Mummpikia*; a calcitic shell seemingly arose through an independent change within this taxon. As such, *Mummpikia* has no direct bearing on the origin of ‘Calciata’, save that shell mineralogy is perhaps less static than commonly assumed.

More generally, our results identify Class Obolellata as polyphyletic: *Alisina* (Trematobolidae) plots within Rhynchonellata; *Tomteluva* is harder to place, but tends to group with *Salanygolina* stemwards of the chileids.

Paterinids Paterinids have traditionally been placed within the Linguliforms on the basis of their phosphatic shell (Williams et al., 2007), which our analysis identifies as ancestral within the brachiopod crown group; our analysis places them within the Rhynchonelliforms instead. Characters supporting this position include the strophic hinge line, planar cardinal area, the absence of a pedicle nerve impression, and the morphology of the mantle canals.

More generally, although some lingulids can be found which share more generic characters (e.g. shell growth direction) with paterinids, the particular combination of characters exhibited in paterinids does not occur anywhere in the linguliform lineage, but is more similar to that of basal rhynchonelliforms, particularly *Salanygolina*.

Tommotiids Tommotiids represent a basal grade, paraphyletic to phoronids and crown-group brachiopods, in line with previous interpretations.

Micrina and *Mickwitzia* are the most crownwards of the tommotiids, but beyond this, their position is somewhat difficult to pin down; certain analytical configurations reconstruct them as stem-brachiopods; others place them closer to the discinids, the lingulids or the craniiforms. *Heliomedusa* is commonly associated closely with *Mickwitzia*, reflecting the similarities emphasized by Holmer and Popov in Williams et al. (2007), but plots instead within the Craniiforms under certain analytical conditions, in line with earlier interpretations (Williams et al., 2000).

Hyoliths Hyoliths are interpreted as stem-group Brachiopods, which refines the broader phylogenetic position proposed by Moysiuk et al. (2017). This is to say, they sit closer to brachiopods than the phoronids do, but no analysis places them within the Brachiopod crown group.

Hyoliths thus represent derived tommotiids, and are the closest relatives to the Brachiopod crown group.

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