

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 45 early brachiozoan taxa, including hyoliths, tommotiids and mickwitzziids, which were coded for 206 morphological characters (128 neomorphic, 78 transformational).

Namacalathus was incorporated as a 46th 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 9476 character codings, of which 775 are inapplicable and 3929 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 206 characters, the number that were coded with an applicable token for each taxon is:

<u>_Cotyledion tylodes_</u>	59 ;	<u>_Alisina_</u>	79 ;	<u>_Longtancunella chengjiangensis_</u>
<u>_Loxosomella_</u>	154 ;	<u>_Askepasma toddense_</u>	68 ;	<u>_Micrina_</u>
<u>_Flustra_</u>	156 ;	<u>_Antigonambonites planus_</u>	75 ;	<u>_Micromitra_</u>
<u>_Novocrania_</u>	174 ;	<u>_Botsfordia_</u>	67 ;	<u>_Mickwitzia muralensis_</u>
<u>_Lingula_</u>	185 ;	<u>_Clupeafumosus socialis_</u>	69 ;	<u>_Mummpikia nuda_</u>
<u>_Phoronis_</u>	145 ;	<u>_Coolinia pecten_</u>	71 ;	<u>_Nisusia sulcata_</u>
<u>_Sipunculus_</u>	158 ;	<u>_Craniops_</u>	59 ;	<u>_Orthis_</u>
<u>_Serpula_</u>	159 ;	<u>_Eccentrotheca_</u>	41 ;	<u>_Paterimitra_</u>
<u>_Tonicella_</u>	173 ;	<u>_Eoobolus_</u>	73 ;	<u>_Pedunculotheca diania_</u>
<u>_Dentalium_</u>	157 ;	<u>_Glyptoria_</u>	68 ;	<u>_Salanygolina_</u>
<u>_Pelagodiscus atlanticus_</u>	137 ;	<u>_Gasconsia_</u>	63 ;	<u>_Siphonobolus priscus_</u>
<u>_Terebratulina_</u>	141 ;	<u>_Haplophrentis carinatus_</u>	68 ;	<u>_Ussunia_</u>
<u>_Wiwaxia corrugata_</u>	65 ;	<u>_Heliomedusa orienta_</u>	61 ;	<u>_Tomteluva perturbata_</u>
<u>_Halkieria evangelista_</u>	57 ;	<u>_Kutorgina chengjiangensis_</u>	77 ;	<u>_Yuganotheca elegans_</u>
<u>_Dailyatia_</u>	42 ;	<u>_Lingulosacculus_</u>	53 ;	
<u>_Acanthotretella spinosa_</u>	63 ;	<u>_Lingulellotreta malongensis_</u>	74 ;	

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_6-1-2018_715.nex.

Chapter 2

Parsimony analysis

The phylogenetic dataset contains a considerable proportion of inapplicable codings ($775/9476 = 8.2\%$ 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$Namacalathus <- NULL # Exclude Namacalathus
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

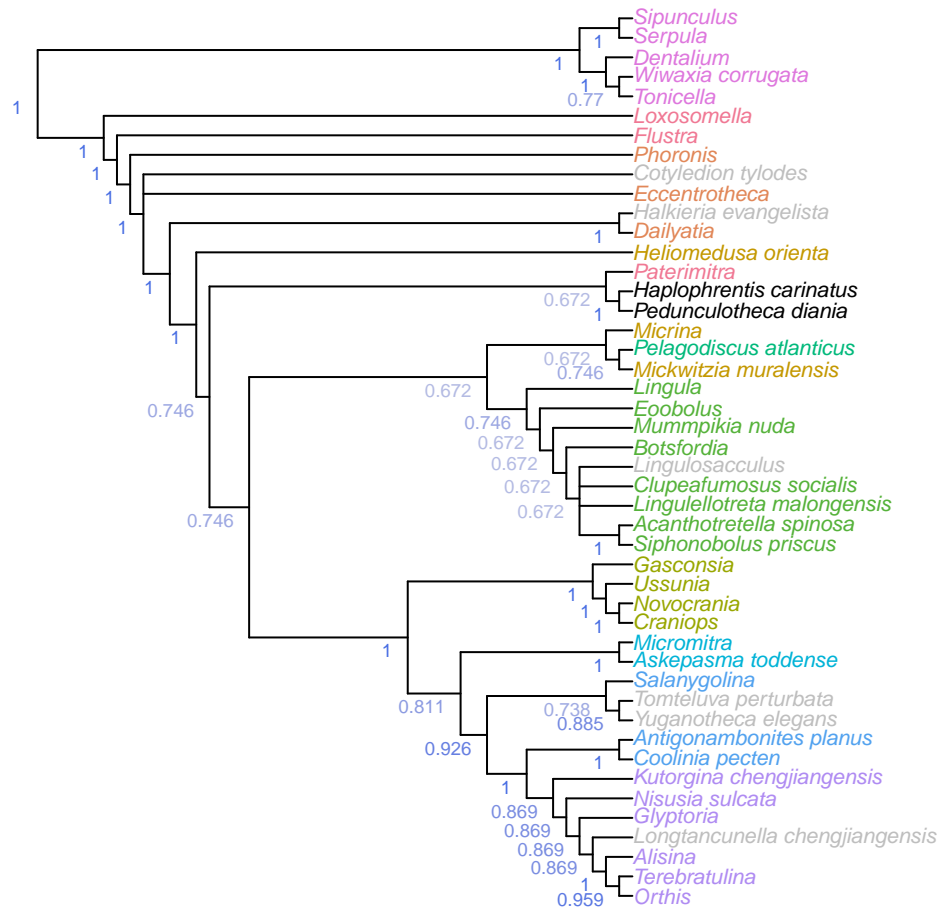


Figure 2.1: Consensus of all parsimony results. Node labels denote the proportion of trees obtained under all analytical conditions that support the clade.

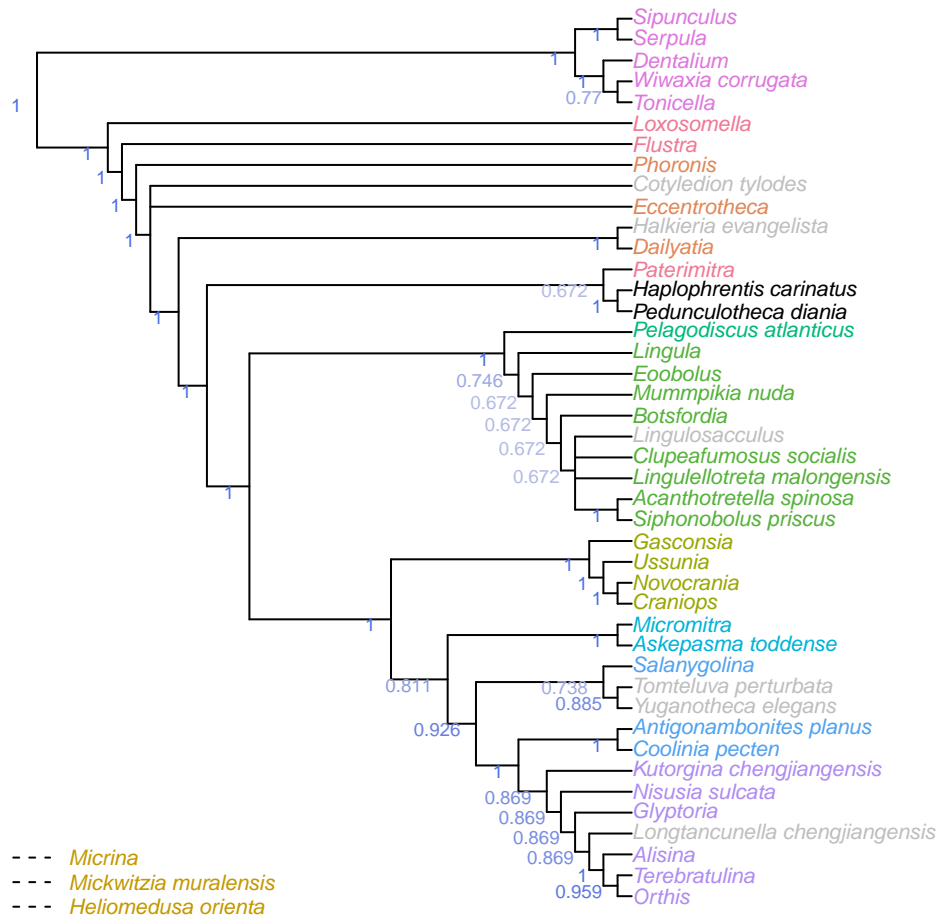


Figure 2.2: Consensus of all parsimony results, with taxa omitted to show underlying clade support. Node labels denote the proportion of trees obtained under all analytical conditions that support the clade.

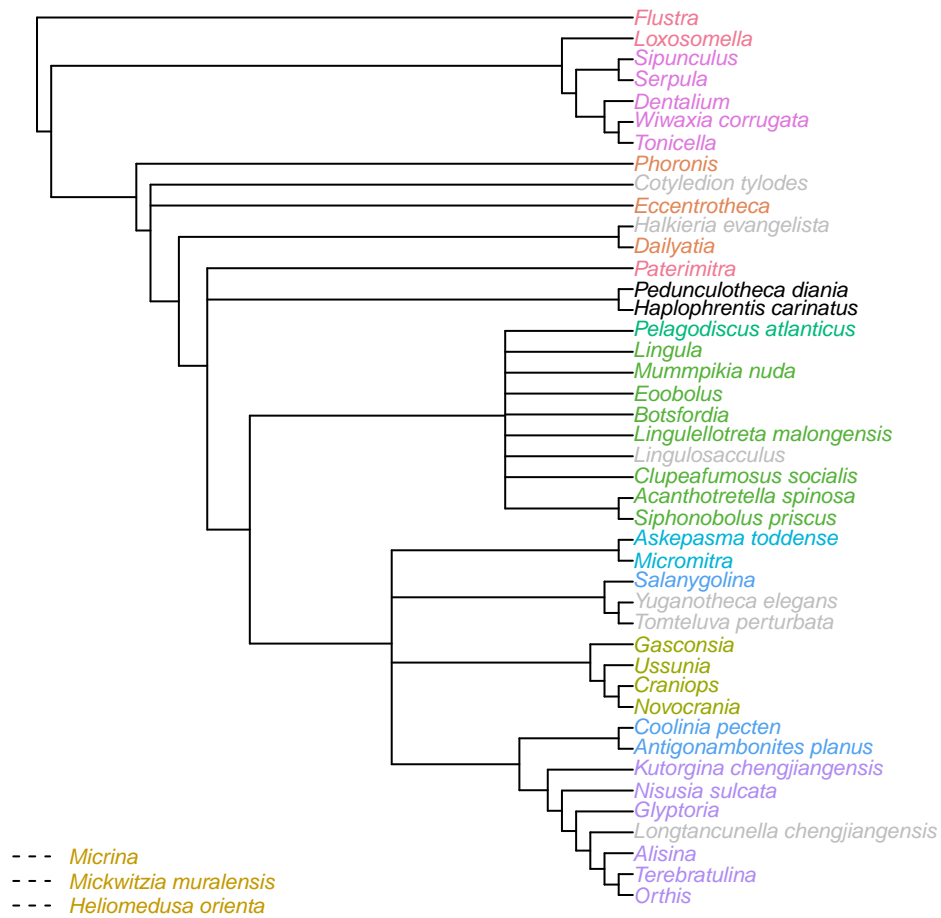


Figure 2.3: Strict consensus of implied weights analyses at all values of k . Wildcard taxa have been excluded from the consensus tree shown above to improve resolution.

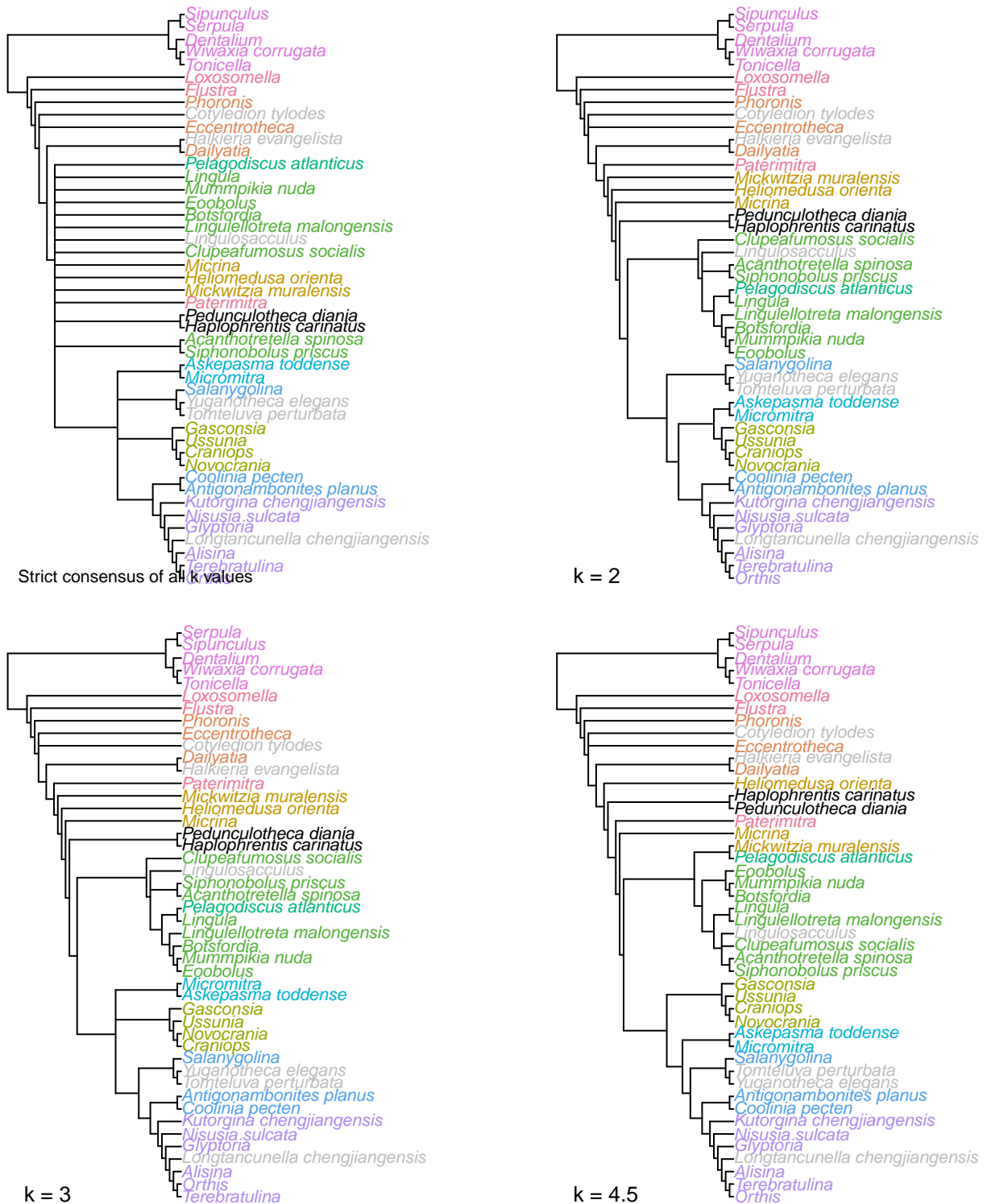
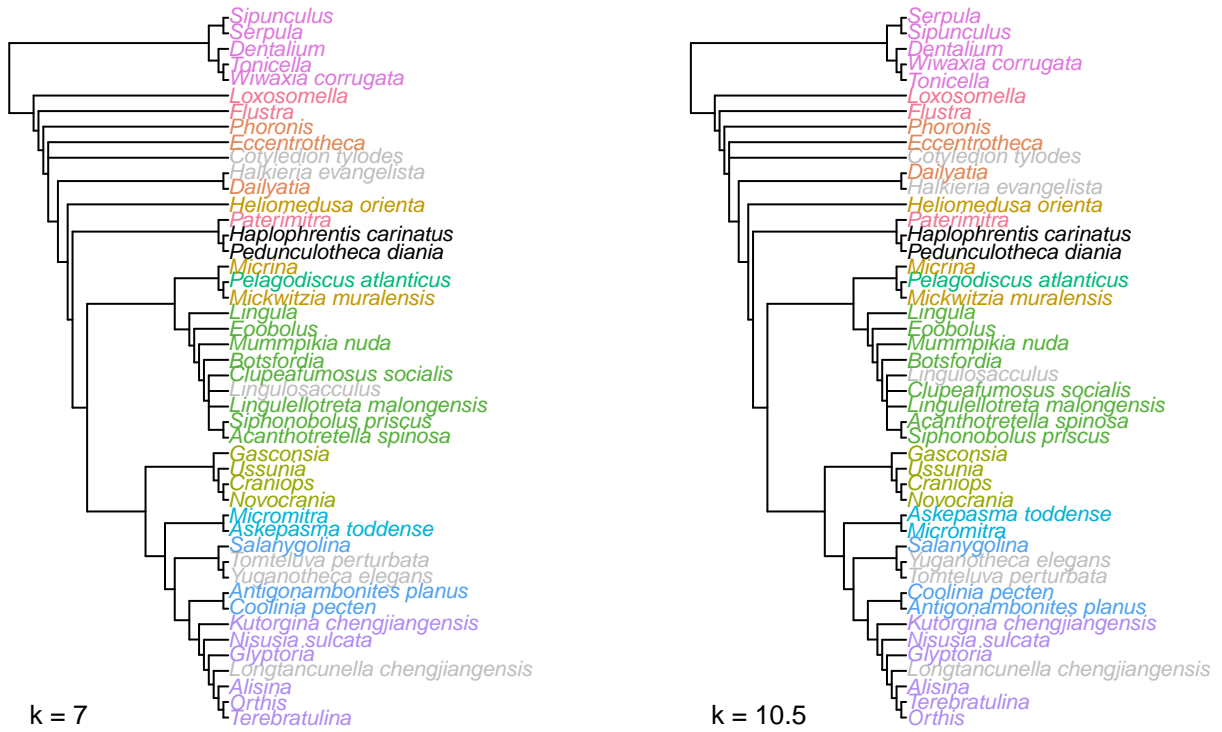


Figure 2.4: Consensus trees of implied weights analyses at all values of k , and at the individual values $k = 2, 3$ and 4.5 .

Figure 2.5: Consensus trees of implied weights analyses at $k = 7, 10.5, 16$ and 24 .

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

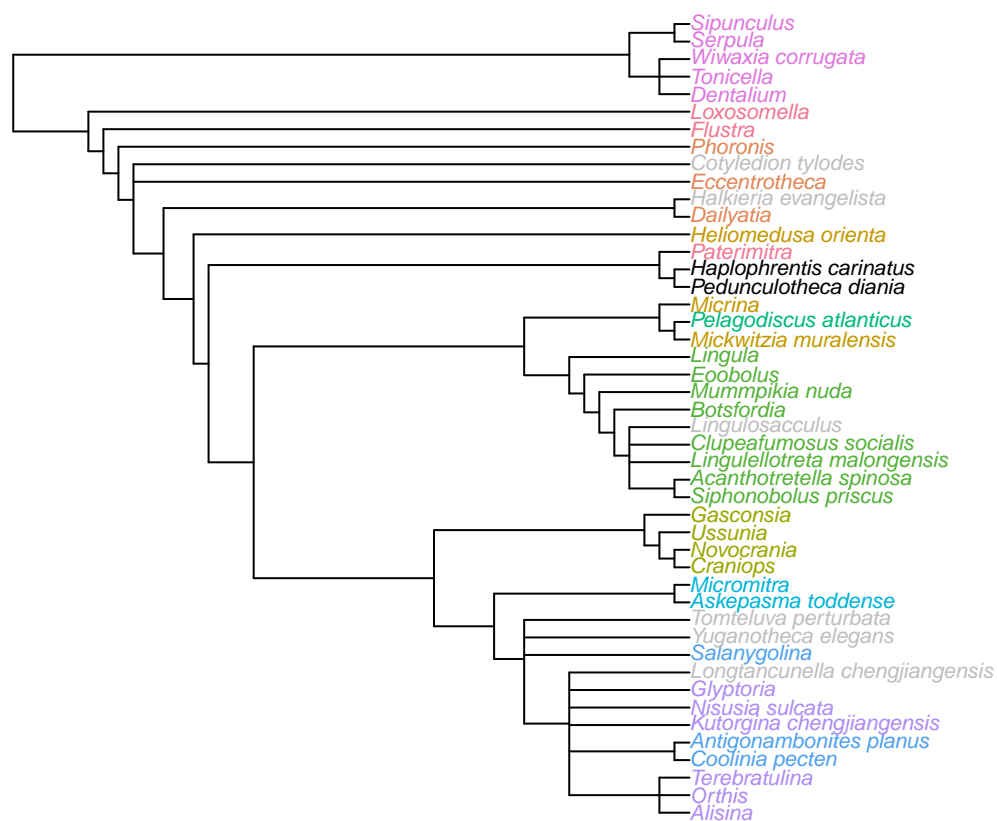


Figure 2.6: Strict consensus of most parsimonious trees under equally weighted parsimony

Chapter 3

Character reconstructions

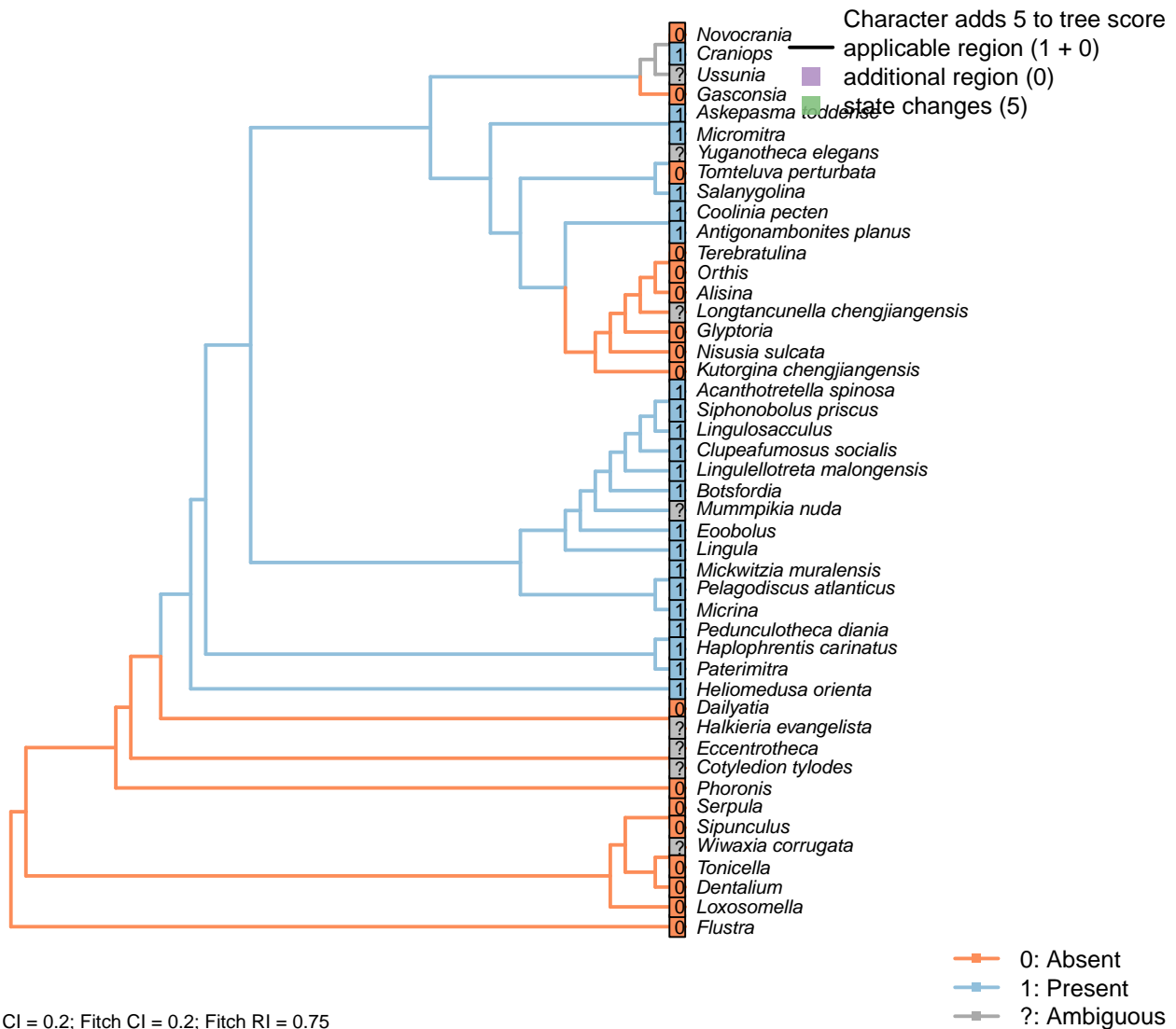
This page provides definitions for each of the characters in our matrix, and justifies codings in particular taxa where relevant. Further citations for codings that are not discussed in the text can be viewed by browsing the morphological dataset on MorphoBank (project 2800). This link will become live 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.

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

Dentalium: 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).

Loxosomella: 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.

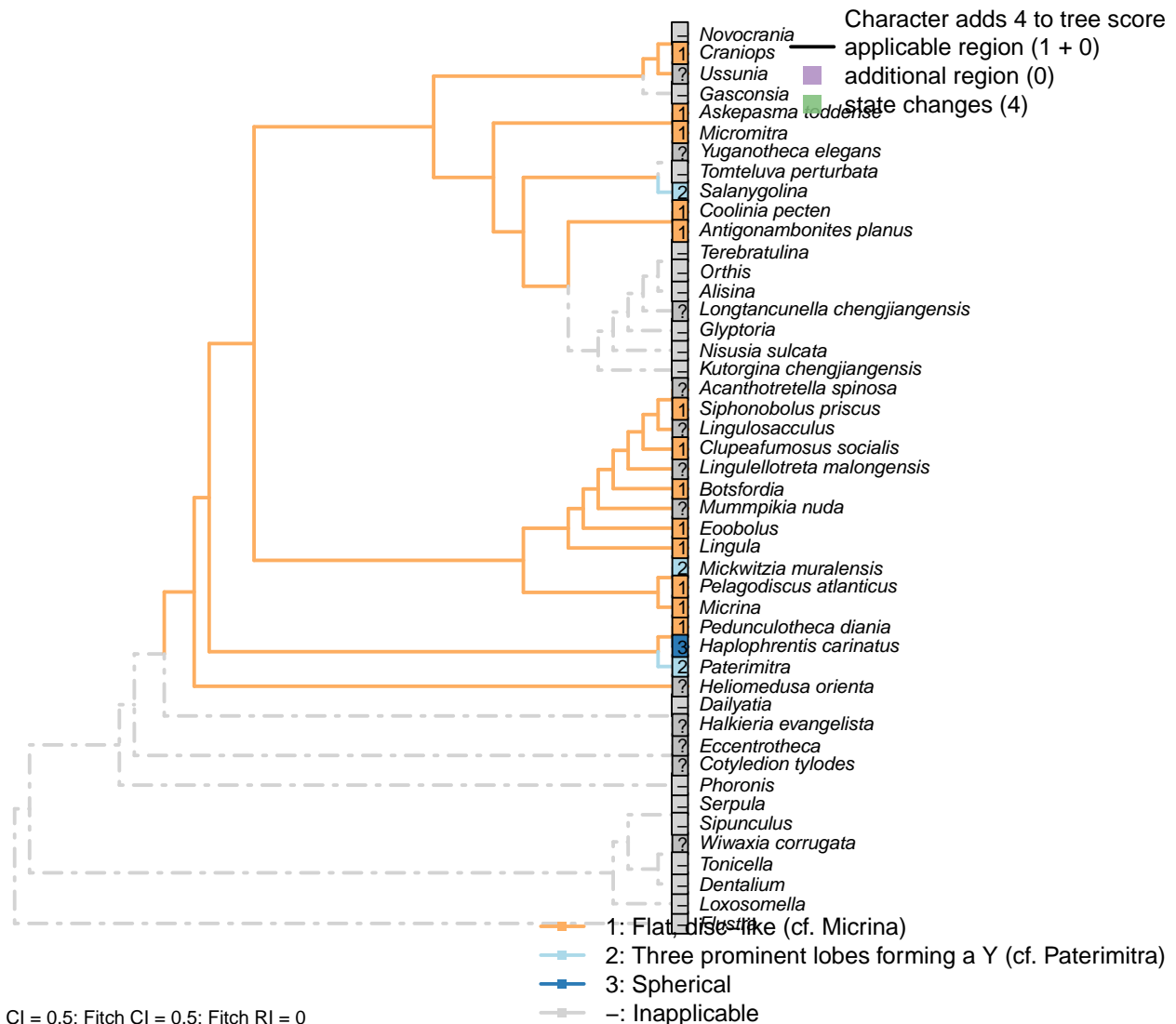
Novocrania: Shell not secreted until after metamorphosis (Popov et al., 2010).

Tonicella: 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).

[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.

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

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

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

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

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

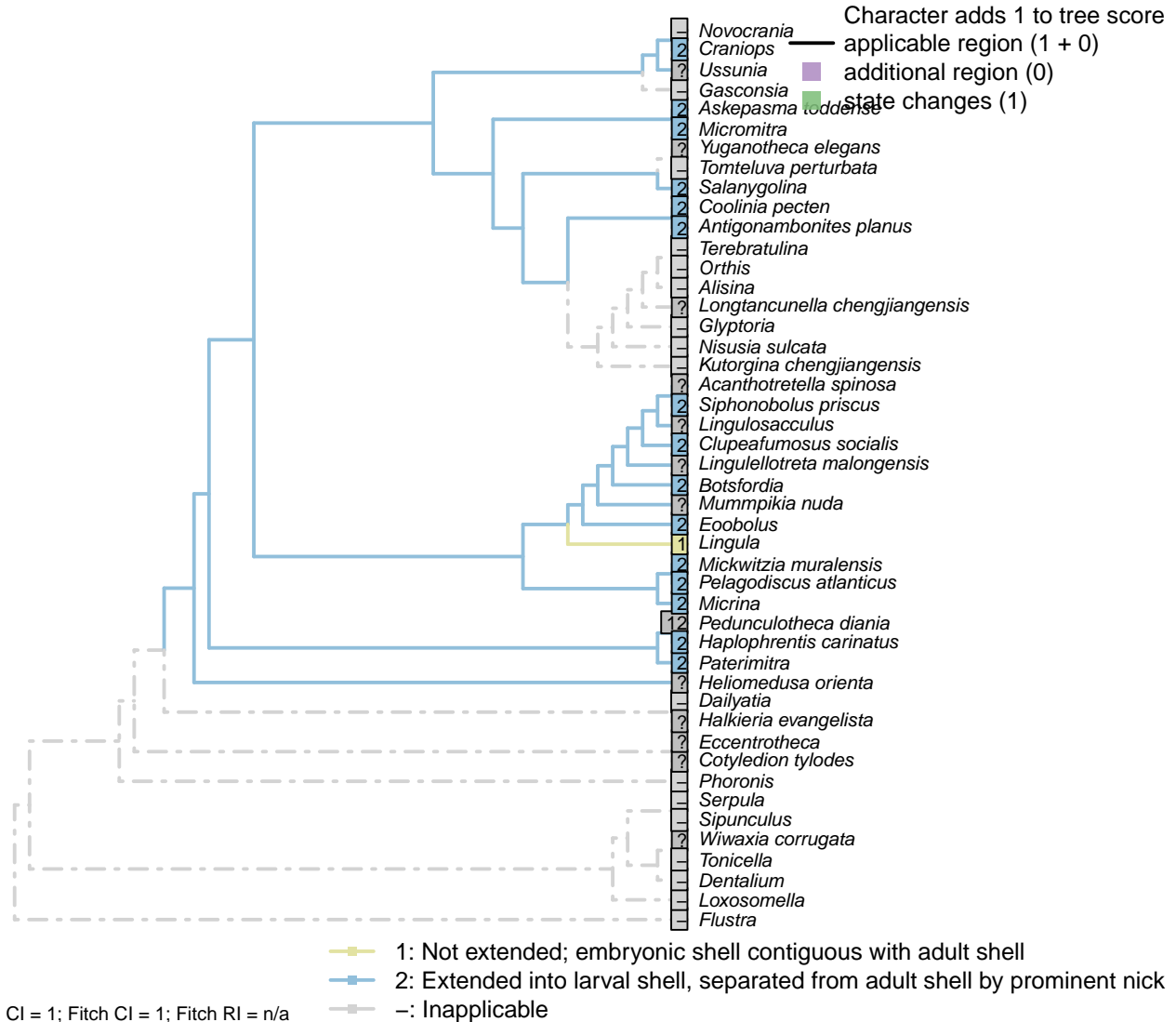
Mickwitzia muralensis: Trifoliate appearance results from prominent attachment rudiment and bunching of setal sacs (Balthasar, 2009).

Micromitra: Subtriangular – essentially round.

Pelagodiscus atlanticus: See e.g. fig 169 in Williams *et al.* (1997).

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

[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).

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

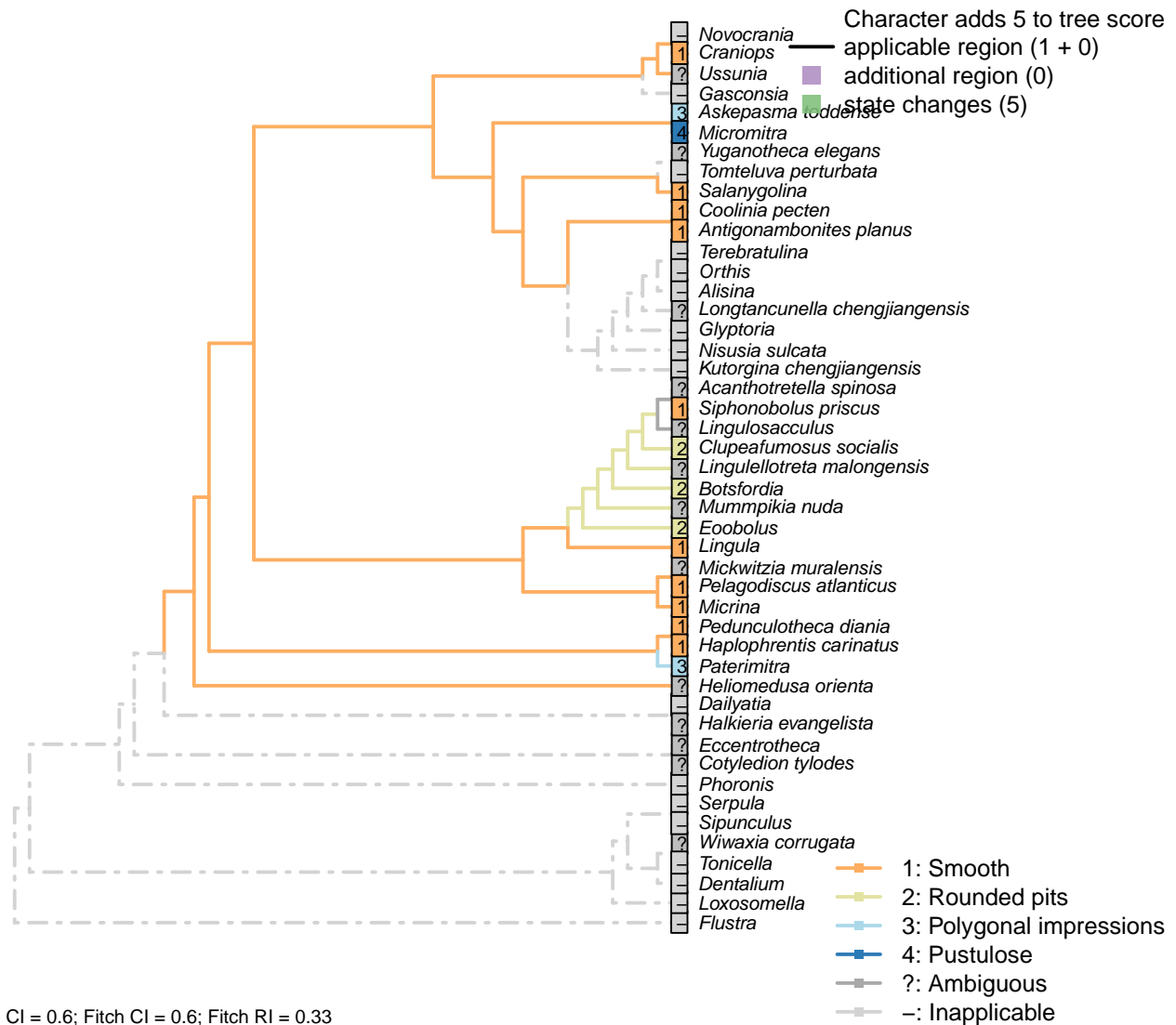
Craniops: Prominent nick; see Freeman and Lundelius (1999), fig. 6A.

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

Pedunculotheca diania: 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.

Tonicella: Wanninger and Haszprunar (2002a).

[4] Surface ornament



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

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

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

Lingula, *Pelagodiscus atlanticus*: Smooth, following family-level codings of Williams *et al.* (2000), table 6.

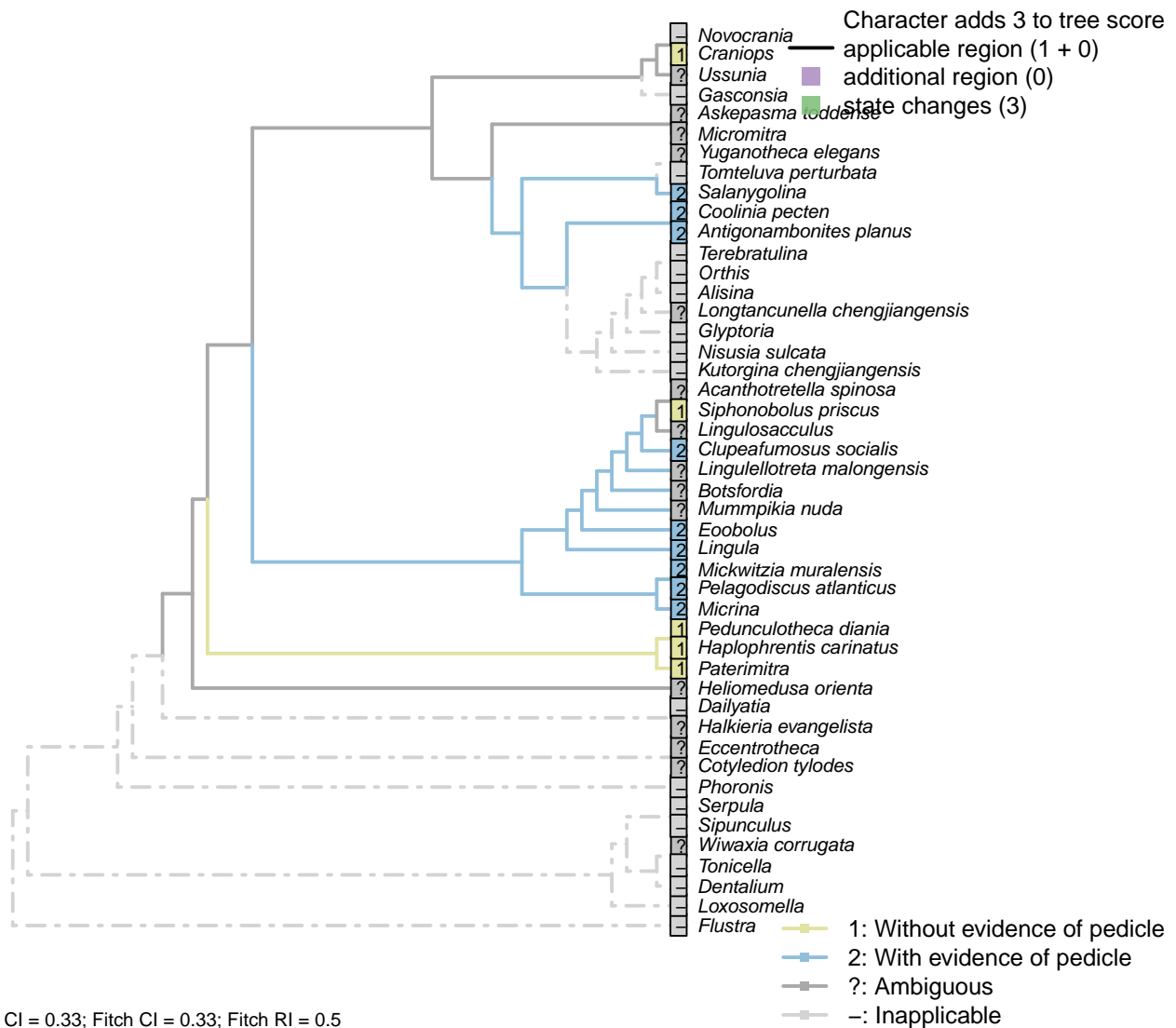
Micrina: Smooth (Holmer *et al.*, 2011).

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

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

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

[5] Larval attachment structure



Character 5: Brephic shell: Larval attachment structure

1: Without evidence of pedicle

2: With evidence of pedicle

Transformational character.

Embryonic shells of *Micrina* and certain linguliforms exhibit a transversely folded posterior extension that speaks of the original presence of a pedicle in the embryo.

This is independent of the presence of an adult pedicle, which may arise after metamorphosis.

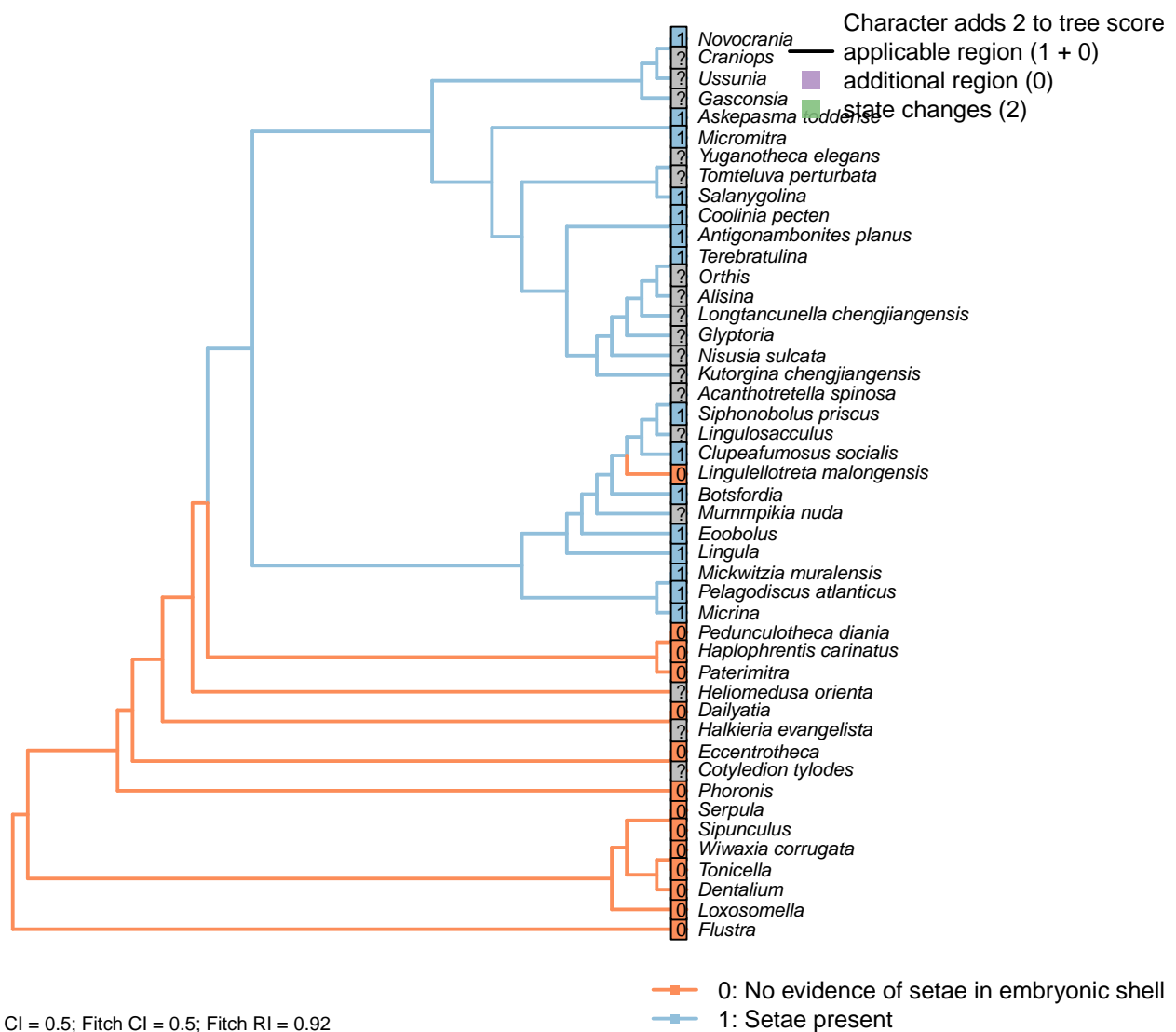
Clupeafumosus socialis: The larval shell embraces the pedicle foramen, suggesting a larval attachment. See fig. 4 of Topper *et al.* (2013a).

Eoobolus: Lobe related to the attachment rudiment (Balthasar, 2009, fig. 2).

Mickwitzia muralensis: Note the posterior lobe related to the attachment rudiment in fig. 2 of Balthasar (2009).

Siphonobolus priscus: 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).

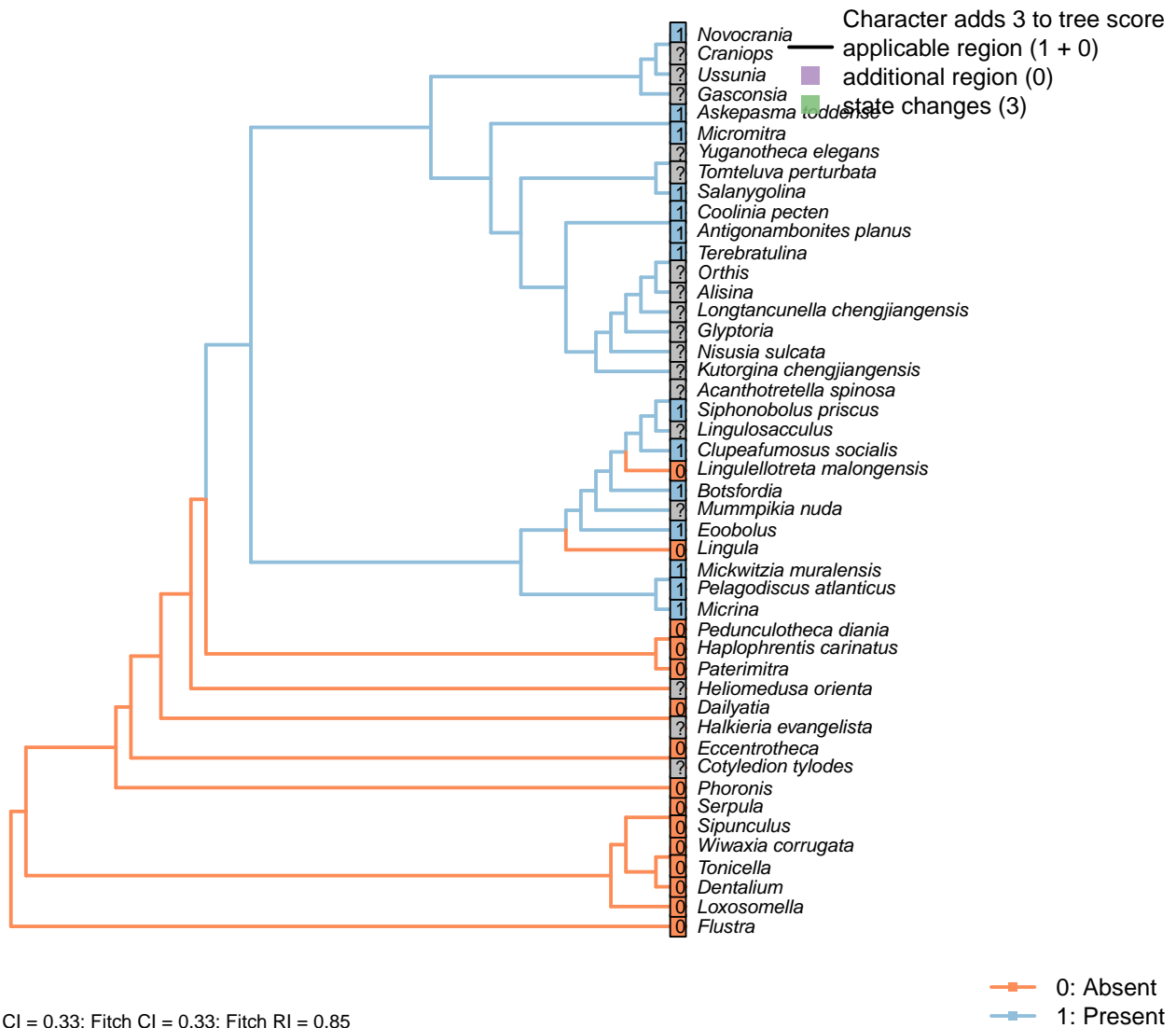
Botsfordia: “One specimen shows fine capillae running laterally from the posterior tubercles on the dorsal valve (Pl. 3, fig. 5b). This is possibly the imprints of setae.” – Ushatinskaya and Korovnikov (2016).

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

Lingulellotreta malongensis: Familial character: larval shell smooth (Williams *et al.*, 2000, p.72).

Mickwitzia muralensis: Four setal sacs.

3.2 Brephic shell: Setal sacs [7]



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).

Botsfordia: 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.

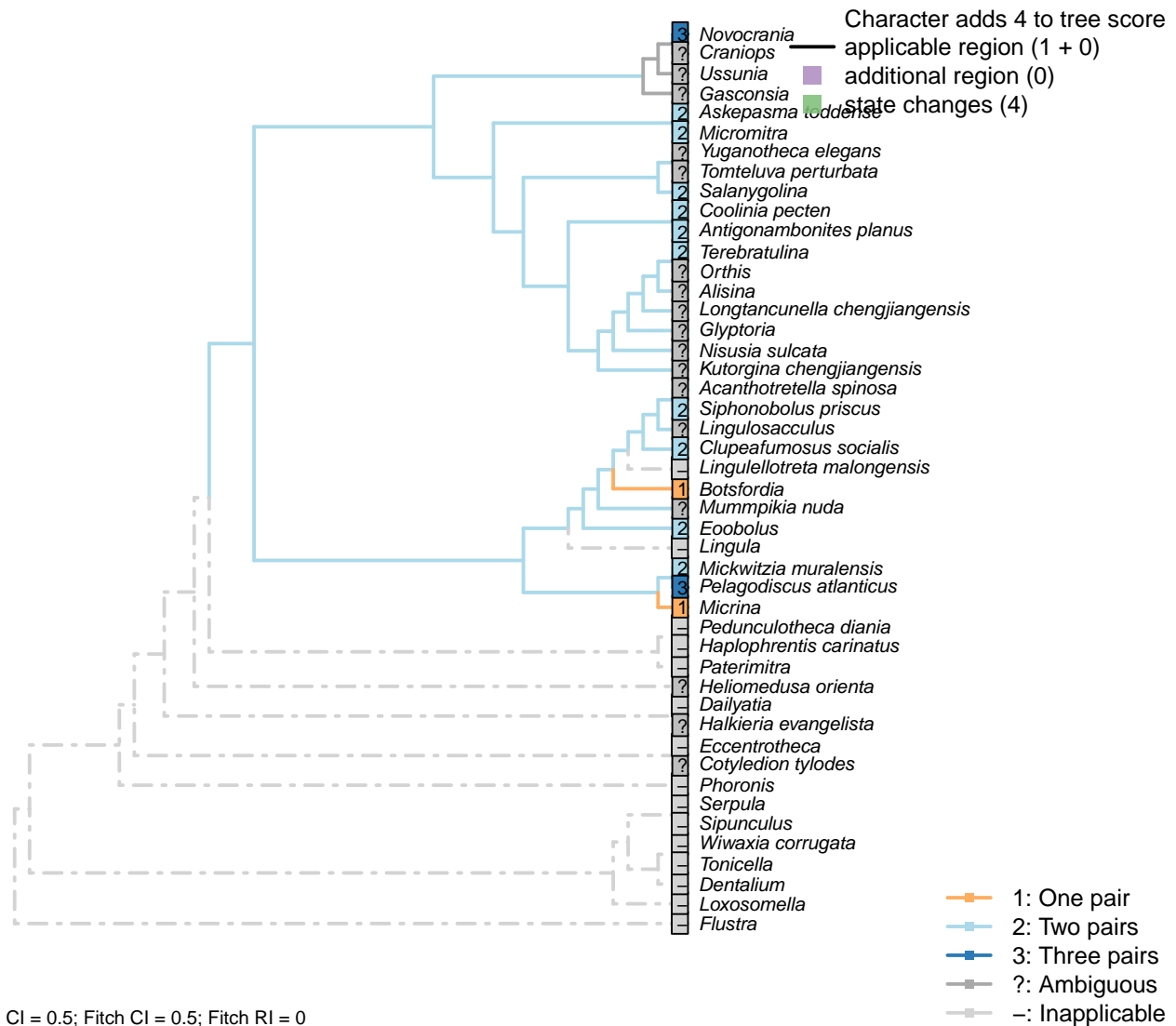
Clupeafumosus socialis: Setal bundles interpreted as present in acrotretids by Ushatinskaya (2016).

Lingula: Lingulids’ larval setae are not arranged in bundles (Carlson, 1995).

Lingulellotreta malongensis: Familial character: larval shell smooth (williams *et al.*, 2000, p.72).

Novocrania, *Pelagodiscus atlanticus*: Three pairs (Carlson, 1995).

[8] Number

**Character 8: Brephic shell: Setal sacs: Number**

- 1: One pair
- 2: Two pairs
- 3: Three pairs

Transformational character.

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

Botsfordia: “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.

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

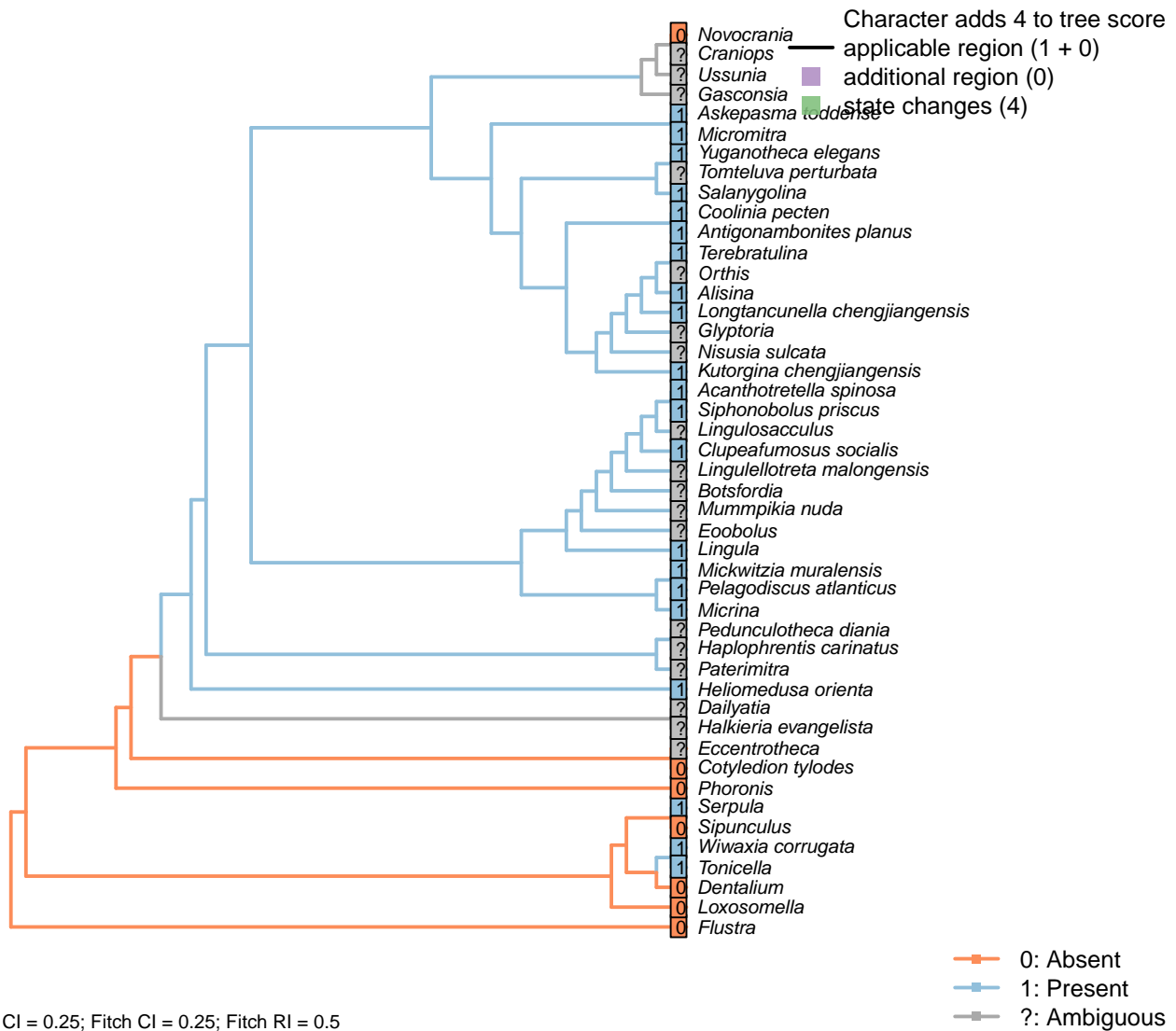
Mickwitzia muralensis: See fig. 2 in Balthasar (2009).

Novocrania, *Pelagodiscus atlanticus*: Three pairs (Carlson, 1995).

Siphonobolus priscus: 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: 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).

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

Flustra: The teeth of the Bryozoan gizzard have been homologized with annelid setae (Gordon, 1975), but a gizzard is not present in all bryozoan species and has not been reported in *Flustra*.

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

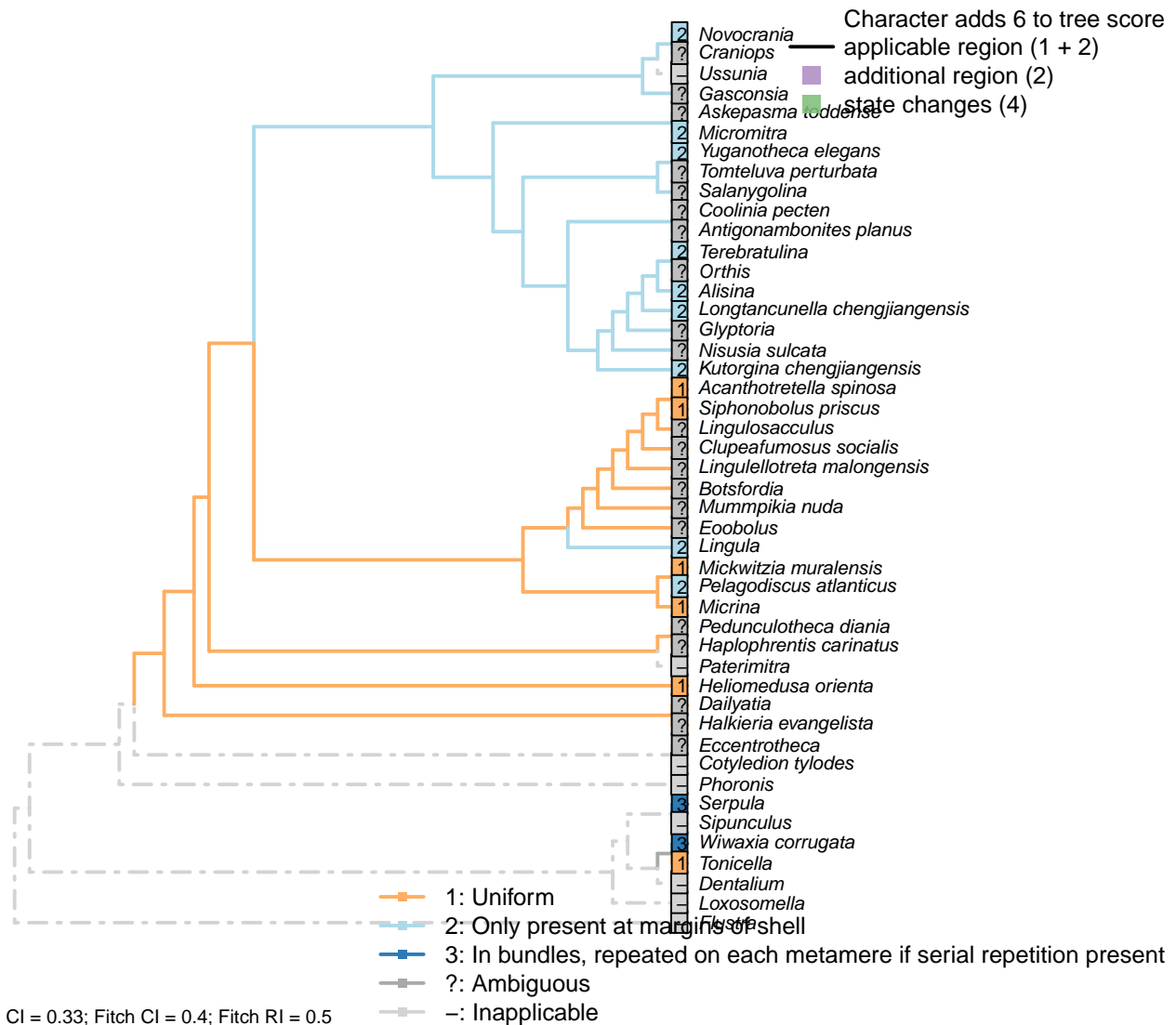
Siphonobolus priscus: Phosphatised setae emerge from hollow spines (Popov et al., 2009).

Sipunculus: The absence of chitin or microvillar lineations in sipunculan hooks argues against their interpretation as setae.

Tonicella: 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.

Wiwaxia corrugata: Sclerites likely correspond with lophotrochozoan setae (Butterfield, 1990; Smith, 2014; Zhang et al., 2015).

[10] Distribution

**Character 10: Setae: Distribution**

- 1: Uniform
 - 2: Only present at margins of shell
 - 3: In bundles, repeated on each metamere if serial repetition present
- Transformational character.

Setae penetrate the valves of many brachiopods. In certain taxa, they are apparent only at the margins of the valves, in association with the commissure, being reduced or lost over the surface of the shell.

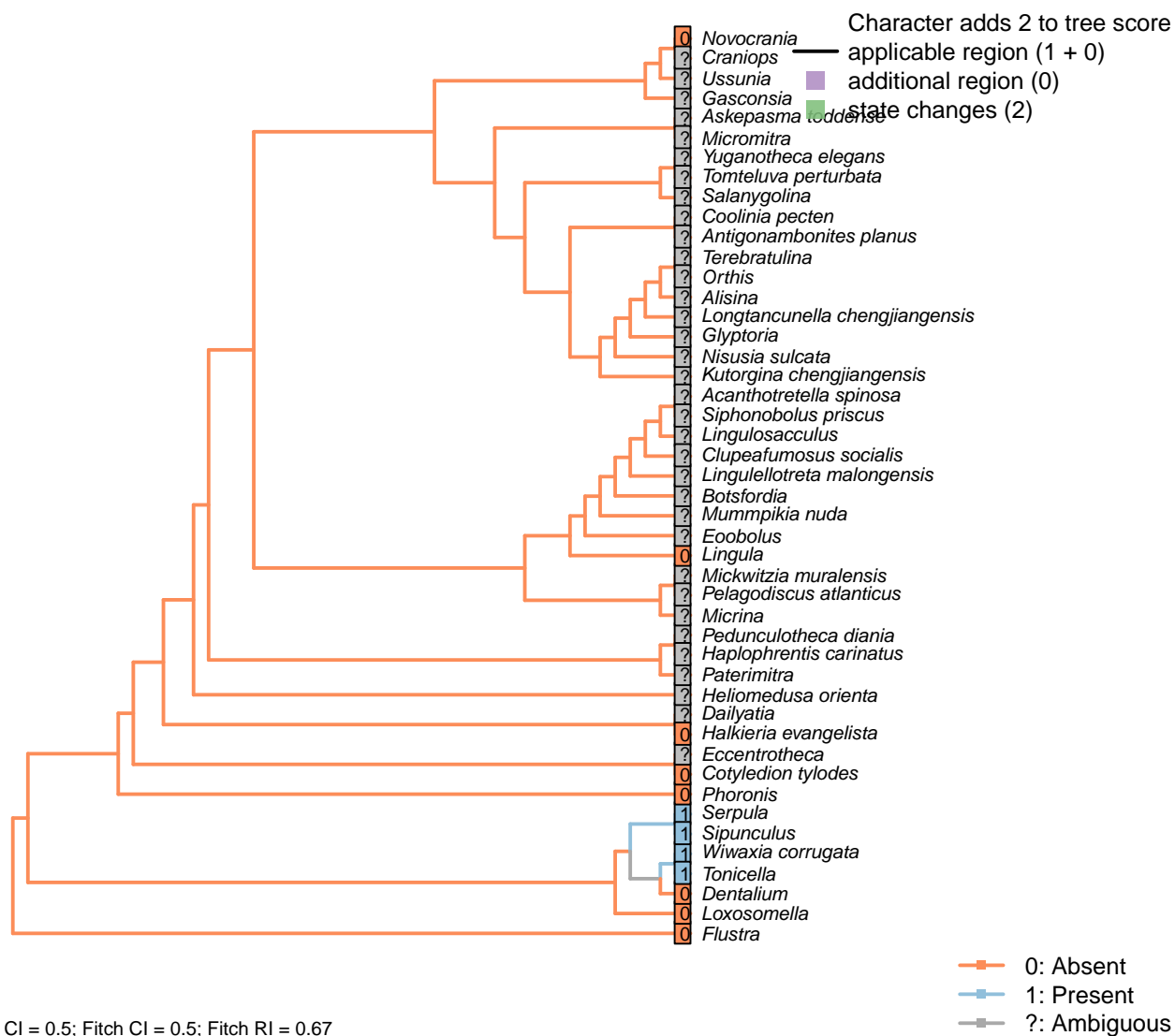
Eccentrotheca: Skovsted *et al.* (2011) assumed the setae may have been present along the margin of the adapical opening, but there is no fossil evidence.

Heliomedusa orienta: Throughout the shell – see Williams *et al.* (2007) – causing the pustulose appearance remarked upon by Chen *et al.* (2007).

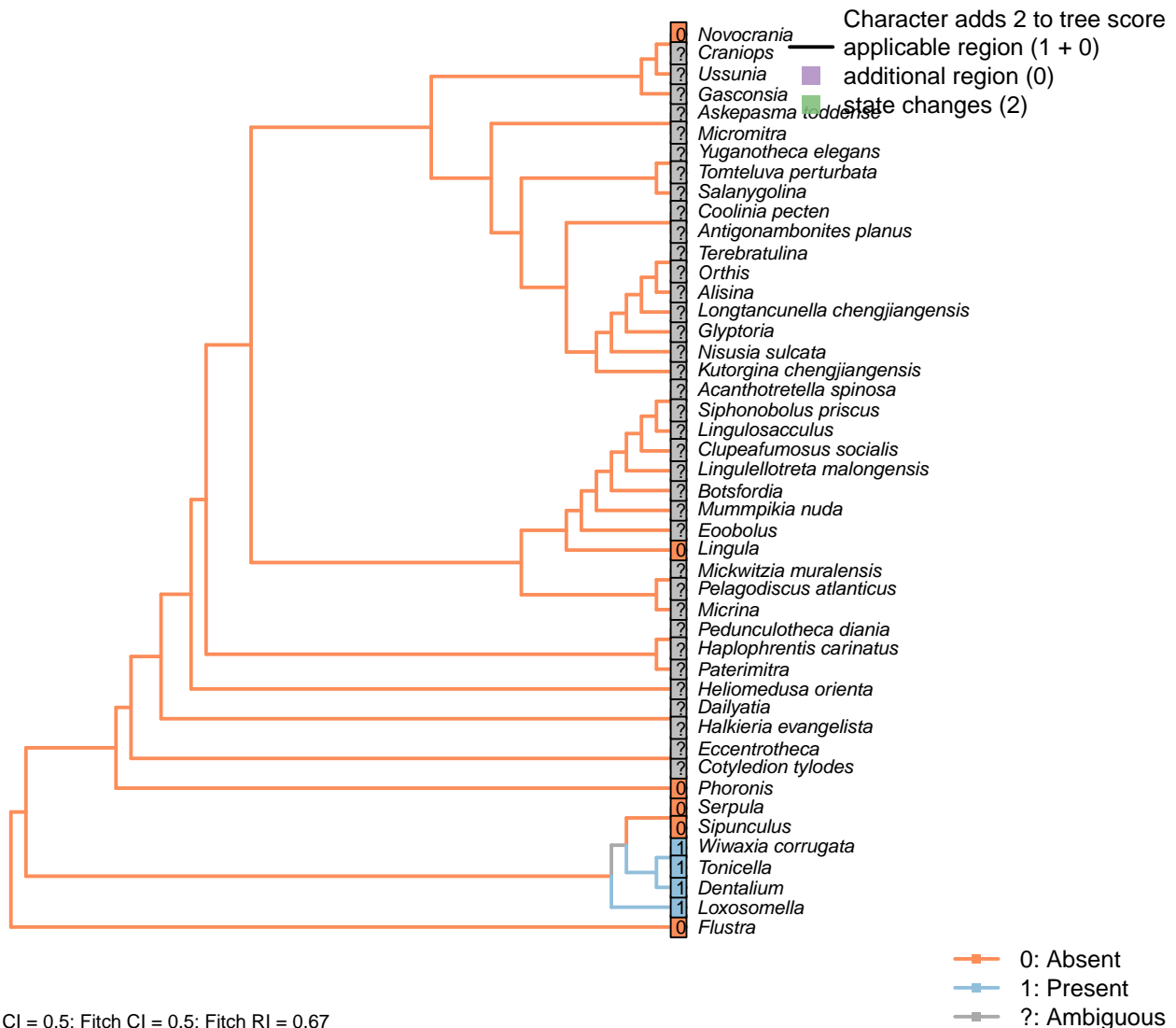
Tonicella: Uniformly distributed around girdle (though not within shell) with no serial repetition (?Leise, 1988).

3.4 Body organization

[11] Serial repetition



[12] Foot

**Character 12: 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.

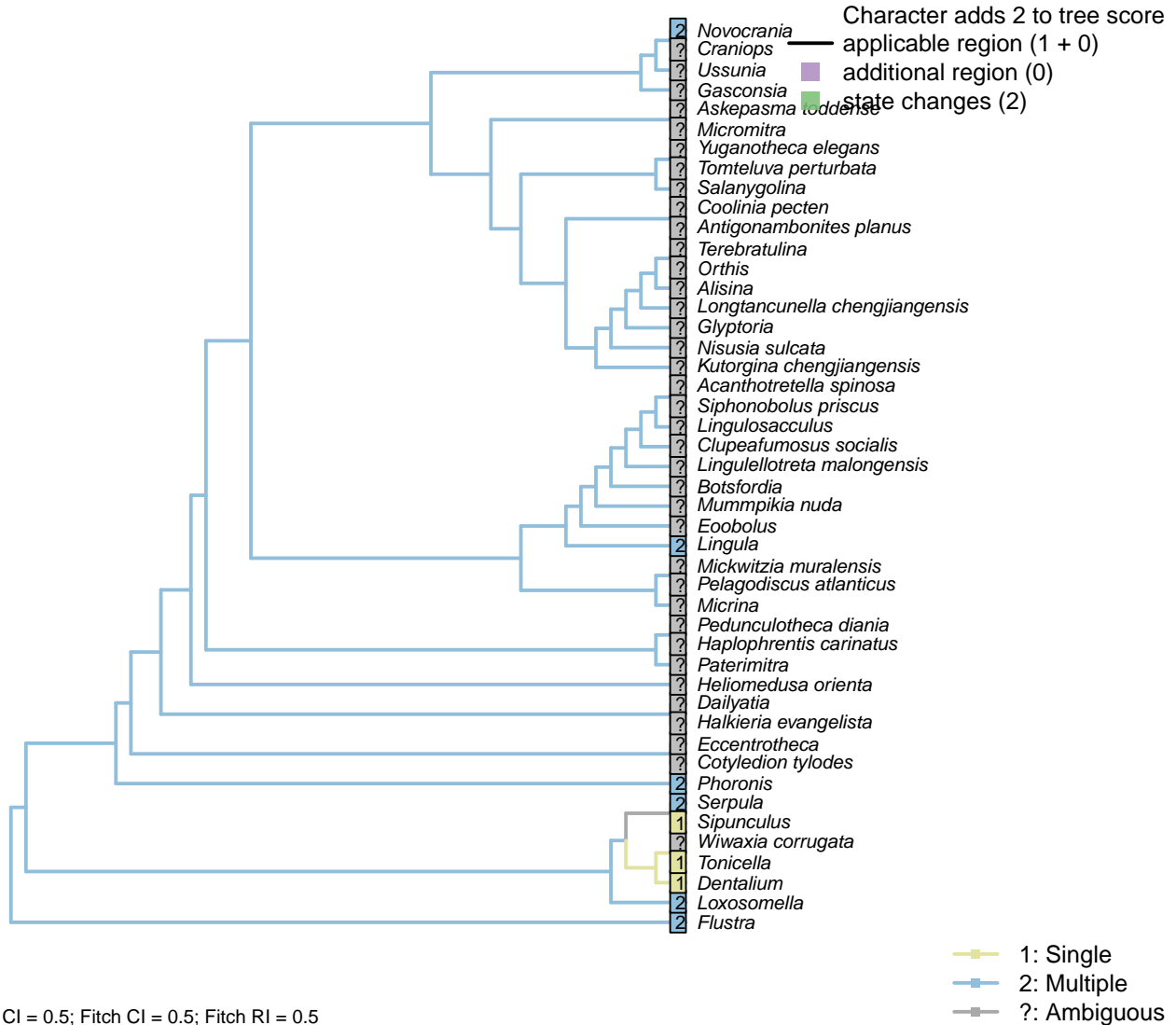
Cotyledion tylodes: The stalk may conceivably be homologous with the entoproct foot, but the evidence for homology is weak.

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

Loxosomella: See Haszprunar and Wanninger (2008).

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

[13] Number

**Character 13: Body organization: Coelomoducts: Number**

1: Single

2: Multiple

Transformational character.

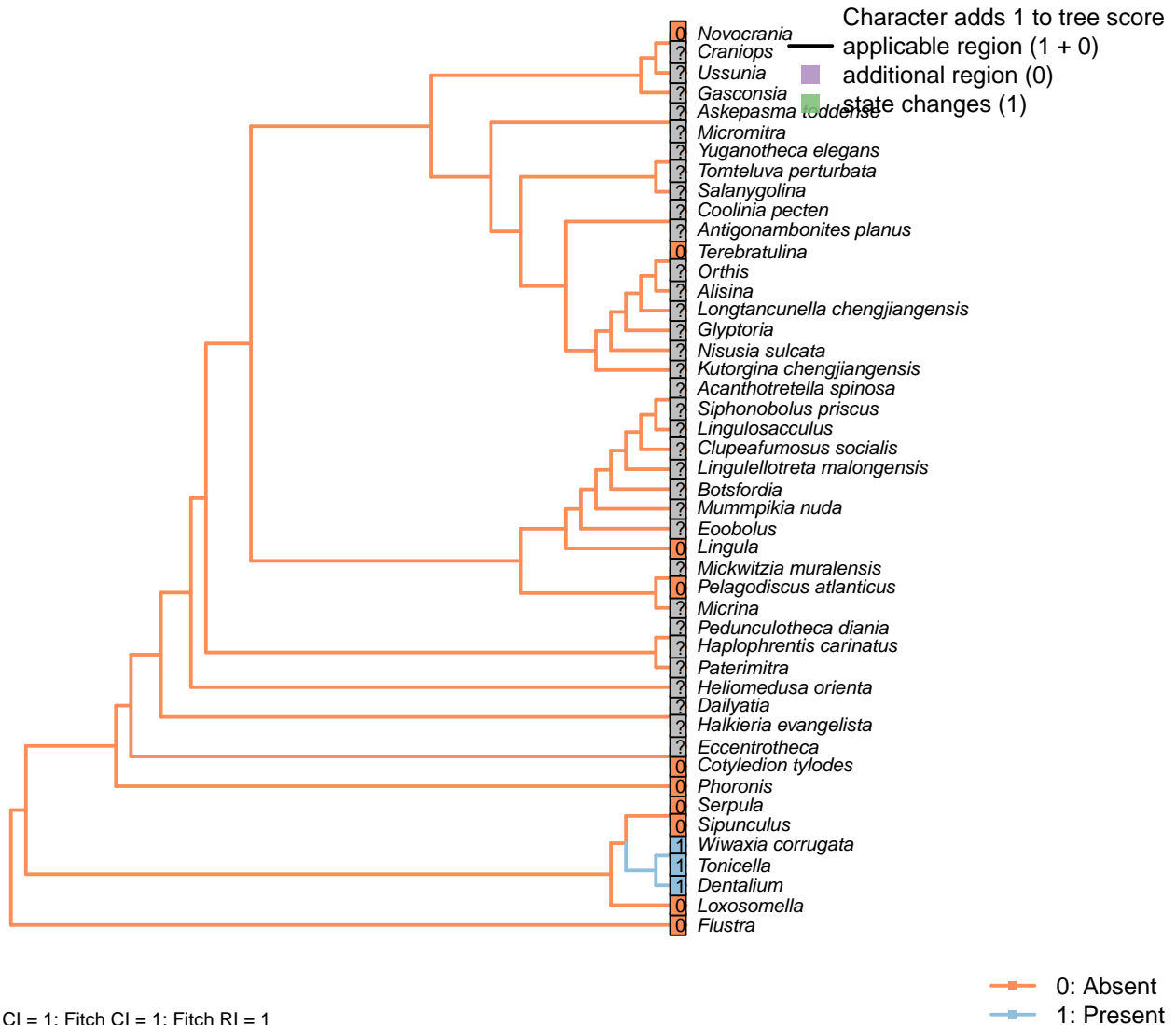
Character 27 in Haszprunar (2000). Coelomoducts are excretory organs derived from the coelom, also in some cases serving as genital ducts (gonoducts); they replace (and may resemble) nephridia (Goodrich, 1945).

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

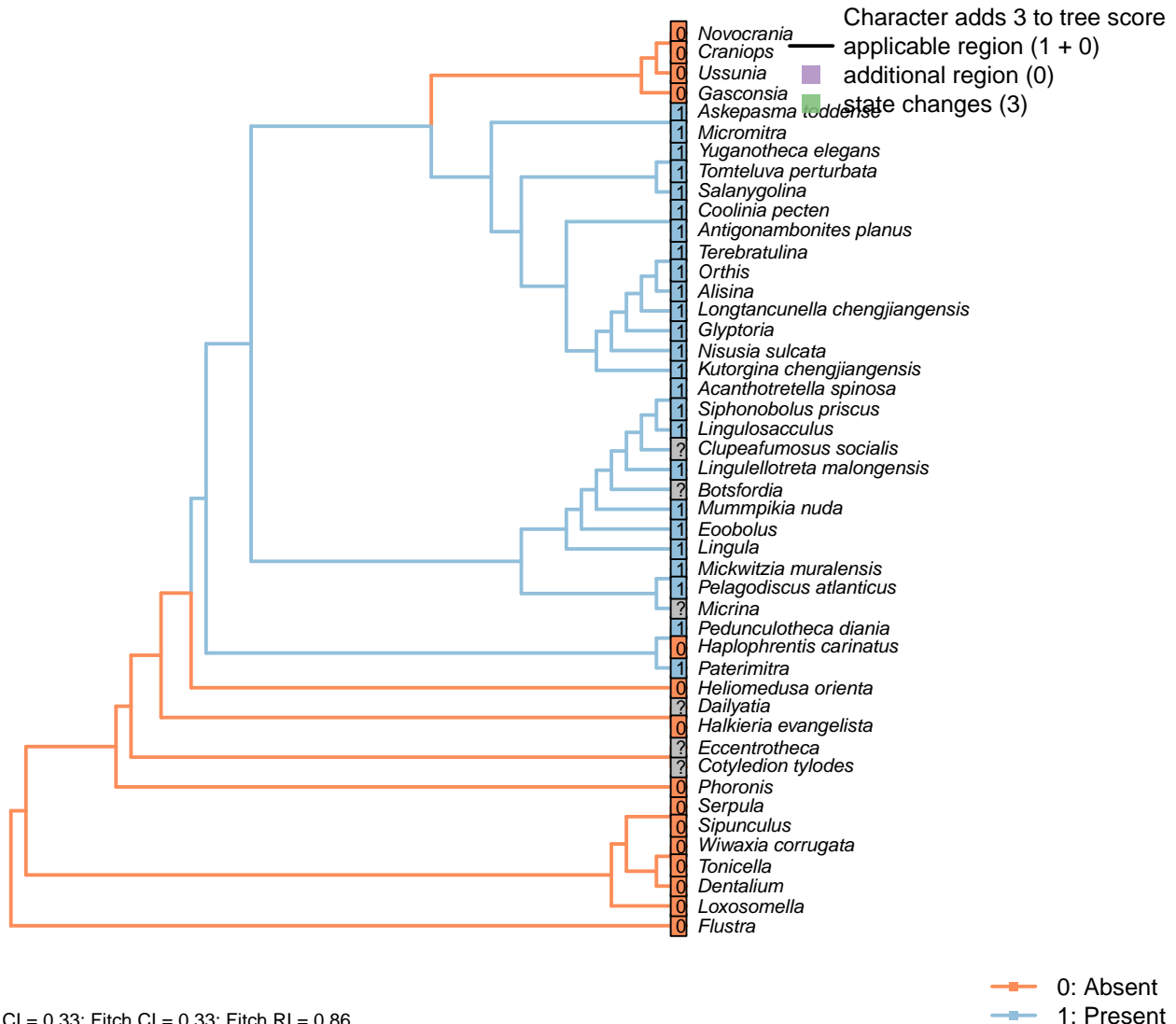
Loxosomella: Two coelomoducts pass outwards, meet, and open by a common pore (Goodrich, 1945).

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

3.5 Body organization: Gills [14]



3.6 Pedicle [15]



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.

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

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

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

Craniops: Attached apically by cementation.

Flustra: Grows directly onto the substrate.

Heliomedusa orientalis: “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).

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

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

Mickwitzia muralensis: 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.

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

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

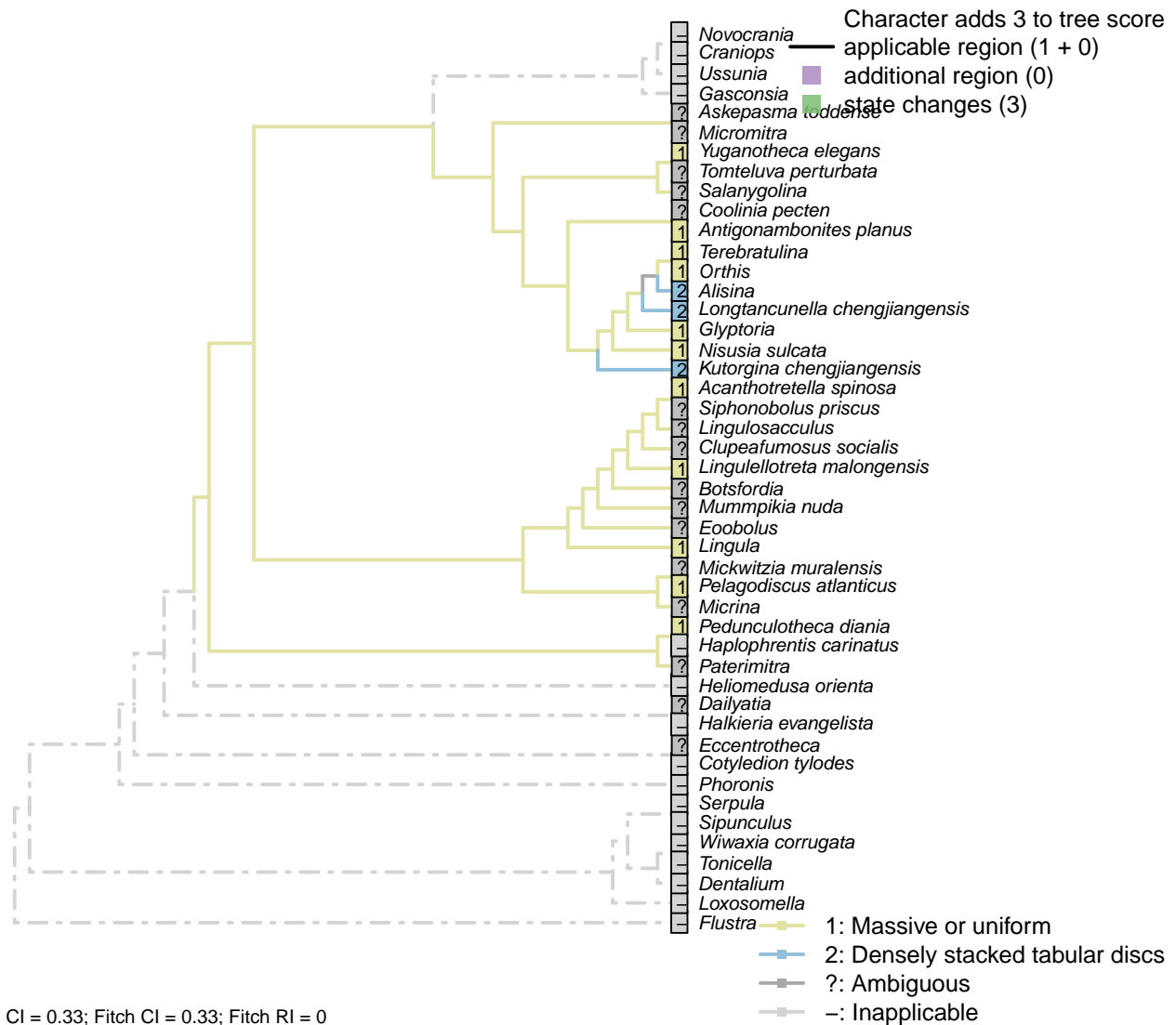
Paterimitra: “*Paterimitra* is interpreted to have attached to hard substrates via a pedicle that emerged through the small posterior opening” – Skovsted *et al.* (2009).

Phoronis: 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.

Siphonobolus priscus: Presumed present, based on ventral foramen with colleplax.

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

[16] Constitution

**Character 16: Pedicle: Constitution**

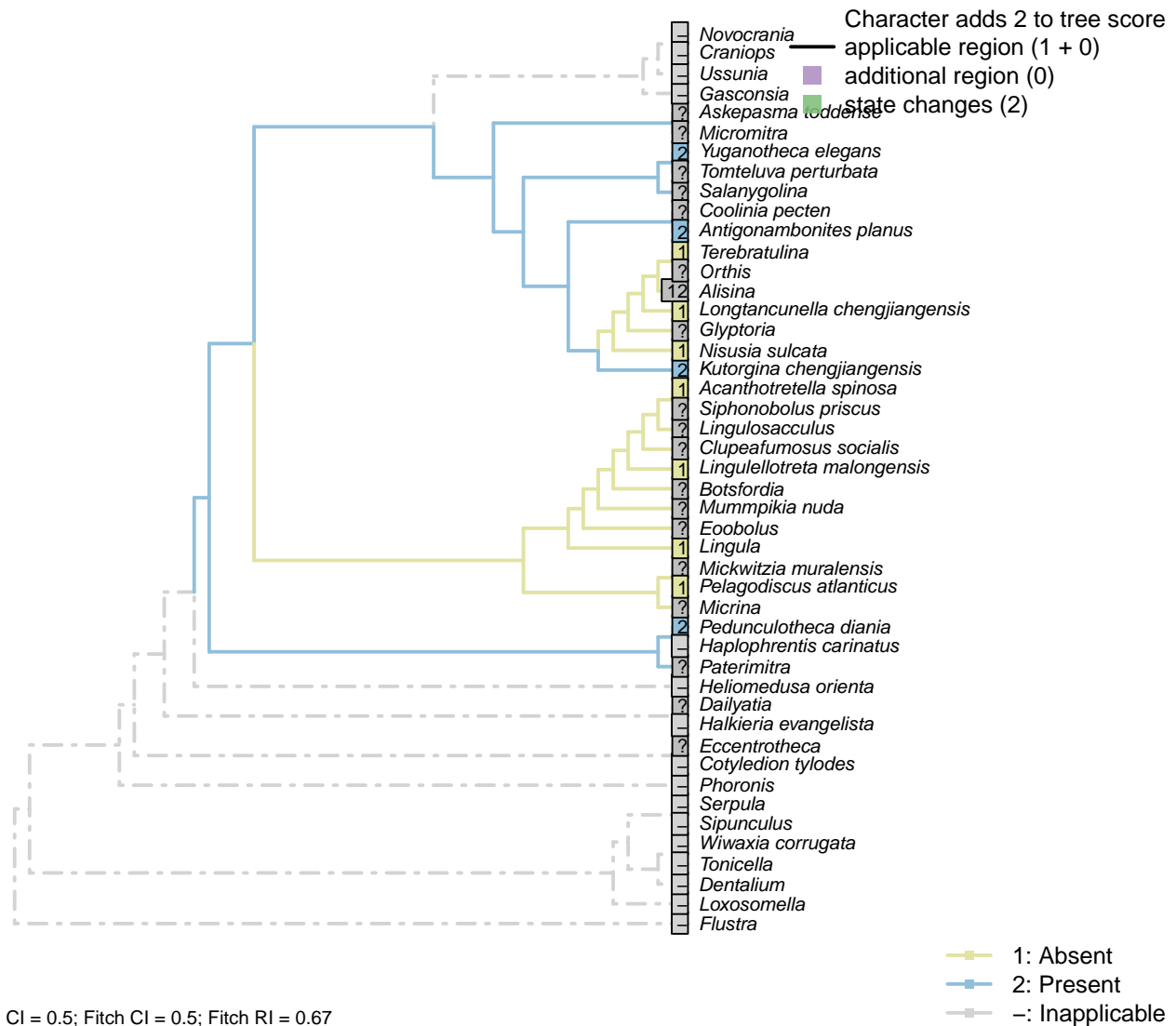
- 1: Massive or uniform
 - 2: Densely stacked tabular discs
- Transformational character.

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.

Terebratulina: 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).

[17] Biomineralization

**Character 17: Pedicle: Biomineralization**

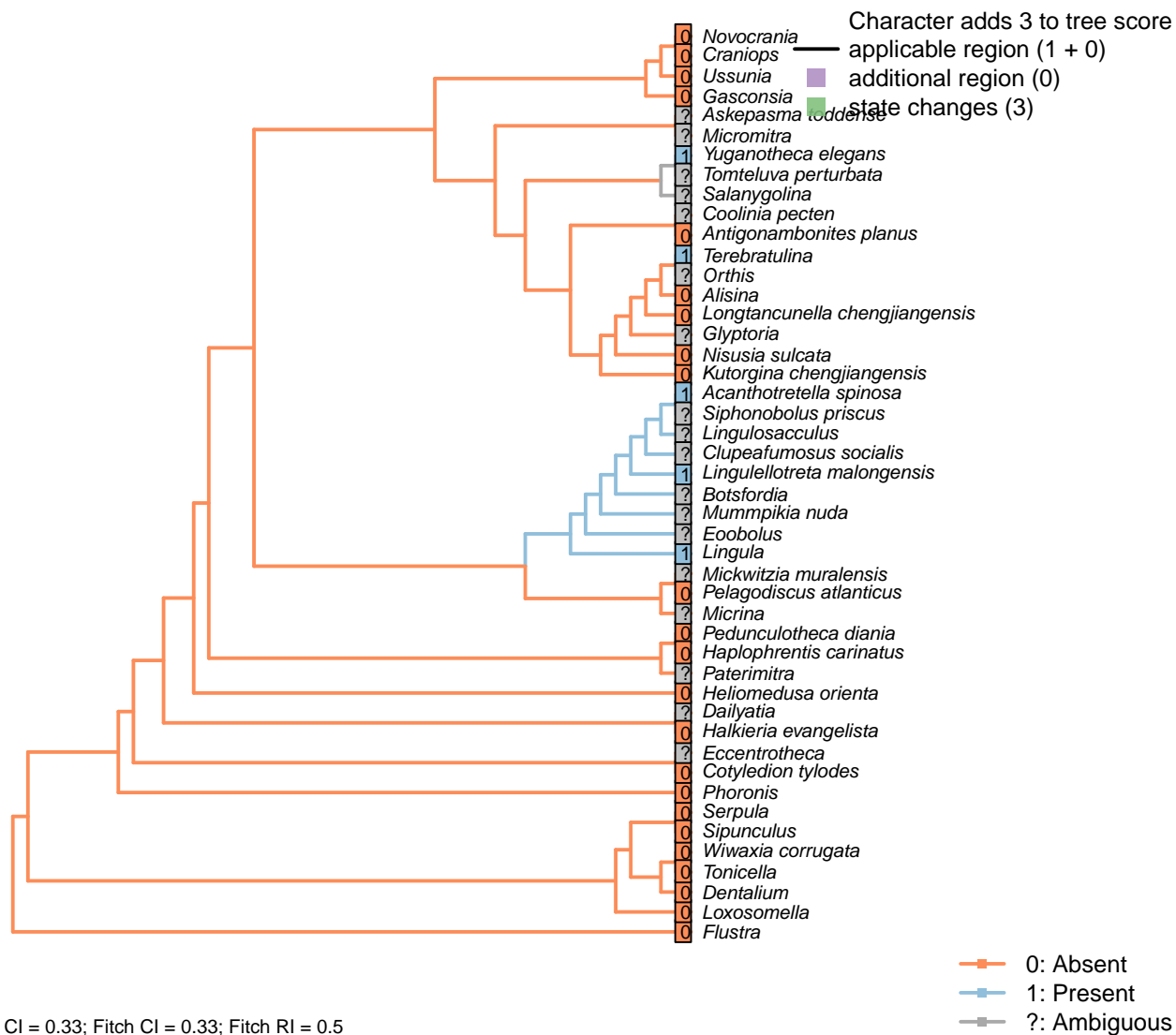
1: Absent

2: Present

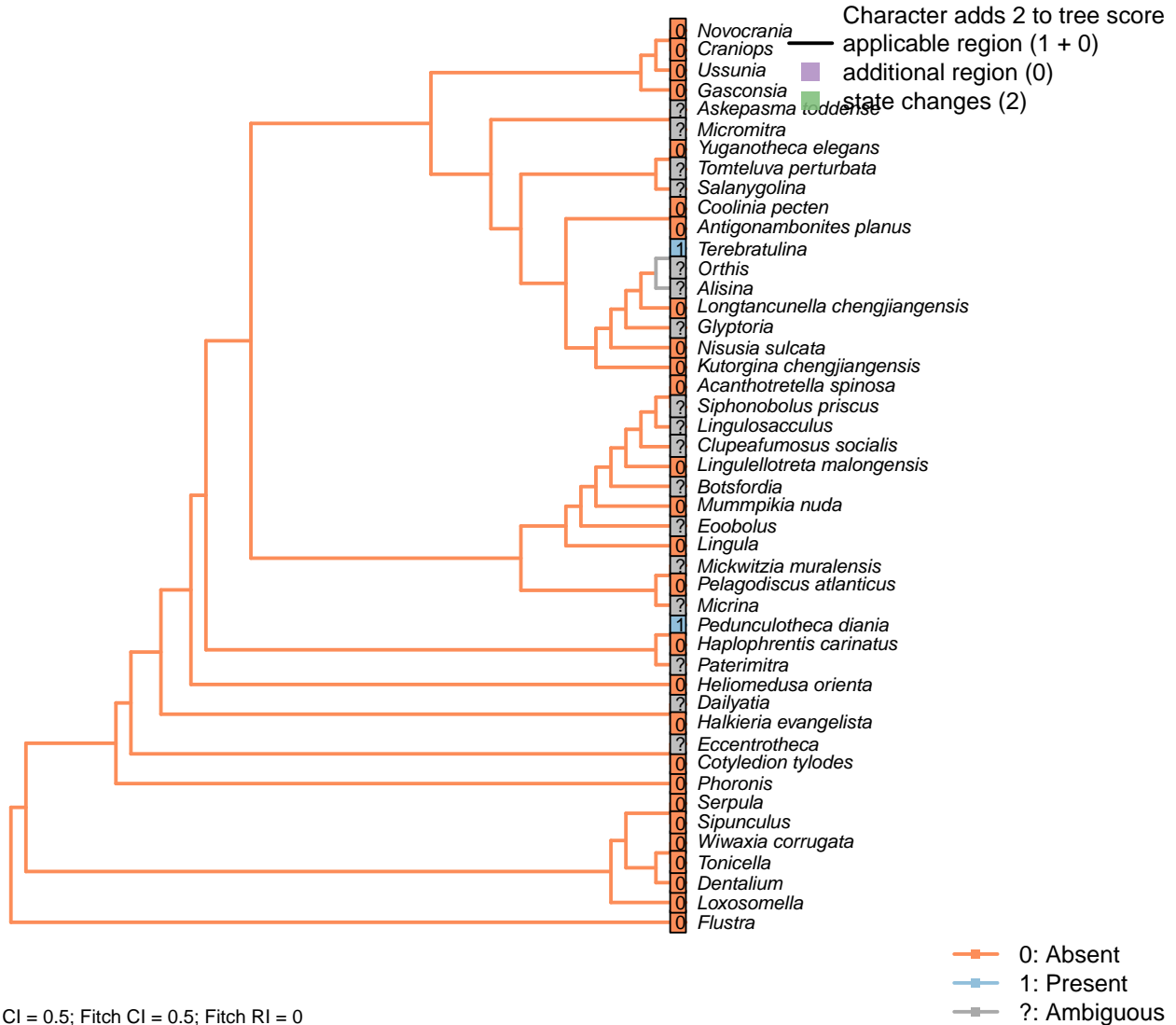
Transformational character.

The pedicle of strophomenates such as *Antigonambonites* is biomineralized (Holmer et al., 2018a).

[18] Bulb



[19] Distal rootlets

**Character 19: Pedicle: Distal rootlets**

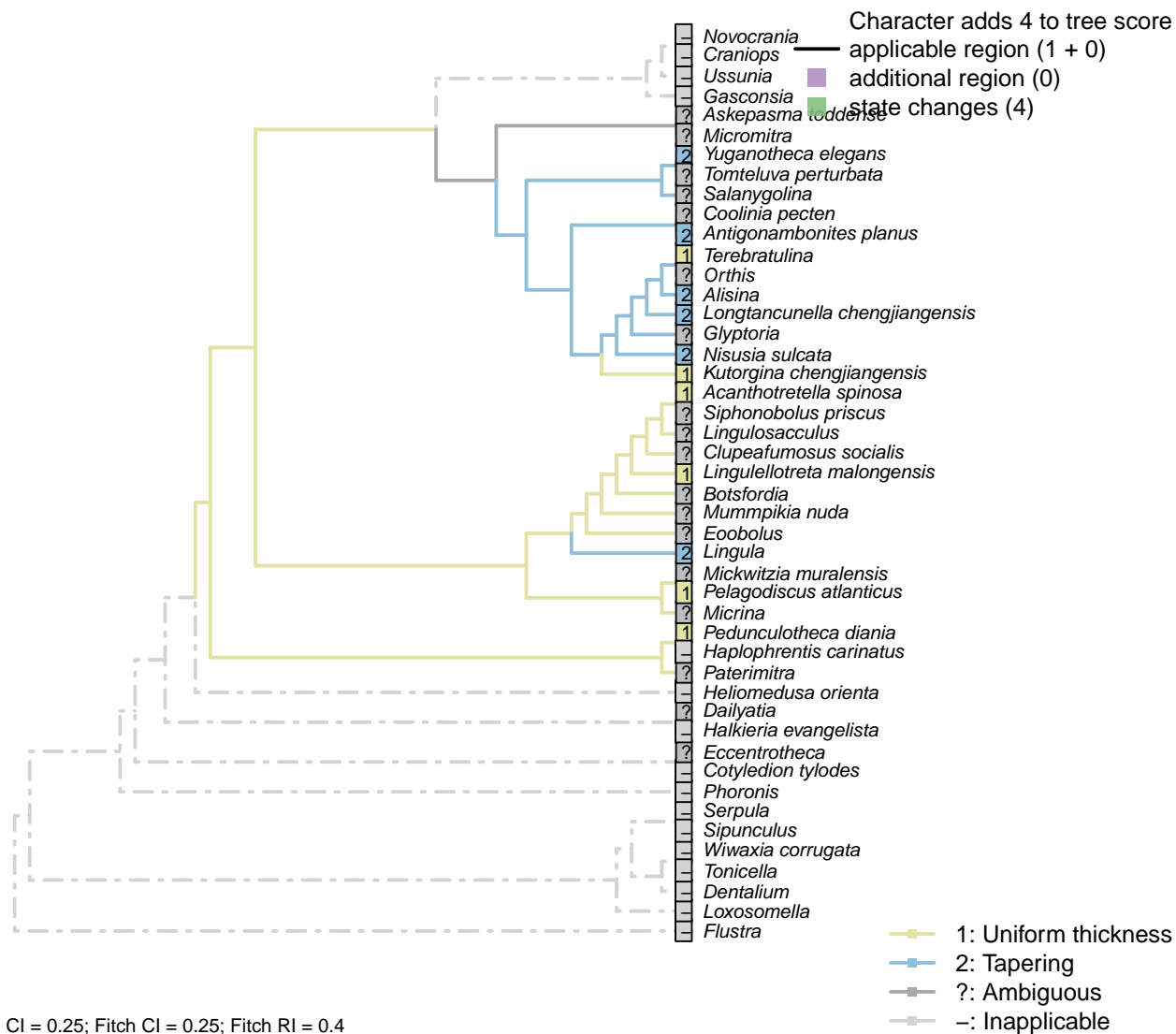
0: Absent

1: Present

Neomorphic character.

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

[20] Tapering

**Character 20: Pedicle: Tapering**

1: Uniform thickness

2: Tapering

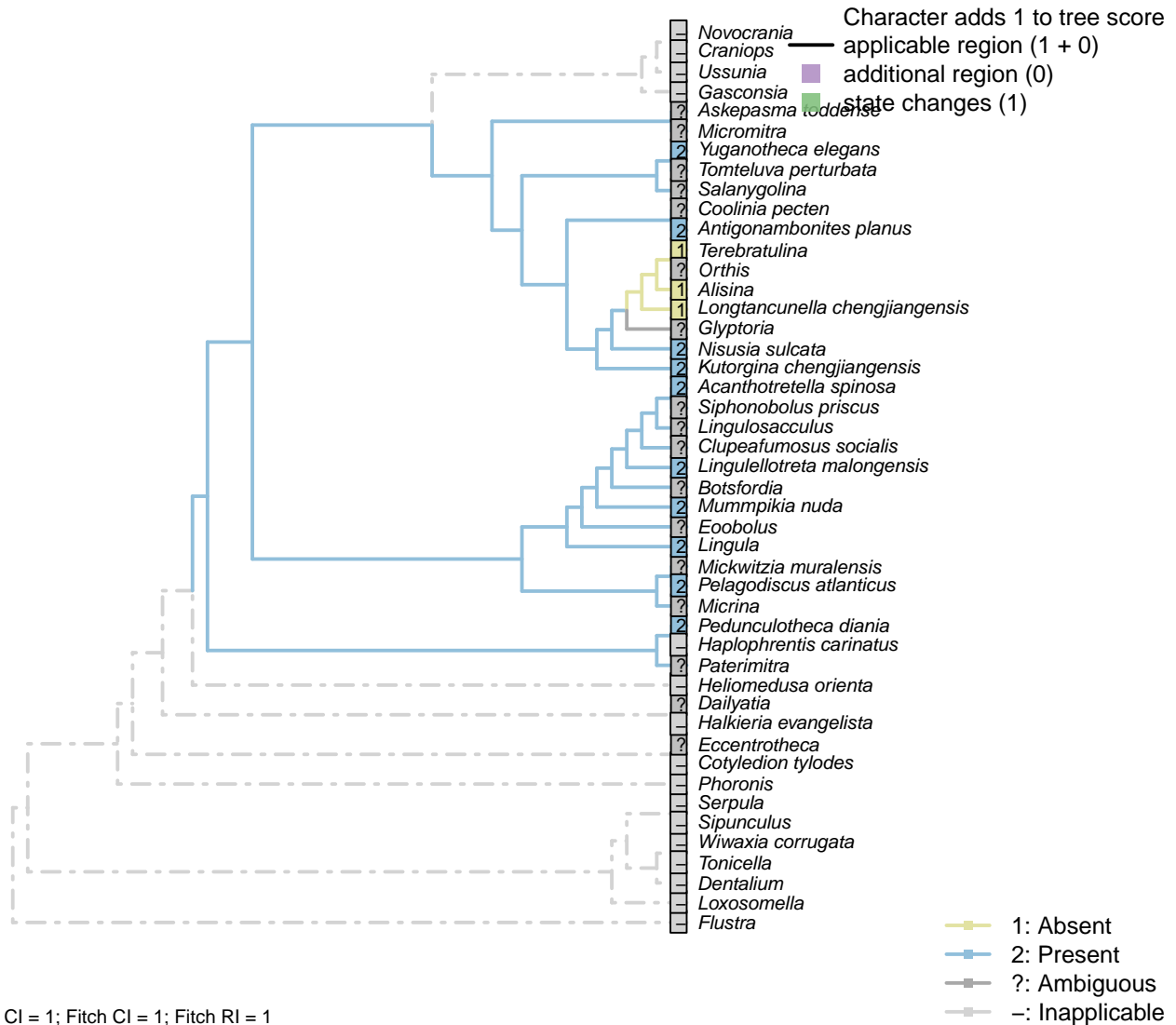
Transformational character.

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.

Antigonambonites planus: Tapered pedicle sheath with holdfast.

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

[21] Coelomic region

**Character 21: Pedicle: Coelomic region**

1: Absent

2: Present

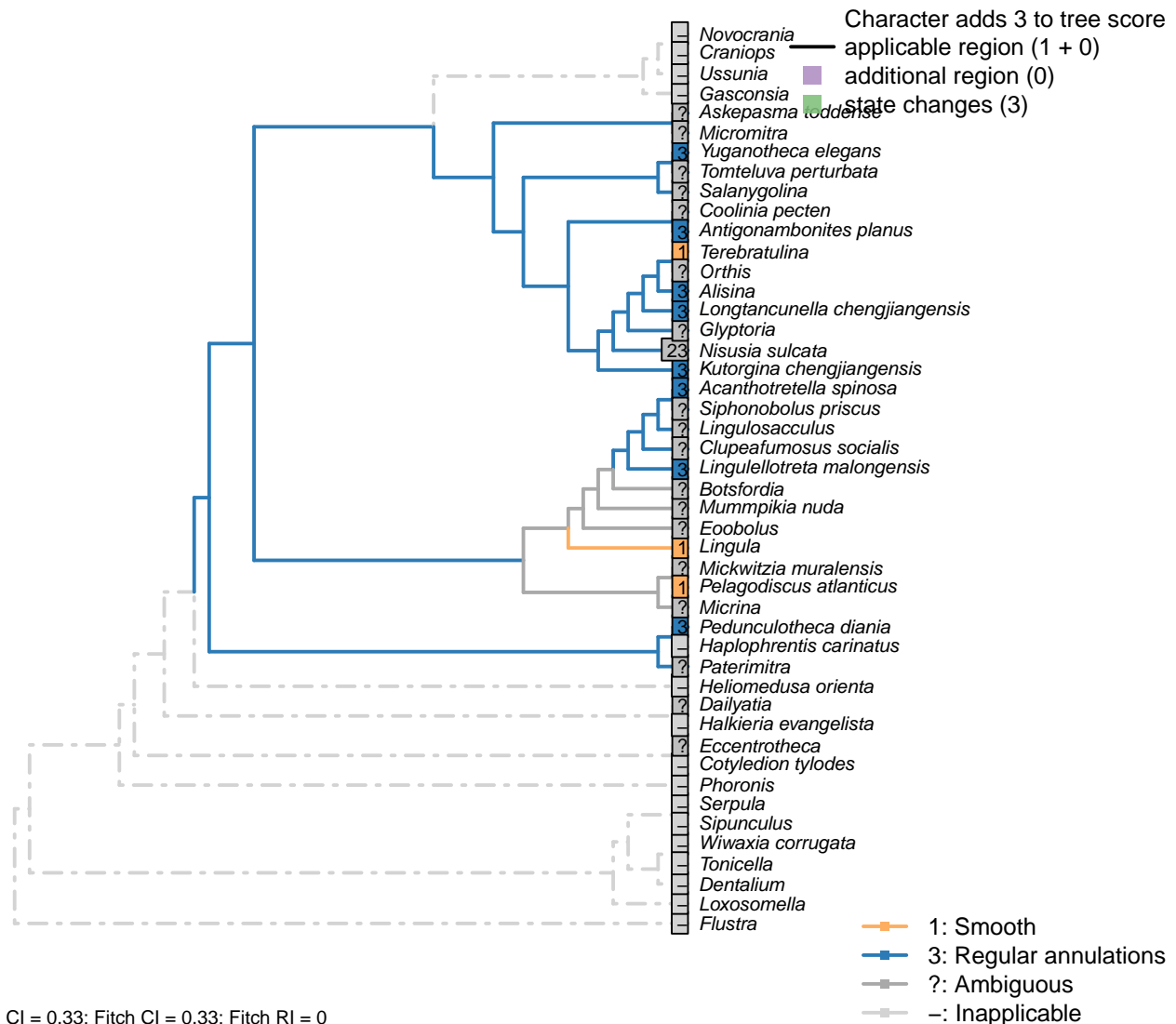
Transformational character.

Certain brachiopods, such as *Acanthotretella*, exhibit a coelomic cavity within the pedicle or pedicle sheath.

Treated as transformational as it is not clear that either state is necessarily ancestral.

Nisusia sulcata: A coelomic canal is inferred based on the ease with which the pedicle is deformed (Holmer et al., 2018a), but its presence is not known for certain so is coded ambiguous.

[22] Surface ornament

**Character 22: 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.

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

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

Antigonambonites planus: “The emerging pedicle has a consistent shape in all the available specimens and

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

Kutorgina chengjiangensis: “Pronounced concentric annular discs disposed at intervals of 0.6–1.0 mm”.

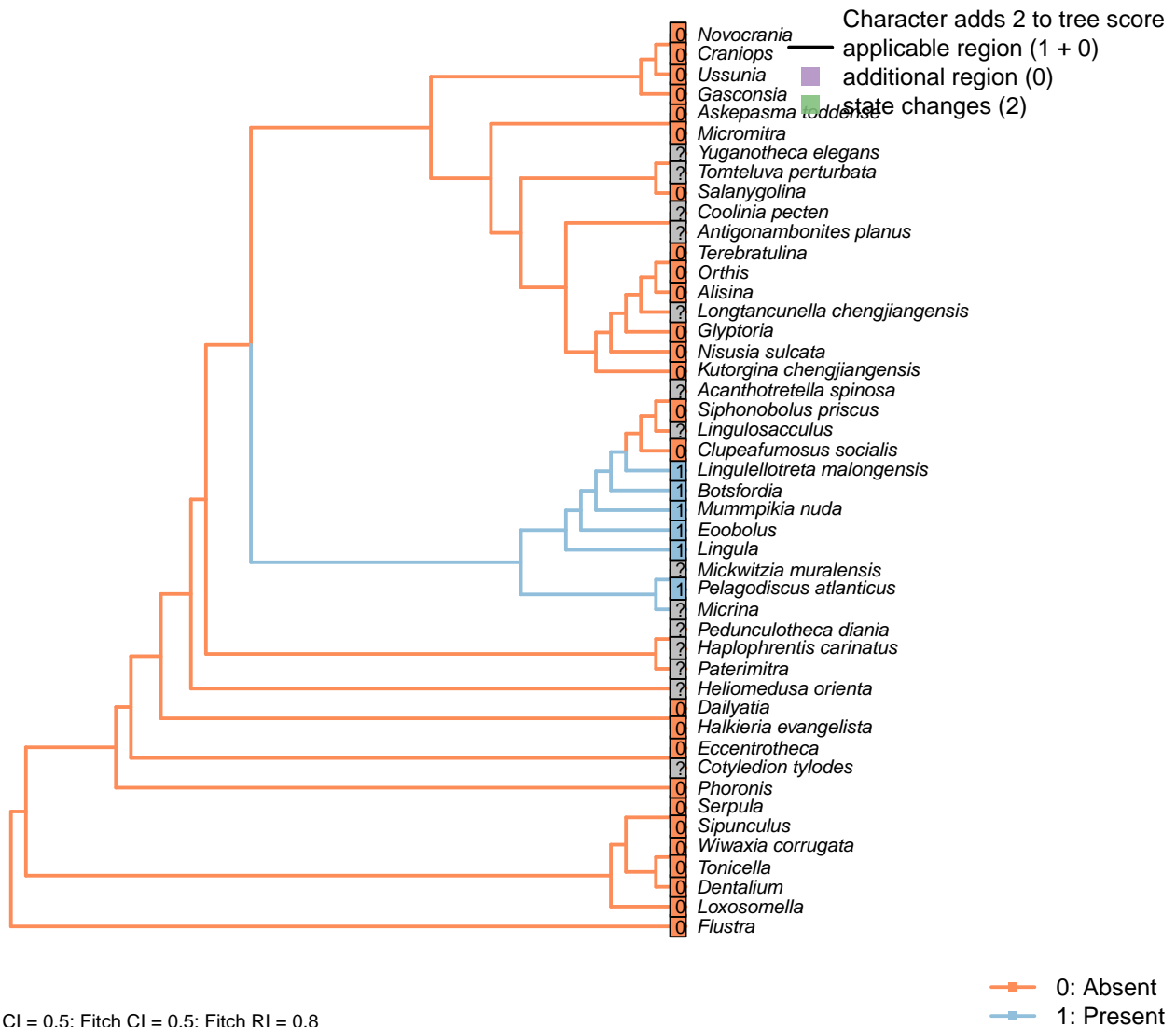
Lingulellotreta malongensis: Regularly annulated (see fig. 14.9 in Hou et al., 2017).

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

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

Yuganotheca elegans: Annulations present in median collar.

[23] Nerve impression



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.

Alisina: Not described by Williams et al. (2000).

Askepasma toddense, *Glyptoria*, *Kutorgina chengjiangensis*, *Micromitra*, *Salanygolina*: Following Williams et al. (1998), appendix 2.

Botsfordia: Documented by Skovsted et al. (2017).

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

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

Lingulellotreta malongensis: Coded as present in Lingulellotretidae (Williams et al., 2000, table 6).

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

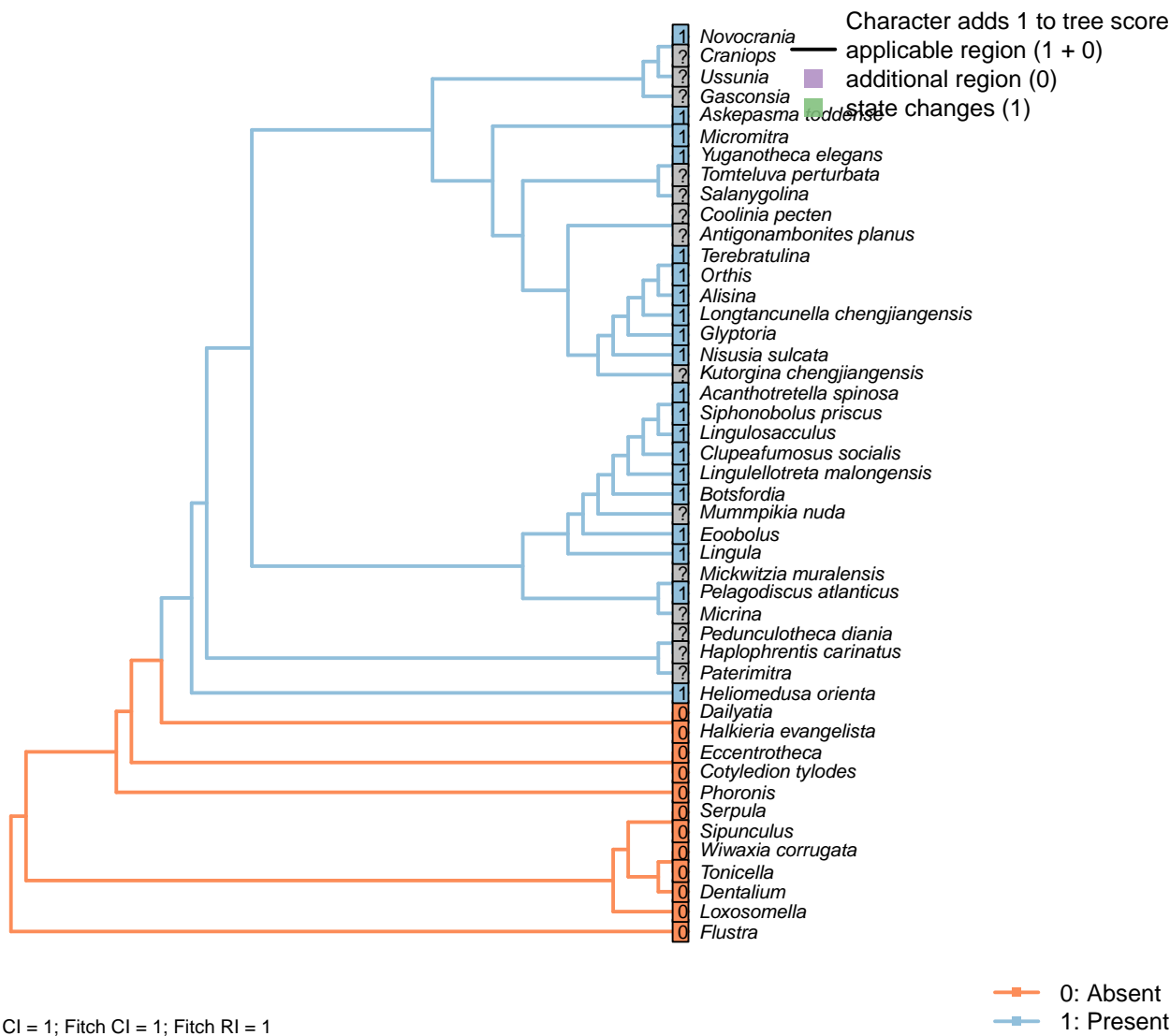
Nisusia sulcata, *Orthis*: Not reported in Williams et al. (2000).

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

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

3.7 Mantle canals

[24] Presence

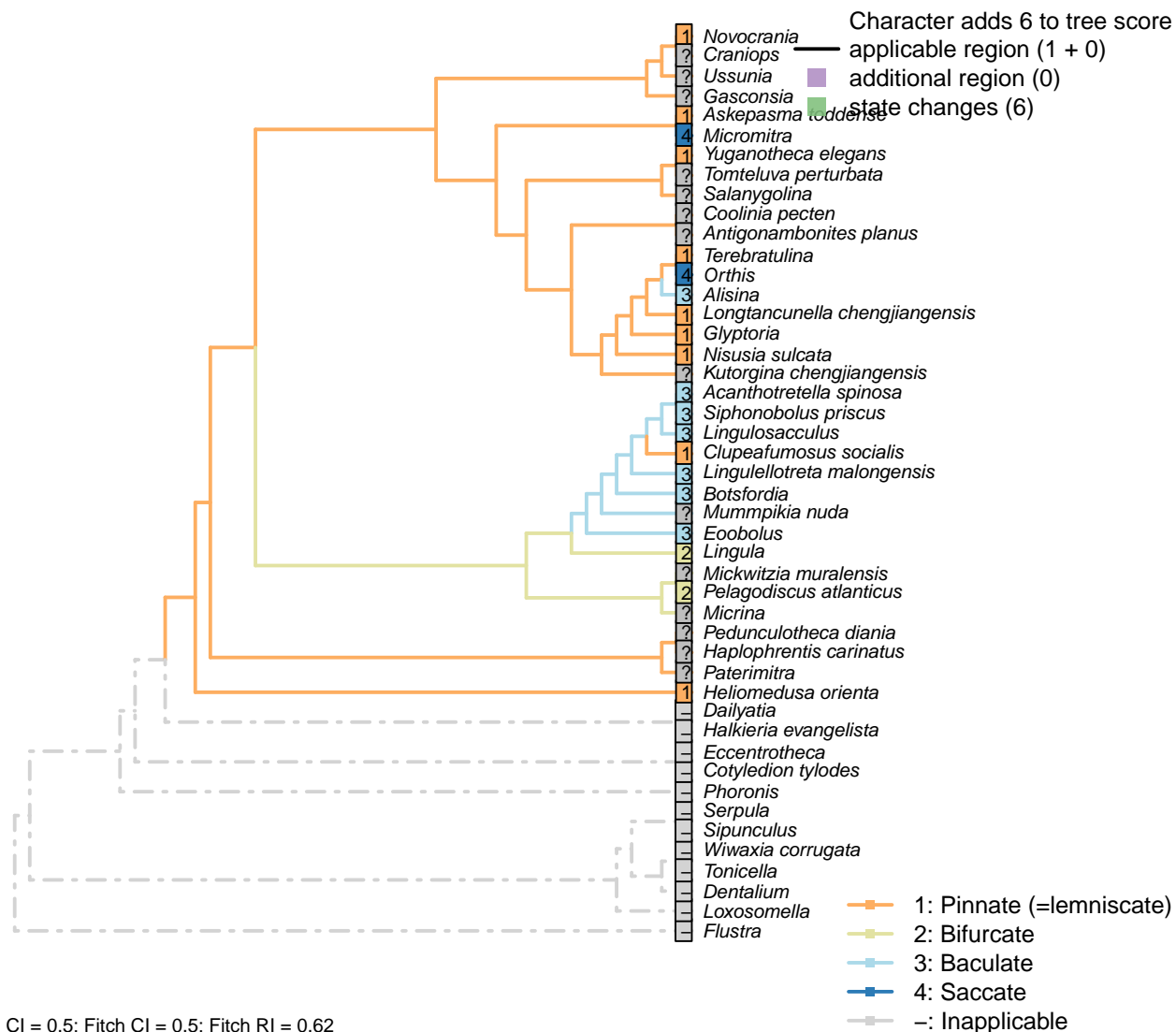


Character 24: Mantle canals: Presence

0: Absent
1: Present
Neomorphic character.

Whether impressed on a shell or expressed solely in soft tissue.

[25] Morphology

**Character 25: 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).

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

Alisina, *Nisusia sulcata*: Following Table 15 in Williams *et al.* (2000).

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

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

Botsfordia, *Eoobolus*: Following Williams *et al.* (1998), appendix 2, and Williams *et al.* (2000), table 8.

Clupeafumosus socialis: 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.

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

Craniops: Not reported from fossil material.

Gasconsia: 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.

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

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

Kutorgina chengjiangensis, *Novocrania*: Following table 15 in Williams *et al.* (2000) (for *Neocrania*).

Lingula, *Lingulellotreta malongensis*: Following table 6 in Williams *et al.* (2000).

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

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

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

Mummpikia nuda: “Poorly resolved” – Balthasar (2008).

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

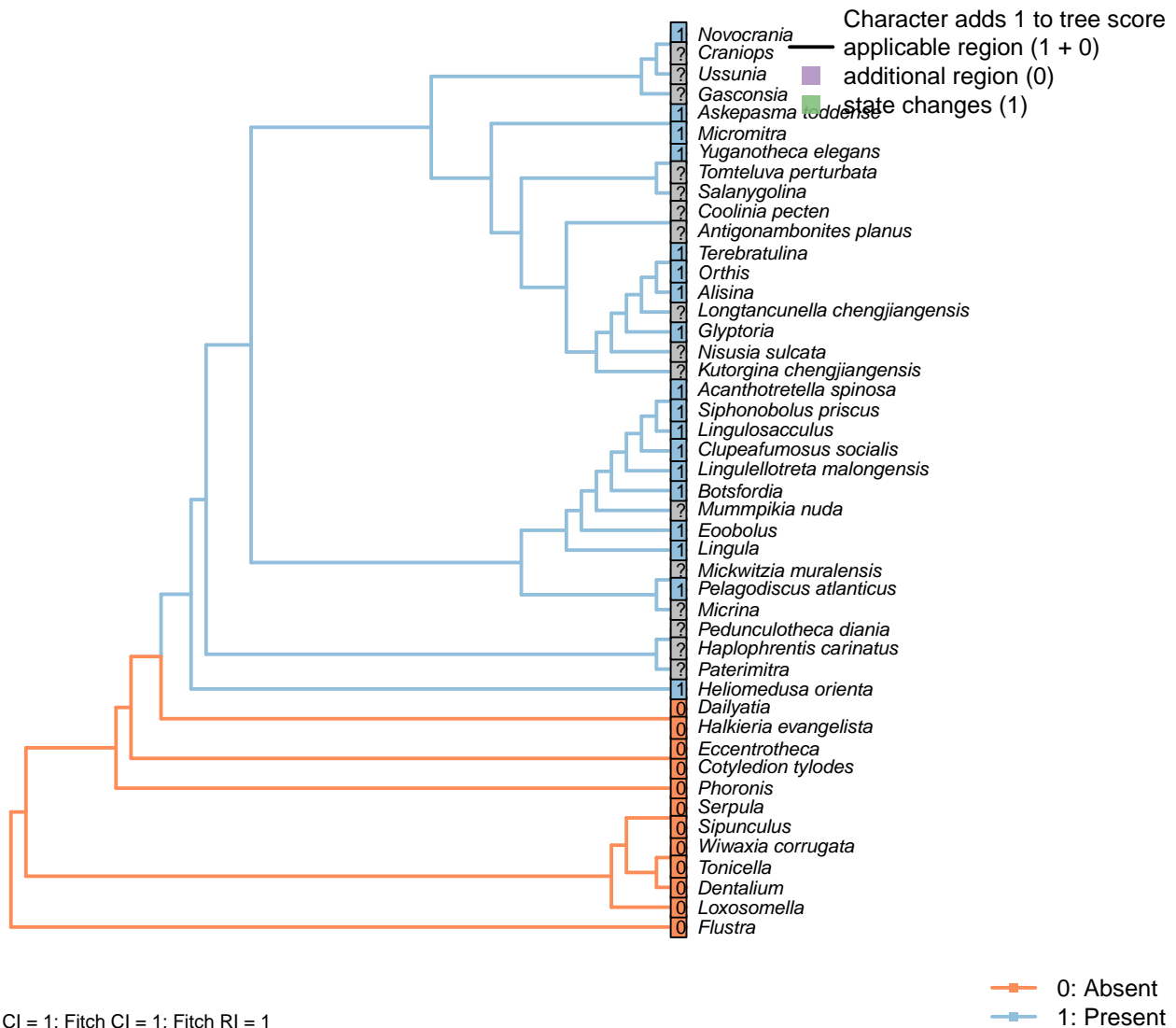
Pelagodiscus atlanticus: Following table 6, for Discinidae, in Williams *et al.* (2000).

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

Siphonobolus priscus: Interpreted as baculate, following Havlicek (1982).

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

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

[26] *vascula lateralia***Character 26: Mantle canals: *vascula lateralia***

0: Absent

1: Present

Neomorphic character.

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).”

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

Alisina, *Kutorgina chengjiangensis*, *Nisusia sulcata*: Following table 15 in Williams *et al.* (2000).

Askepasma toddense, *Micromitra*: “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).

Botsfordia: Following Popov (1992).

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

Gasconsia: 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.

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

Lingulellotreta malongensis: Present (Williams *et al.*, 2000).

Longtancunella chengjiangensis: 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: 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.

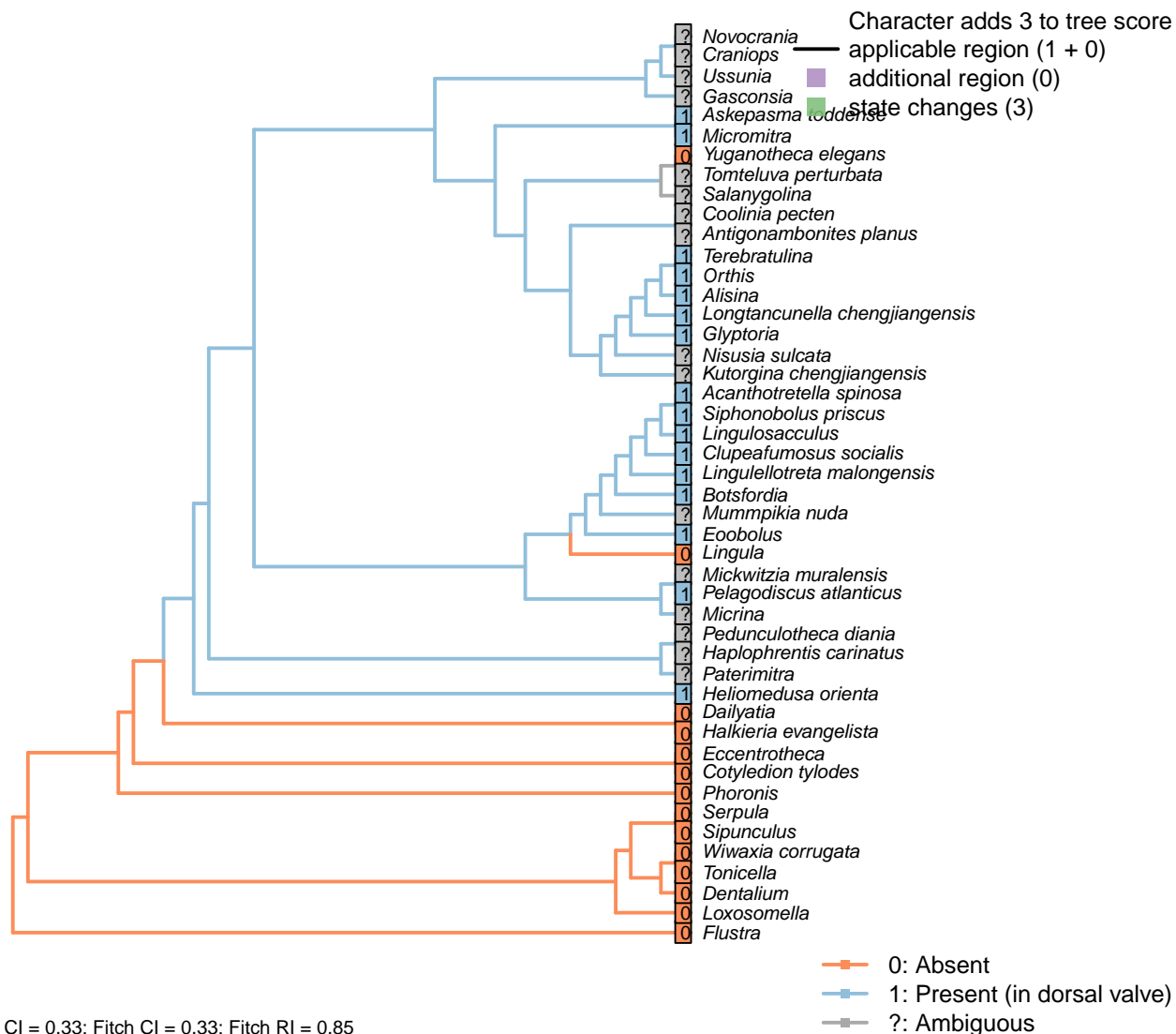
Orthis, *Terebratulina*: = *vascula genitalia*.

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

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

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

Yuganotheca elegans: 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.

[27] *vascula media*

necessary.

Acanthotretella spinosa: Following table 6 (for Siphonotretidae) in Williams *et al.* (2000).

Alisina, *Kutorgina chengjiangensis*, *Nisusia sulcata*: Following table 15 in Williams *et al.* (2000).

Askepasma toddense: Following table 6 (for Paterinidae) in Williams *et al.* (2000).

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

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

Eoobolus: Fig. 5 in Balthasar (2009).

Gasconsia: 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.

Glyptoria: Present and divergent (Williams *et al.*, 2000).

Heliomedusa orientalis: Present: Williams *et al.* (2000) p162, Jin & Wang (1992).

Lingula, *Lingulellotreta malongensis*: Following table 6 in Williams *et al.* (2000).

Longtancunella chengjiangensis: Reported by Zhang *et al.* (2007c) though the interpretation is tentative.

Micromitra: Reported by Williams *et al.* (1998).

Novocrania: Williams *et al.* (2000) write “Holocene craniids have only a single pair of main trunks in both valves, corresponding to the *vascula lateralia*” – an observation reflected in their table 15 (for *Neocrania*). But in contrast, Williams *et al.* (2007), p. 2875, identify the dorsal valve’s canals as a *vascula media* in living craniids (though both are *lateralialia* in Ordovician craniids). This character is therefore coded as ambiguous.

Orthis: From idealised morphology in Williams *et al.* (2000).

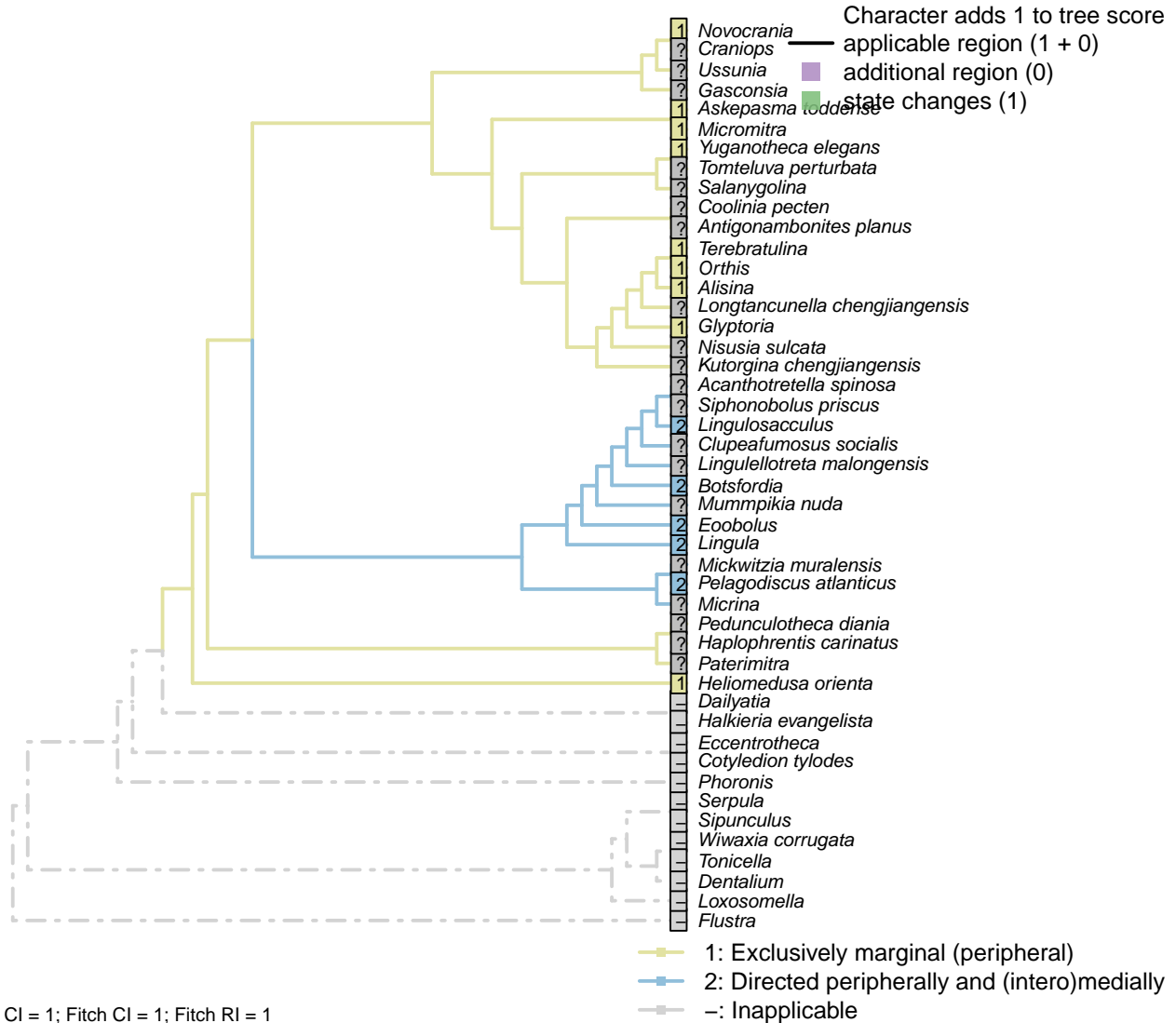
Pelagodiscus atlanticus: Following table 6 (for Discinidae) in Williams *et al.* (2000).

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

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

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

Yuganotheca elegans: 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.

[28] *vascula terminalia***Character 28: 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.

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

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

Askepasma toddense, *Micromitra*: Peripheral only (Williams *et al.*, 1998, 2000).

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

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

Heliomedusa orienta: Inferred from Jin & Wang (1992).

Kutorgina chengjiangensis, *Salanygolina*: Coded uncertain in appendix 2 in Williams *et al.* (1998).

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

Lingulellotrete malongensis: Not described in Williams *et al.* (2000).

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

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

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

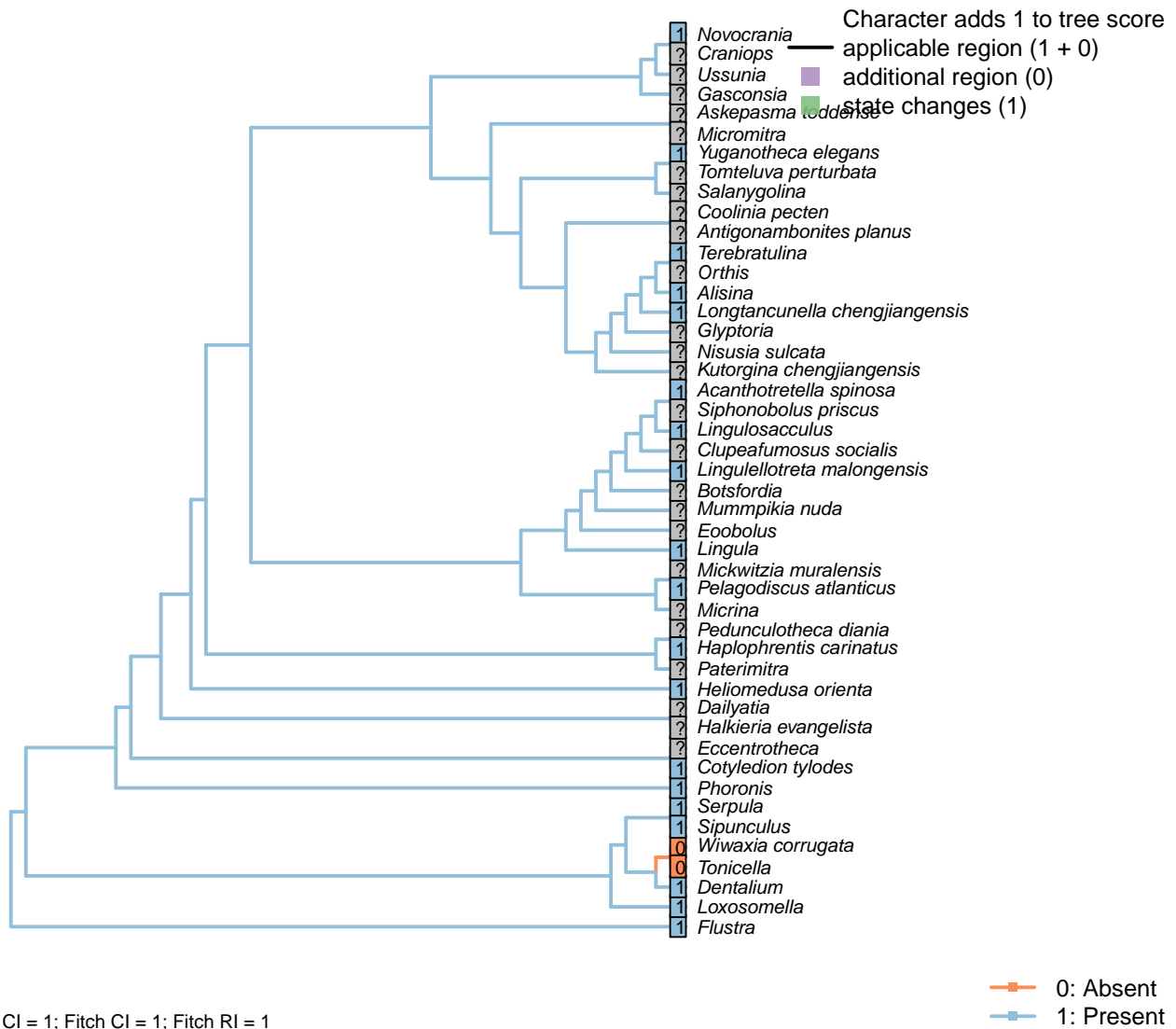
Pelagodiscus atlanticus: Following *Lochkothele* (Discinidae), fig. 43.4a in Williams *et al.* (2000).

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

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

3.8 Perioral tentacular apparatus

[29] Presence



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,

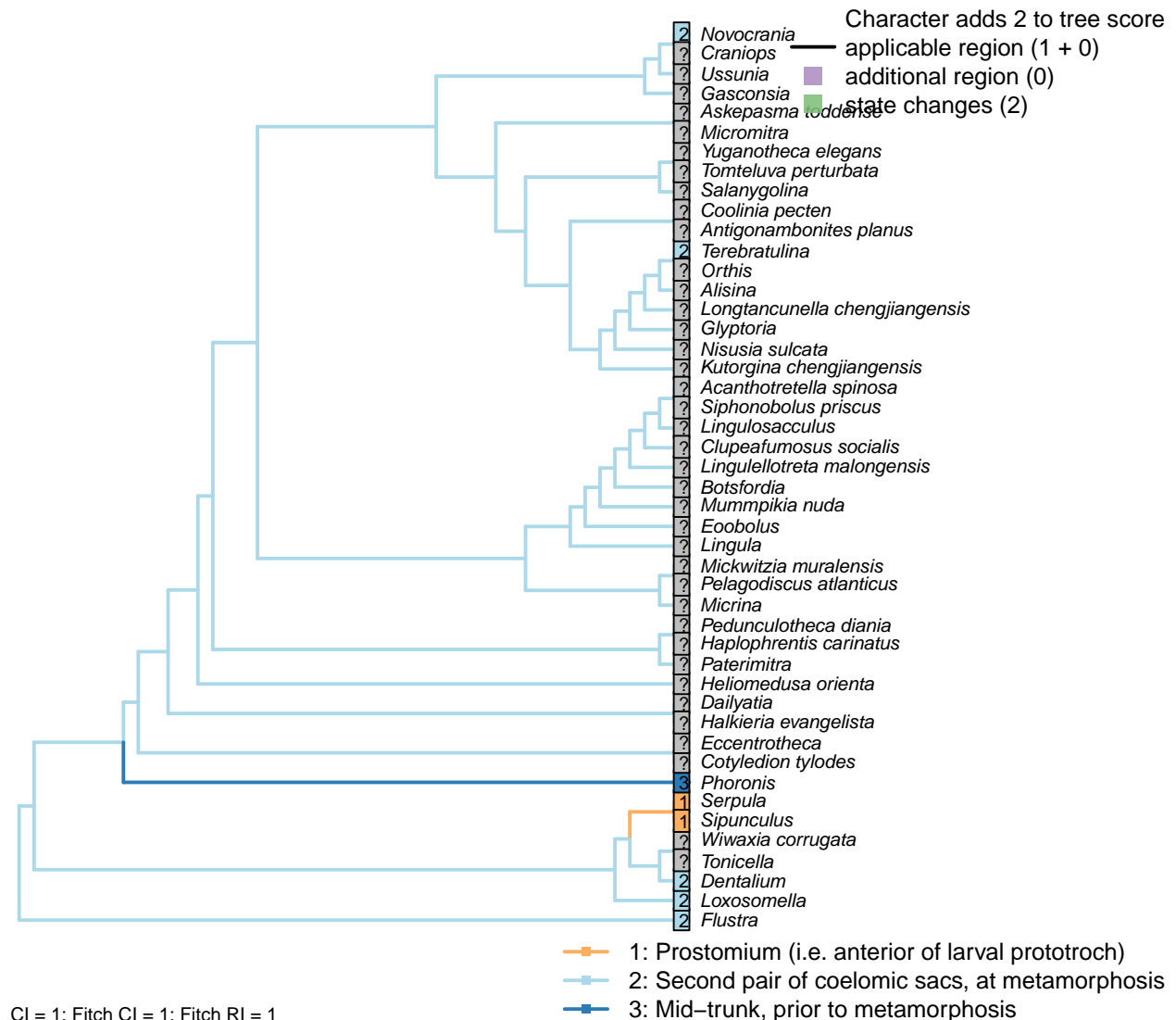
with arguments against homology reflected in separate transformation series.

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

Dentalium: 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).

Haplophrentis carinatus: Moysiuk et al. (2017).

[30] Origin



Character 30: 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).

Dentalium: 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).

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

Loxosomella: Arising after metamorphosis (Nielsen, 1971).

Novocrania: “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)

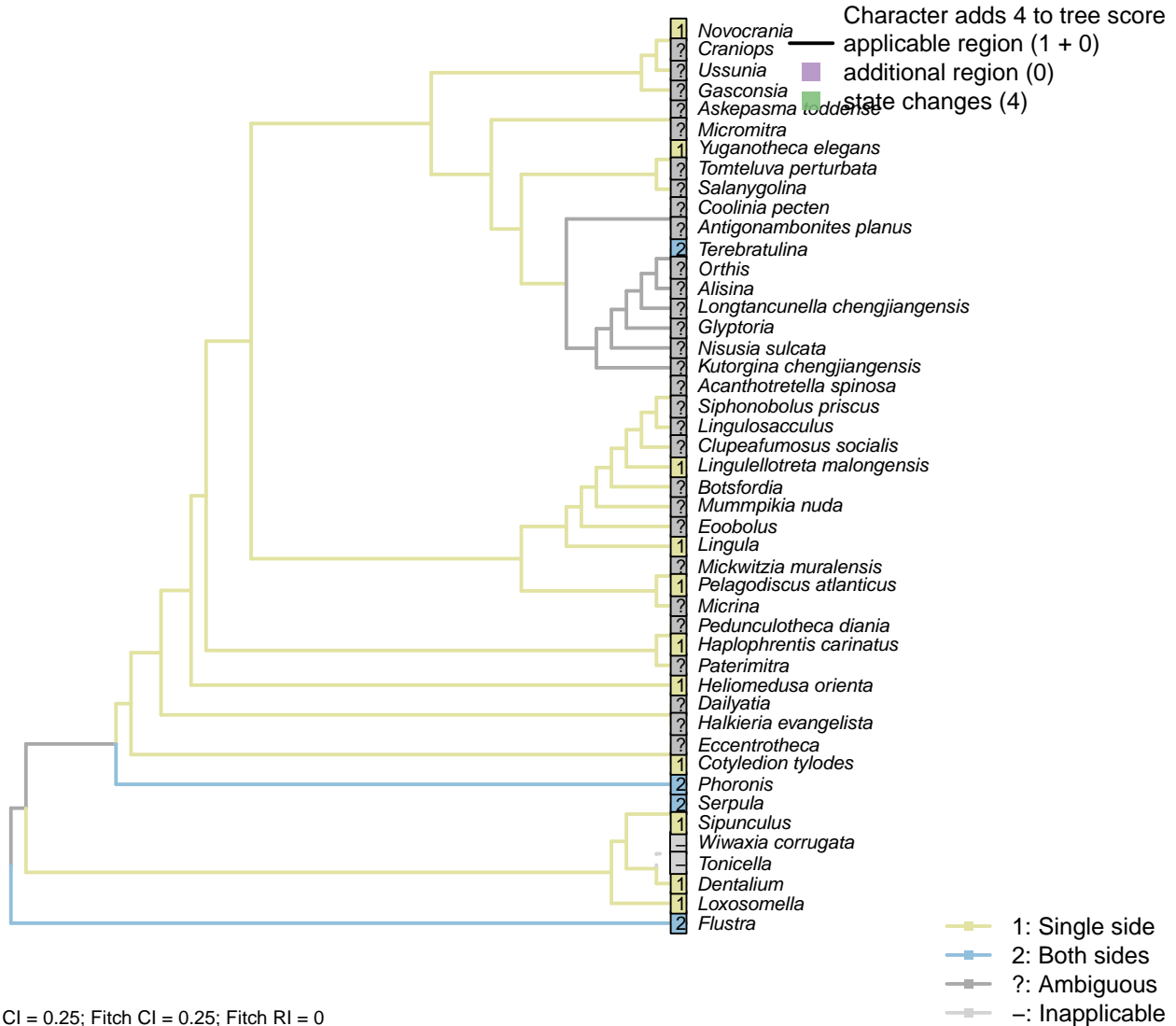
“The larval lobes are retained during the first steps of metamorphosis and are subsequently remodeled to form the lophophore and other adult organs” – Altenburger et al. (2013).

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

Sipunculus: (Adrianov et al., 2006).

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

[31] Tentacle disposition

**Character 31: 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).

Acanthotretella spinosa: Preservation insufficient to evaluate (Holmer and Caron, 2006).

Alisina: Preservation inadequate.

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

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

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

Heliomedusa orientalis: “Each lophophoral arm bears a row of long, slender flexible tentacles” – Zhang et al.

(2009).

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

Lingula, *Novocrania*, *Pelagodiscus atlanticus*, *Phoronis*, *Terebratulina*: Following coding for higher group in Carlson (1995), appendix 1, character 36.

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

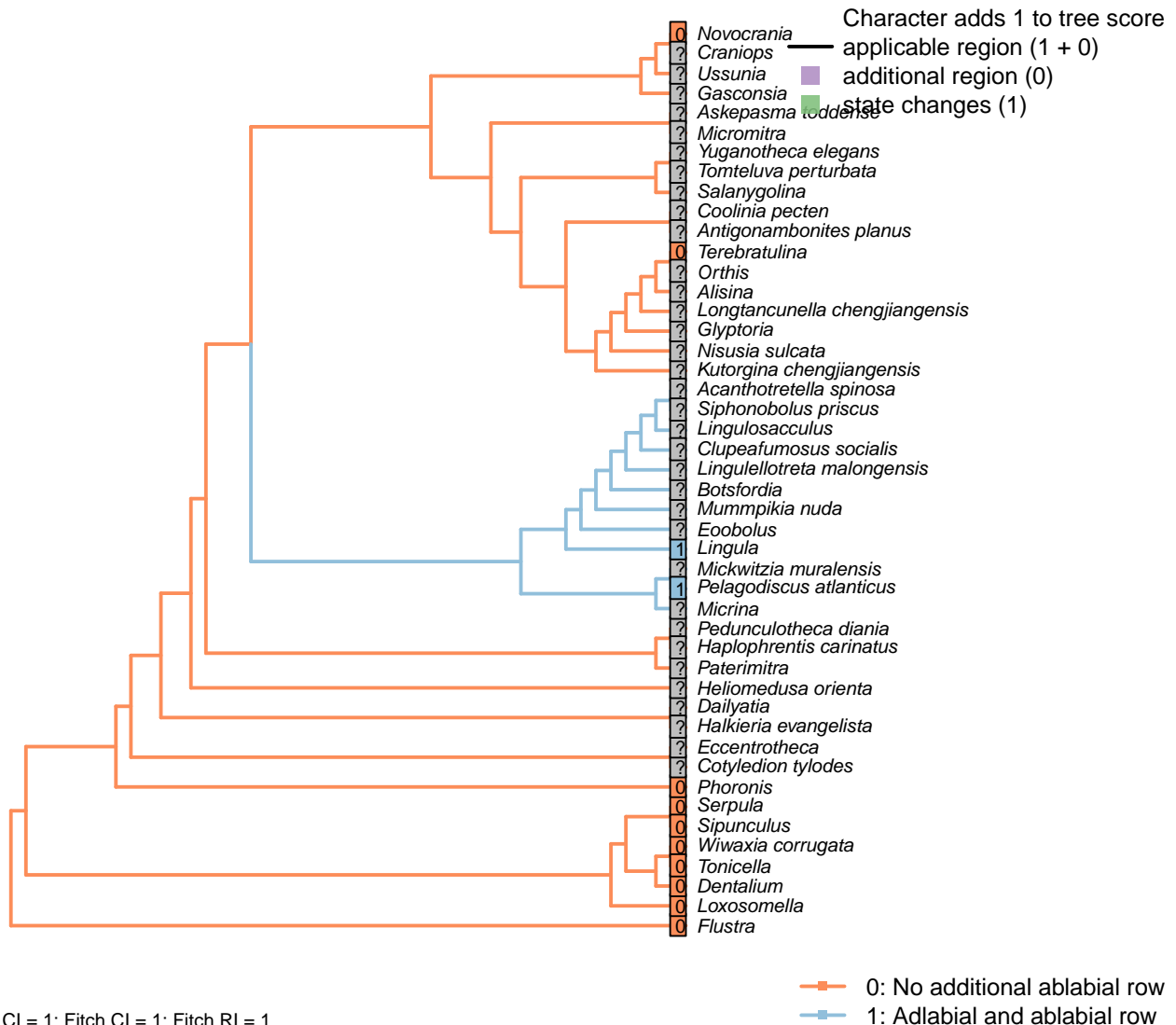
Lingulosacculus: Preservation insufficient to evaluate.

Longtancunella chengjiangensis: Inadequately preserved to evaluate.

Loxosomella: Single side (Nielsen, 1966).

Sipunculus: 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).

[32] Tentacle rows per side in trocholophe stage



Character 32: Perioral tentacular apparatus: Tentacle rows per side in trocholophe stage

0: No additional ablabial row

1: Adlabial and ablabial row

Neomorphic character.

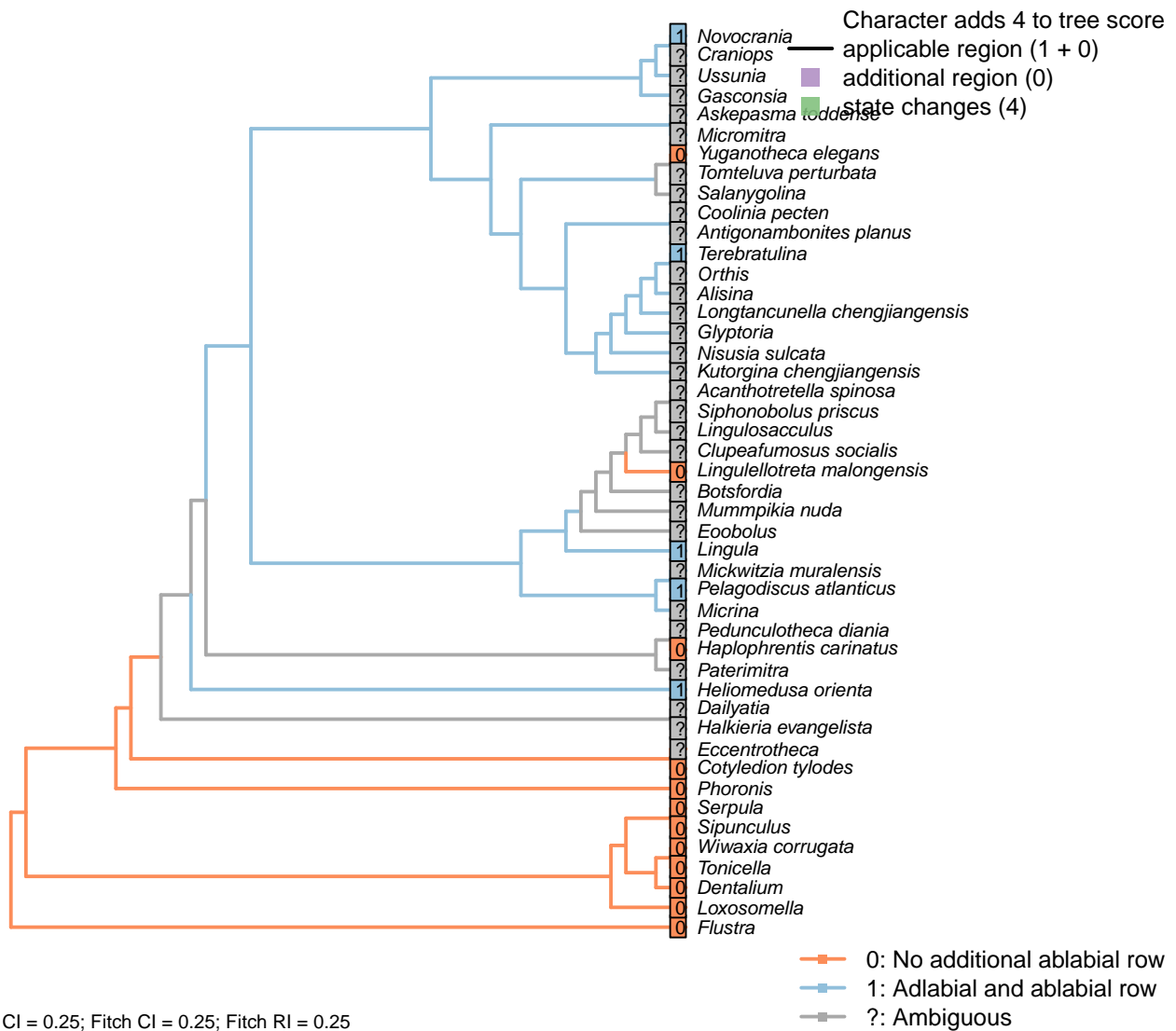
After Carlson (1995), character 37. Lophophore tentacles are commonly arranged into an ablabial and adlabial row, with ablabial tentacles sometimes added later in development.

Flustra, *Loxosomella*: Inapplicable.

Lingula, *Pelagodiscus atlanticus*, *Phoronis*, *Terebratulina*: Following coding for higher taxon in Carlson (1995), appendix 1, character 37.

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

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



Character 33: 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).

Acanthotretella spinosa: Preservation insufficient to evaluate (Holmer and Caron, 2006).

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

Heliomedusa orientalis: “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).

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

Lingula, *Novocrania*, *Pelagodiscus atlanticus*, *Phoronis*, *Terebratulina*: Following coding for higher taxon in Carlson (1995), appendix 1, character 37.

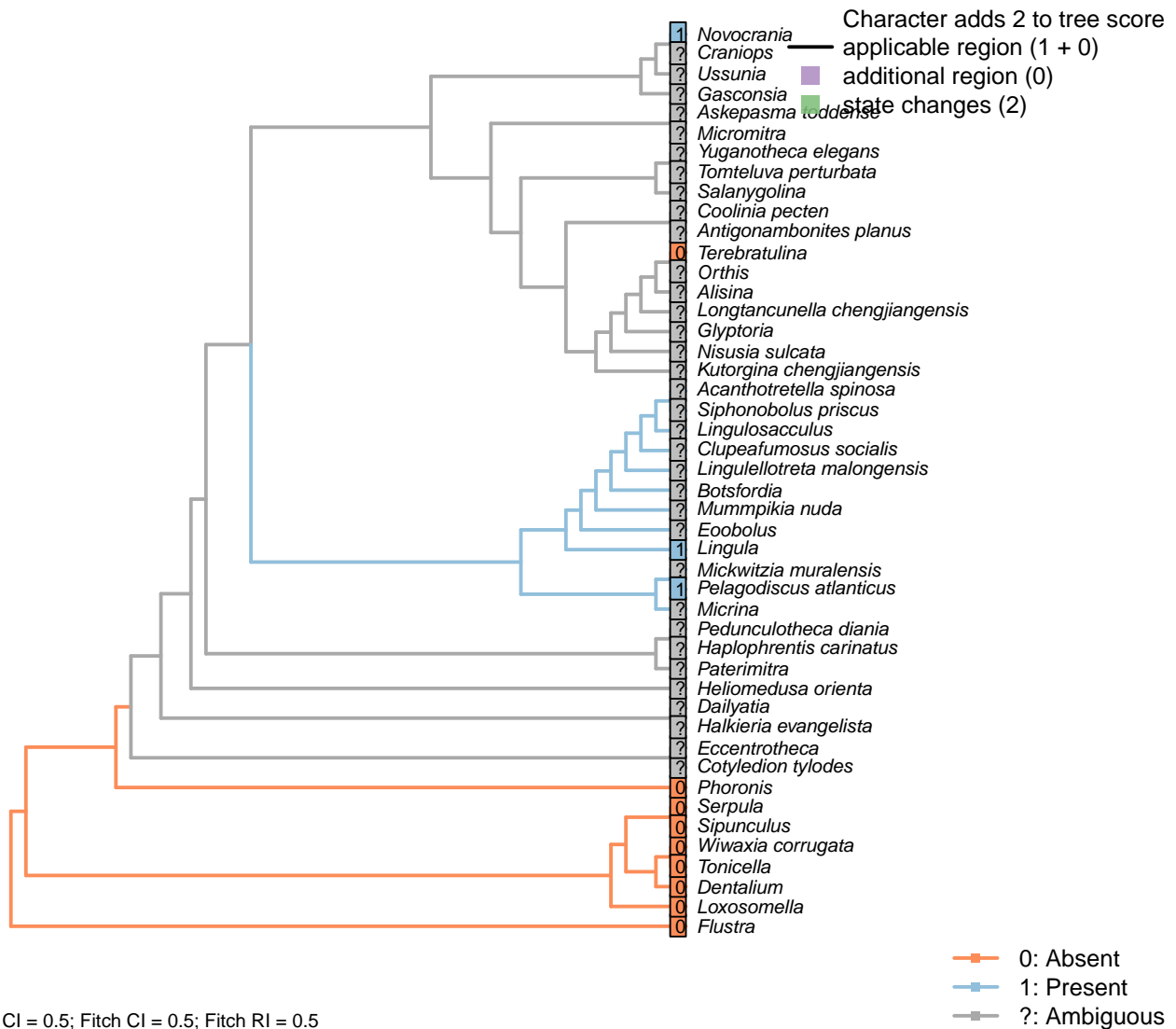
Lingulellotreta malongensis: Single palisade (Zhang et al., 2004).

Lingulosacculus: Preservation insufficient to evaluate.

Loxosomella: Nielsen (1966).

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

[34] Median tentacle in early development

**Character 34: Perioral tentacular apparatus: Median tentacle in early development**

0: Absent

1: Present

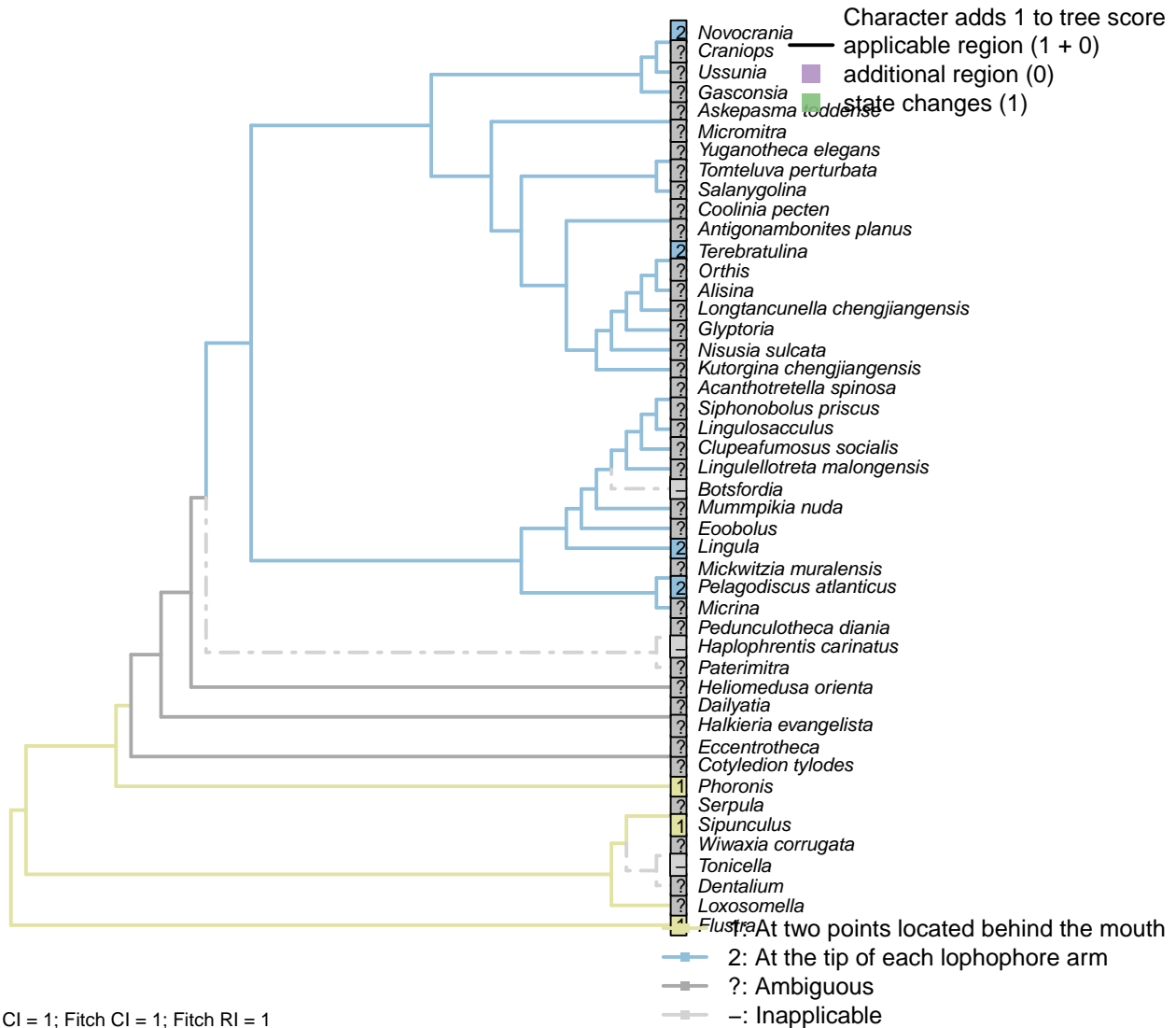
Neomorphic character.

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

Acanthotretella spinosa, *Alisina*, *Antigonombonites planus*, *Askepasma toddense*, *Clupeafumosus socialis*, *Coolinia pecten*, *Dailyatia*, *Eccentrotheca*, *Gasconsia*, *Glyptoria*, *Haplophrentis carinatus*, *Heliomedusa orienta*, *Kutorgina chengjiangensis*, *Lingulellotreta malongensis*, *Lingulosacculus*, *Longtancunella chengjiangensis*, *Micrina*, *Micromitra*, *Mummipikia nuda*, *Namacalathus*, *Nisusia sulcata*, *Orthis*, *Paterimitra*, *Pedunculotheca diania*, *Salanygolina*, *Tomteluva perturbata*, *Yuganotheca elegans*: Lophophore ontogeny presently unknown.

Loxosomella: Nielsen (1966).

[35] Site of tentacle addition

**Character 35: Perioral tentacular apparatus: Site of tentacle addition**

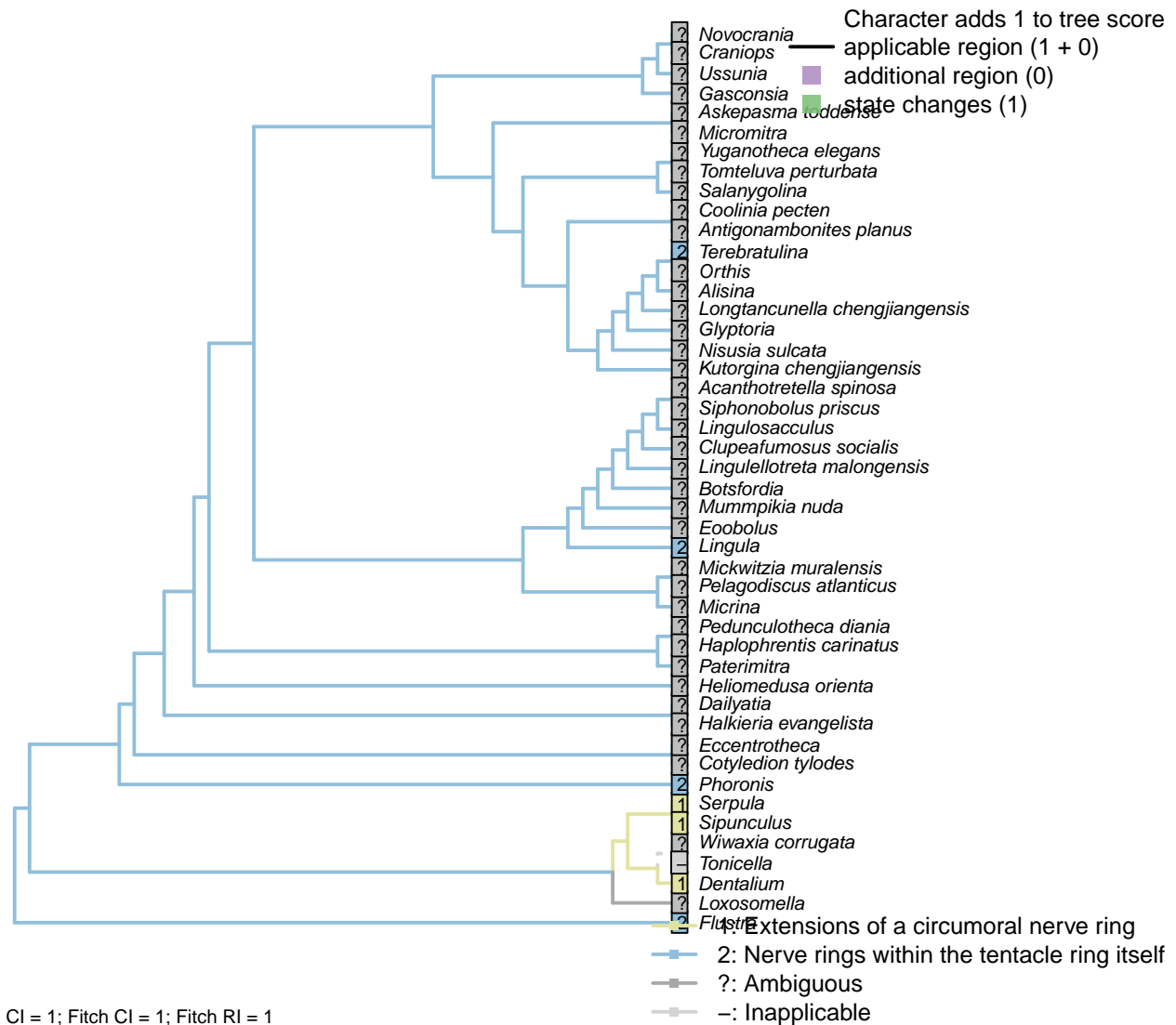
1: At two points located behind the mouth

2: At the tip of each lophophore arm

Transformational character.

Following Temereva (2017).

Flustra, *Lingula*, *Novocrania*, *Pelagodiscus atlanticus*, *Terebratulina*: Following Temereva (2017).*Phoronis*: Following Temereva (2017) – though in larvae, tentacles are added at the tips of the developing lophophore.*Sipunculus*: New branches added at each lateral extreme, behind mouth (Adrianov et al., 2006).

[36] Innervation**Character 36: Perioral tentacular apparatus: Innervation**

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

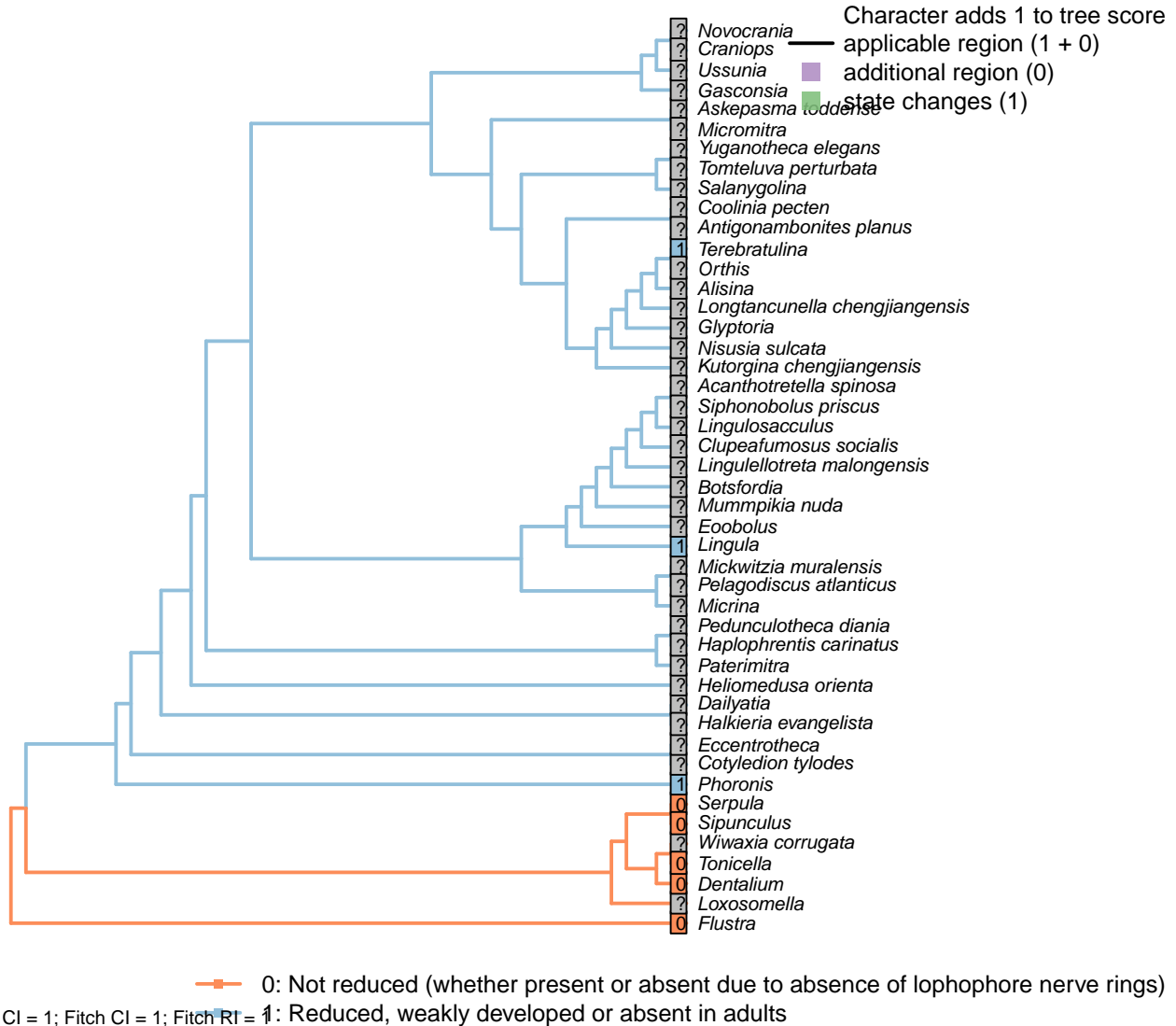
Annelid tentacles are innervated by palp nerves (Orrhage and Müller, 2005); lophophores ancestrally contained a pair of nerve rings (Temereva, 2017).

Dentalium: 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.

Serpula: Orrhage and Müller (2005).

Sipunculus: Rice (1993).

[37] Inner nerve ring

**Character 37: 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).

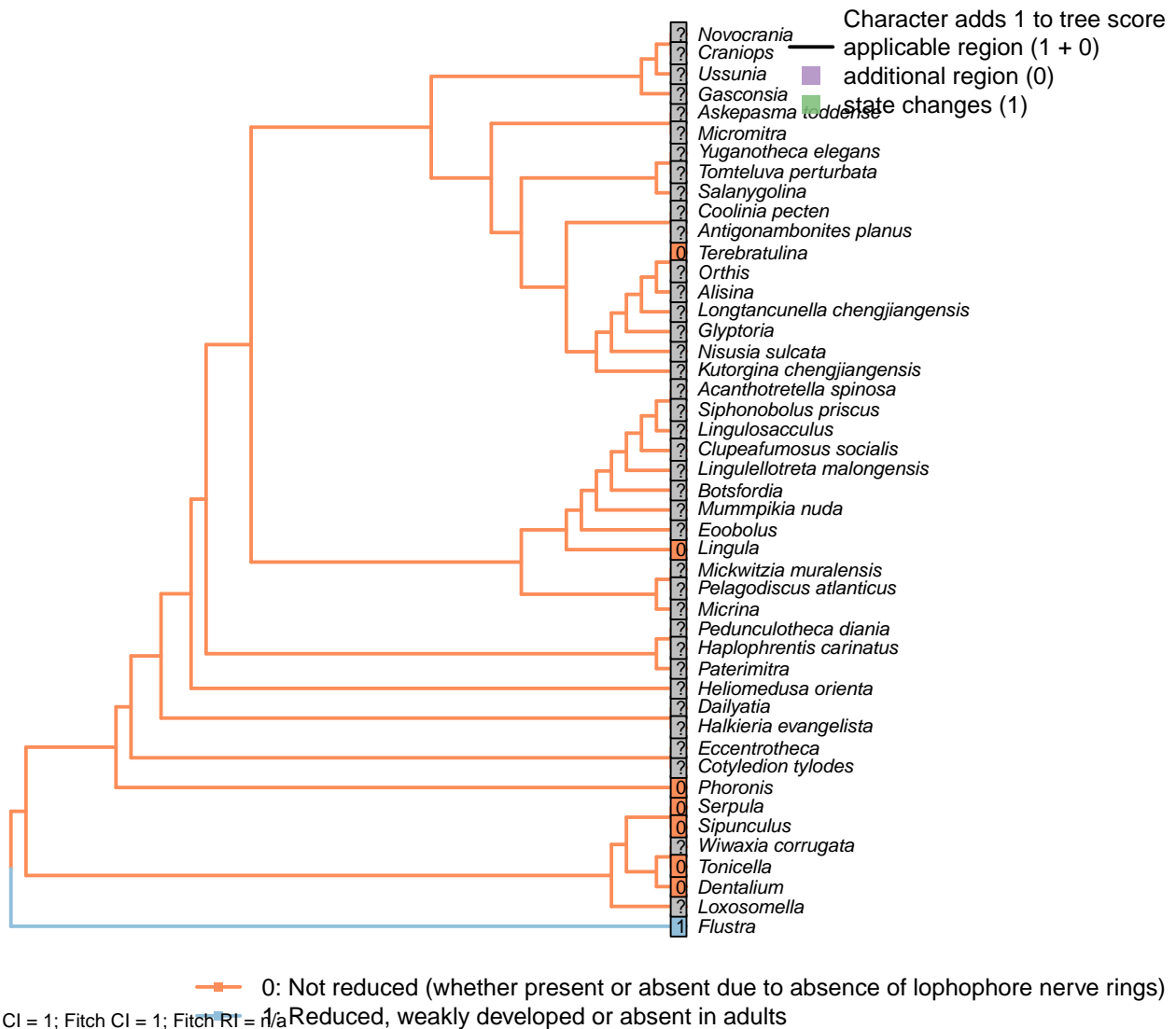
Flustra: Following Temereva (2017).

Lingula: Temereva and Kuzmina (2017).

Phoronis: (Temereva, 2017).

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

[38] Outer nerve ring

**Character 38: 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.

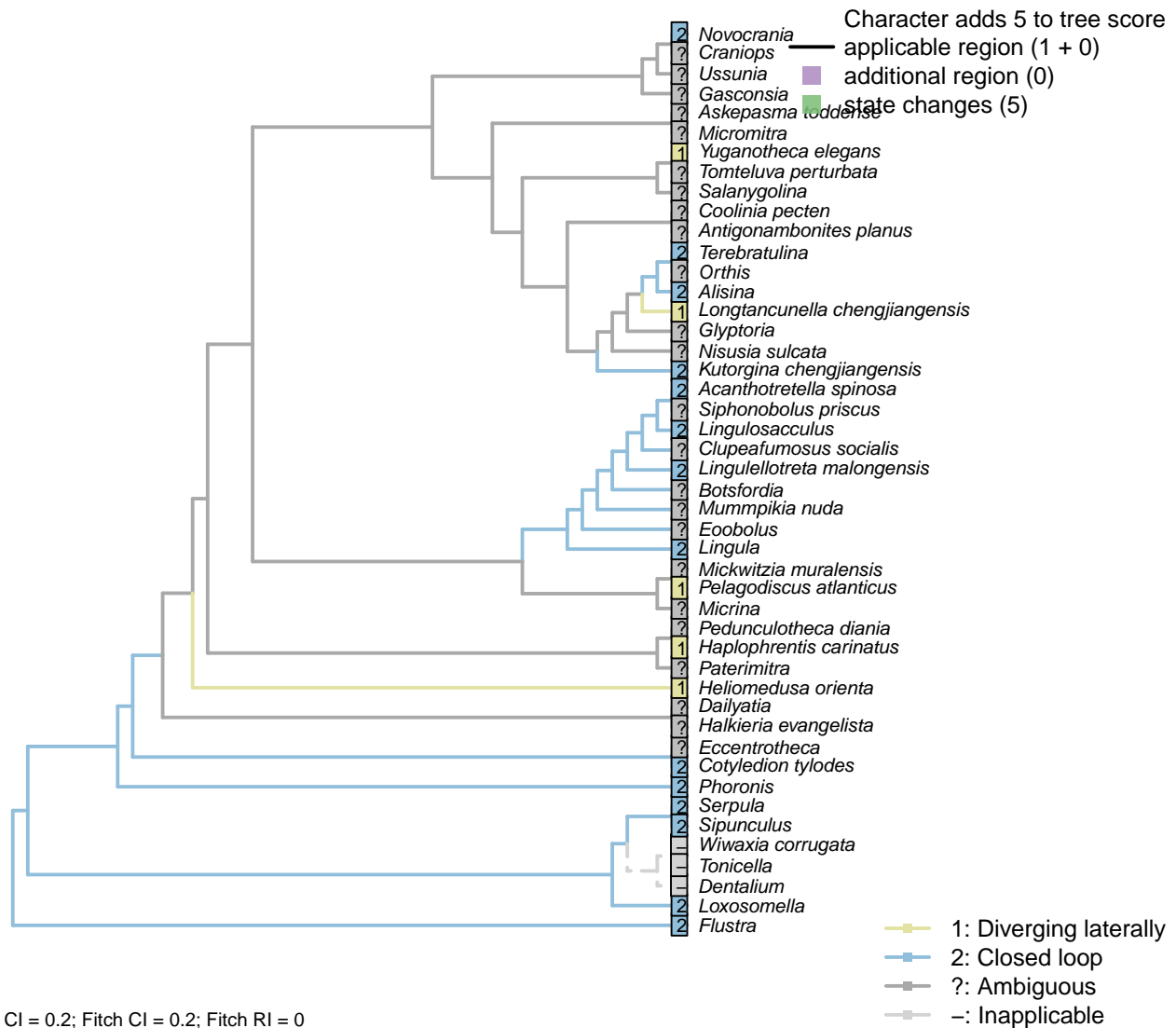
Juvenile lophophorates exhibit two nerve rings in the tentacles; one of these rings is often reduced or lost at adulthood (Temereva, 2017).

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

Lingula, *Terebratulina*: Temereva (2017).

Phoronis: Temereva and Kuzmina (2017).

[39] Forms closed loop

**Character 39: 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).

Cotyledion tylodes: Tentacles form almost complete circular crown.

Flustra: Two arms of lophophore but tentacles surround mouth in closed loop (Schwaha and Wanninger,

2015).

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

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

Loxosomella: Nielsen (1966).

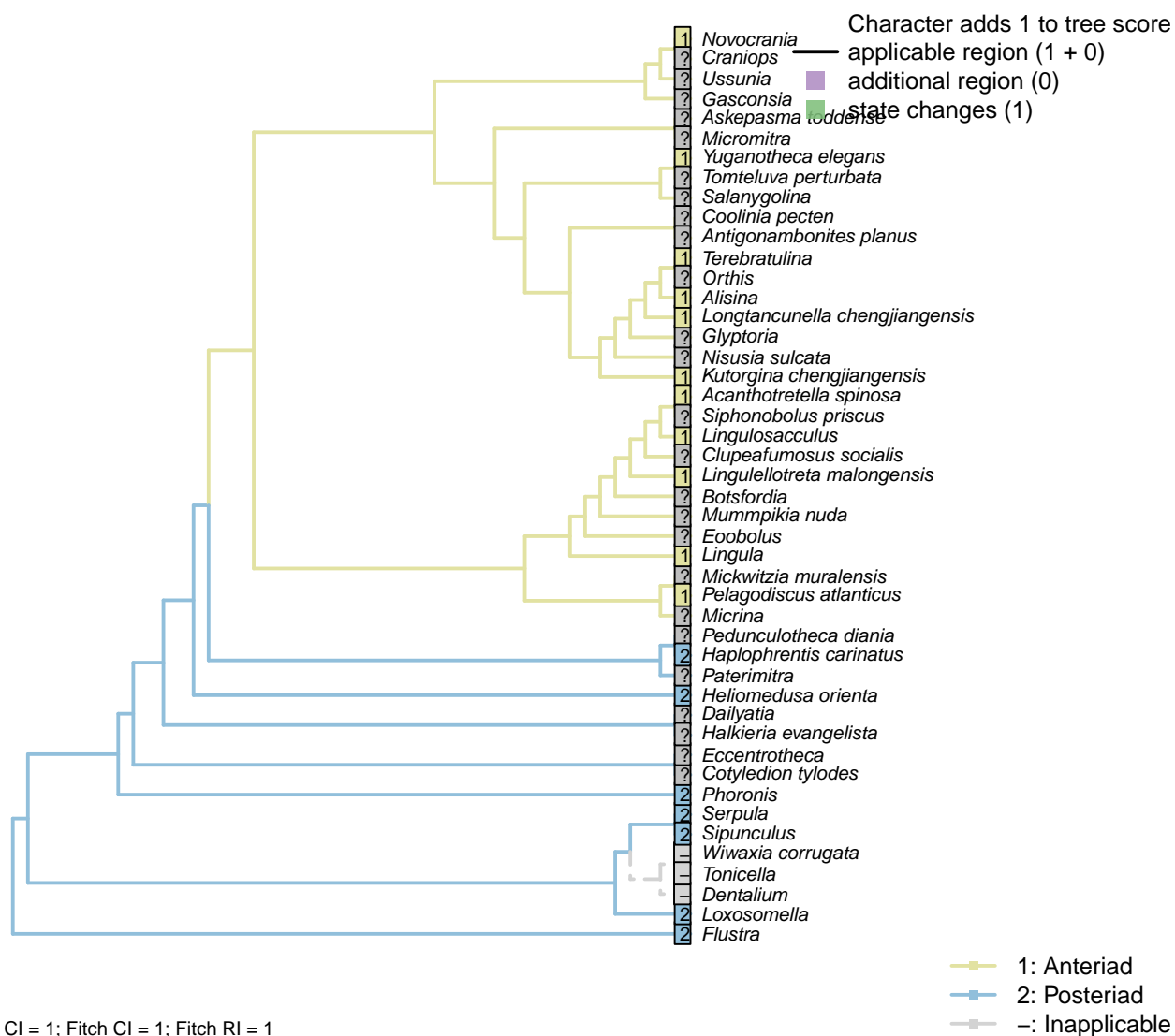
Namacalathus: The existence of a lophophore is speculative.

Nisusia sulcata: No specimens of *Nisusia* preserve the lophophore.

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

Serpula, *Sipunculus*: Growing to encircle mouth in adults.

[40] 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).

Acanthotretella spinosa, *Lingulellotreta malongensis*: Arms proceed anteriad before recurving.

Cotyledion tylodes: Cannot establish without distinguishing gut from anus.

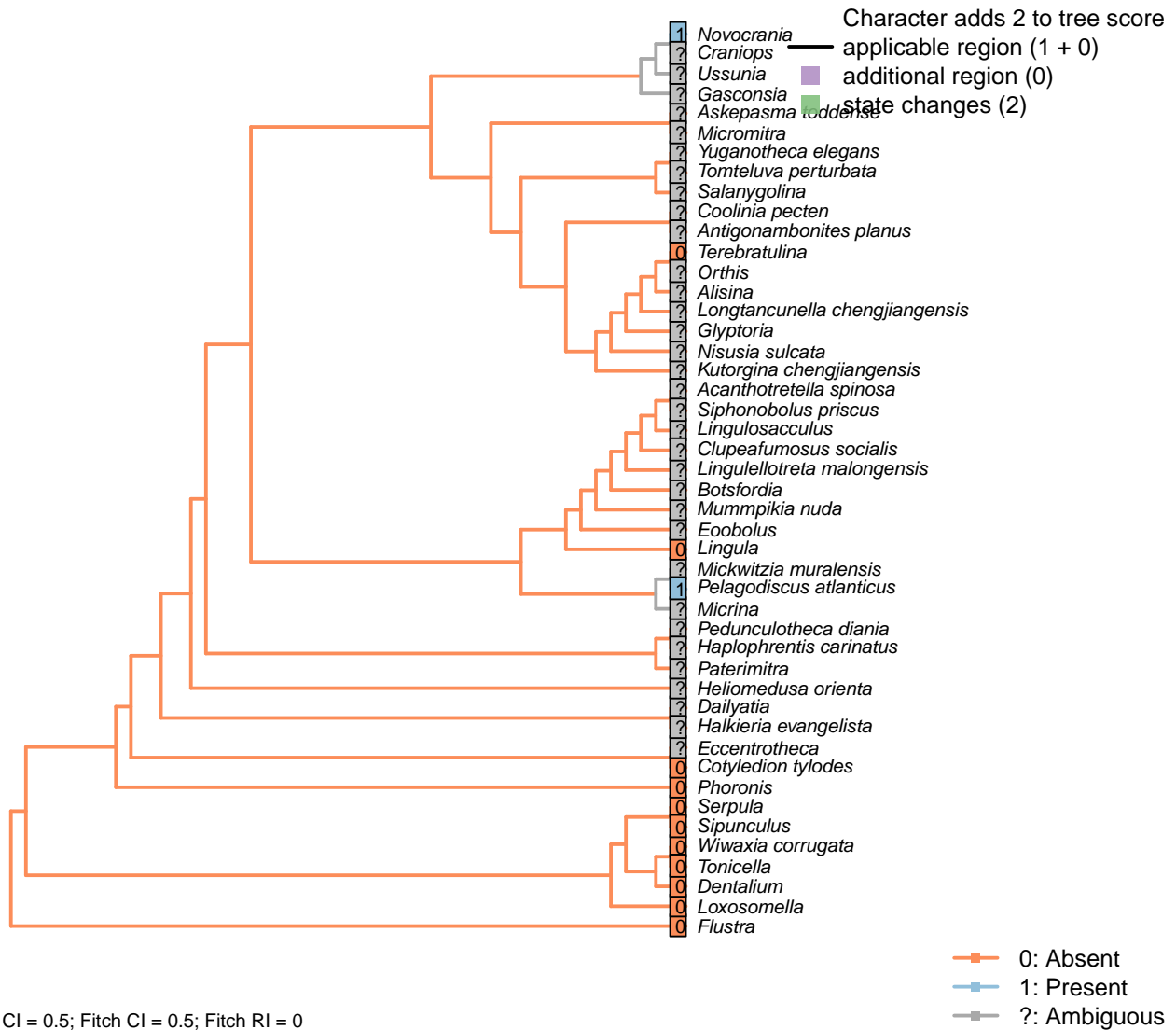
Flustra: Arms reach in anal (i.e. posterior) direction (Shunkina et al., 2015).

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

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

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

[41] Adjustor muscle



Character 41: Perioral tentacular apparatus: Adjustor muscle

0: Absent

1: Present

Neomorphic character.

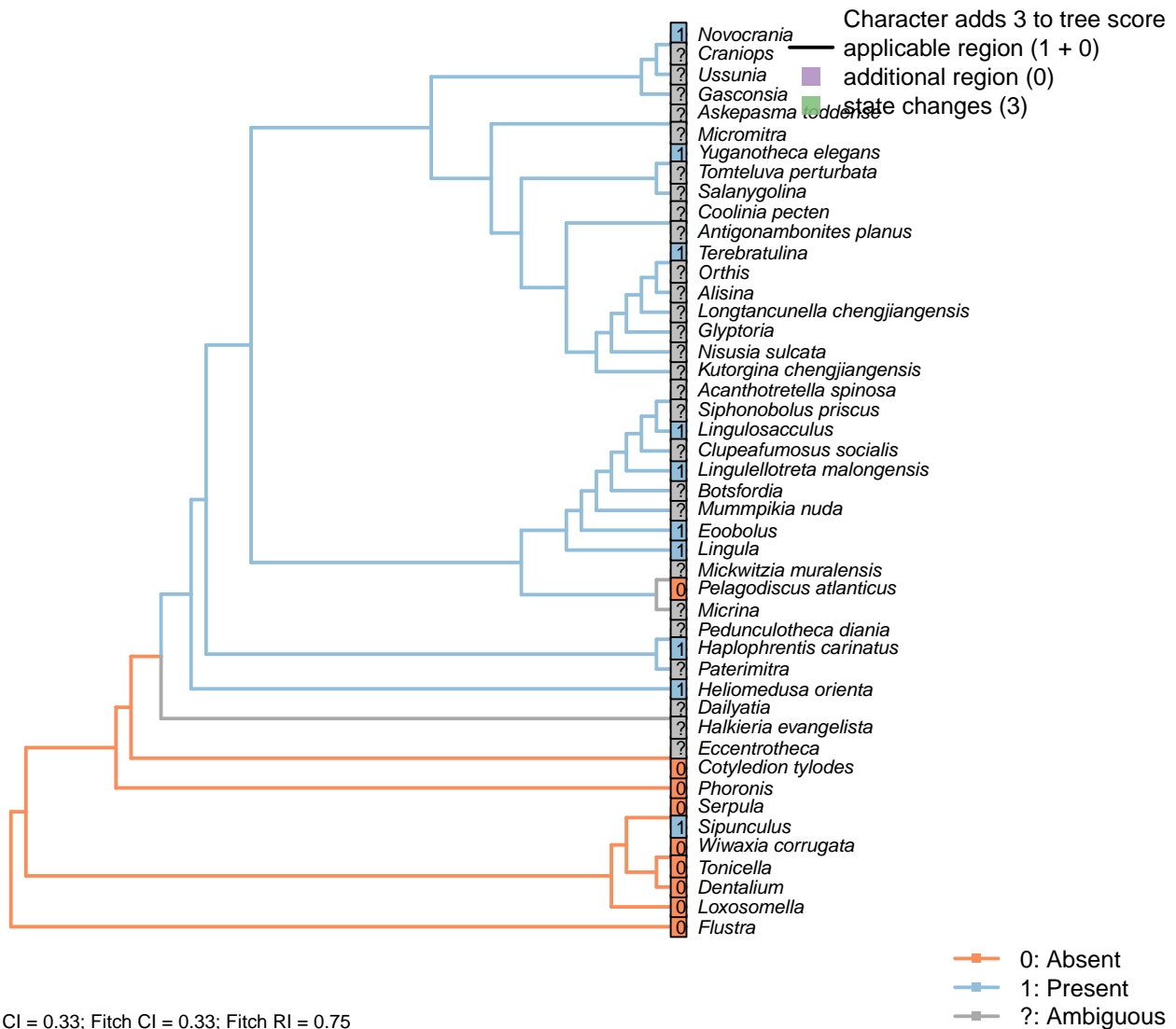
Following character 55 in Carlson (1995). Not possible to code in most fossil taxa.

Acanthotretella spinosa, *Alisina*, *Antigonambonites planus*, *Askepasma toddense*, *Clupeafumosus socialis*, *Coolinia pecten*, *Dailyatia*, *Eccentrotheca*, *Gasconsia*, *Glyptoria*, *Haplophrentis carinatus*, *Heliomedusa orientalis*, *Kutorgina chengjiangensis*, *Lingulelloireta malongensis*, *Lingulosacculus*, *Longtancunella chengjiangensis*, *Micrina*, *Micromitra*, *Mummpikia nuda*, *Namacalathus*, *Nisusia sulcata*, *Orthis*, *Paterimitra*, *Pedunculotheca diania*, *Salanygolina*, *Tomteluva perturbata*, *Yuganotheca elegans*: Preservation not adequate to evaluate presence or absence of this muscle.

Lingula, *Novocrania*, *Pelagodiscus atlanticus*, *Phoronis*, *Terebratulina*: Following coding for higher taxon in Carlson (1995), appendix 1, character 55.

3.9 Digestive tract

[42] Prominent pharynx



Character 42: Digestive tract: Prominent pharynx

0: Absent

1: Present

Neomorphic character.

Hyaloliths 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*.

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

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

Lingulellotreta malongensis: An anterior projection of the visceral area is noted by Williams et al. (2000)

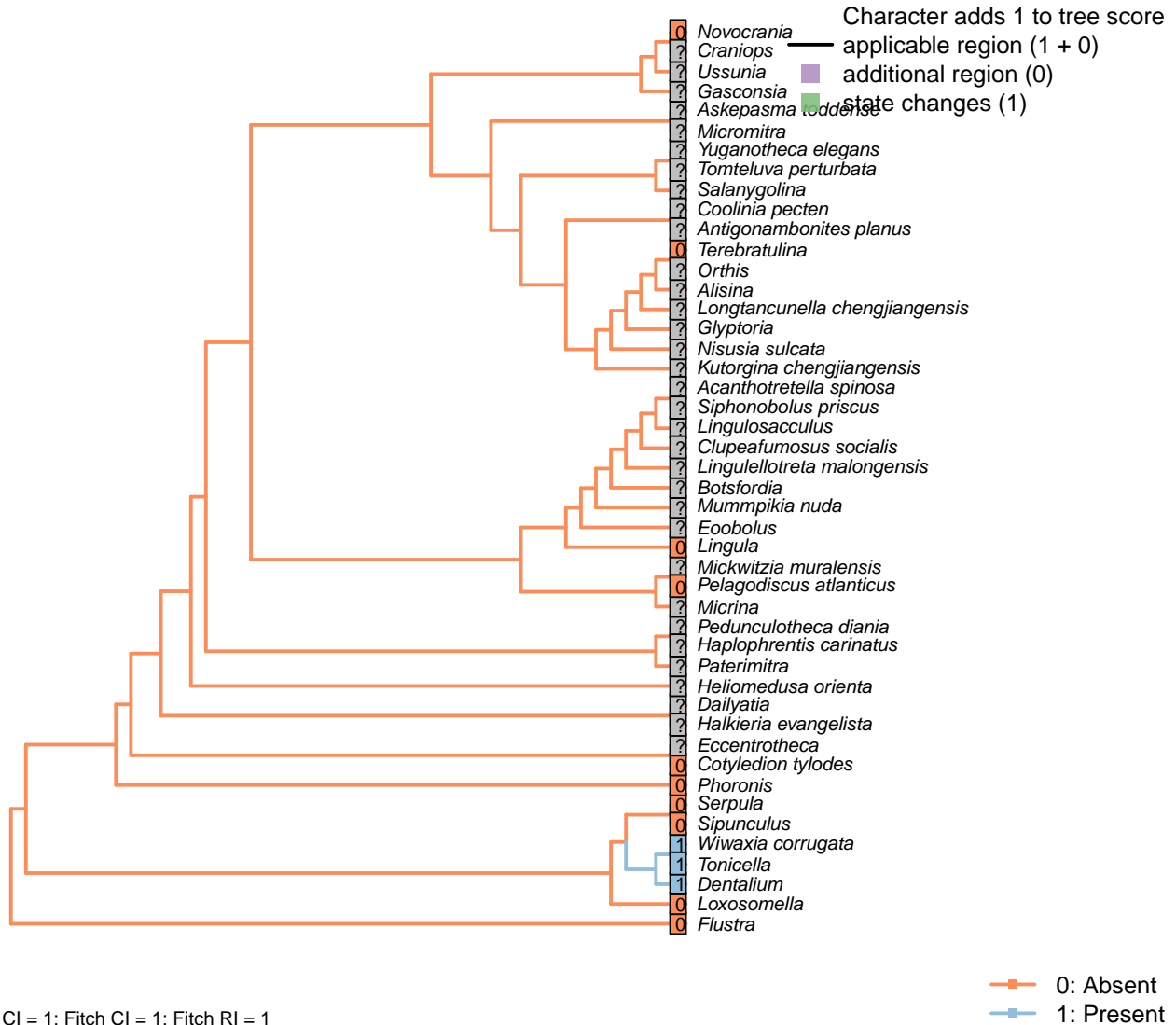
and considered equivalent to that observed in *Lingulosacculus* (Balthasar and Butterfield, 2009).

Lingulosacculus: 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).

Sipunculus: Eversible pharynx (introvert).

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

[43] Radula



Character 43: Digestive tract: Radula

0: Absent

1: Present

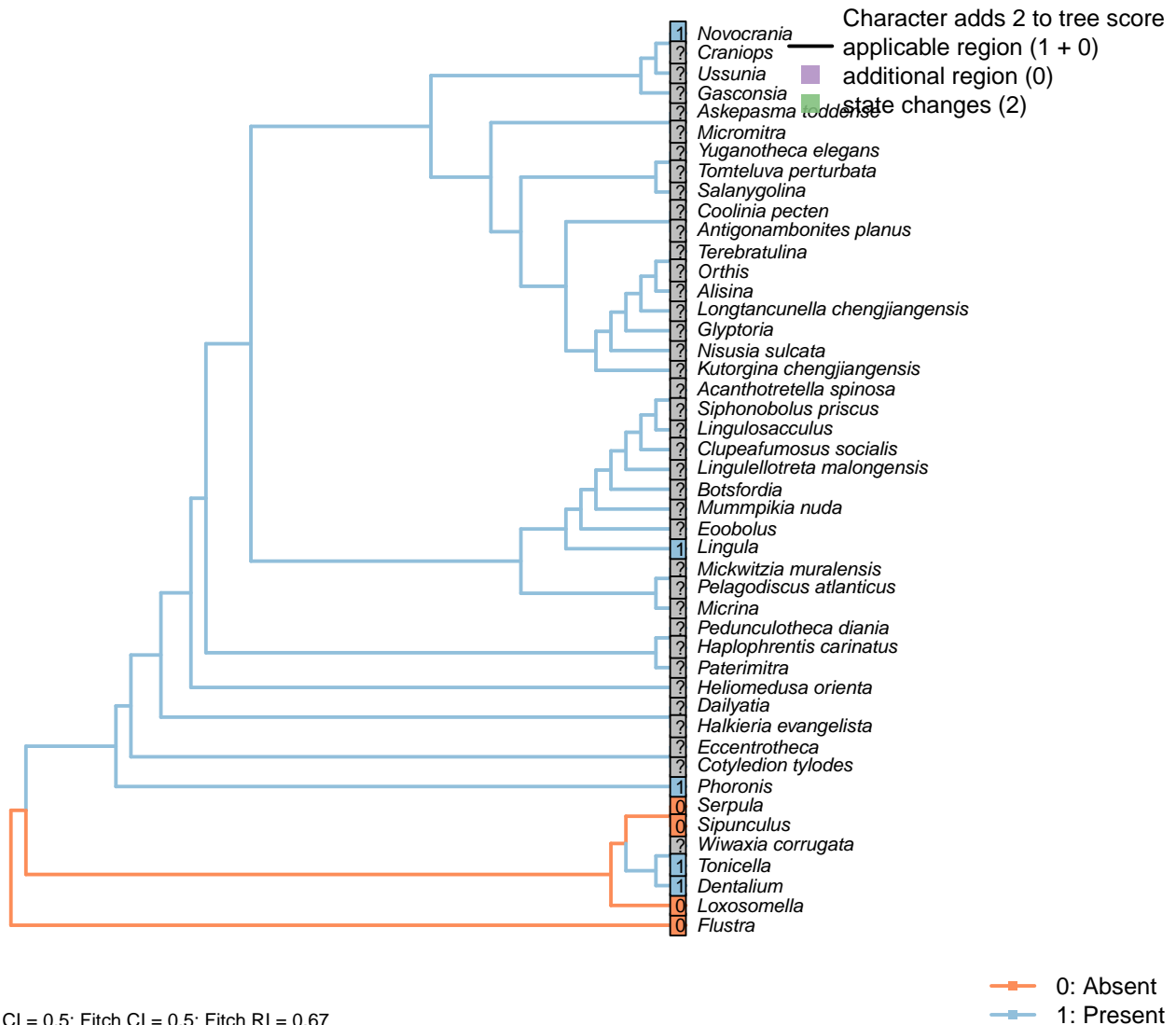
Neomorphic character.

Any apparatus comprising multiple denticulate rows arranged serially in the sagittal plane is treated as

potentially homologous with the molluscan radula.

Wiwaxia corrugata: Smith (2012b).

[44] Oesophageal folds



Character 44: Digestive tract: Oesophageal folds

0: Absent

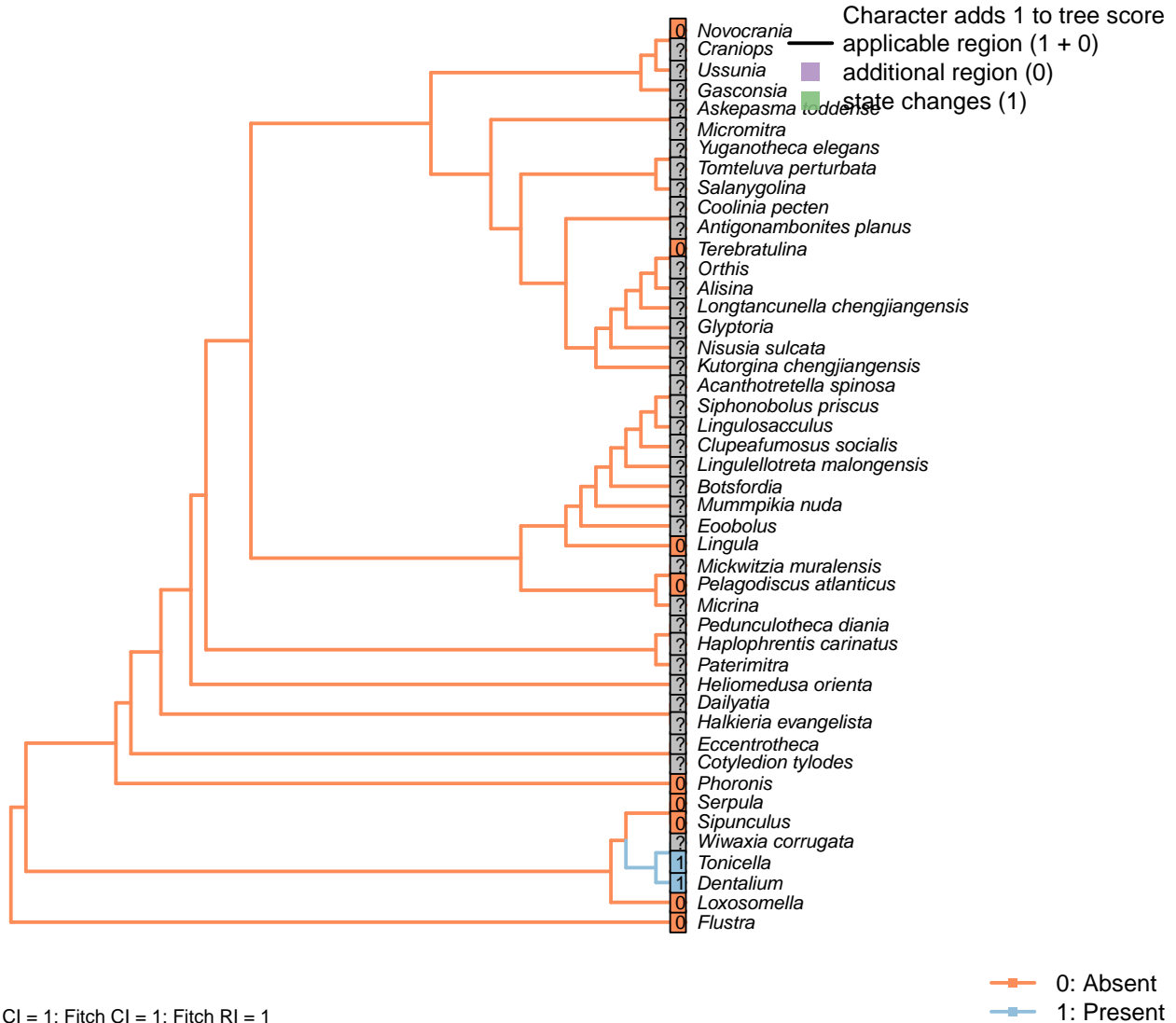
1: Present

Neomorphic character.

Following character 86 in Giribet and Wheeler (2002).

Phoronis: Ciliated ridge in oesophagus (Torrey, 1901).

[45] Oral sphincter



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

Character 45: Digestive tract: Oral sphincter

0: Absent

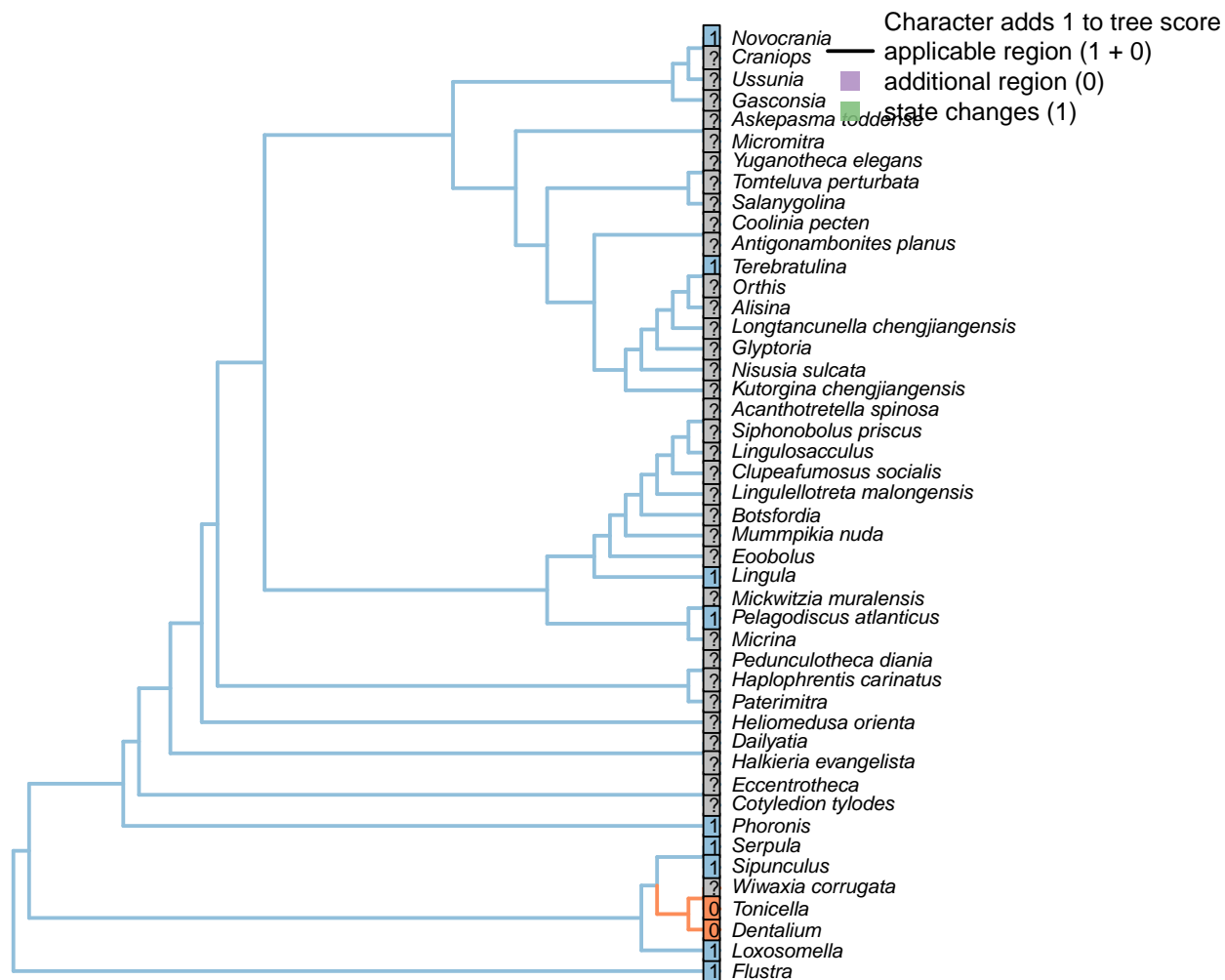
1: Present

Neomorphic character.

Character 133 in Grobe (2007).

Dentalium: Present, but secondarily reduced.

[46] Locomotory cilia



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

0: Absent
 1: Present

Character 46: Digestive tract: Foregut: Locomotory cilia

0: Absent

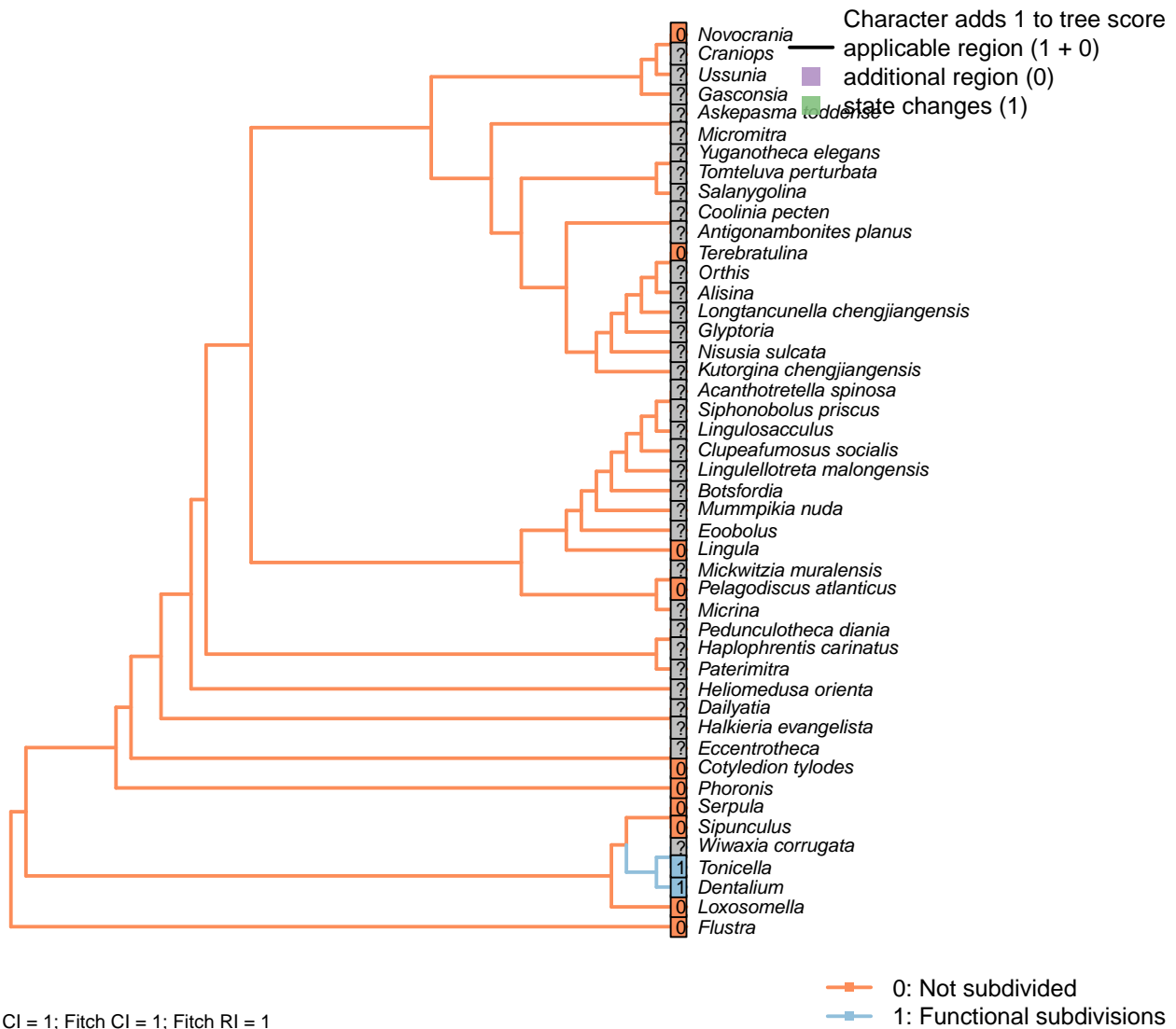
1: Present

Neomorphic character.

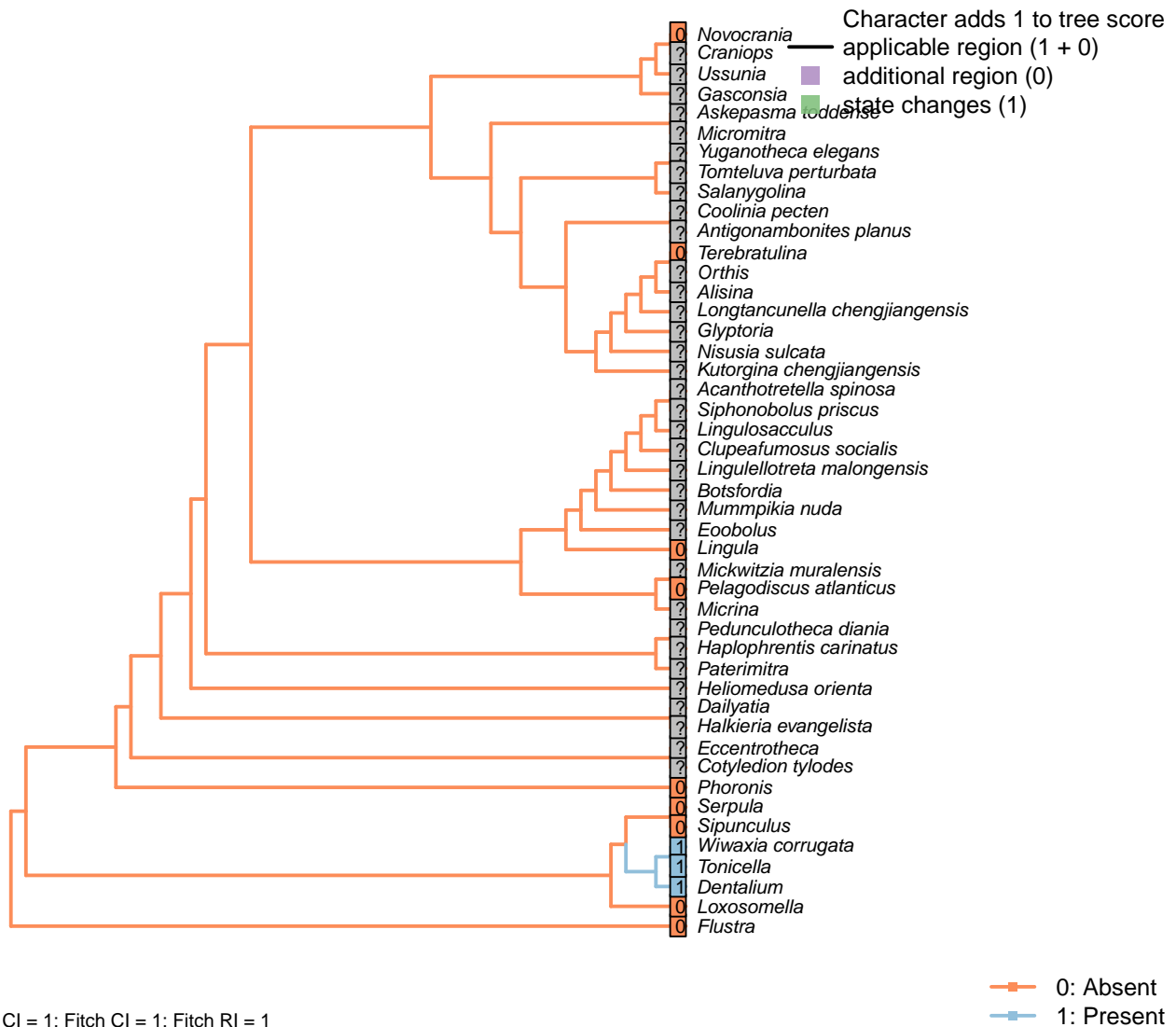
Character 66 in Haszprunar (2000).

3.10 Digestive tract: Midgut

[47] Subdivisions

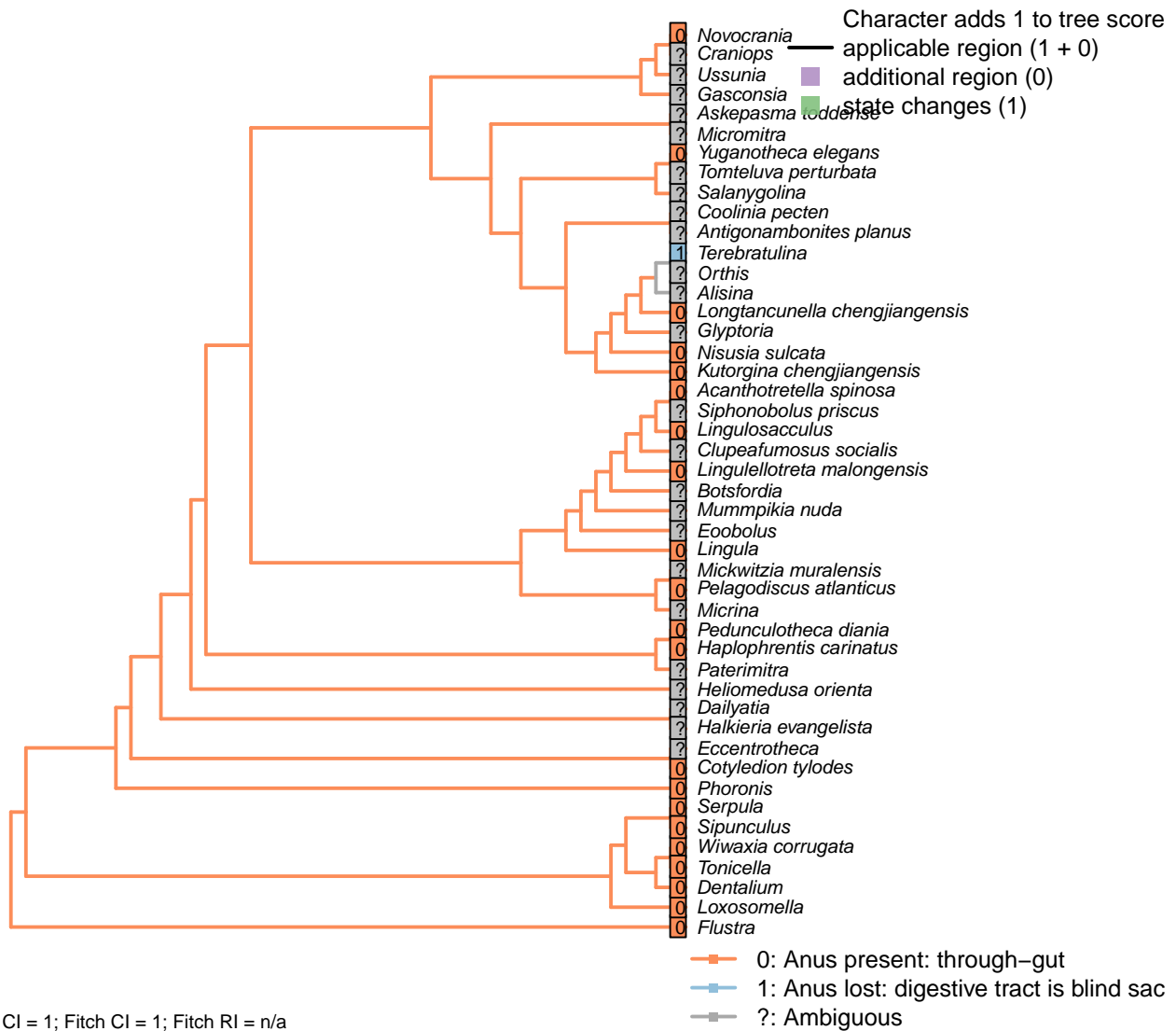


[48] Glands



3.11 Digestive tract: Anus

[49] Presence



Character 49: Digestive tract: Anus: Presence

0: Anus present: through-gut

1: Anus lost: digestive tract is blind sac

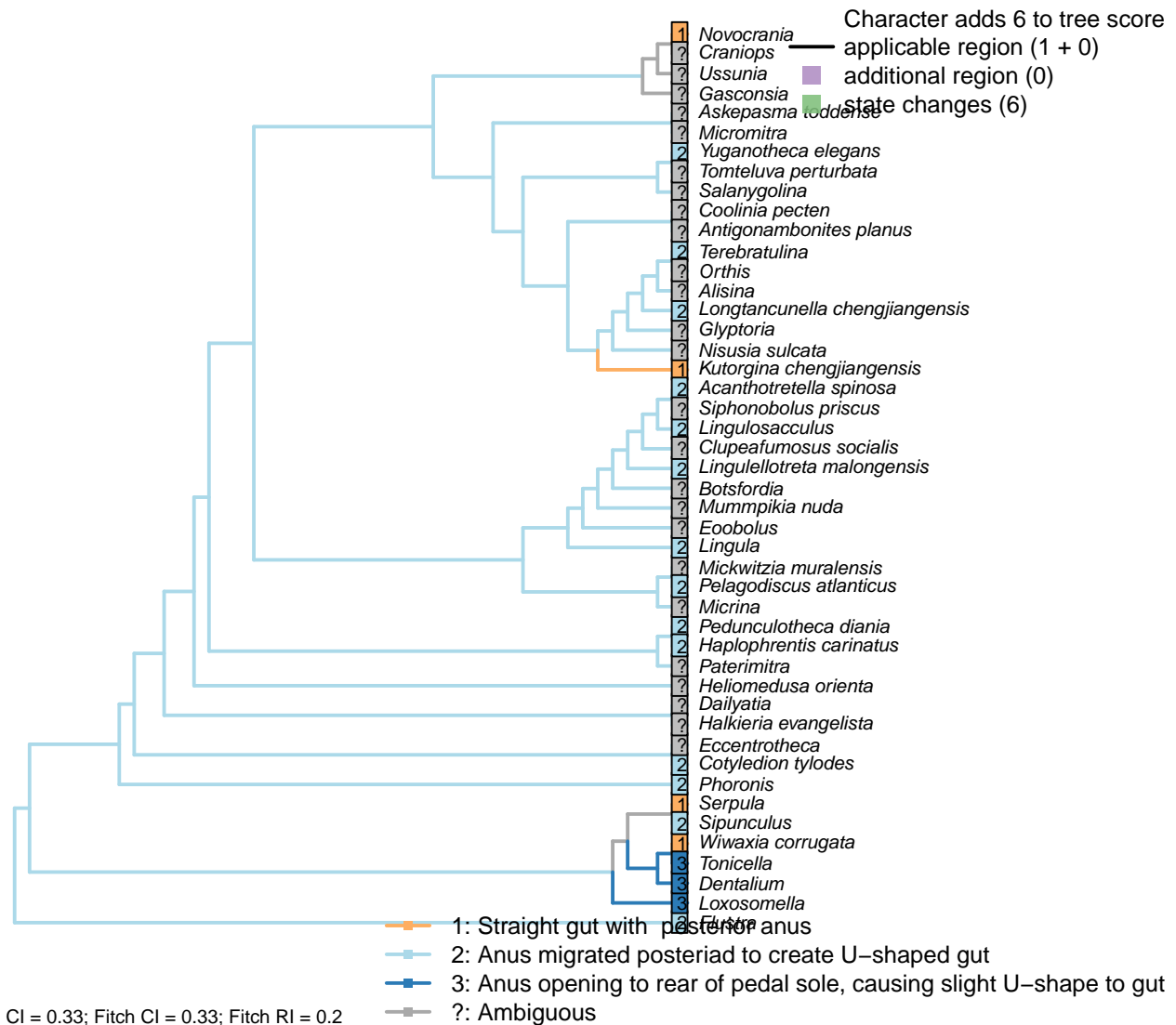
Neomorphic character.

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.

Glyptoria: Scored according to familial level feature.

Kutorgina chengjiangensis: 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.

[50] Location

**Character 50: 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).

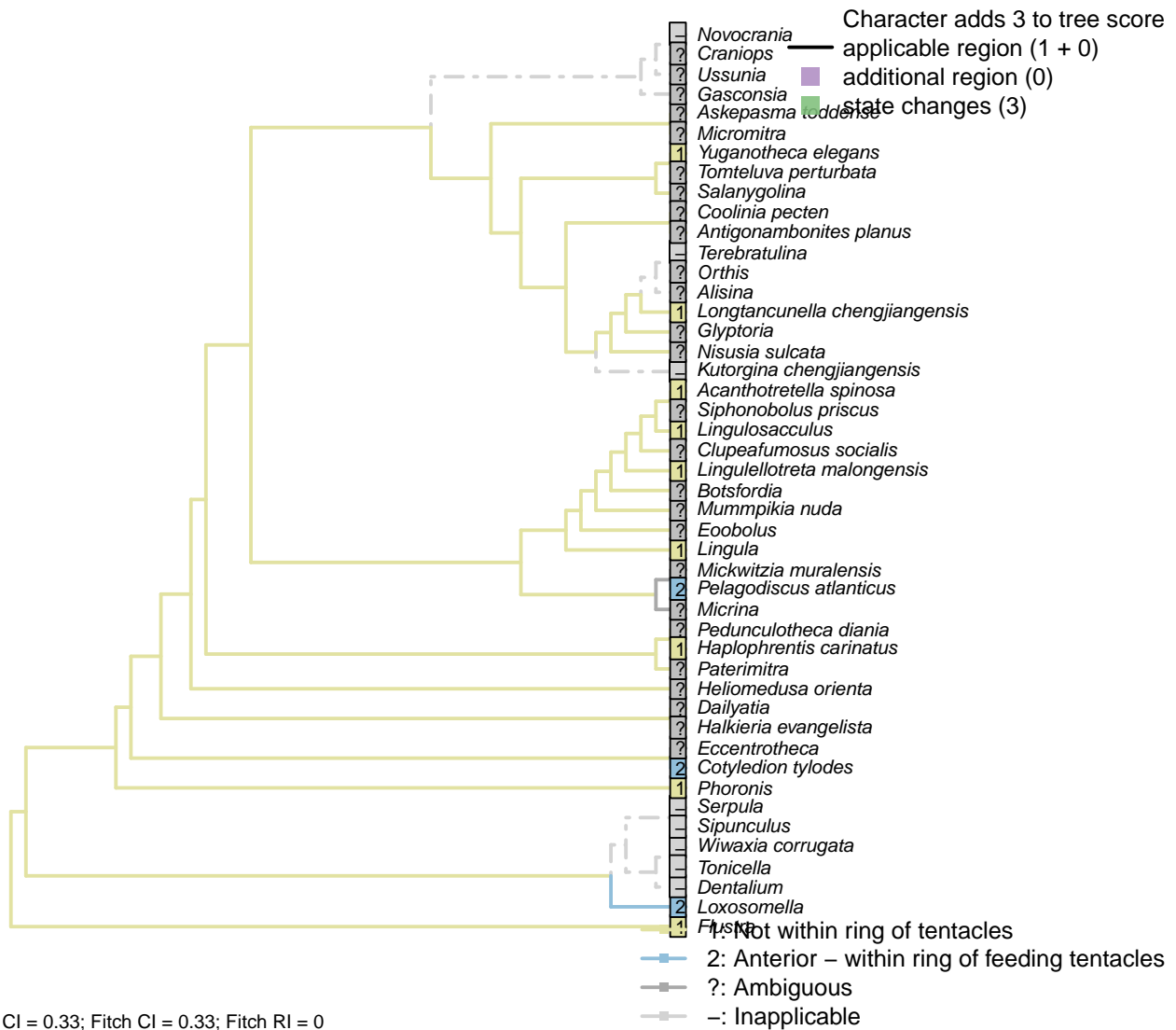
Dentalium: The U-shaped gut of scaphopods arises by exaggeration of the dorsal surface, rather than migration of the anus (Steiner, 1992).

Kutorgina chengjiangensis: “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).

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

2884.

[51] Migration: Within ring of tentacles

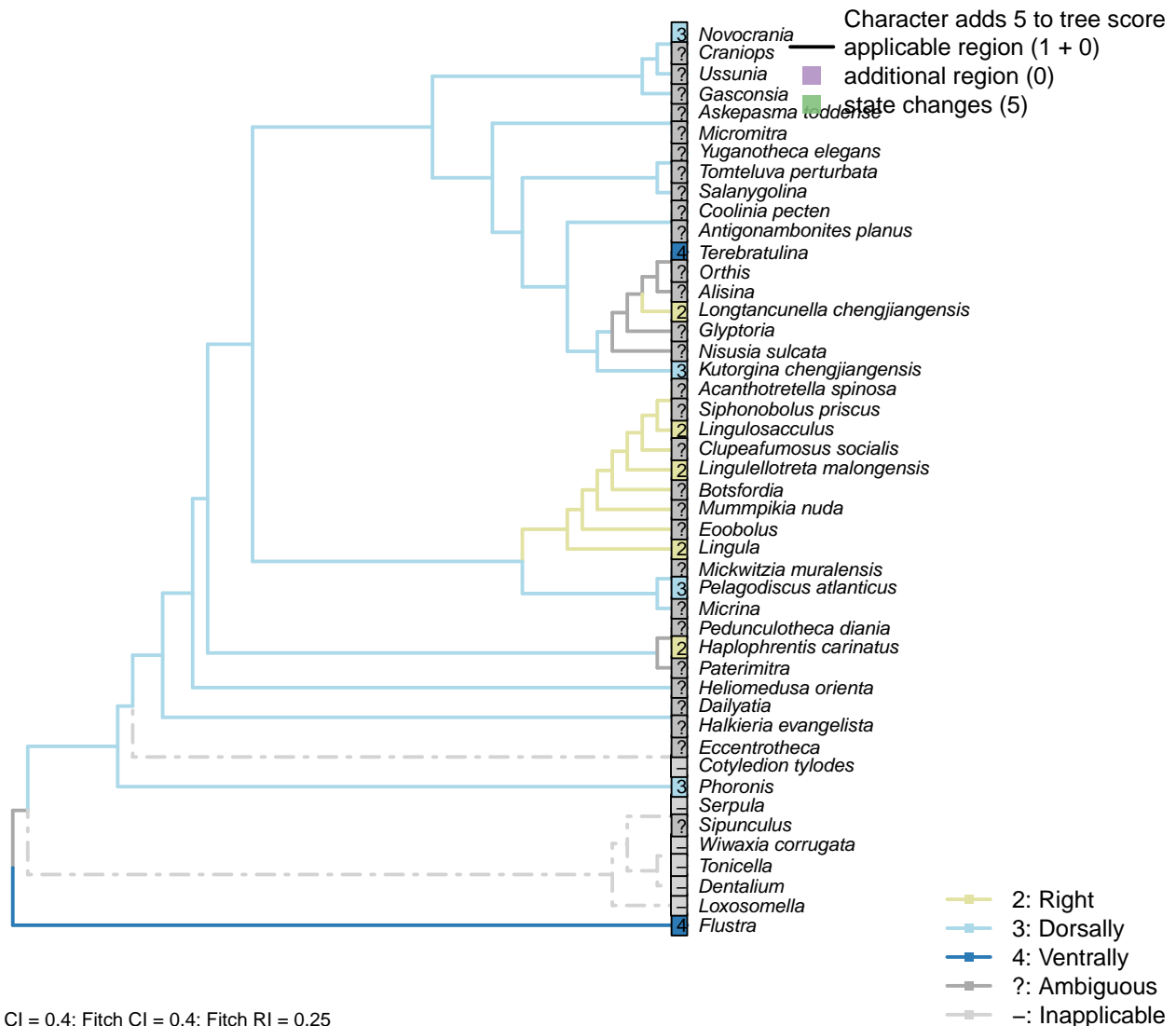
**Character 51: Digestive tract: Anus: Migration: Within ring of tentacles**

- 1: Not within ring of tentacles
 - 2: Anterior - within ring of feeding tentacles
- Transformational character.

A migrated anus may be located laterally or within the lophophore ring (as in entoprocts).

Kutorgina chengjiangensis: “Presumed to terminate in a functional anus located near the proximal end of the pedicle.” – Zhang et al. (2007b).

[52] Migration: Position

**Character 52: Digestive tract: Anus: Migration: Position**

- 1: Left
- 2: Right
- 3: Dorsally
- 4: Ventrally

Transformational character.

If the anus is not within the ring of tentacles, in which direction is it oriented?.

Dentalium: An alternative interpretation would be that the posterior of the scaphopod has been extended to generate the relatively anterior position of the originally ventral anus.

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

Haplophrentis carinatus: Opening to the right – see figures 1, 3, and extended data 5 in Moysiuk *et al.* (2017).

The text states in error that the anus is to the left of the midline.

Kutorgina chengjiangensis: “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).

Lingula: “In the lingulids, the [intestine] follows an oblique course anteriorly to open at the anus on the right body wall.” – Williams et al. (1997), p. 89.

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

Lingulosacculus: “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).

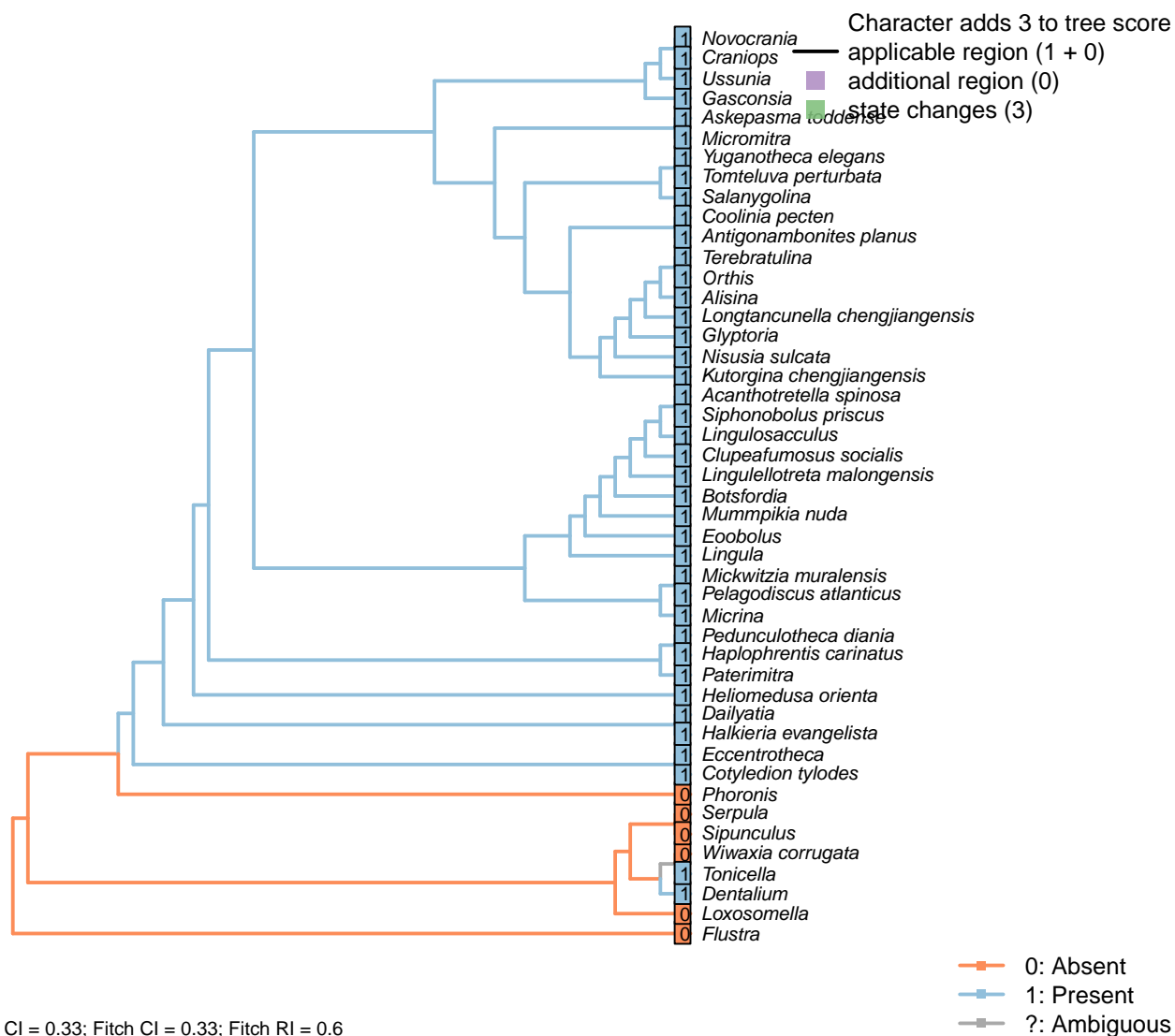
Longtancunella chengjiangensis: “The intestine extends posteriorly, and then turns right to continue as a tortuous strand, finally terminating at the latero-median position of the anterior body wall” – Zhang et al. (2007c).

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

Yuganotheca elegans: 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.

3.12 Sclerites

[53] Present in adult



Character 53: 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).

Dentalium, *Tonicella*: Molluscan valves are treated as potential homologues of brachiopod valves.

Halkieria evangelista: Halkieriid sclerites are interpreted as potentially homologous with those of *Dailyatia*

and hence the brachiopods (Zhao et al., 2017).

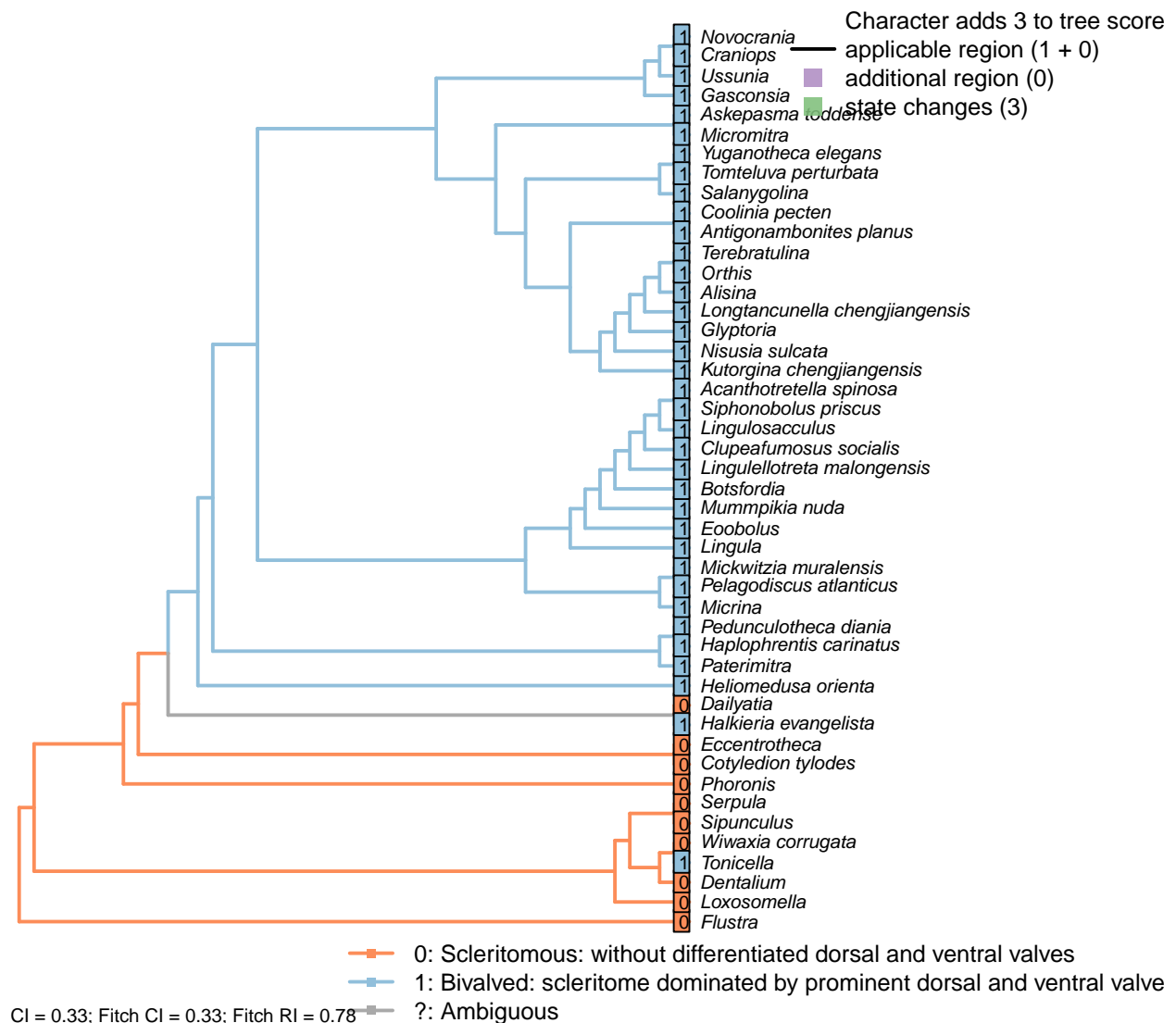
Namacalathus: The mineralized endoskeleton of *Namacalathus* is not interpreted as a sclerite.

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

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

Wiwaxia corrugata: 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.

3.13 Sclerites: Bivalved [54]



Character 54: Sclerites: Bivalved

0: Scleritinous: without differentiated dorsal and ventral valves

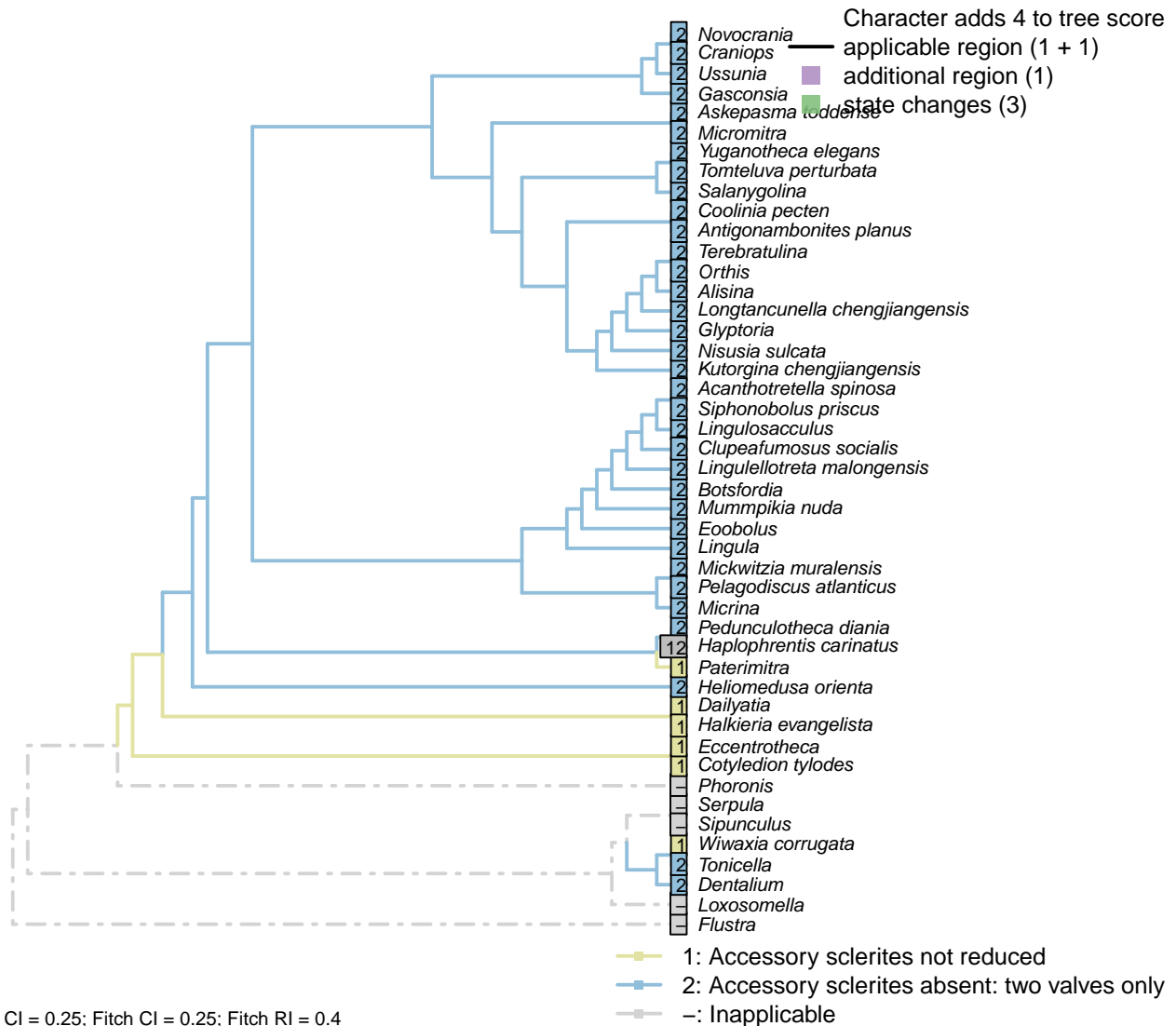
1: Bivalved: scleritome dominated by prominent dorsal and ventral valve

Neomorphic character.

Scleritome dominated by prominent differentiated dorsal and ventral valves.

Tonicella: As larvae, polyplacophorans exhibit an anterior and a posterior shell field (Wanninger 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.

[55] Accessory sclerites reduced



origin of brachiozoans (and Lophotrochozoans more generally) from a scleritinous organism.

Dentalium: 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.

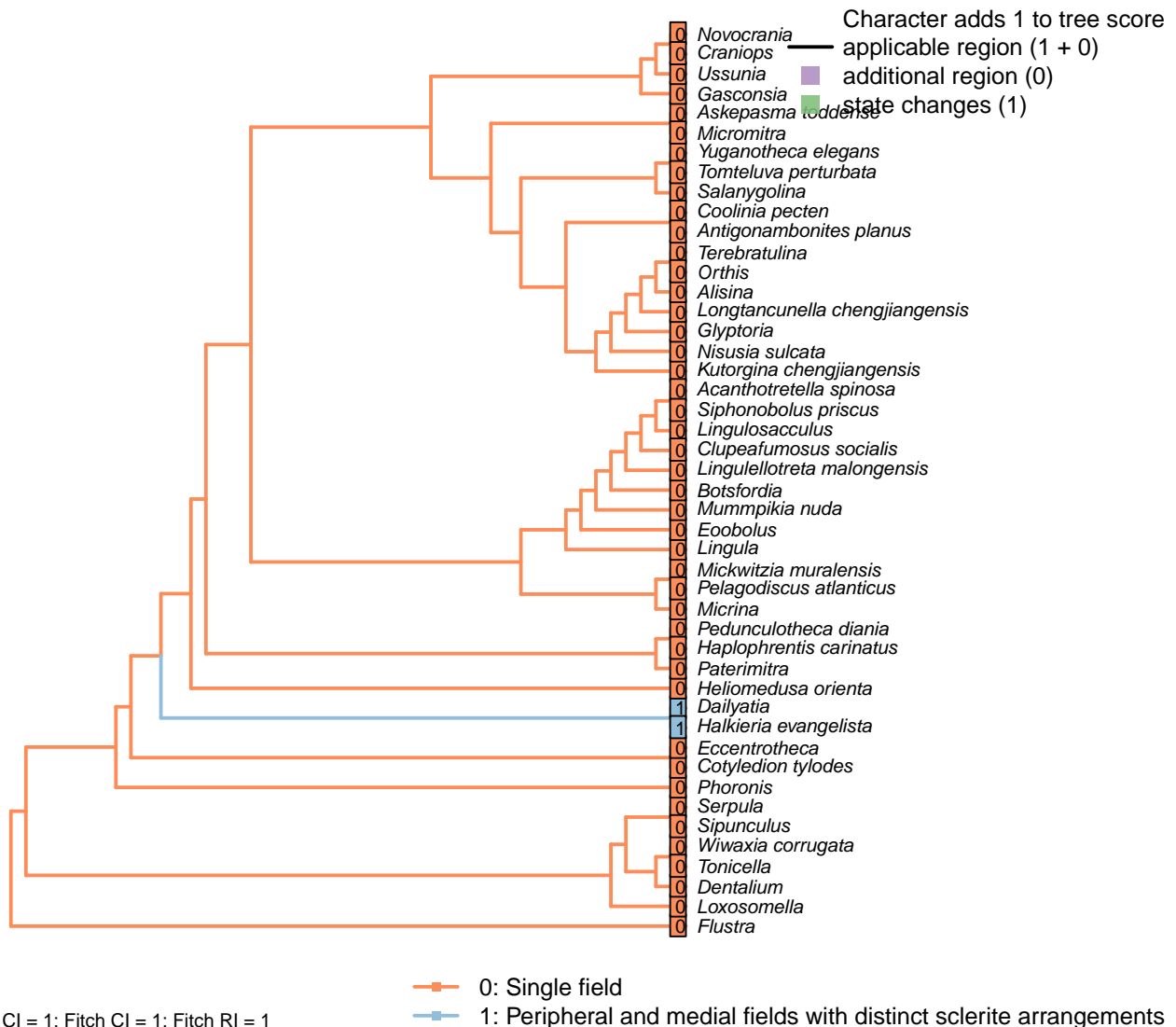
Haplophrentis carinatus: Coded as ambiguous to recognize the possibility that helens may correspond to L-elements of *Paterimitra* (Moysiuk et al., 2017).

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

Tonicella: The intermediate shell plates arise by subdivision of the posterior shell field (Wanninger 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.

3.14 Sclerites: Accessory sclerites

[56] Arrangement



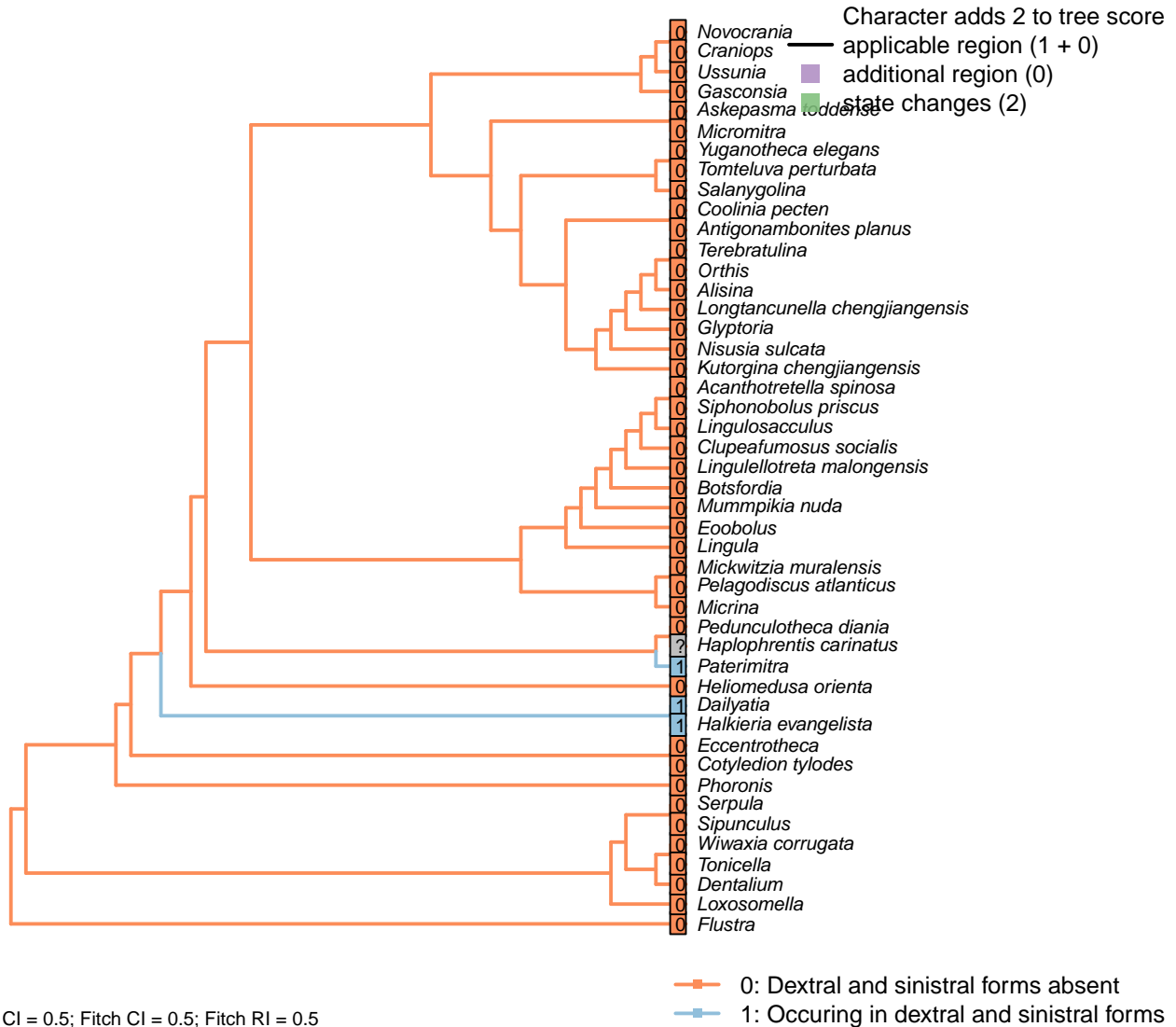
Character 56: Sclerites: Accessory sclerites: Arrangement

0: Single field

1: Peripheral and medial fields with distinct sclerite arrangements

Neomorphic character.

Following Zhao et al. (2017).

Dailyatia: Following the reconstruction of Skovsted et al. (2015).**[57] Symmetry****Character 57: Sclerites: Accessory sclerites: Symmetry**

0: Dextral and sinistral forms absent

1: Occuring in dextral and sinistral forms

Neomorphic character.

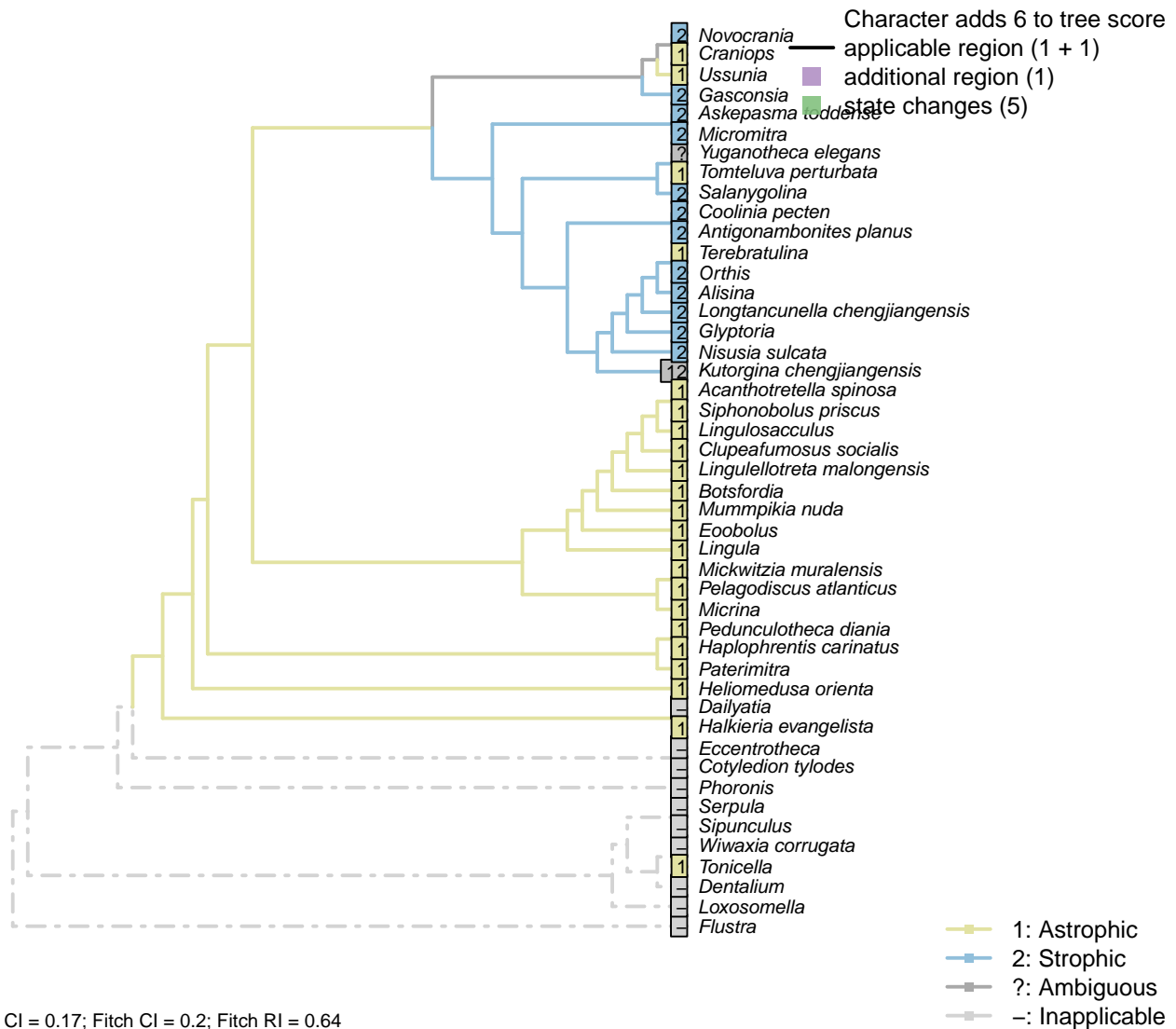
Following Zhao et al. (2017).

Eccentrotheca: Skovsted et al. (2008).

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

3.15 Sclerites: Bivalved

[58] Hinge line shape



Character 58: Sclerites: Bivalved: Hinge line shape

1: Astrophic

2: Strophic

Transformational character.

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

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

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

Halkieria evangelista, *Mickwitzia muralensis*: Non-strophic.

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

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

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

Nisusia sulcata: “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).

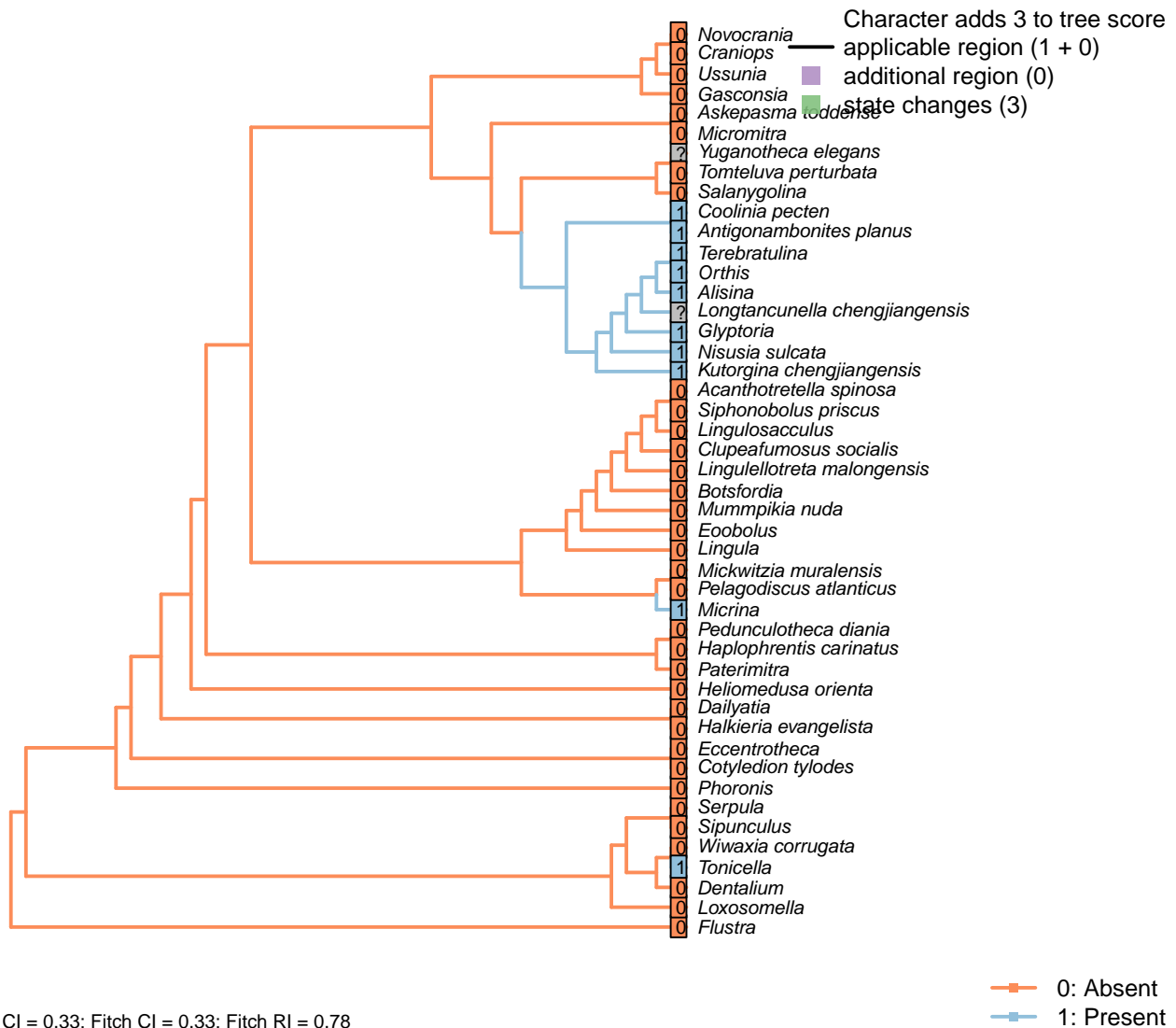
Novocrania: Craniides have a strophic posterior valve edge (Williams *et al.*, 2007, table 39 on p. 2853): *Novocrania*’s “dorsal posterior margin” is “straight” (Williams *et al.*, 2000, p. 171).

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

Tonicella: 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).

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

[59] Apophyses

**Character 59: 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.

Alisina: “Strophic articulation with paired, ventral denticles, composed of secondary shell” – definition of

family Trematobolidae in Williams et al. (2000).

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

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

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

Mummpikia nuda: 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.

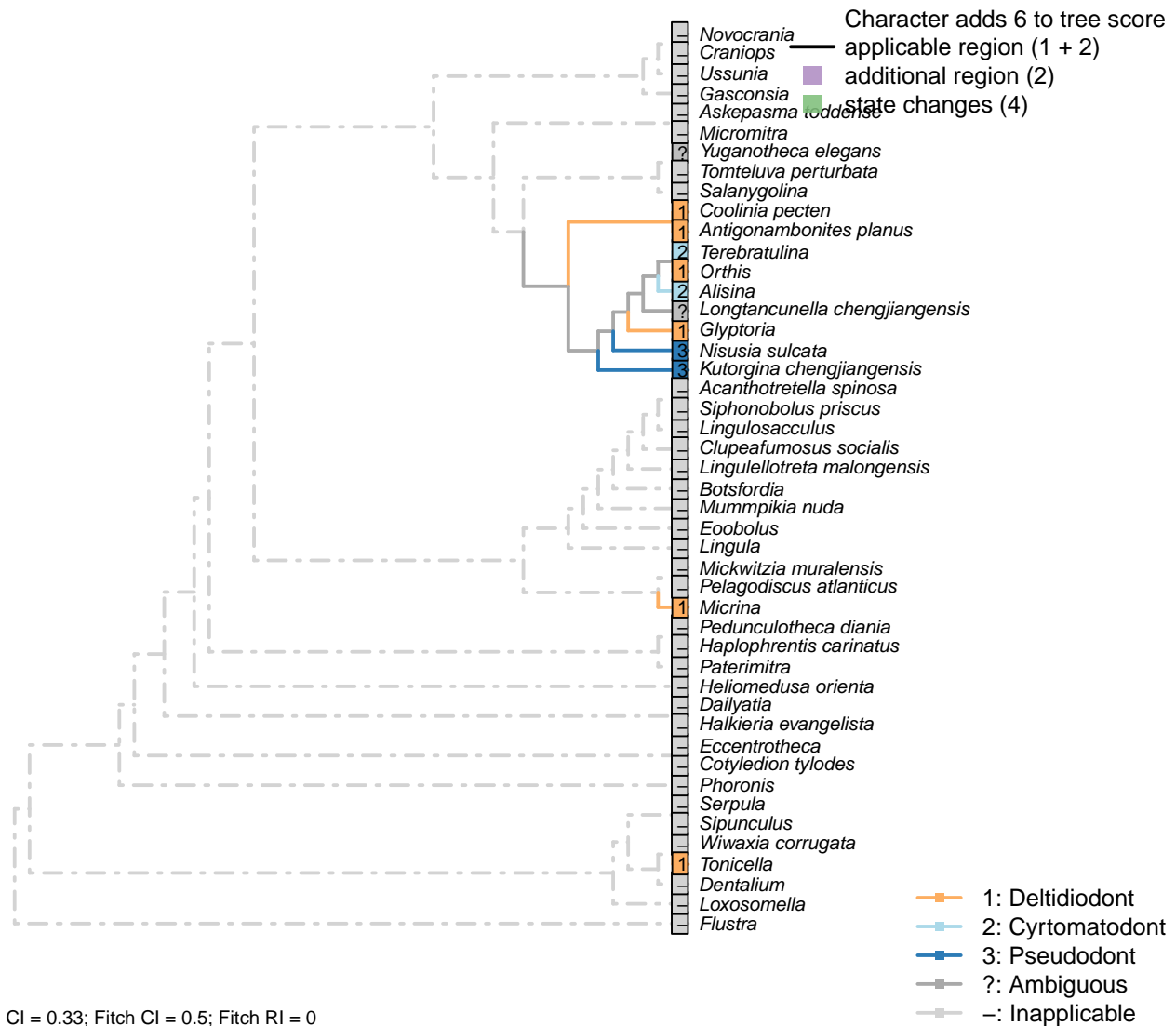
Nisusia sulcata: Pseudodont articulation: teeth formed by distal lateral extensions from the ventral pseudodeltidium – Holmer et al. (2018a).

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

Tonicella: The sutural laminae correspond in function and position to brachiopod apophyses (Connors et al., 2012), and so are coded as potentially homologous.

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

[60] Apophyses: Morphology

**Character 60: 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).

Antigonambonites planus, *Glyptoria*: Coded as deltidiodont in Benedetto (2009).

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

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

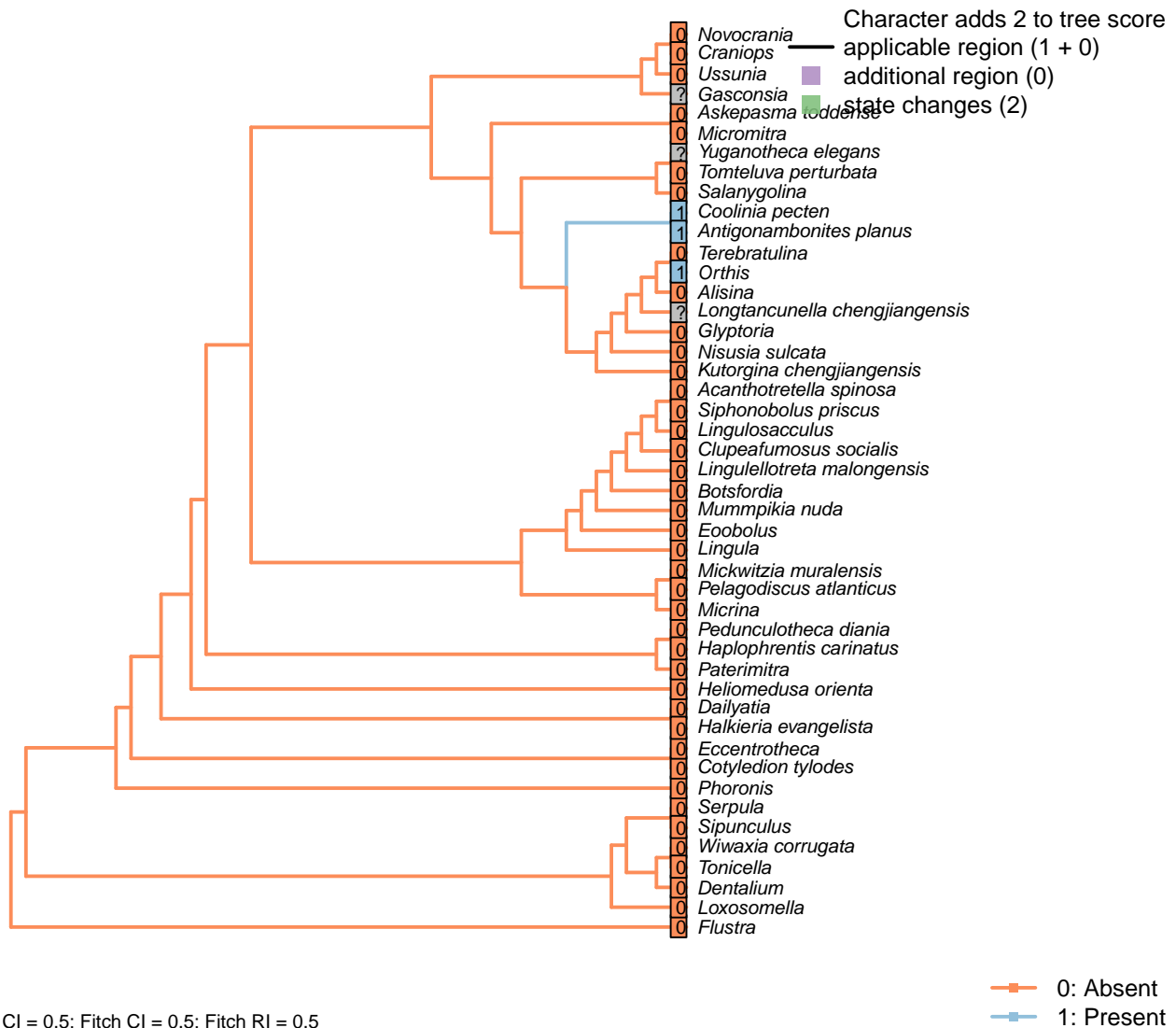
Nisusia sulcata: The ‘teeth’ are formed by the distal lateral extensions from the ventral pseudodeltidium fitting into the ‘sockets’ on the inner side of the dorsal interarea (Holmer et al., 2018a). [Coded as “deltidiodont teeth absent” in Benedetto (2009).].

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

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

Tonicella: 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.

[61] Apophyses: Dental plates

**Character 61: 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.

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

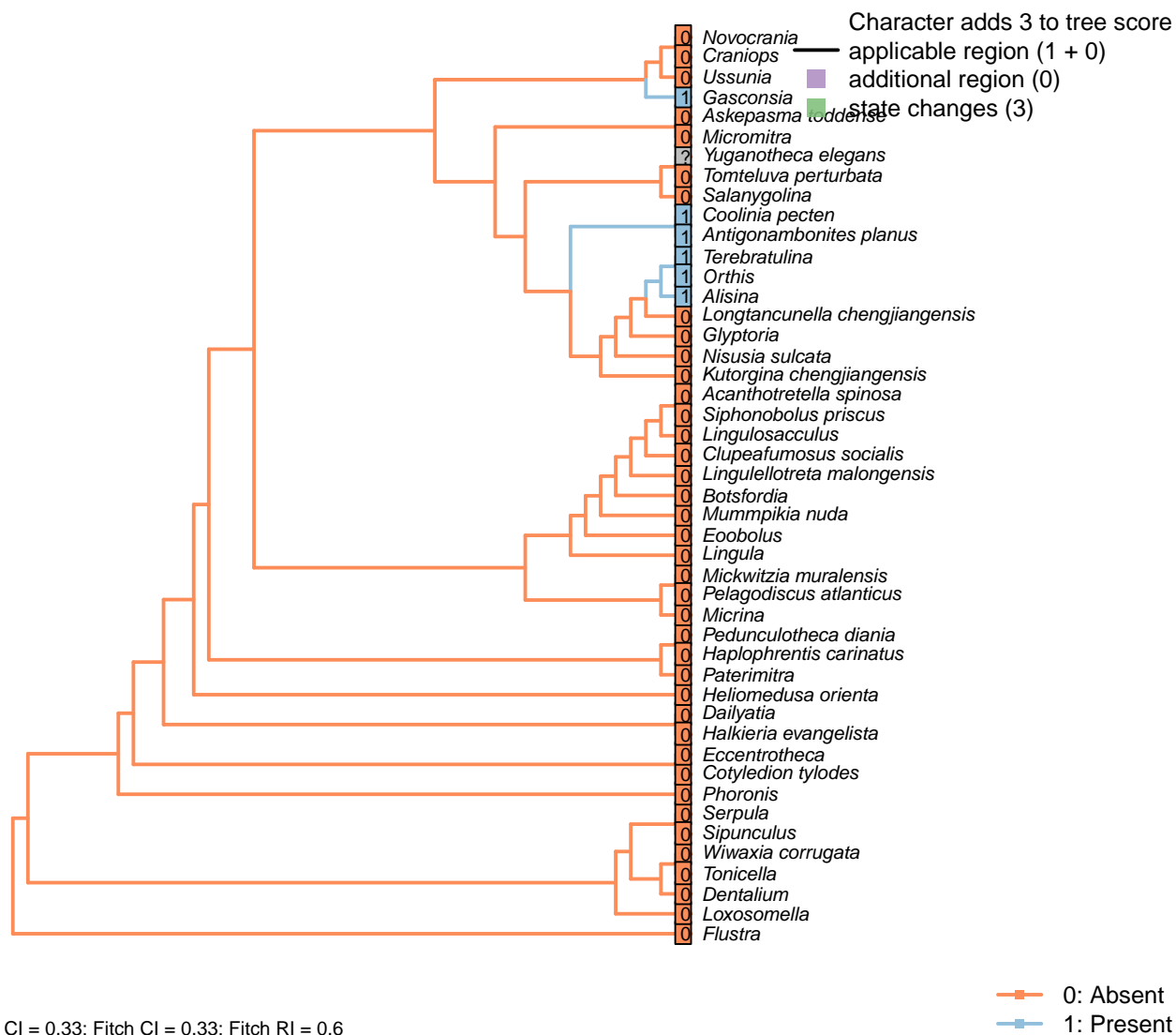
Coolinia pecten: Coded as present following Dewing (2001), who seems to use the term Strophomenoids to encompass *Coolinia*, and attests to the presence of dental plates.

Gasconsia: 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).

Glyptoria, *Nisusia sulcata*: Coded as absent in Benedetto (2009).

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

[62] Sockets



Character 62: Sclerites: Bivalved: Sockets

0: Absent

1: Present

Neomorphic character.

Simplified from Bassett *et al.* (2001) character 16.

This character is independent of apophyses, as several taxa bear sockets without corresponding teeth; the function of these sockets is unknown.

See figs 323ff in Williams *et al.* (1997).

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

Antigonambonites planus: Coded as present in Benedetto (2009).

Gasconsia: “Articulatory structure comprising ventral cardinal socket and dorsal hinge plate” – Williams *et al.* (2000), p. 184.

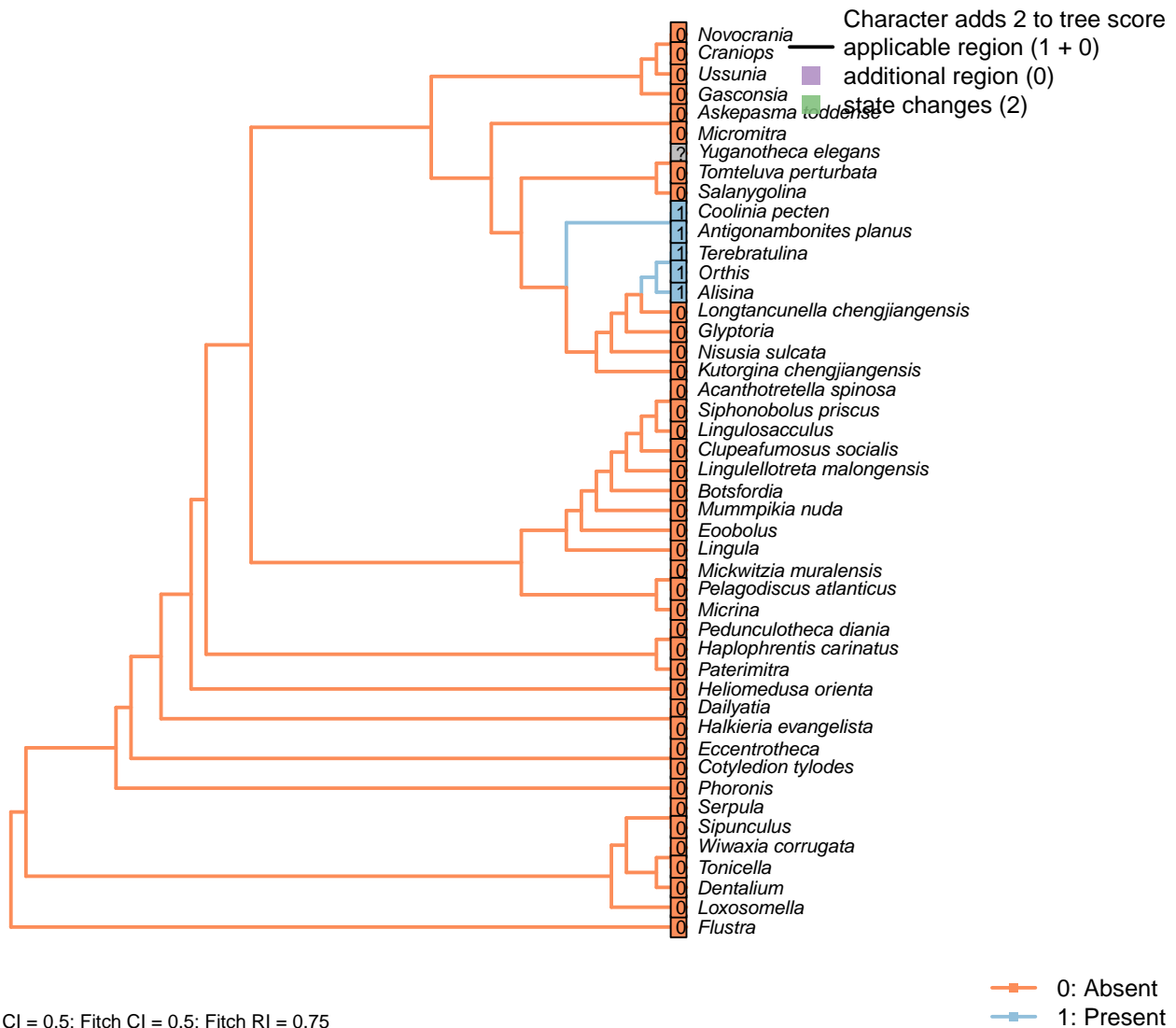
Glyptoria, *Nisusia sulcata*: Coded as absent in Benedetto (2009).

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

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

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

[63] Socket ridges



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.

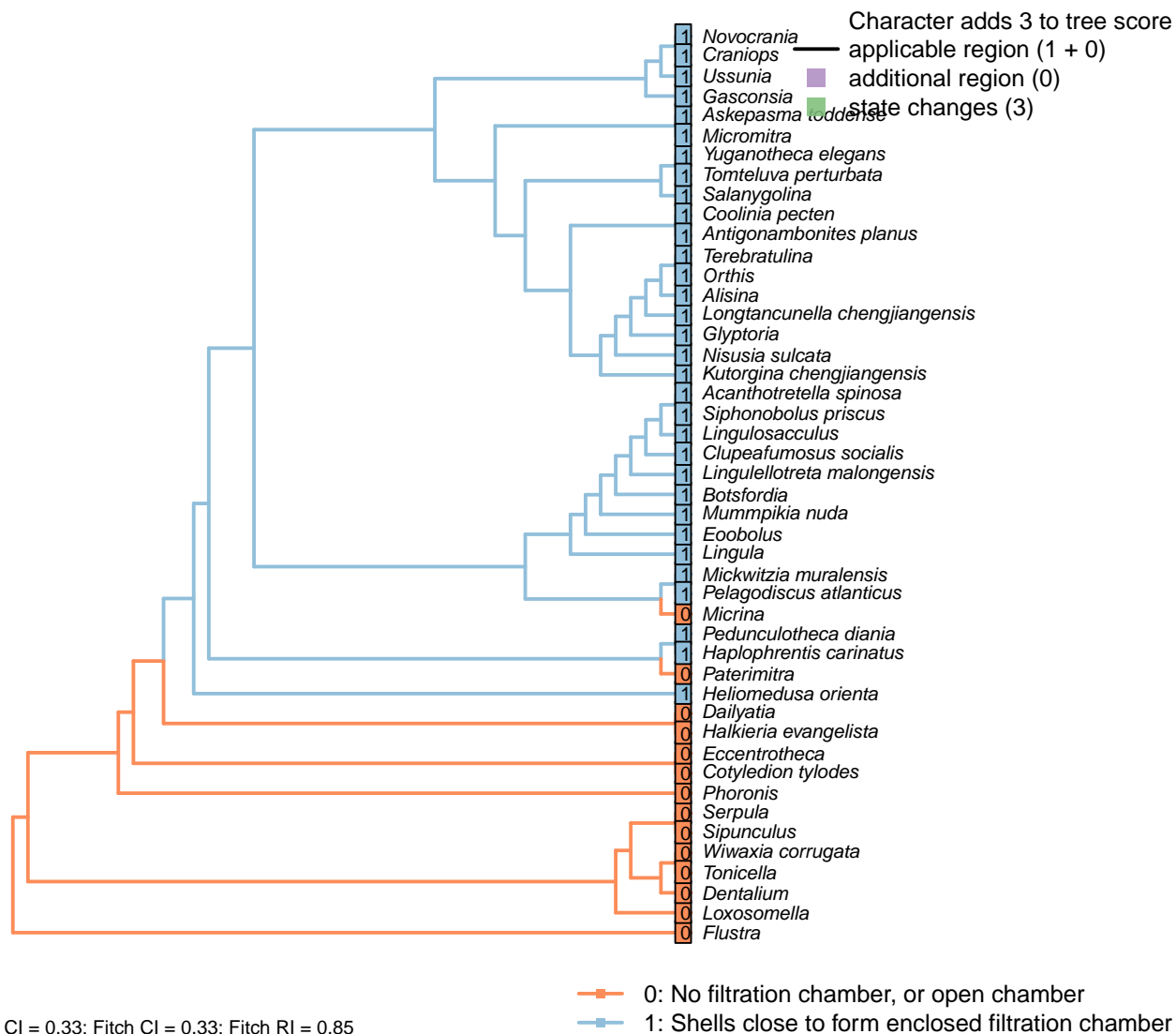
Alisina: “bearing sockets, bounded by low ridges” – Williams *et al.* (2000).

Antigonambonites planus: Coded as present in Benedetto (2009).

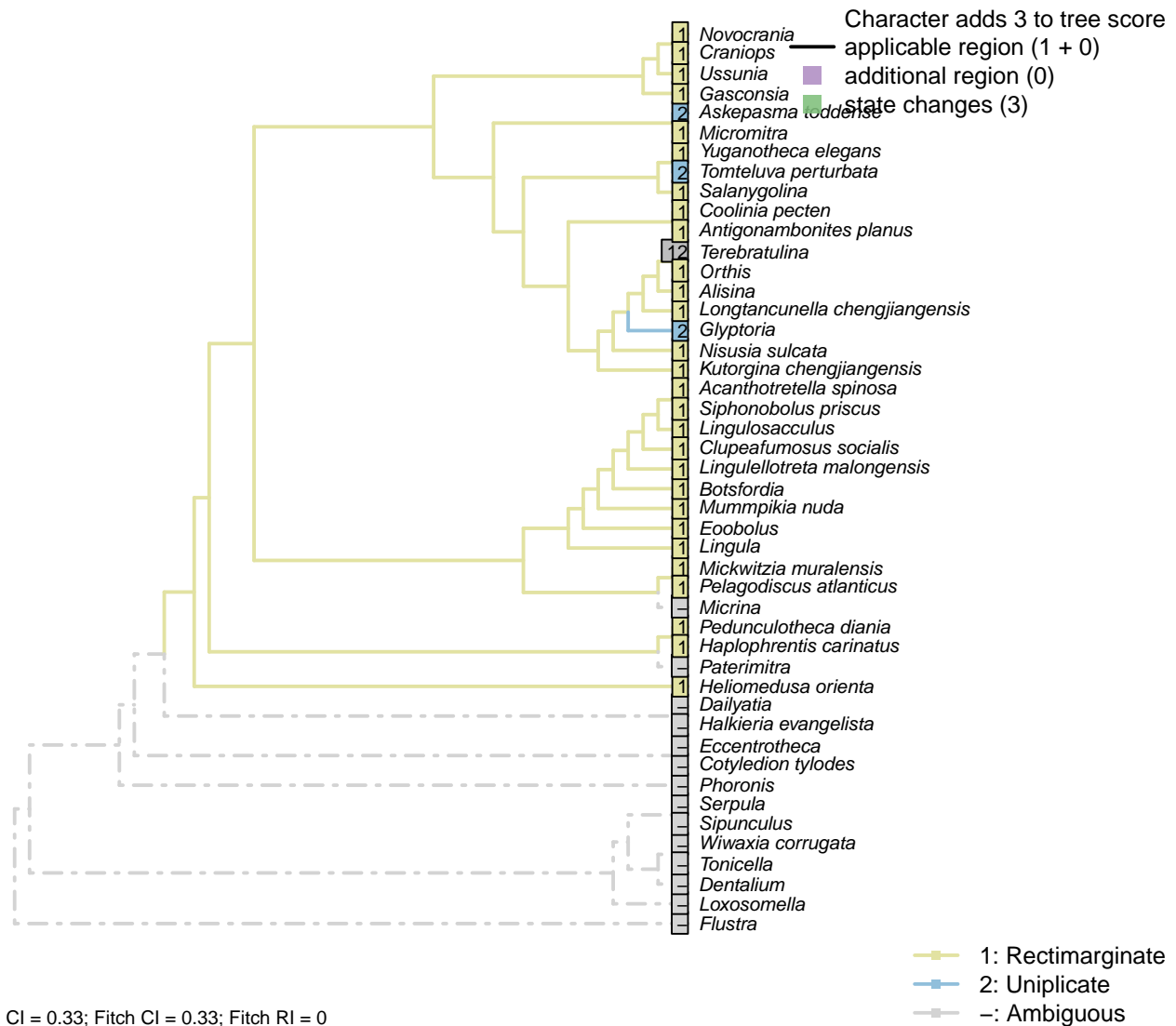
Glyptoria, *Nisusia sulcata*: Coded as absent in Benedetto (2009).

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

[64] Enclosing filtration chamber



[65] Commissure

**Character 65: Sclerites: Bivalved: Commissure**

1: Rectimarginate

2: Uniplicate

3: Sulcate

Transformational character.

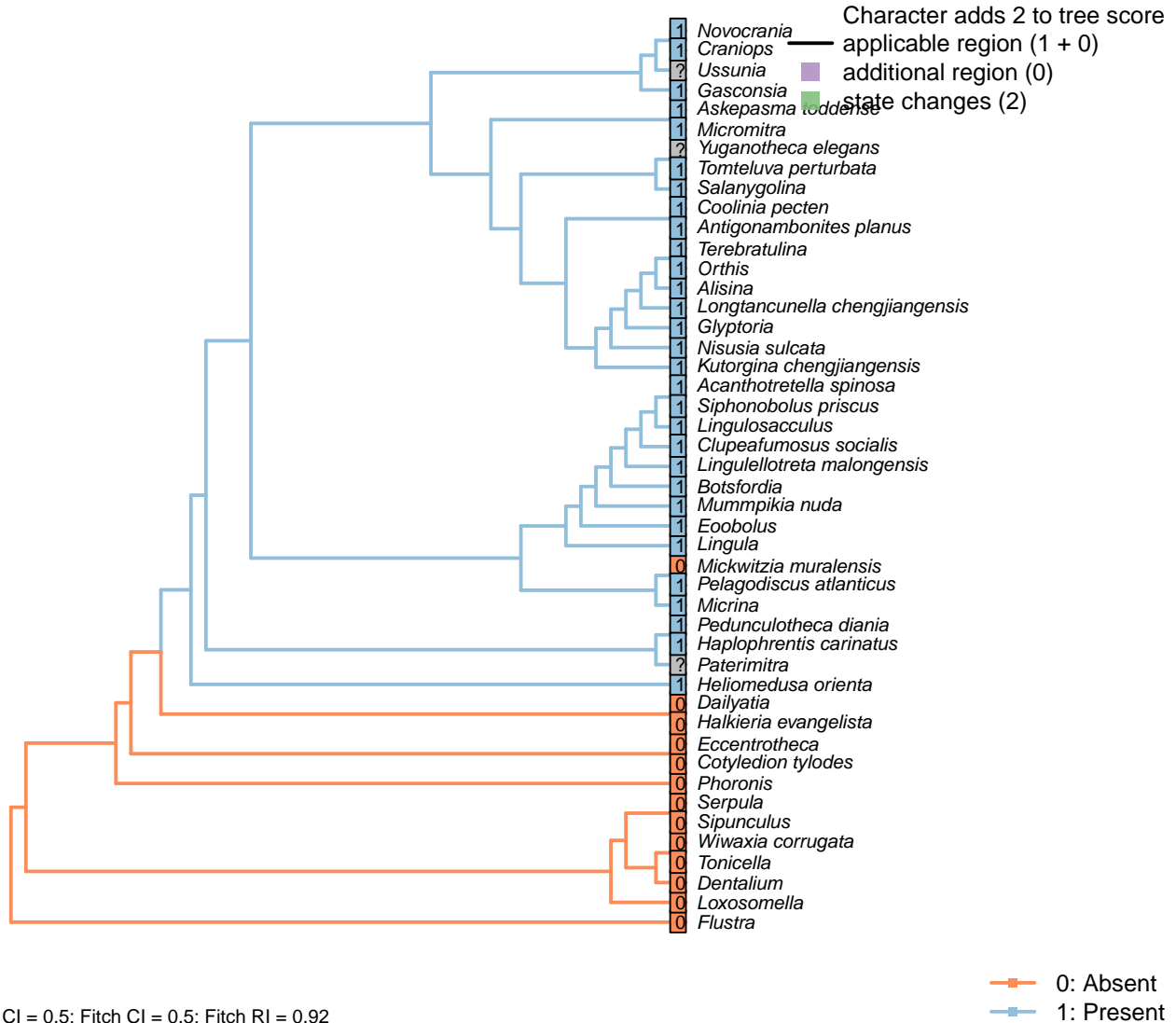
The anterior commissure can be rectimarginate (i.e. straight), uniplicate (i.e. median sulcus in ventral valve), or sulcate (with median sulcus in dorsal valve).

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

Glyptoria, *Kutorgina chengjiangensis*, *Micromitra*, *Salanygolina*: Following appendix 2 in Williams *et al.* (1998).

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

[66] Muscle scars: Ventral

**Character 66: Sclerites: Bivalved: Muscle scars: Ventral**

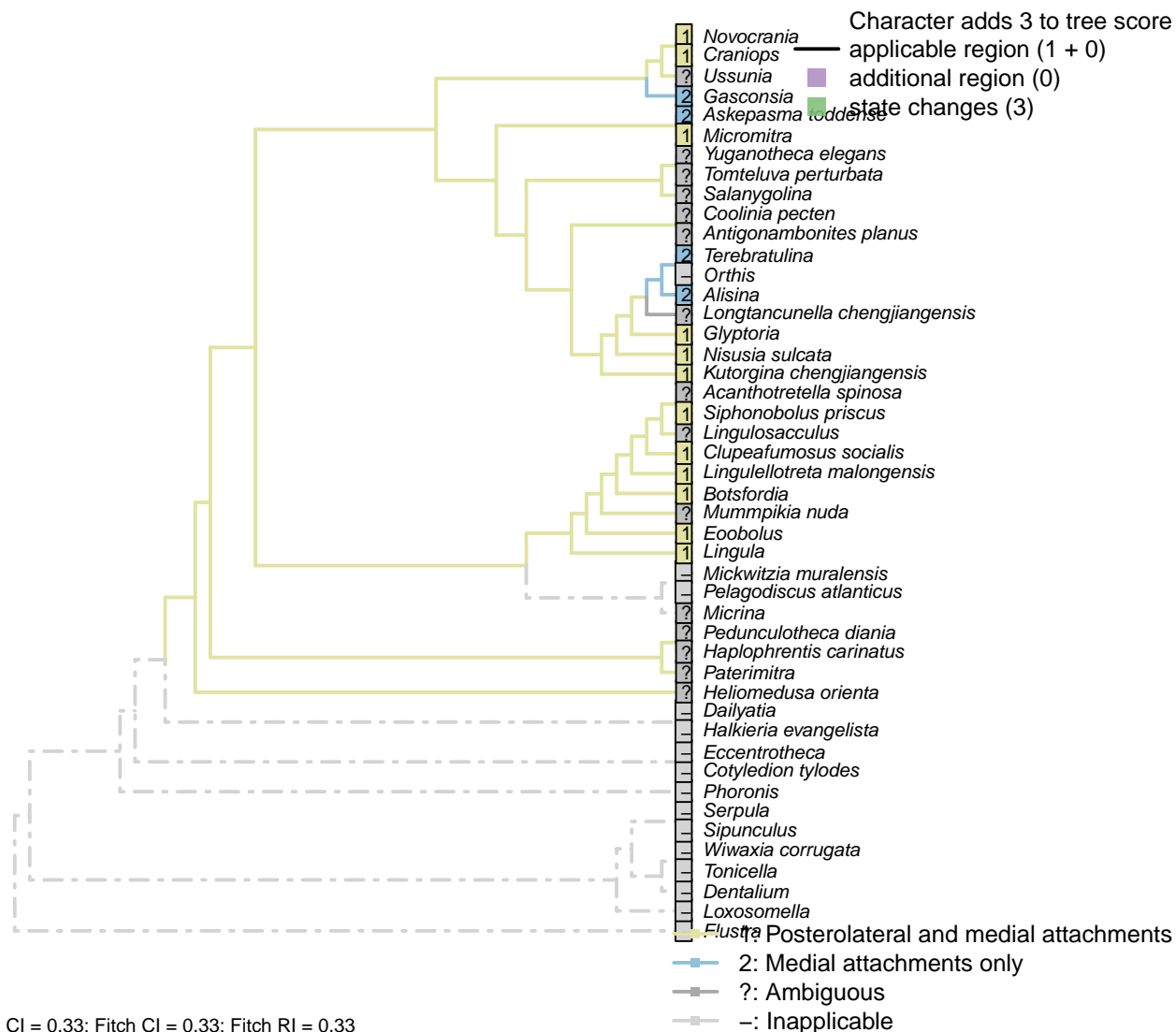
0: Absent

1: Present

Neomorphic character.

After Bassett *et al.* (2001) character 6.*Alisina*: Muscle scars scored based on *Alisina comleyensis* (Bassett *et al.*, 2001).*Halkieria evangelista*: 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).*Mickwitzia muralensis*: Scars absent; instead, cones ornament shell's internal surface.*Micrina*: Prominent ventral muscle scars – see e.g. Holmer *et al.* (2008), fig. 1f.*Tonicella*: Absent (Schwabe, 2010).

[67] Muscle scars: Ventral: Position

**Character 67: 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).

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

Alisina: Following reconstruction of Gorjansky & Popov (1986).

Askepasma toddense: Restricted to medial field, following the interpretation of the musculature presented by

Williams *et al.* (2000), fig. 81.

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

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

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

Gasconsia: Musculature described in Hanken & Harper (1985).

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

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

Lingulellotreta malongensis: See fig. 5 in Holmer *et al.* (1997).

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

Nisusia sulcata: Posterolateral diductors (fig. 18.2 in Bassett *et al.*, 2001).

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

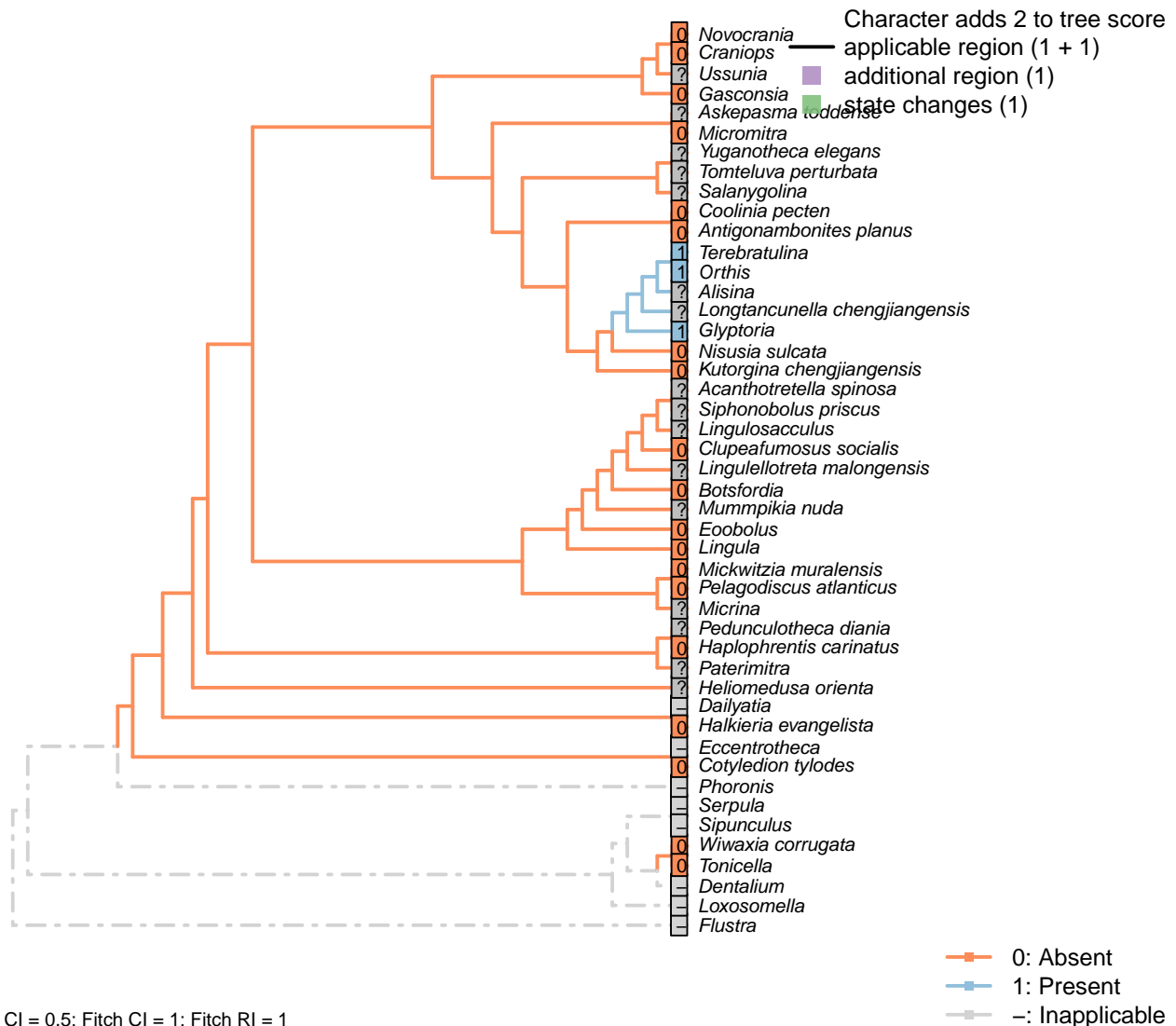
Orthis: Not applicable: *vascula lateralia* not comparable to those of other taxa.

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

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

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

[68] Muscle scars: Adjustor

**Character 68: 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.

Alisina: 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.

Askepasma toddense: Following the interpretation of the musculature presented by Williams *et al.* (2000),

fig. 81.

Botsfordia: Not described in Popov (1992).

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

Gasconsia: 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.

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

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

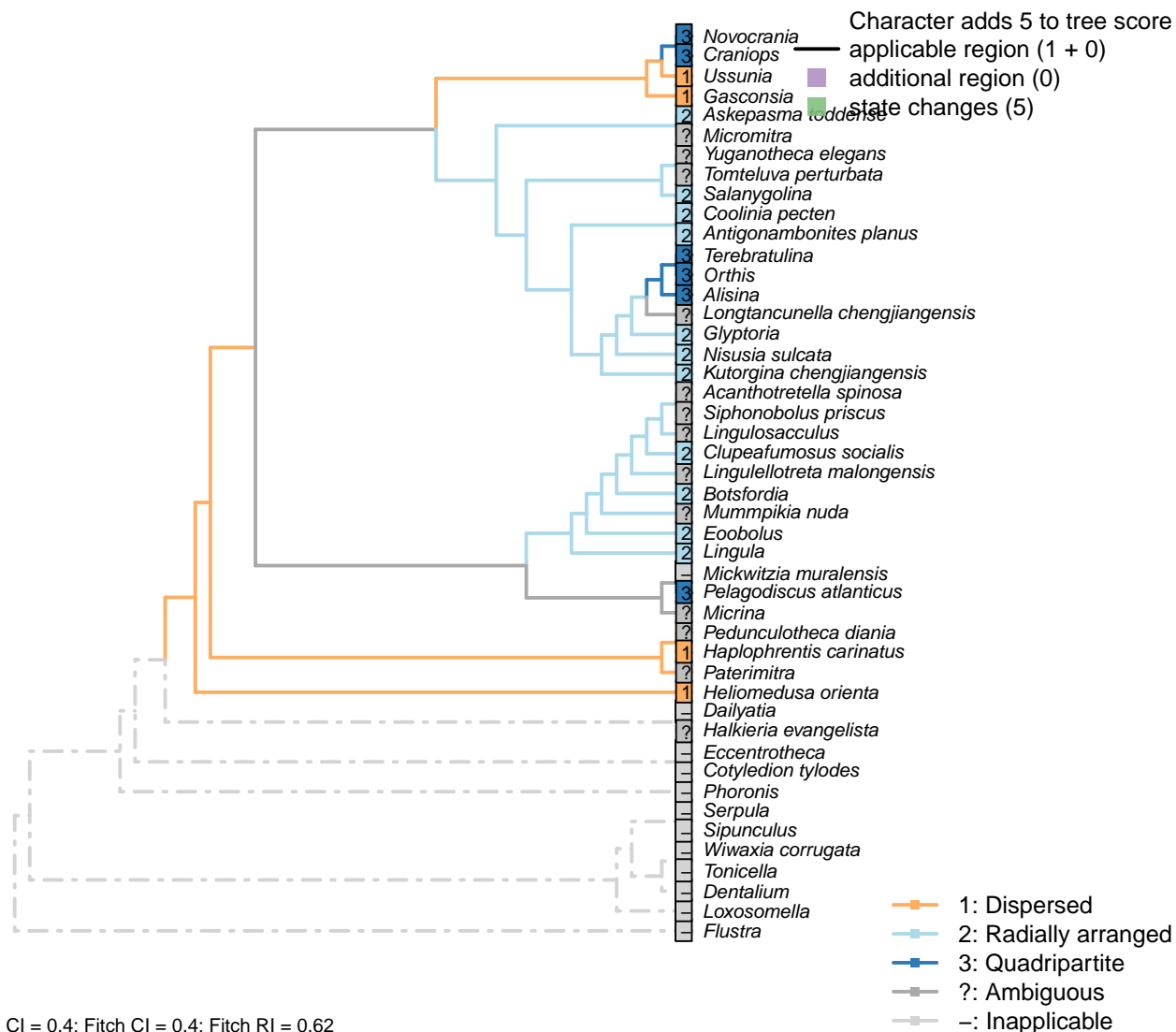
Oh dear! **You included the inapplicable token in a neomorphic character!**

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

- Loxosomella
- Flustra
- Phoronis
- Sipunculus
- Serpula
- Dentalium
- Dailyatia
- Eccentrotheca

[69] Muscle scars: Dorsal adductors

**Character 69: 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”.

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

Antigonambonites planus: Treatise.

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

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

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

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

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

Glyptoria: 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.

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

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

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

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

Micromitra: 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”.

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

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

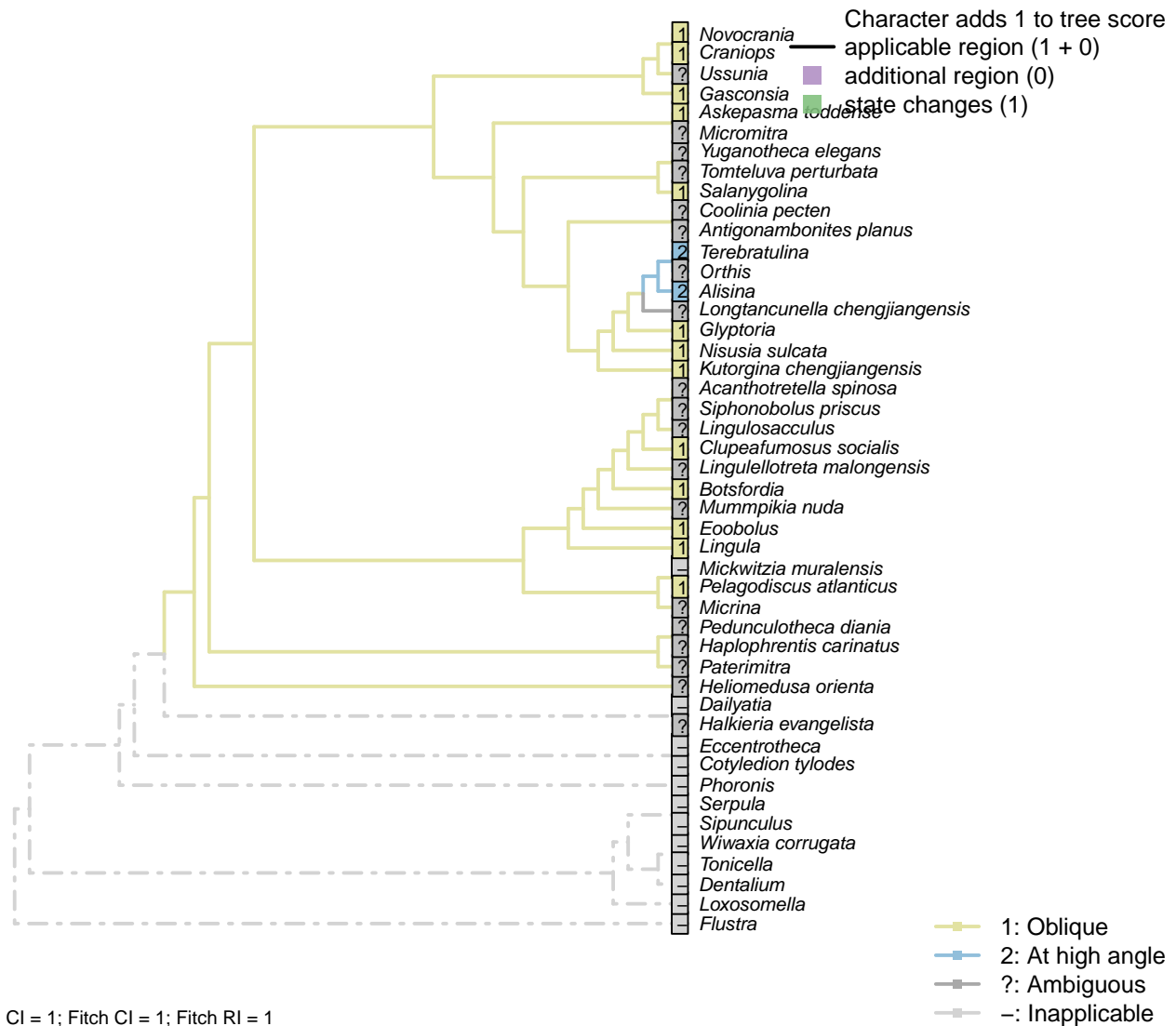
Salanygolina: “The dorsal valve of *Salanygolina* has a radial arrangement of adductor muscle scars and the scars of posteromedially placed internal oblique muscles, which are also characteristic of paterinates and chileates” – Holmer *et al.* (2009).

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

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

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

[70] Muscle scars: Adductors: Position

**Character 70: 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.*Askepasma toddense*: Following the interpretation of the musculature presented by Williams *et al.* (2000), fig. 81.*Botsfordia*: Following description of Popov (1992).*Coolinia pecten*: Not reported by Williams *et al.* (2000), nor Bassett & Popov (2017), nor explicitly by Dewing (2001).*Eoobolus*: “*Eoobolus* should have anterior and posterior adductors and a variety of oblique muscles which

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

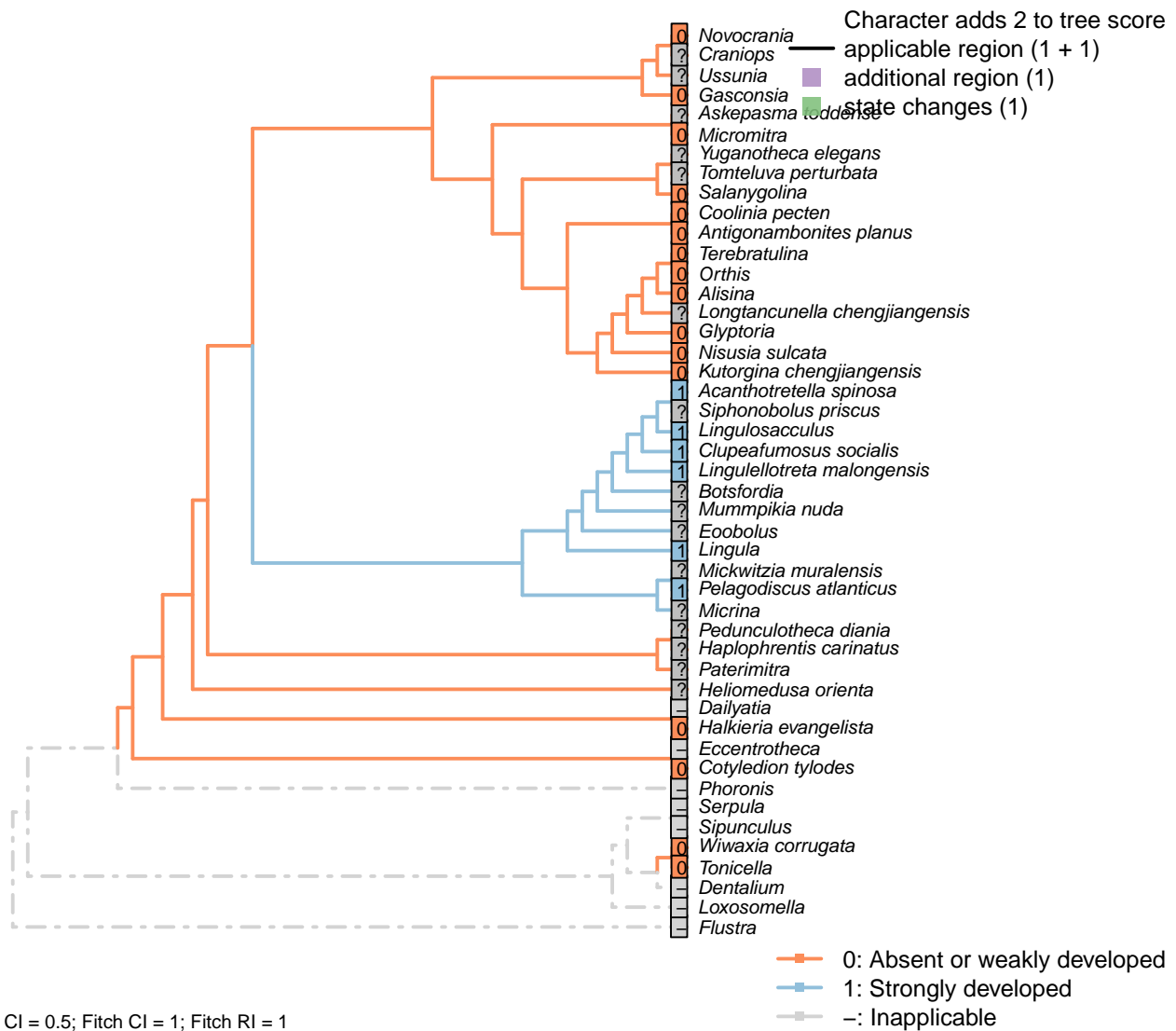
Gasconsia: See discussion under Trimerellida in Williams *et al.* (2000).

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

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

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

[71] Muscle scars: Dermal muscles



Character 71: 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).

Alisina, *Antigonambonites planus*, *Gasconsia*, *Glyptoria*, *Nisusia sulcata*, *Orthis*, *Salanygolina*: According to the statement of Williams *et al.* (2000, p. 32) that these muscle are absent in all carbonate- shelled brachiopods.

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

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

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

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

Eoobolus: Not remarked upon by Balthasar (2009).

Kutorgina chengjiangensis: 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).

Micromitra: 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.

Mummpikia nuda, *Tomteluva perturbata*: 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.

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

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

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

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

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

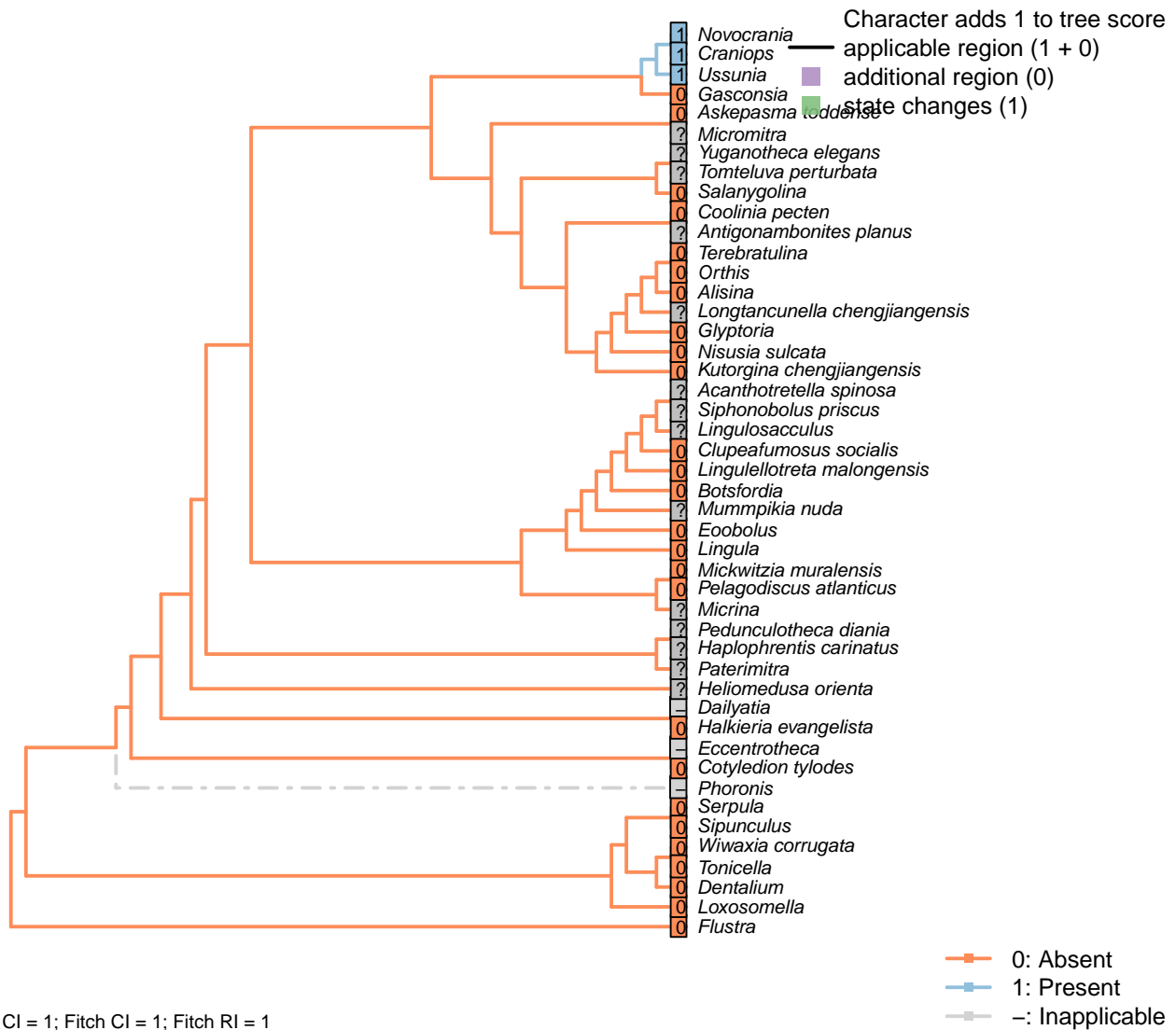
That's really very naughty, as Brazeau *et al.* (2018) will tell you.

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

- Loxosomella
- Flustra
- Phoronis
- Sipunculus
- Serpula
- Dentalium
- Dailyatia

- Eccentrotheca

[72] Muscle scars: Unpaired median (*levator ani*)



Character 72: 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].

Alisina, *Kutorgina chengjiangensis*, *Nisusia sulcata*: Following table 13 in Williams et al. (2000).

Coolinia pecten: Not reported in Dewing (2001).

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

Gasconsia: 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.

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

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

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

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

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

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

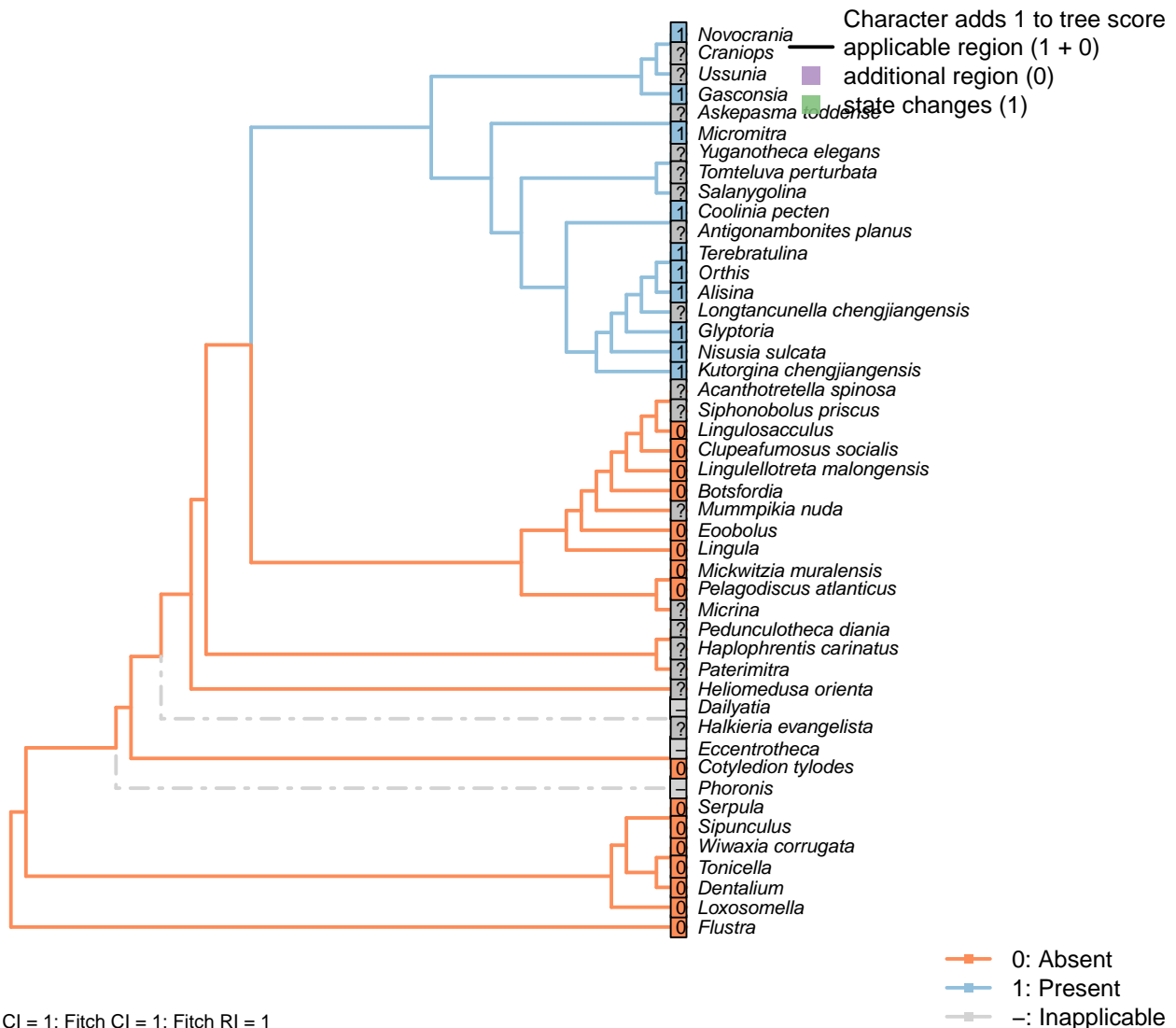
Oh dear! **You included the inapplicable token in a neomorphic character!**

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

- Phoronis
- Dailyatia
- Eccentrotheca

[73] Muscle scars: Dorsal diductor

**Character 73: Sclerites: Bivalved: Muscle scars: Dorsal diductor**

0: Absent

1: Present

Neomorphic character.

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

Acanthotretella spinosa: 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.

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

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

Gasconsia: Internal oblique muscles serve as diductors.

Halkieria evangelista: It is unclear whether the paired muscle scars of *Oikozetetes* are homologous to bra-

chiopod diductors.

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

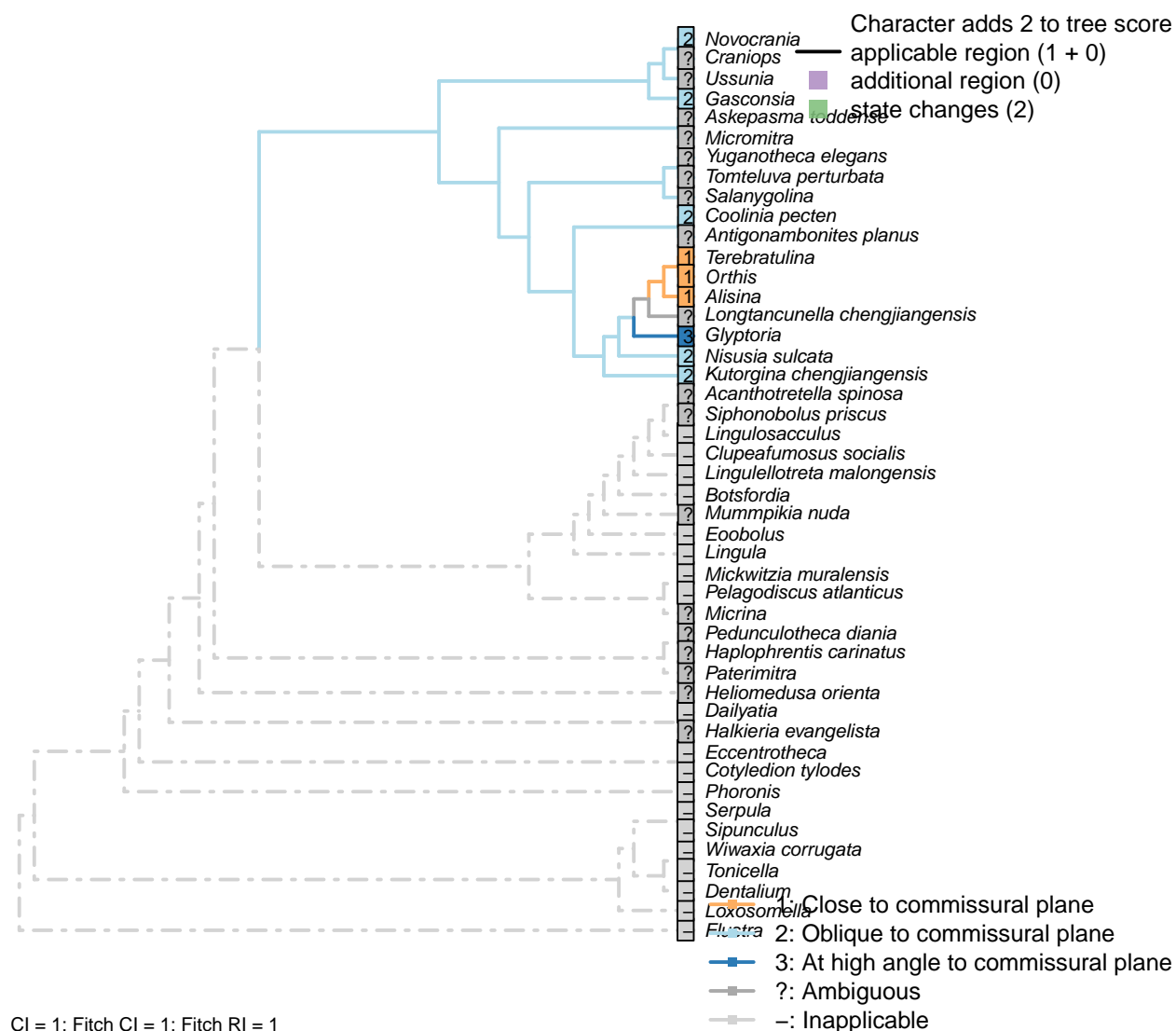
Oh dear! **You included the inapplicable token in a neomorphic character!**

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

- Phoronis
- Dailyatia
- Eccentrotheca

[74] Muscle scars: Dorsal diductor: Position



Character 74: Sclerites: Bivalved: Muscle scars: Dorsal diductor: Position

- 1: Close to commissural plane
- 2: Oblique to commissural plane

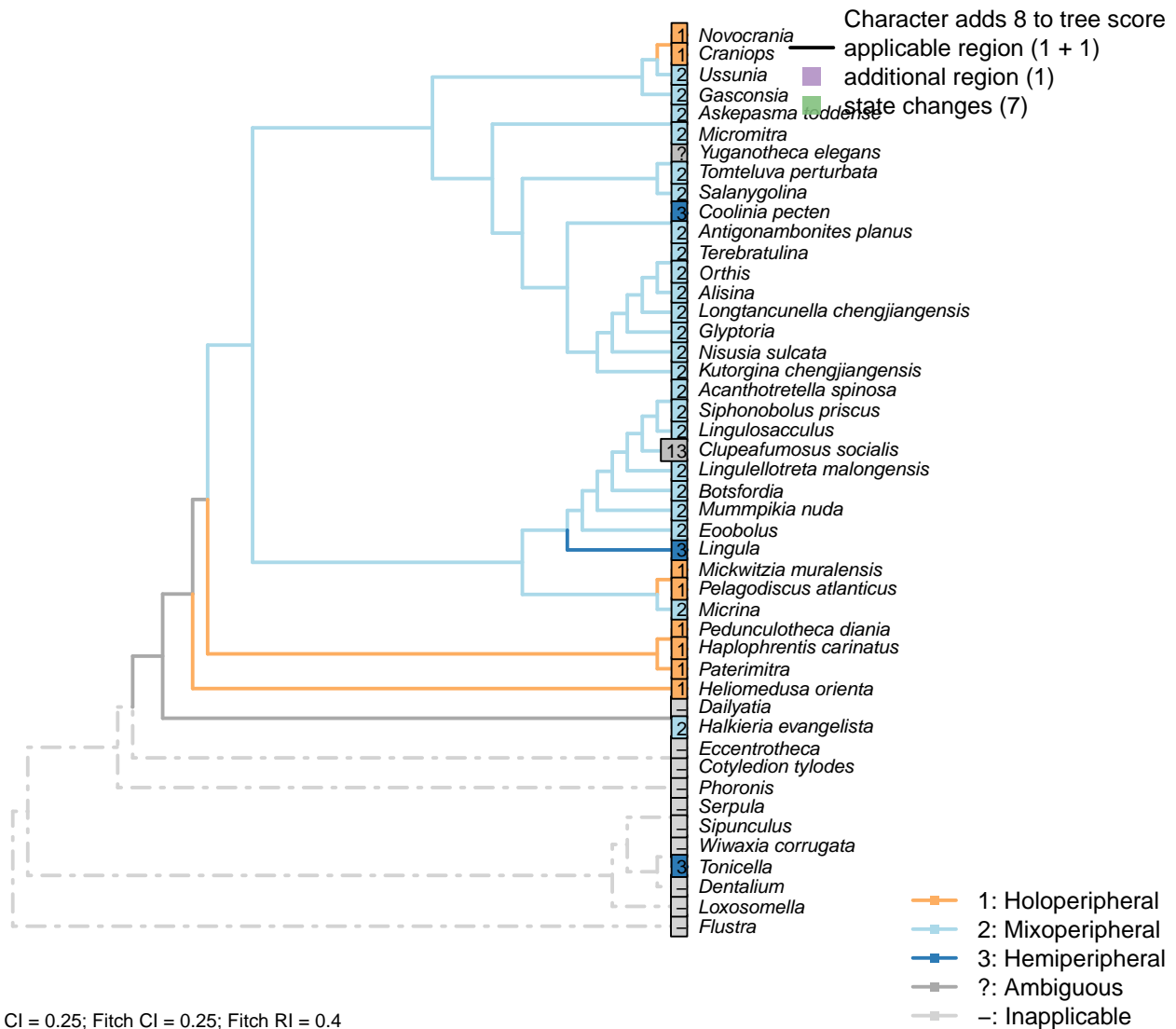
3: At high angle to commissural plane
Transformational character.

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

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

3.16 Sclerites: Dorsal valve

[75] Growth direction



Character 75: 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.

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

Craniops: “both valves with growth holoperipheral” – Williams *et al.* (2000) p164.

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

The insinuation from Zhang *et al.* (2009) is that Chen *et al.* (2007) misidentify the dorsal valve as the ventral valve.

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

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

Tonicella: 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.

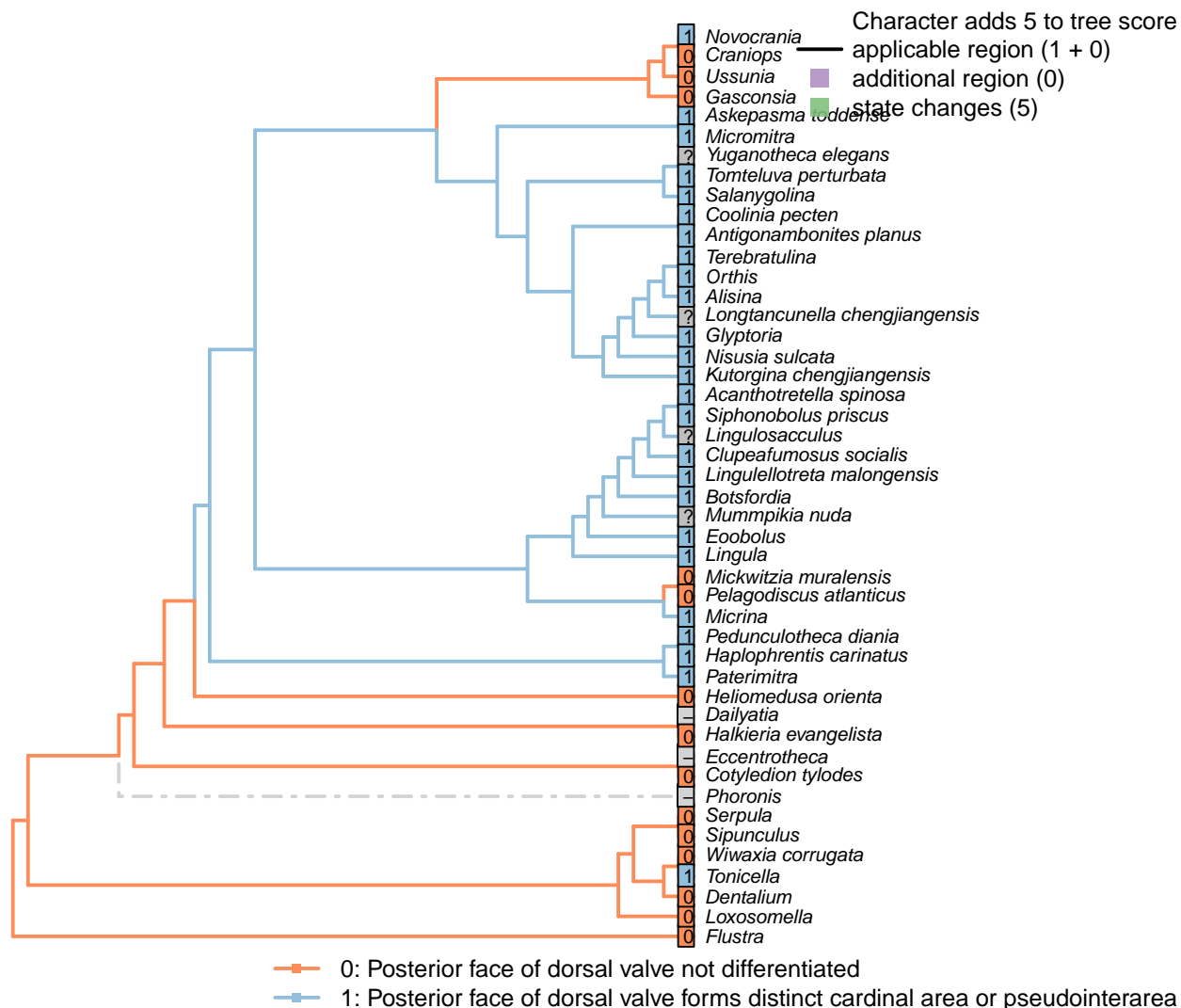
In support of this hypothesis, we note that the posterior (but not anterior) valves of chitons bear apophyses (Schwabe, 2010; Connors *et al.*, 2012), which are most prominent in the ventral (but not dorsal) valves of brachiopods (Williams *et al.*, 1997, fig. 322), and which occur in the morph A shell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

Ussunia: Following description of order in Williams *et al.* (2000).

[76] Posterior surface: Differentiated

**Character 76: 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: Pseudointerarea present, following Siphonotretidae coding in Williams *et al.* (2000), table 6.

Alisina, *Antigonambonites planus*, *Coolinia pecten*, *Glyptoria*, *Kutorgina chengjiangensis*, *Orthis*, *Salany-*

golina, *Tomteluva perturbata*: Cardinal area (interarea) present.

Askepasma toddense: Well-defined pseudointerarea (Williams et al., 2000, p153).

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

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

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

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

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

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

Lingula, *Lingulellotreta malongensis*: Pseudointerarea present, following Williams *et al.* (2000), table 6.

Lingulosacculus: Unclear from fossil material.

Longtancunella chengjiangensis: 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.

Mickwitzia muralensis: Shell flat.

Micrina: = Sellate sclerite duplicature (Holmer et al., 2008).

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

Mummpikia nuda: “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.

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

Novocrania, *Paterimitra*, *Pedunculotheca diania*: Pseudointerarea.

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

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

Terebratulina: Interarea present.

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

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

Yuganotheca elegans: 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.

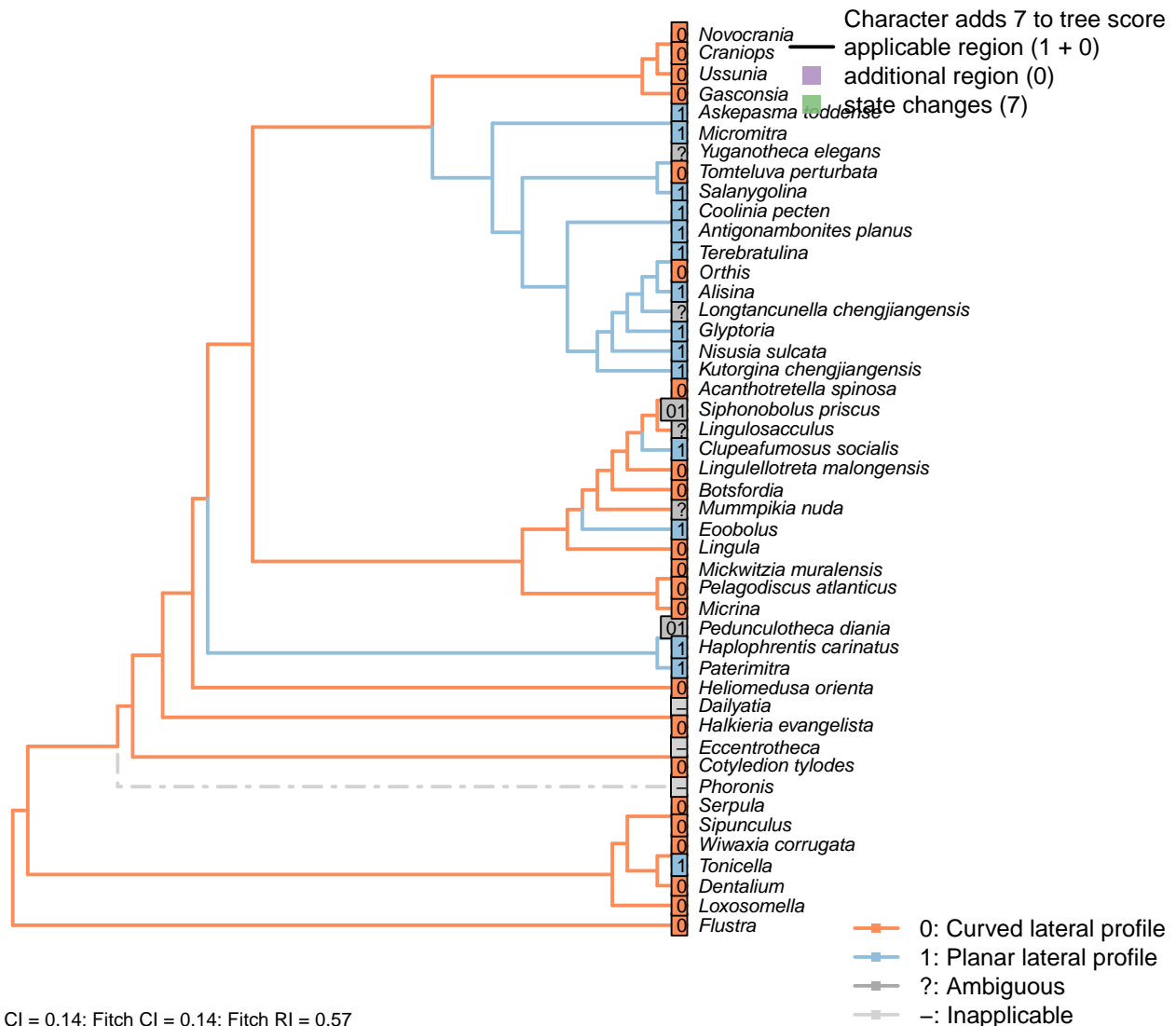
Oh dear! **You included the inapplicable token in a neomorphic character!**

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

- Phoronis
- Dailyatia
- Eccentrotheca

[77] Differentiated posterior surface: Morphology

**Character 77: 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.

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

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

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

Gasconsia, *Heliomedusa orienta*, *Mickwitzia muralensis*, *Pelagodiscus atlanticus*, *Ussunia*: Posterior surface

cannot be flat if it is not differentiated.

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

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

Siphonobolus priscus: 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.

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

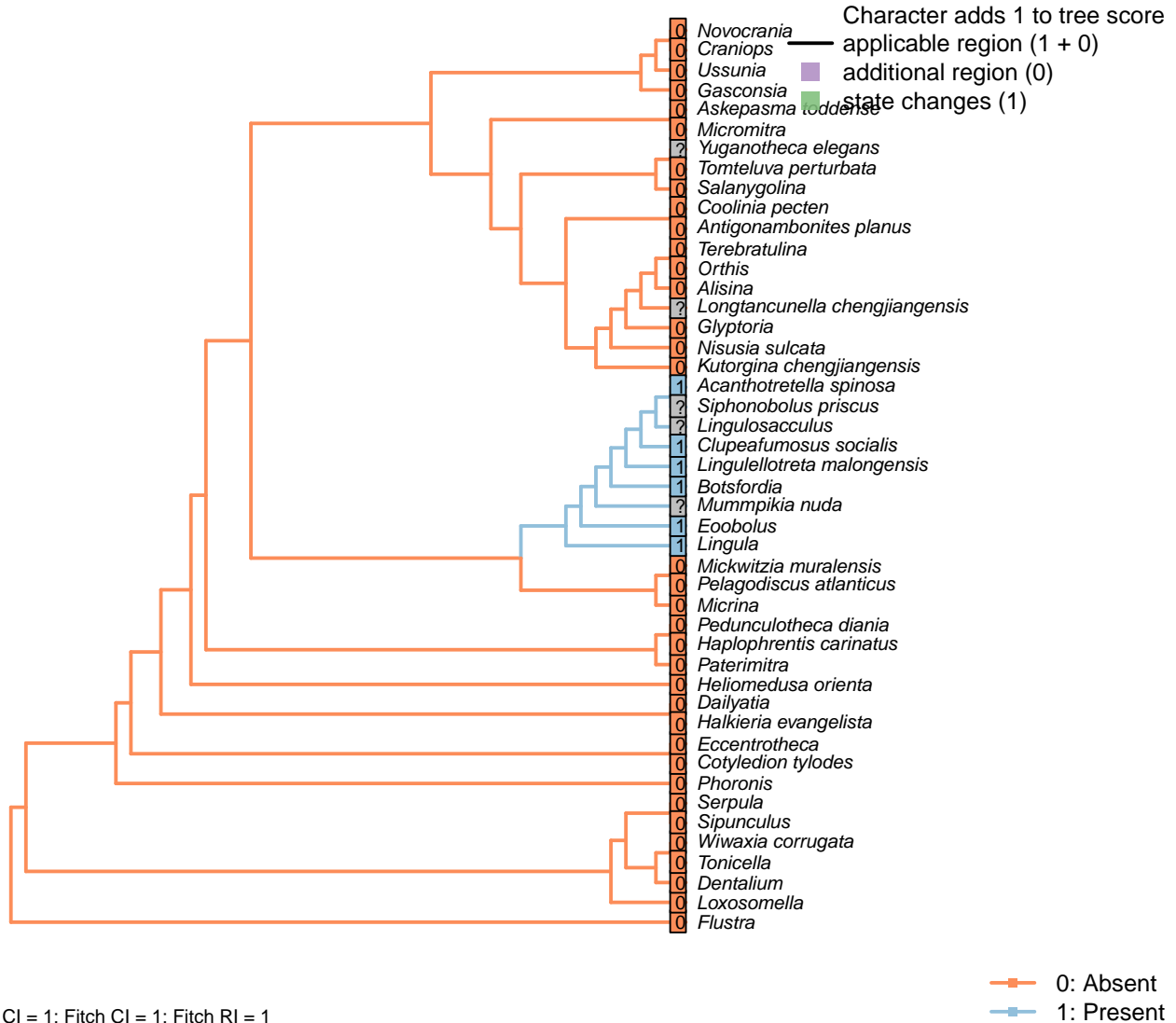
Oh dear! **You included the inapplicable token in a neomorphic character!**

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

- Phoronis
- Dailyatia
- Eccentrotheca

[78] Posterior surface: Medial groove



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

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

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

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

Eoobolus: Prominent medial groove (Balthasar, 2009).

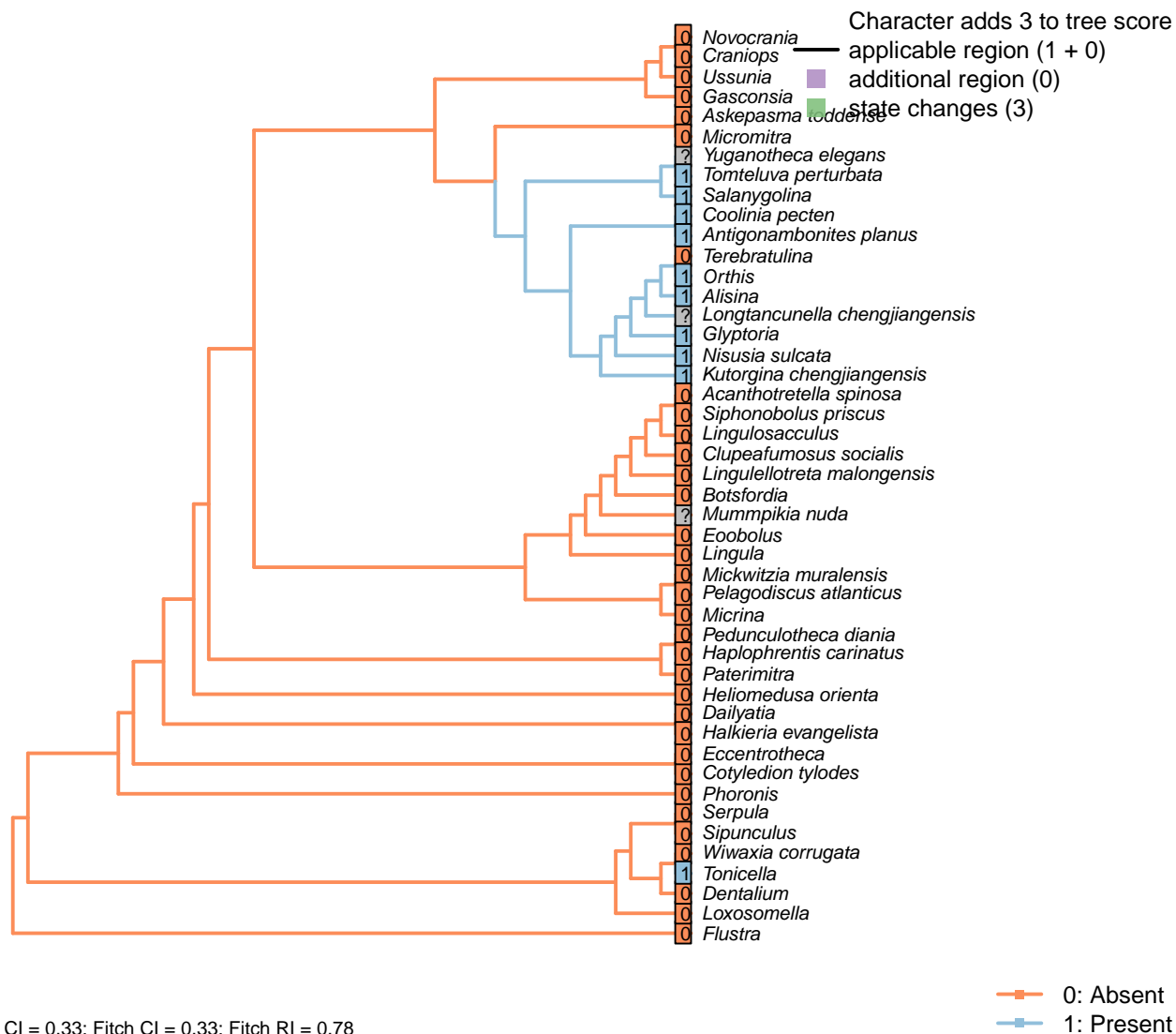
Heliomedusa orientalis: “A posteriorly protruding dorsal pseudointerarea with no median groove and no flexure

lines” – Chen et al. (2007).

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

Siphonobolus priscus: 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.

[79] Posterior surface: Notothyrium



Character 79: Sclerites: Dorsal valve: Posterior surface: Notothyrium

0: Absent

1: Present

Neomorphic character.

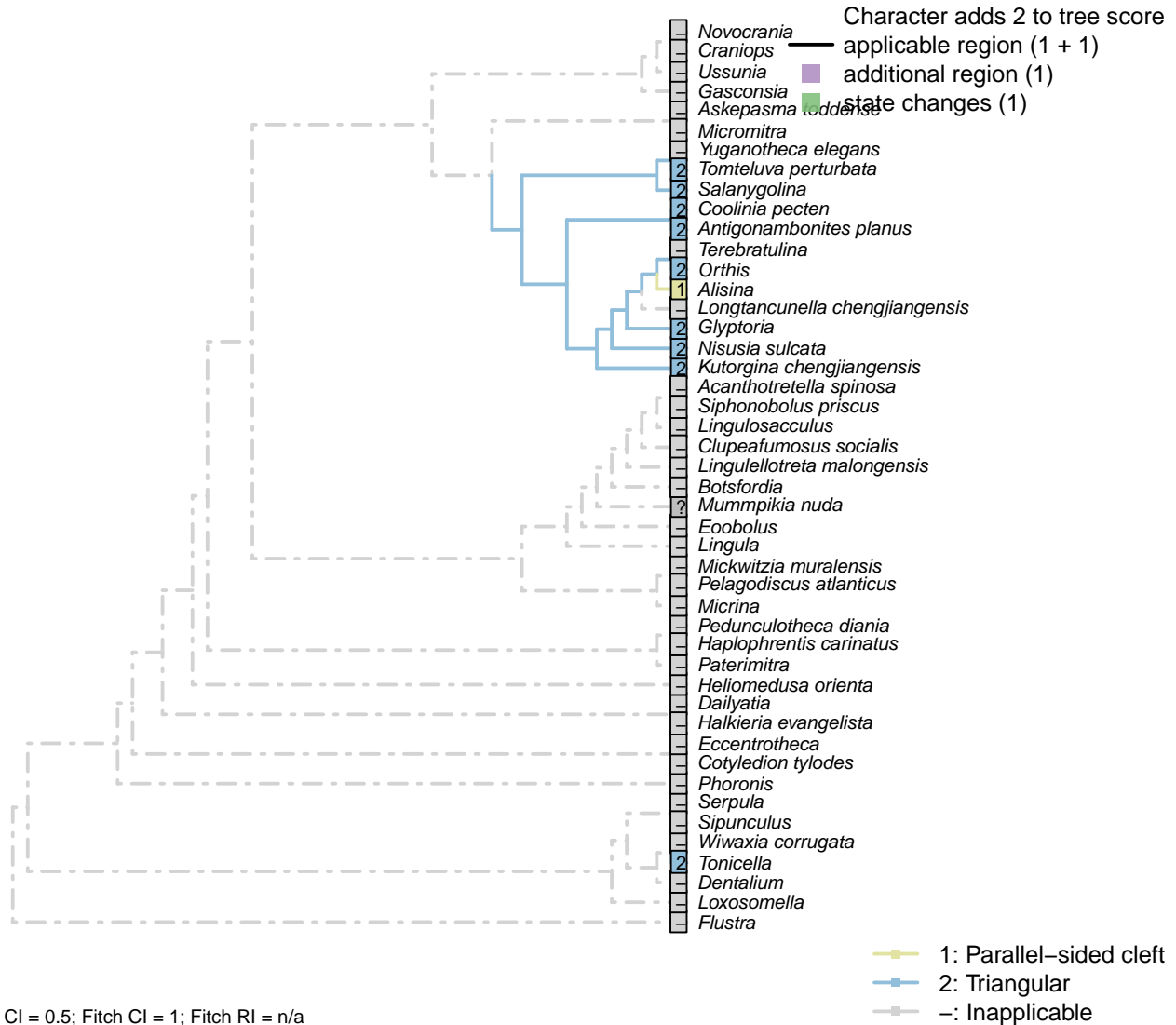
A notothyrium is an opening in an interarea that accommodates the pedicle, and may be filled with plates.

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

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

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

[80] Posterior surface: Notothyrium: Shape



Character 80: Sclerites: Dorsal valve: Posterior surface: Notothyrium: Shape

1: Parallel-sided cleft

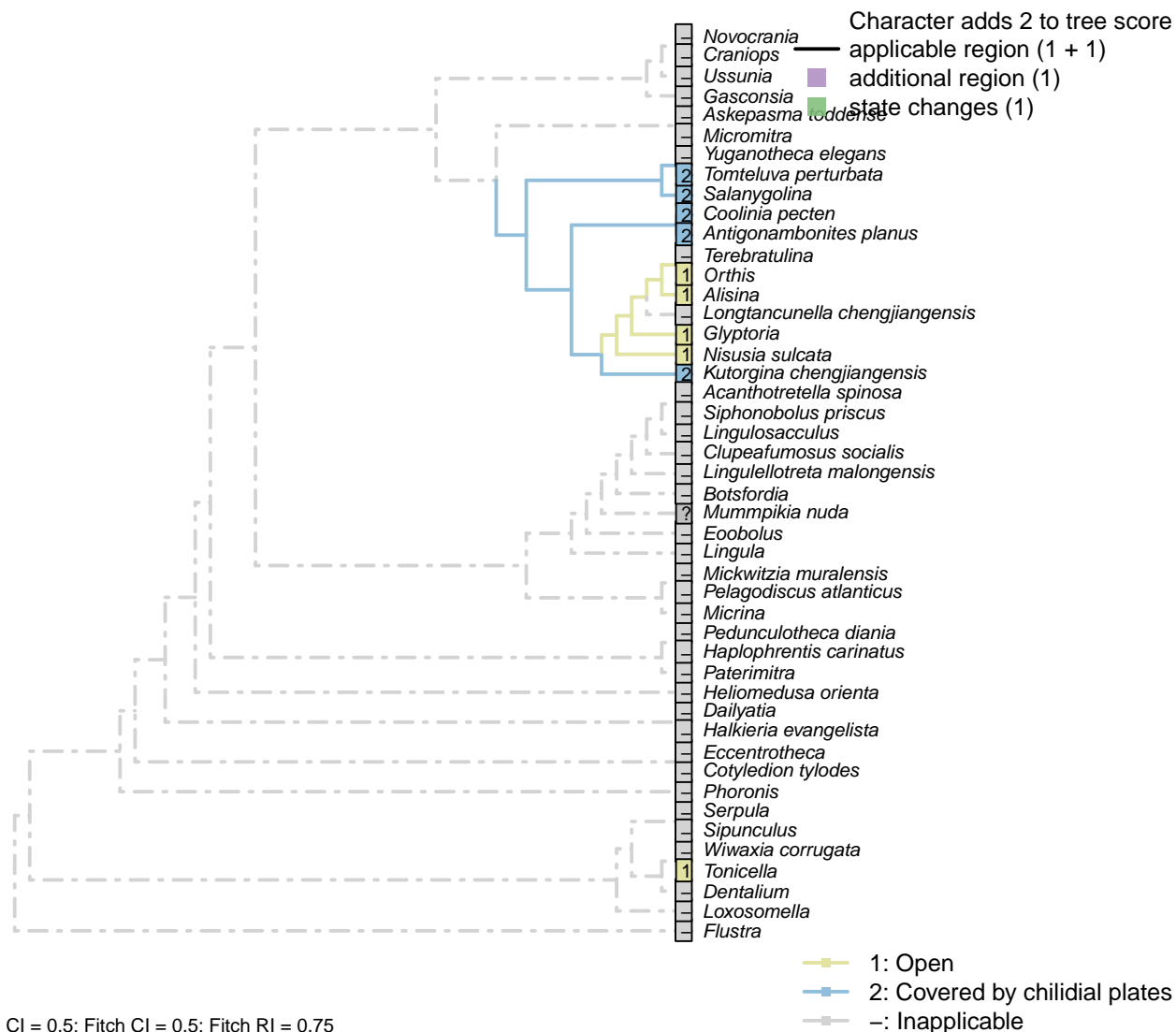
2: Triangular

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).

[81] Posterior surface: Notothyrium: Chilidial plates

**Character 81: Sclerites: Dorsal valve: Posterior surface: Notothyrium: Chilidial plates**

1: Open

2: Covered by chilidial plates

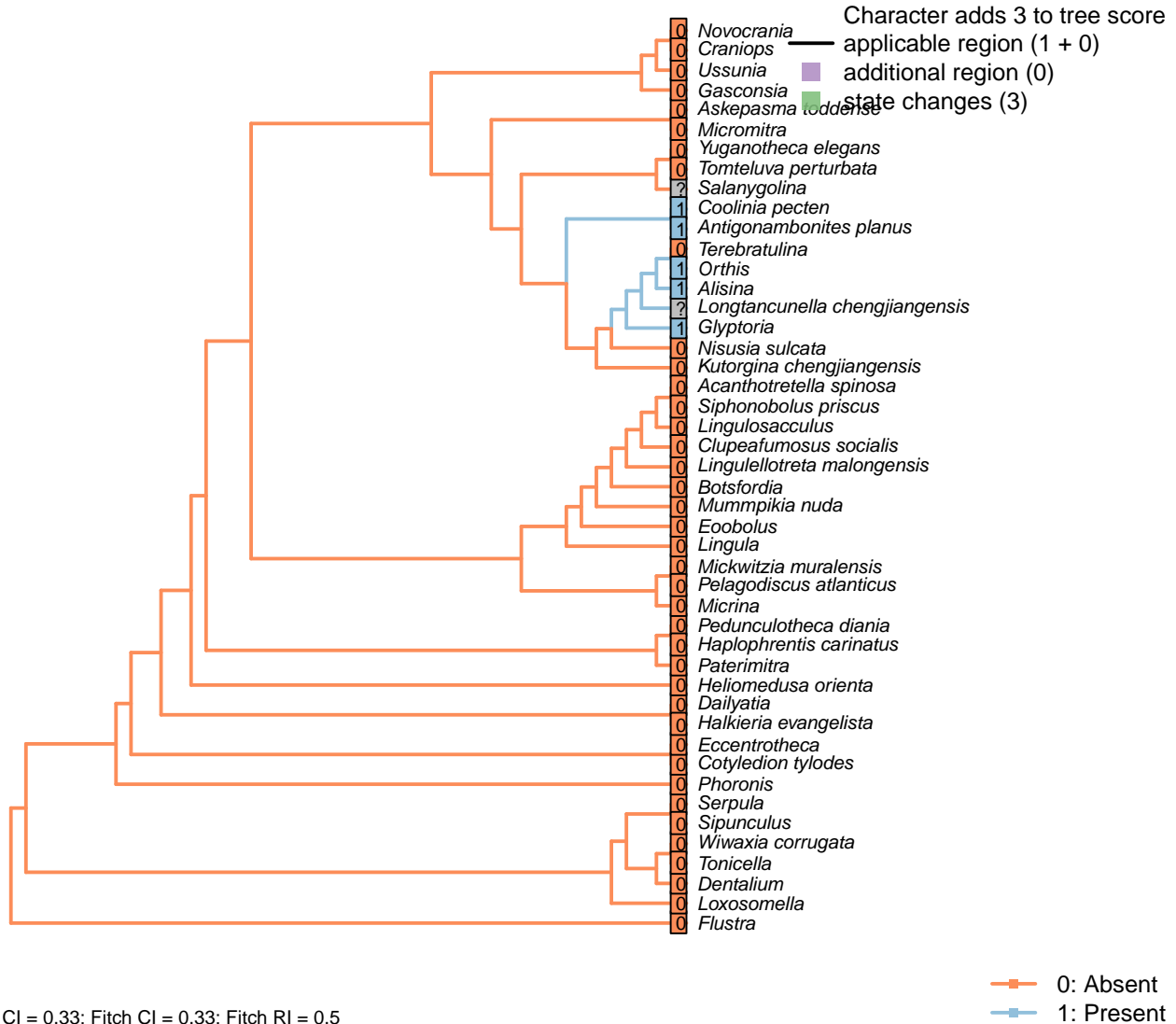
Transformational character.

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.

[82] Notothyrial platform



After Bassett *et al.* (2001) character 12.

The presence or absence of a notothyrial platform, which often serves as an attachment point for the diductors in a similar fashion to the cardinal processes, is independent of the presence of a notothyrium.

Alisina, *Glyptoria*: Bassett *et al.* (2001) score as present in Table 18.1.

Coolinia pecten: Referred to as the “posterior platform” in Dewing (2001).

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

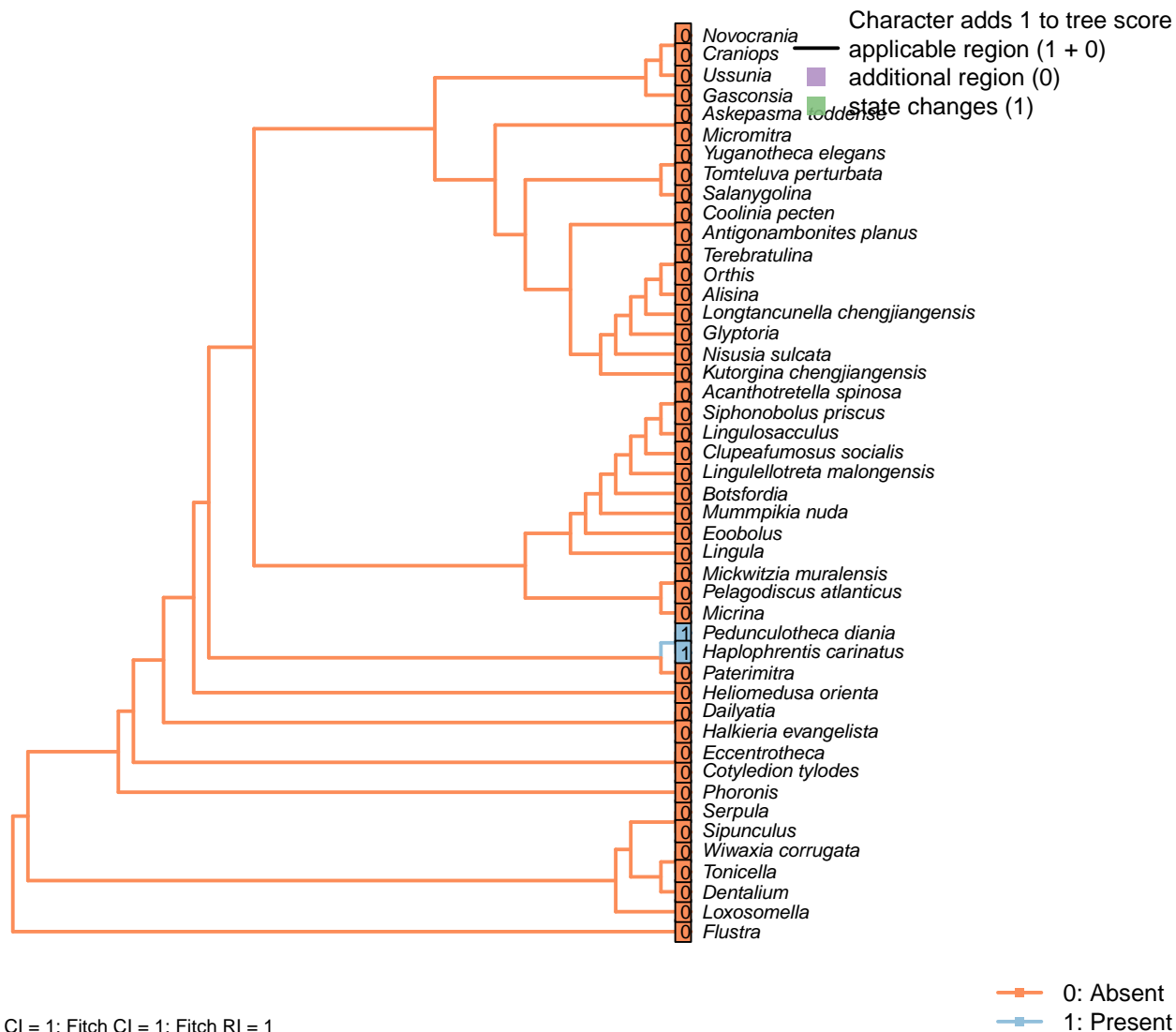
Bassett *et al.* (2001) score as absent in Table 18.1.

Nisusia sulcata: 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 Kurtorginata.

Ussunia: “Visceral platforms absent in both valves” – Williams et al. (2000), p. 192.

[83] Cardinal shield



Character 83: Sclerites: Dorsal valve: Cardinal shield

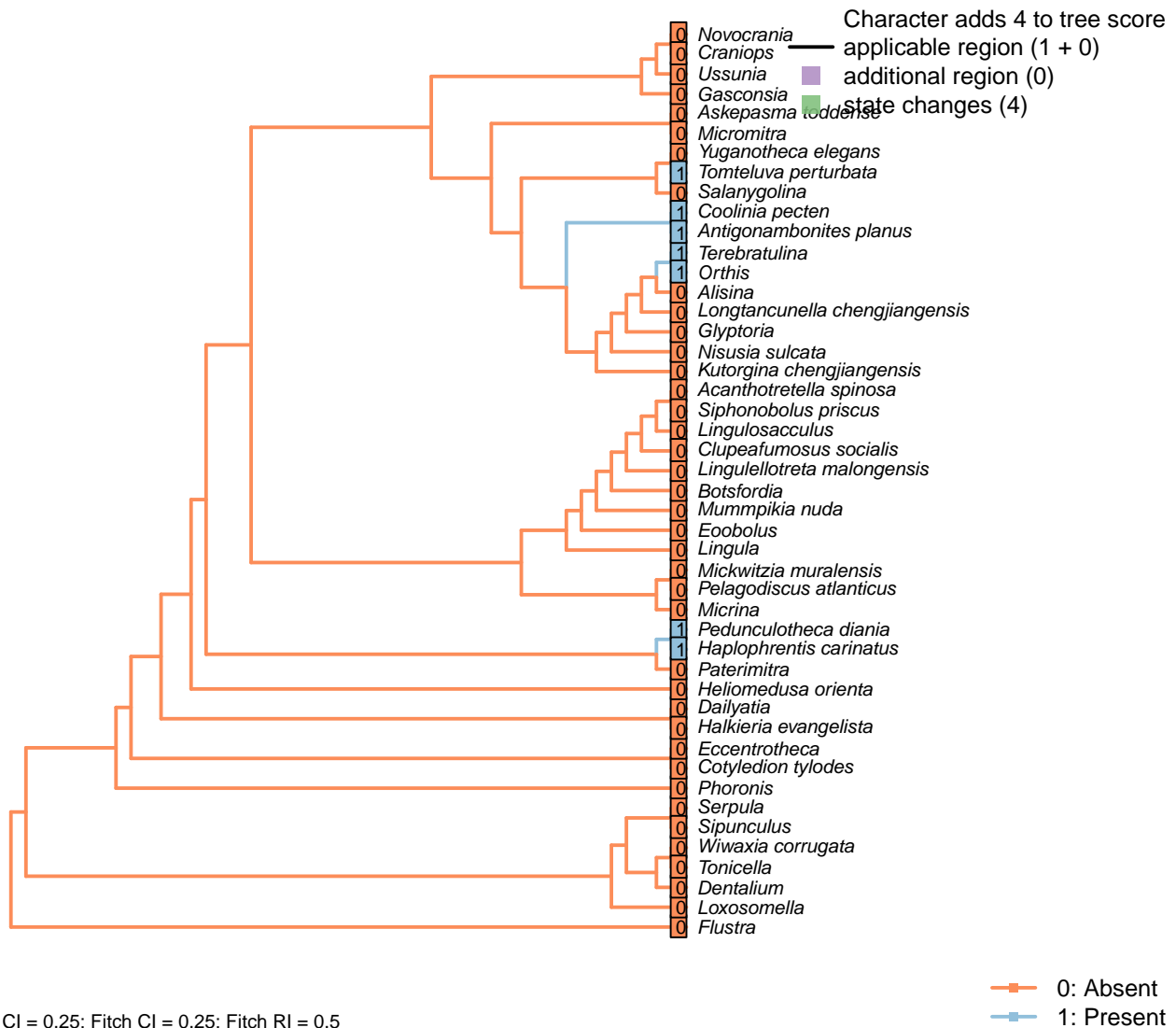
0: Absent

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.

[84] Cardinal processes

**Character 84: Sclerites: Dorsal valve: Cardinal processes**

0: Absent

1: Present

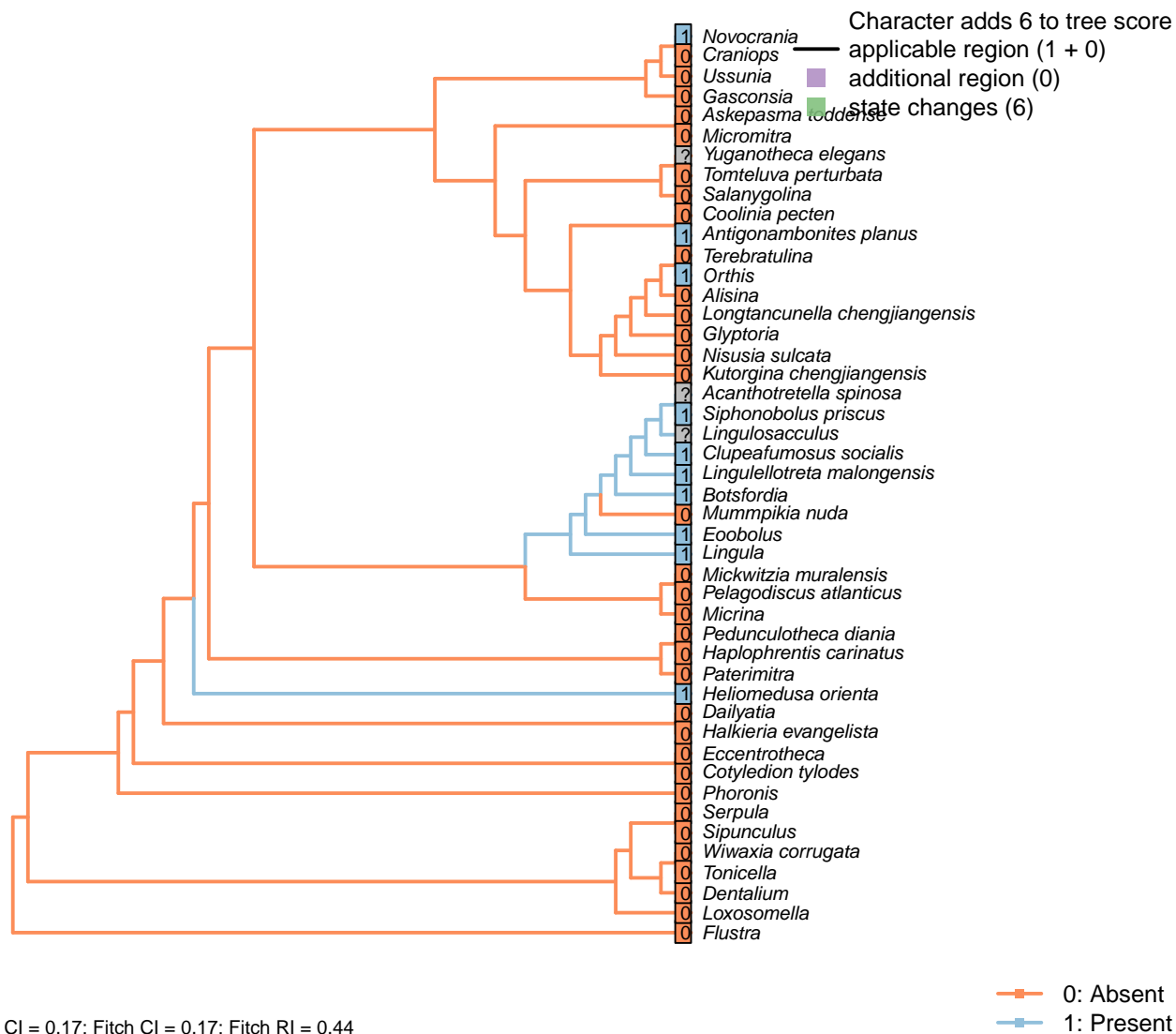
Neomorphic character.

After Bassett *et al.* (2001) character 13.

Cardinal processes are unlikely to be homologous with the notothyrial platform, even if their function is similar.

Clupeafumosus socialis: Not reported by Topper *et al.* (2013a).*Longtancunella chengjiangensis*: Not evident, and ought arguably to be discernable if present given the quality of preservation.

[85] Medial septum

**Character 85: Sclerites: Dorsal valve: Medial septum**

0: Absent

1: Present

Neomorphic character.

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

Acanthotretella spinosa: 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.

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

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

– Williams et al. (2000).

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

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

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

Heliomedusa orientalis: 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).

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

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

Lingulosacculus: 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.

Mummpikia nuda: See pl. 2 panel 6 in Balthasar (2008).

Nisusia sulcata: Fig. 125 in Williams *et al.* (2000).

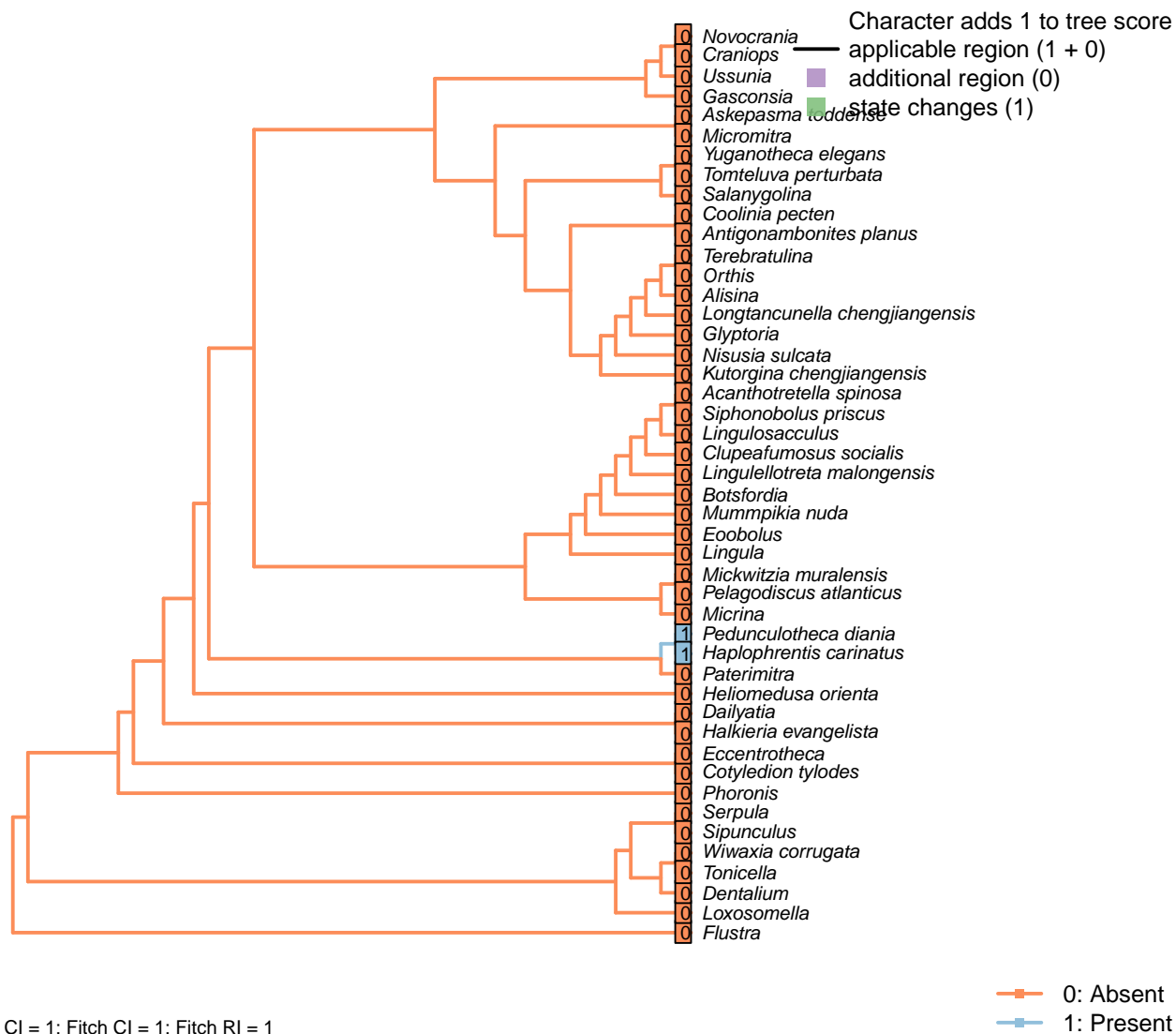
Novocrania: Median process evident: Williams *et al.* (2000) fig. 100.2a, d.

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

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

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

[86] Clavicles

**Character 86: Sclerites: Dorsal valve: Clavicles**

0: Absent

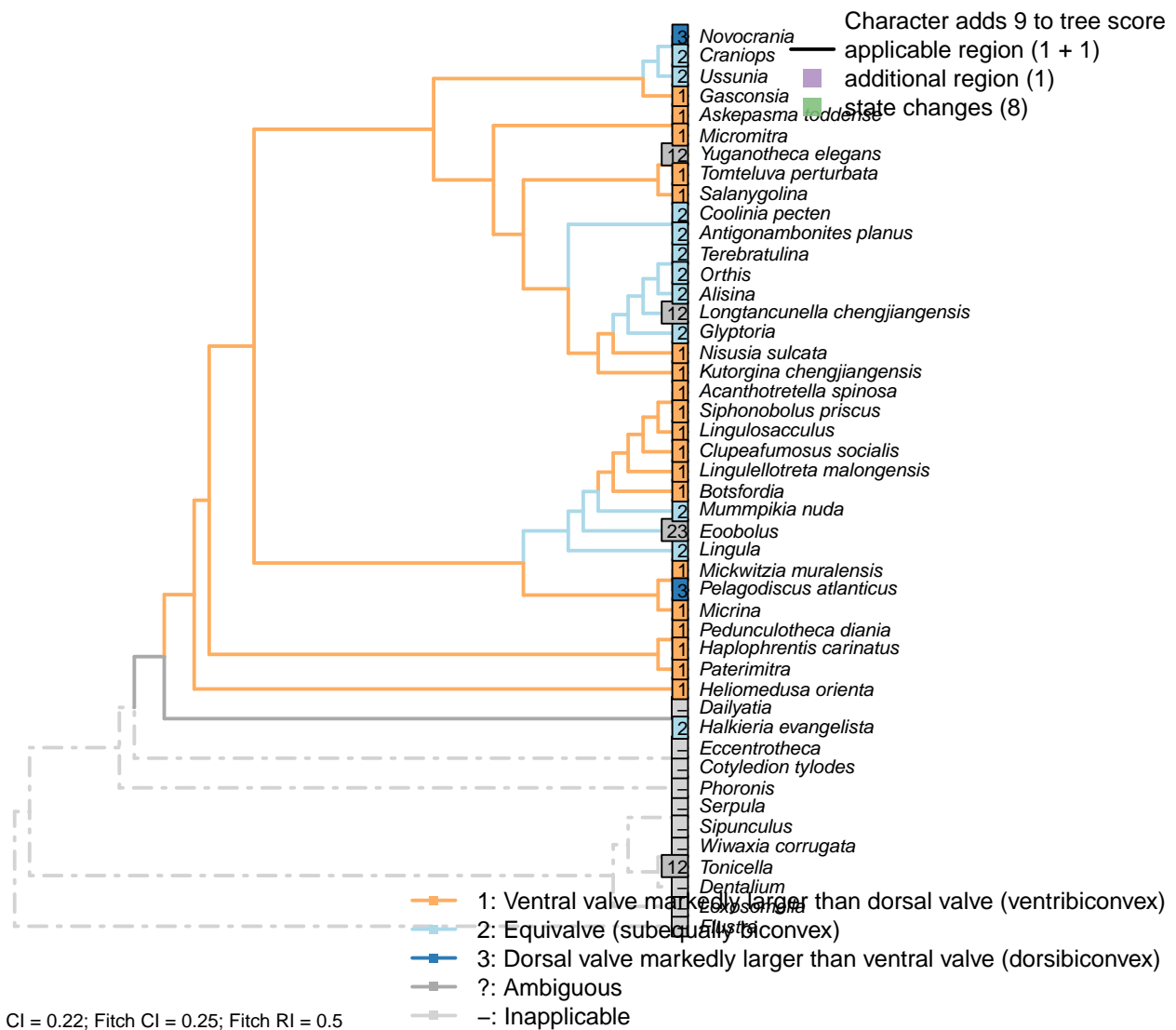
1: Present

Neomorphic character.

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

3.17 Sclerites: Ventral valve

[87] Relative size



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.

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

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

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

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

Gasconsia: Convexiplane (Williams *et al.*, 2000, p. 187).

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

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

Longtancunella chengjiangensis, *Yuganotheca elegans*: The ventral valve is somewhat, but not markedly, larger than the dorsal; as such, this character is coded ambiguous for equivalve/ventral valve larger.

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

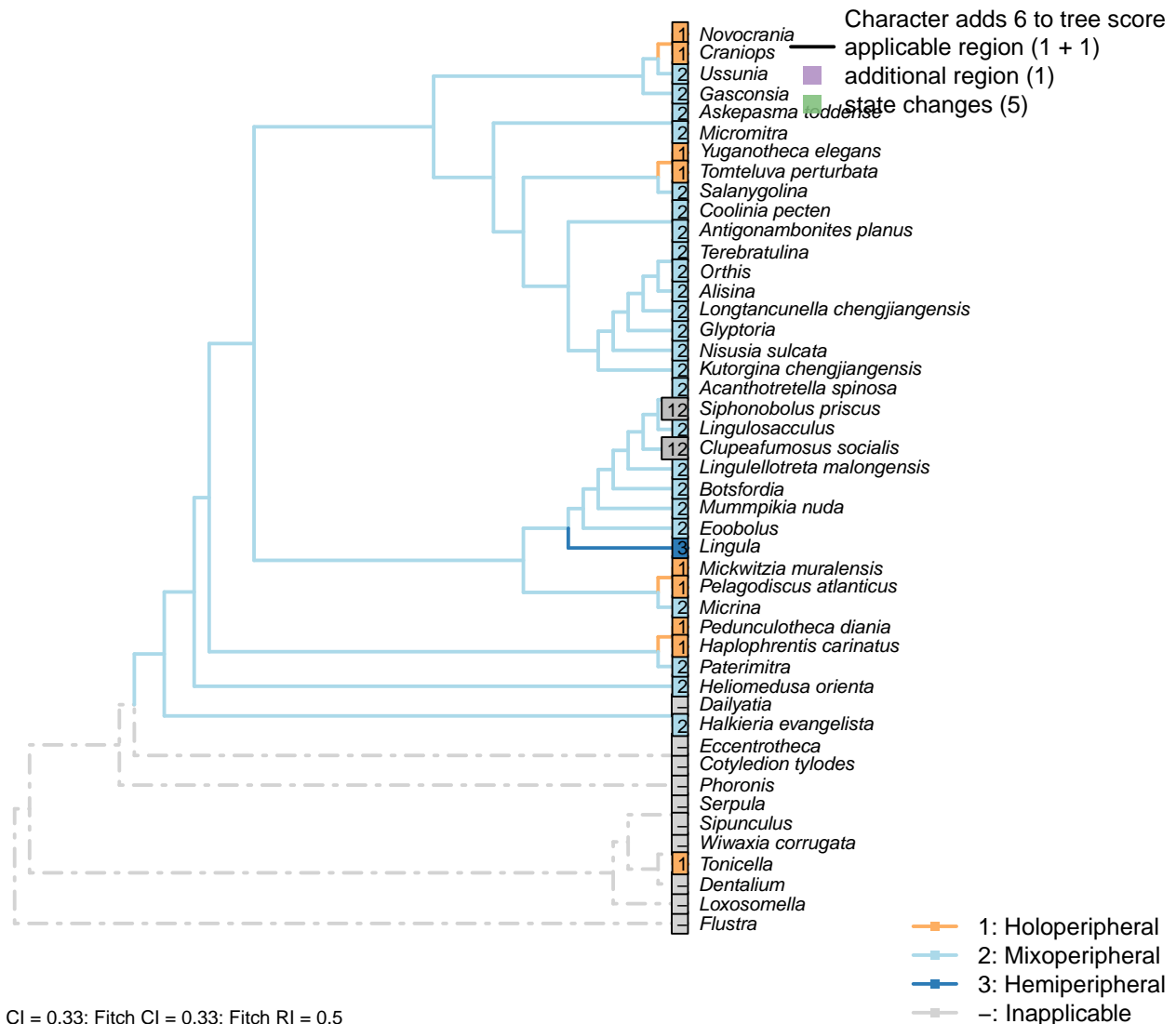
Nisusia sulcata: Ventral valve larger (see Williams *et al.*, 2000, fig. 126.).

Siphonobolus priscus: Ventribiconvex (Popov *et al.*, 2009).

Tonicella: Coded as ambiguous for equivalve/ventral valve larger: the posterior embryonic shell field, treated herein as equivalent to the ventral valve,.

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

[88] Growth direction

**Character 88: 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.

Clupeafumosus socialis: Inferred from Topper *et al.* (2013a).

Heliomedusa orientata: 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].

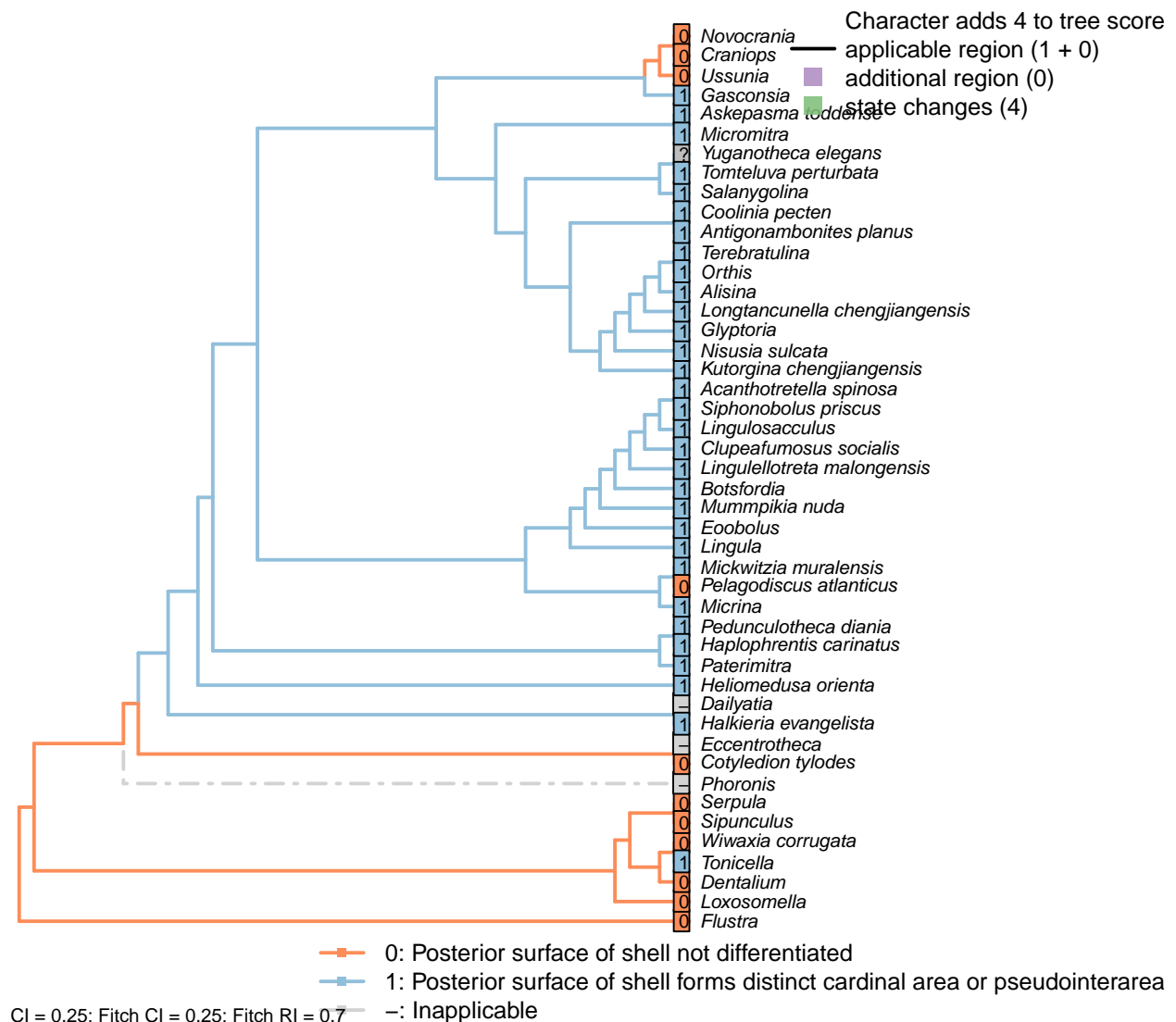
Paterimitra: The apical flange notwithstanding, the umbo of the S1 sclerite is posterior of the hinge line and the posterior edge of the lateral plate – see Larsson et al. (2014), fig. 2a, c.

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

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

Ussunia: Following description of order in Williams et al. (2000).

[89] Posterior surface: Differentiated



Character 89: 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".

Alisina, *Antigonambonites planus*, *Coolinia pecten*, *Glyptoria*, *Kutorgina chengjiangensis*, *Nisusia sulcata*, *Orthis*, *Salanygolina*, *Tomteluva perturbata*: Interarea present.

Clupeafumosus socialis: Described by Topper et al. (2013a).

Gasconsia: 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.

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

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

Longtancunella chengjiangensis: 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.

Mickwitzia muralensis: Termed an interarea by Balthasar (2004).

Mummpikia nuda: 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".

Paterimitra: Triangular notch and subapical flange.

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

Terebratulina: Interarea.

Tonicella: 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.

Ussunia: Following char 17 in table 15 in Williams et al. (2000).

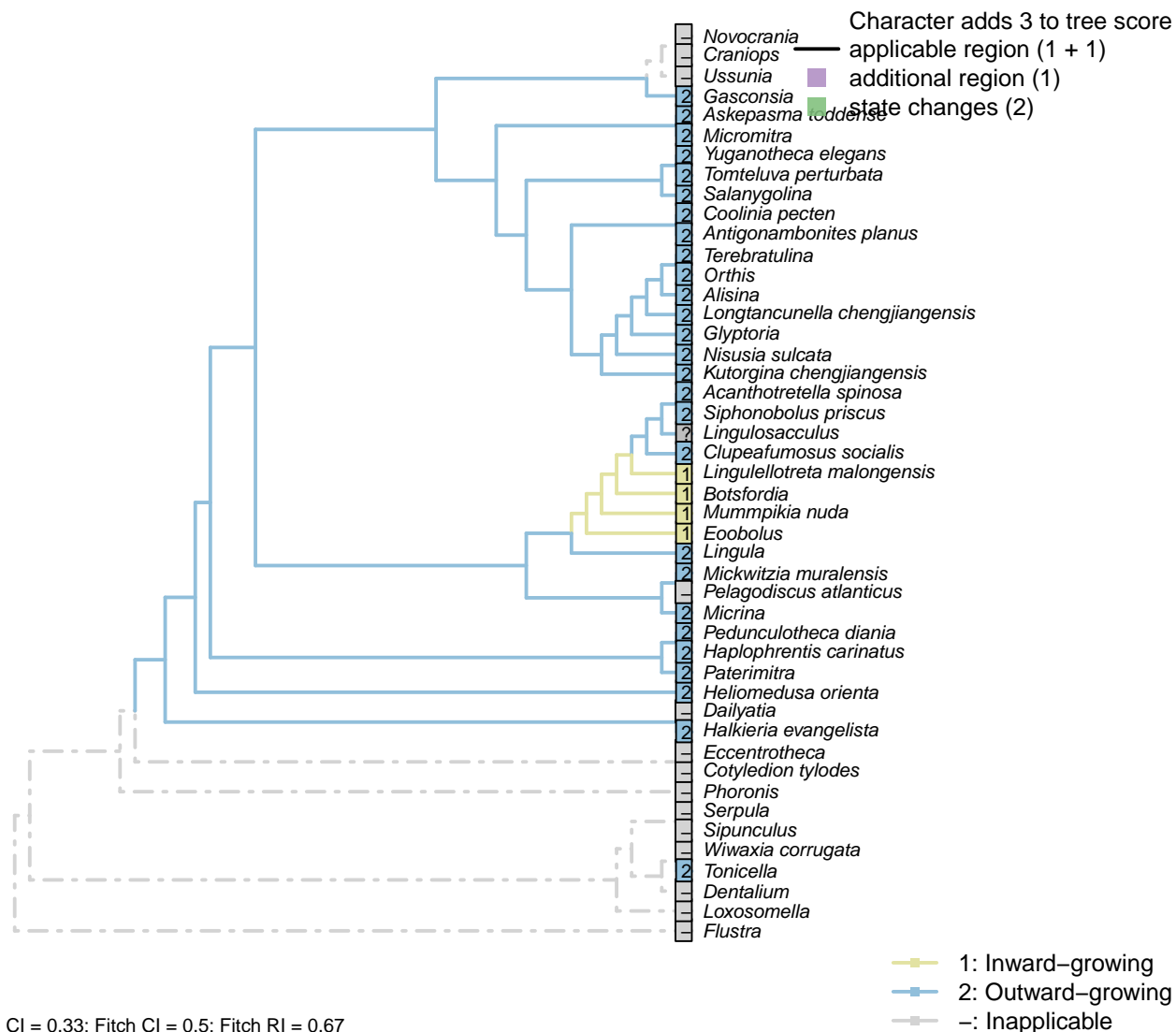
Oh dear! **You included the inapplicable token in a neomorphic character!**

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

- Phoronis
- Dailyatia
- Eccentrotheca

[90] Posterior margin growth direction

**Character 90: 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.

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

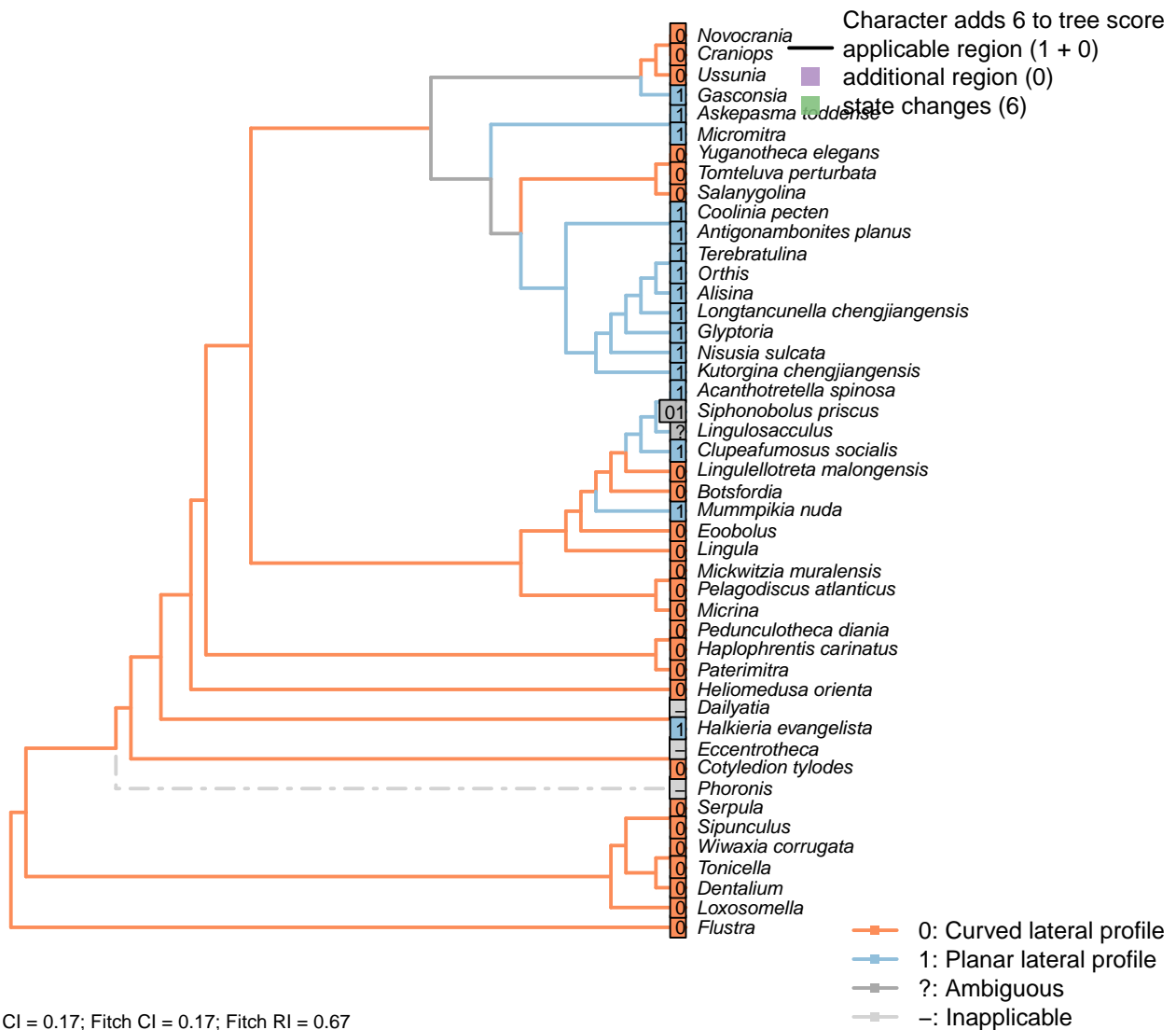
Clupeafumosus socialis: See Topper *et al.* (2013a).

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

Lingulellotreta malongensis: Transverse cross section of ventral pseudointerarea concave.

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

[91] Posterior surface: Planar



Character 91: 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: ventral pseudointerareas are most similar to those found within the Order Siphonotretida.

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

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

Eoobolus: Some curvature retained.

Lingulellotreta malongensis: Transverse cross section of ventral pseudointerarea concave.

Longtancunella chengjiangensis: Flattened, reflecting the strophic hinge line.

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

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

Tonicella: (Schwabe, 2010).

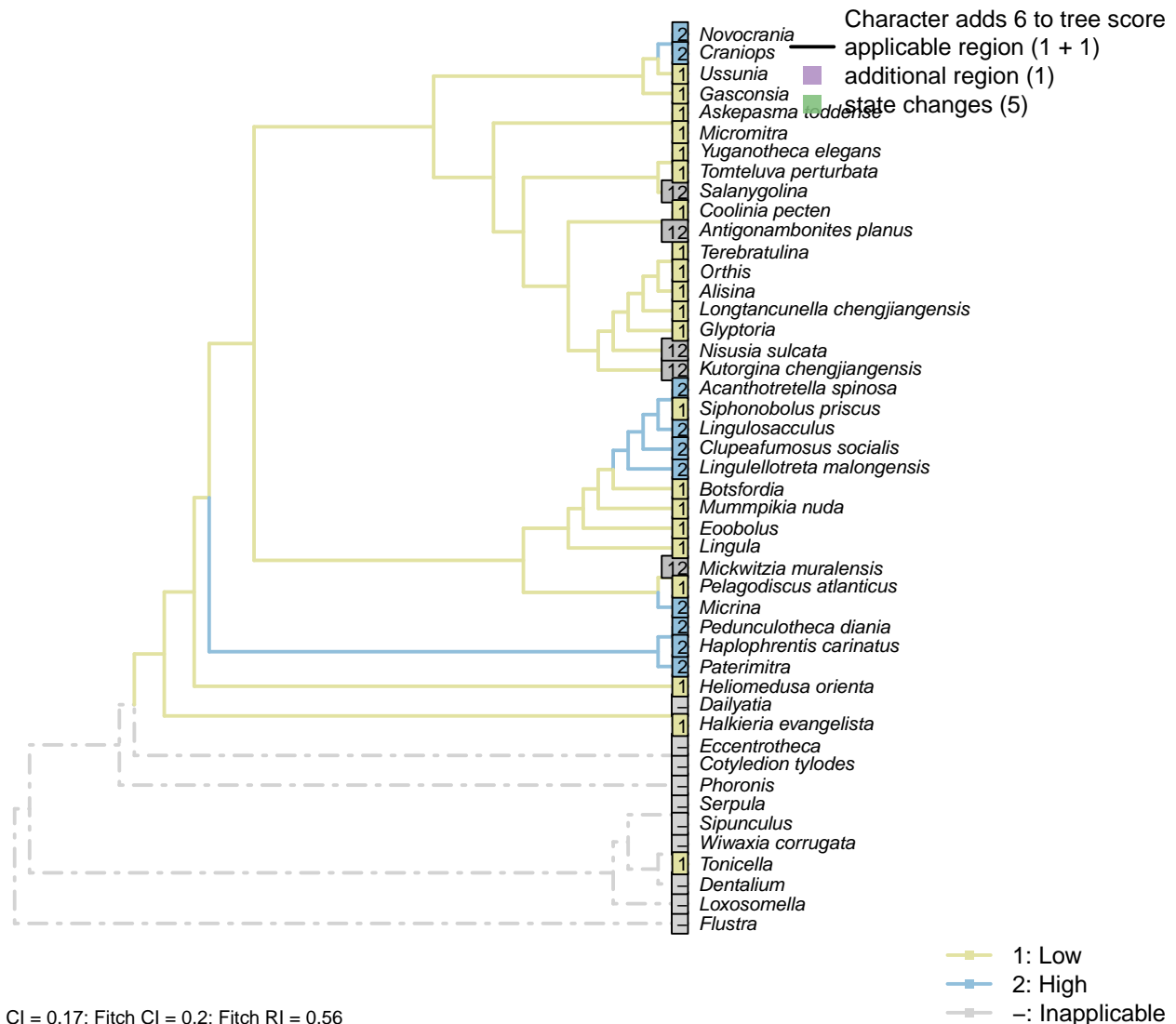
Oh dear! **You included the inapplicable token in a neomorphic character!**

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

- Phoronis
- Dailyatia
- Eccentrotheca

[92] Posterior surface: Extent

**Character 92: Sclerites: Ventral valve: Posterior surface: Extent**

1: Low

2: High

Transformational character.

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

Antigonambonites planus: 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.

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

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

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

Kutorgina chengjiangensis: 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.

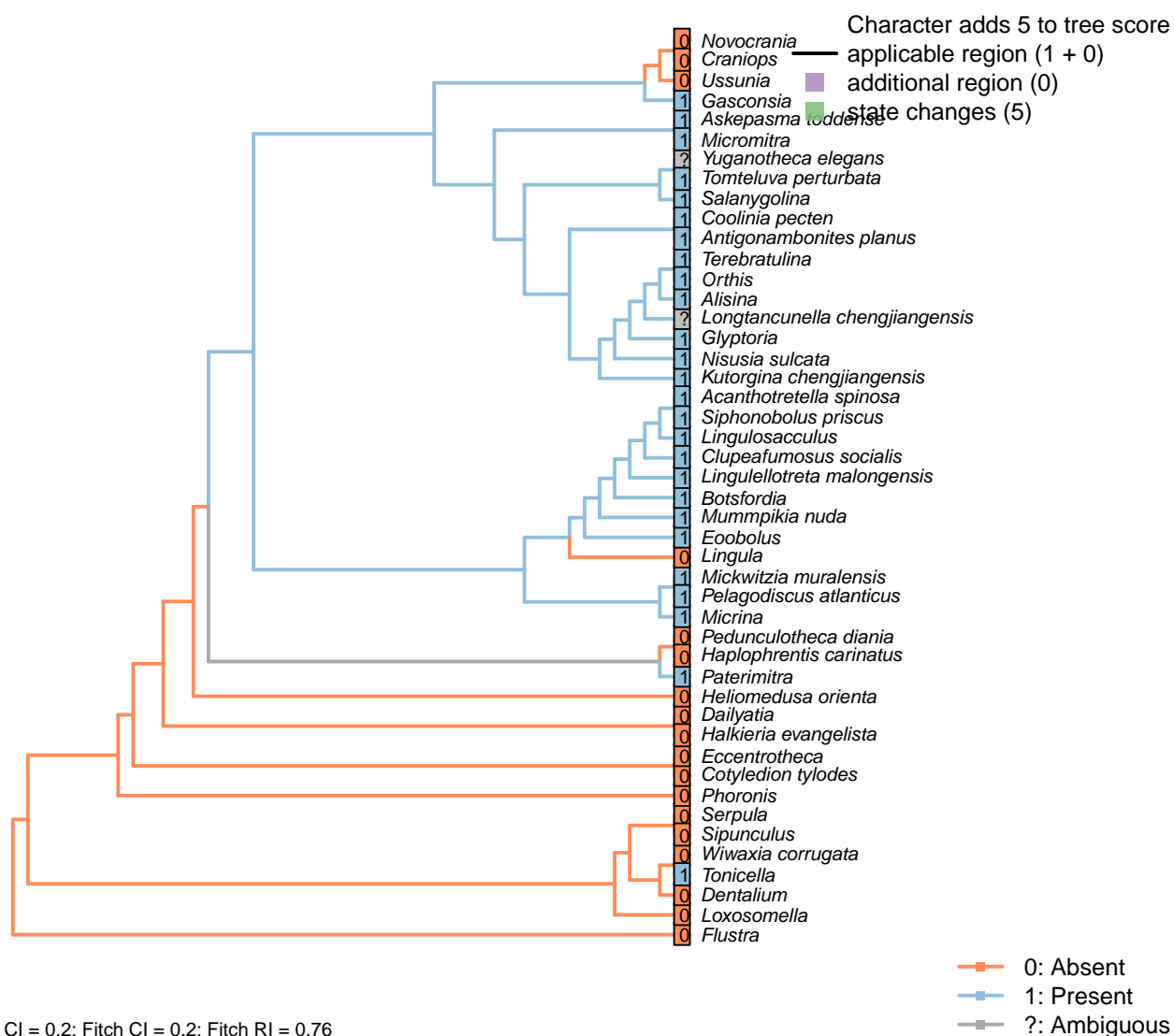
Mickwitzia muralensis: Often not prominently high (Skovsted and Holmer, 2003; Balthasar, 2004), though in some cases (e.g. Butler *et al.*, 2015) the ventral valve approaches the conical shape that this character is intended to capture. Coded as polymorphic.

Nisusia sulcata: 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.

Orthis: Scored 'Low' for *Eoorthis* by Benedetto (2009); assumed same in *Orthis*.

Salanygolina: 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.

[93] Posterior surface: Delthyrium



Character 93: 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: Origin modelled on *Siphonobolus*.

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

Botsfordia: 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.

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

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

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

Longtancunella chengjiangensis: 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.

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

Micrina: Opening inferred by Holmer et al. (2008).

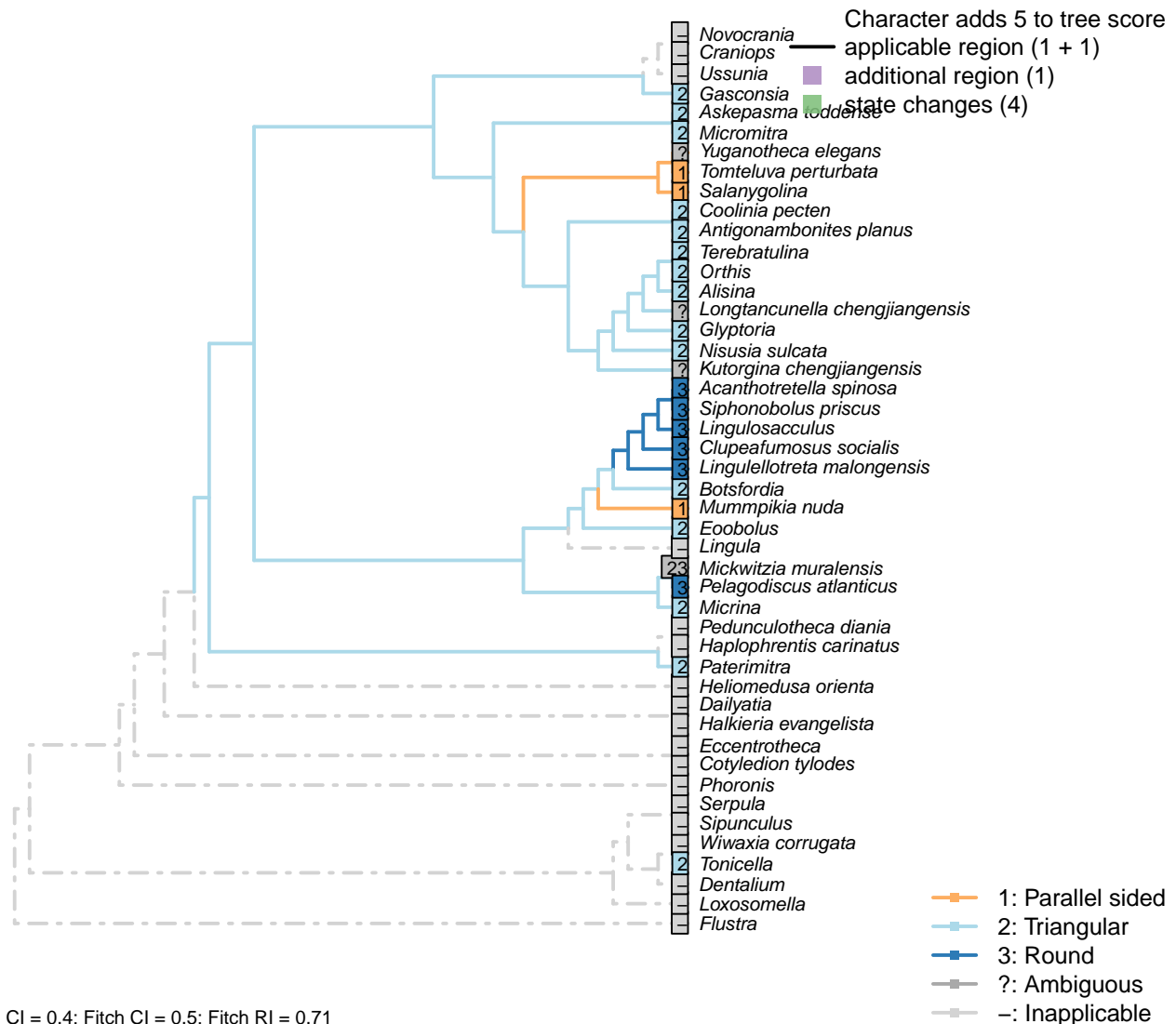
Pelagodiscus atlanticus: The listrum (pedicle opening) is interpreted as originating via a similar mechanism to that of acrotretids (Popov, 1992), and hence corresponding to a basally sealed delthyrium.

Siphonobolus priscus: Ontogeny presumed to resemble that of acrotretids.

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

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

[94] Posterior surface: Delthyrium: Shape

**Character 94: 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.

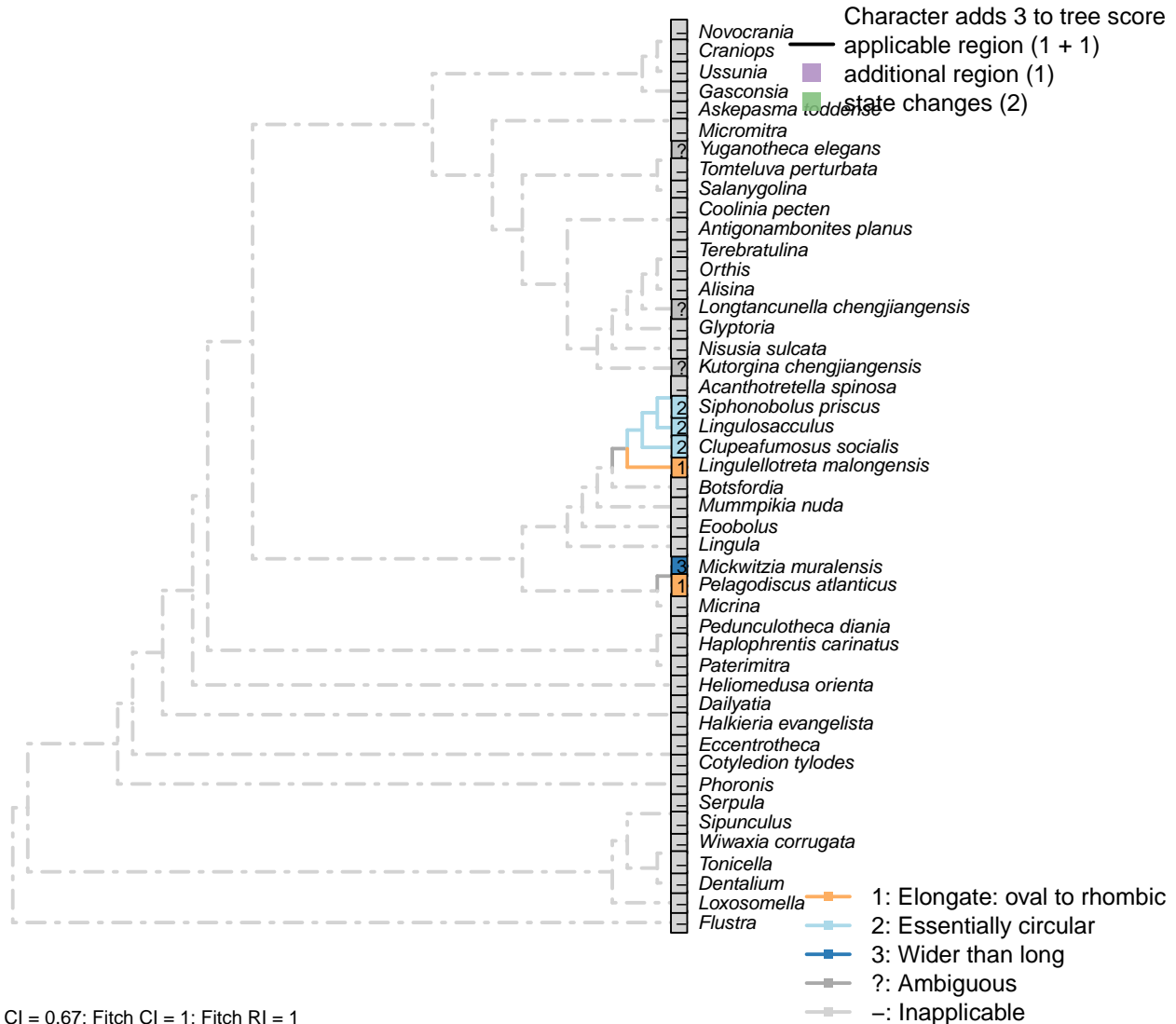
Askepasma toddense: Prominently triangular (see Topper et al., 2013b, fig. 2).

Clupeafumosus socialis: Following the model of Popov (1992).

Mickwitzia muralensis: 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).

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



Character 95: Sclerites: Ventral valve: Posterior surface: Delthyrium: Shape: Aspect of rounded opening

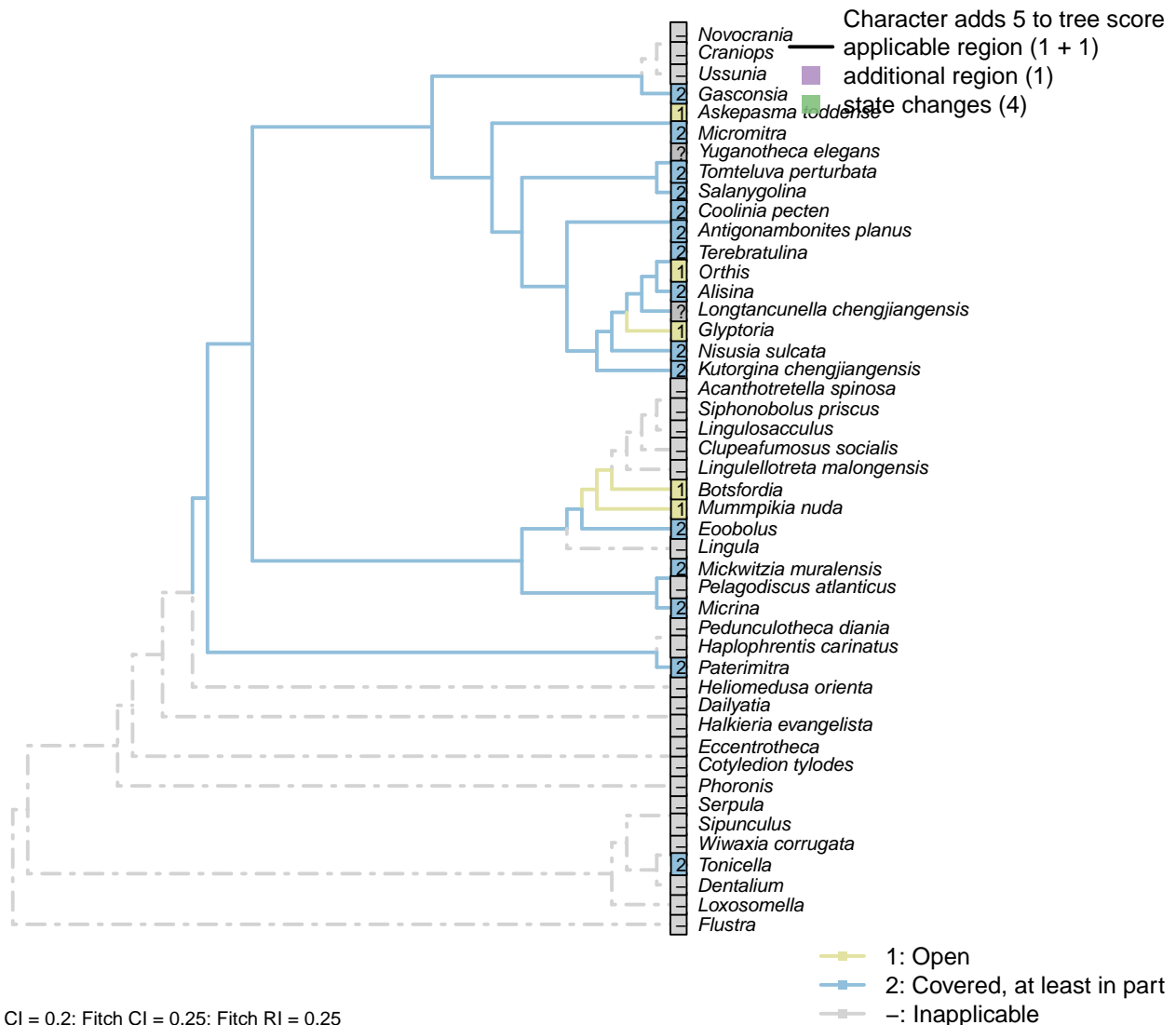
- 1: Elongate: oval to rhombic
 - 2: Essentially circular
 - 3: Wider than long
- Transformational character.

Chen *et al.* (2007) propose that an oval to rhombic foramen characterises the discinids [and *Heliomedusa*, though the foramen in this taxon has since been reinterpreted by Zhang *et al.* (2009) as an impression of internal tissue].

Lingulellotretra malongensis: Oval (Williams *et al.*, 2000).

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

[96] Posterior surface: Delthyrium: Cover

**Character 96: Sclerites: Ventral valve: Posterior surface: Delthyrium: Cover**

1: Open

2: Covered, at least in part

Transformational character.

An open delthyrium links *Mummpikia* with the Obolellidae (Balthasar, 2008).

The delthyrial opening can be covered by one or more deltidial plates, or a pseudodeltitium.

Inapplicable in taxa with a round delthiruyum (generated by overgrowth of the delthyrial opening by postero-

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

Askepsasma toddense: Open (Topper et al., 2013b).

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

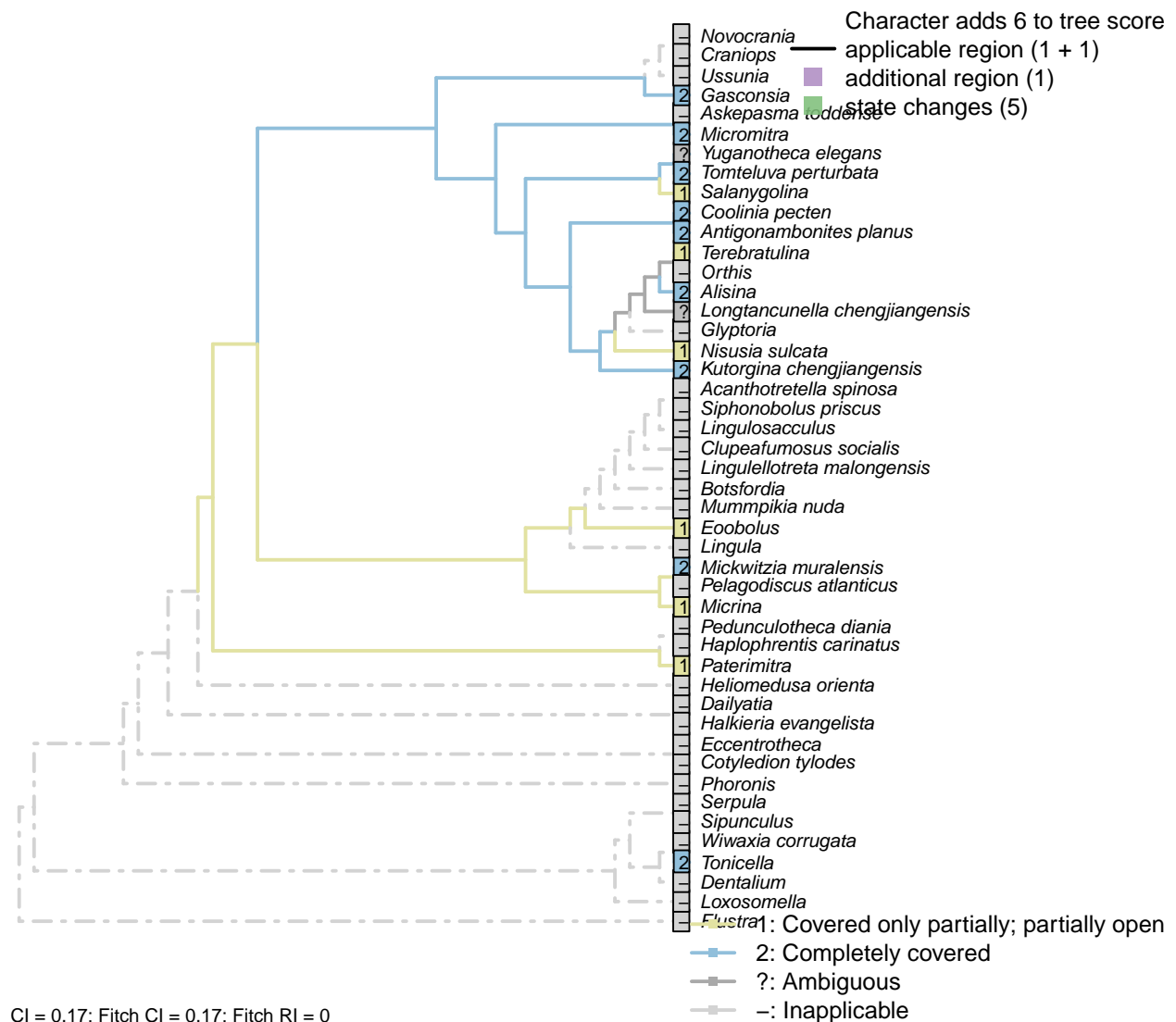
Coolinia pecten: A convex pseudodeltidium completely covers the delthyrium in *Coolinia*.

Glyptoria: Coded as open by Williams et al. (1998).

Nisusia sulcata: “Covered only apically by a small convex pseudodeltidium” – Holmer et al. (2018a).

Paterimitra: Covered by subaical flange, in part.

[97] Posterior surface: Delthyrium: Cover: Extent



Character 97: Sclerites: Ventral valve: Posterior surface: Delthyrium: Cover: Extent

1: Covered only partially; partially open

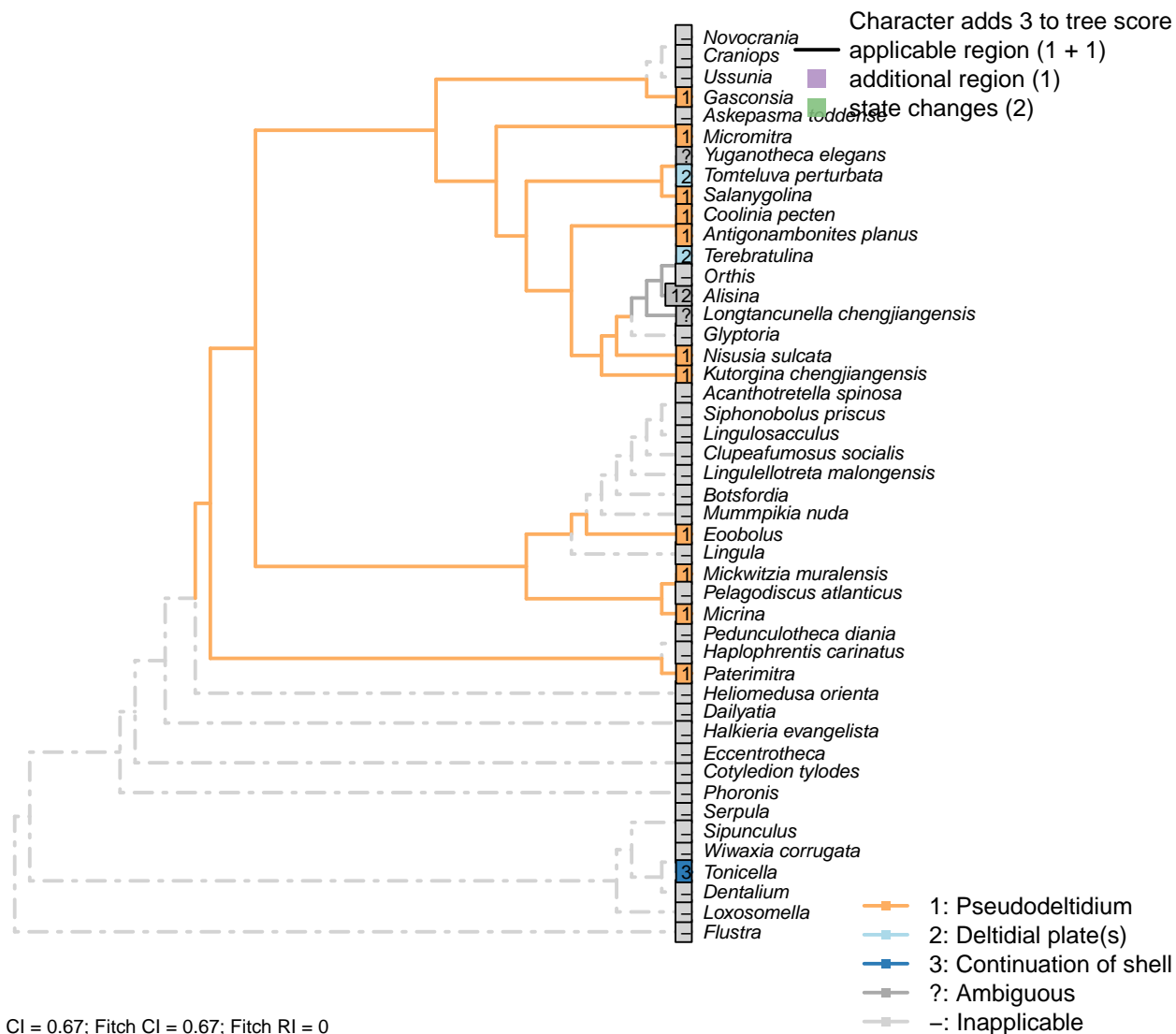
2: Completely covered

Transformational character.

Micrina: Remains somewhat open.

Nisusia sulcata: A well-defined pseudo-deltidium [...] closes only the apical part of the delthyrium (Rowell and Caruso, 1985).

[98] Posterior surface: Delthyrium: Cover: Identity



Character 98: 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.

Alisina: Stated as “concave pseudodeltidium with median plication” – Williams et al. (2000)

Coded as “Pseudodeltidium: Covered by concave plate” by Bassett *et al.* (2001).

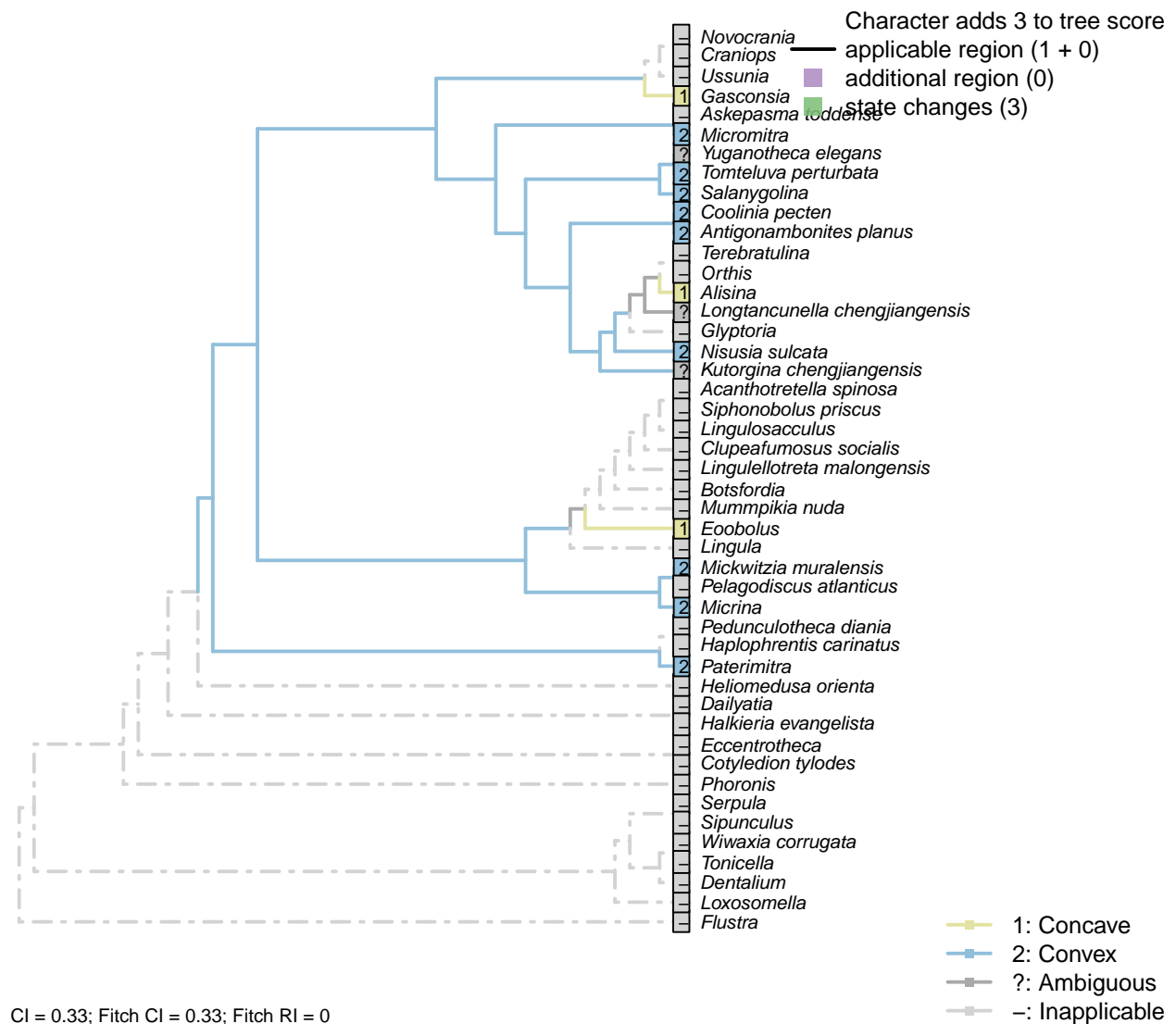
Askepasma toddense: No pseudodeltidium (Williams et al., 2000, p. 153).

Lingulellotreta malongensis: The subapical flange of the *Paterimitra* S1 sclerite has been homologised with the ventral homeodeltidium of *Micromitra* (Larsson et al., 2014).

Mickwitzia muralensis: Termed a homoedeltidium by Balthasar (2004).

Micrina: “Ventral valve convex with apsacline interarea bearing delthyrium, covered by a convex pseudodeltidium” – Holmer et al. (2008).

[99] Posterior surface: Delthyrium: Pseudodeltidium: Shape



Character 99: 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).

Alisina: “concave pseudodeltidium with median plication” – Williams et al. (2000)

Coded as “Pseudodeltidium: Covered by concave plate” by Bassett *et al.* (2001).

Antigonambonites planus: Convex (Williams et al., 2000, fig. 508).

Gasconsia: *Gasconsia* possesses narrow concave homeodeltidium, but absent pseudodeltidium.

Kutorgina chengjiangensis: 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).

Mickwitzia muralensis: Convex (see Balthasar, 2004, fig. 4B).

Micrina: Convex deltoid (Holmer et al., 2008).

Micromitra: Gently convex (see Williams et al., 2000, fig. 83.3).

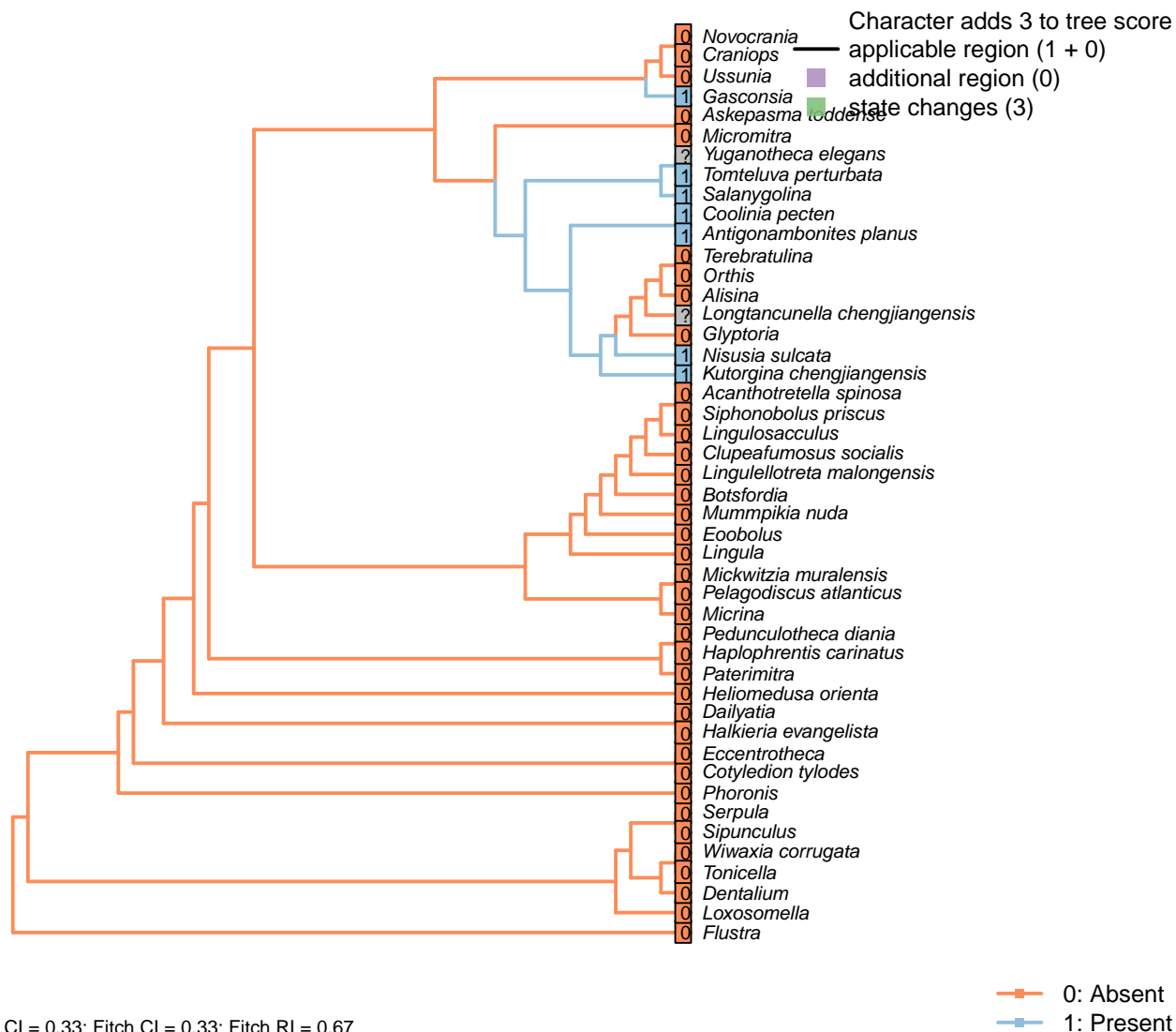
Nisusia sulcata: Convex in *Nisusia* (see Rowell and Caruso, 1985, fig. 8.4).

Paterimitra: Gently convex (see Williams et al., 2000, fig. 83.1).

Salanygolina: “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.

Tomteluva perturbata: Convex (Streng et al., 2016).

[100] Posterior surface: Delthyrium: Pseudodeltidium: Hinge furrows

**Character 100: Sclerites: Ventral valve: Posterior surface: Delthyrium: Pseudodeltidium: Hinge furrows**

0: Absent

1: Present

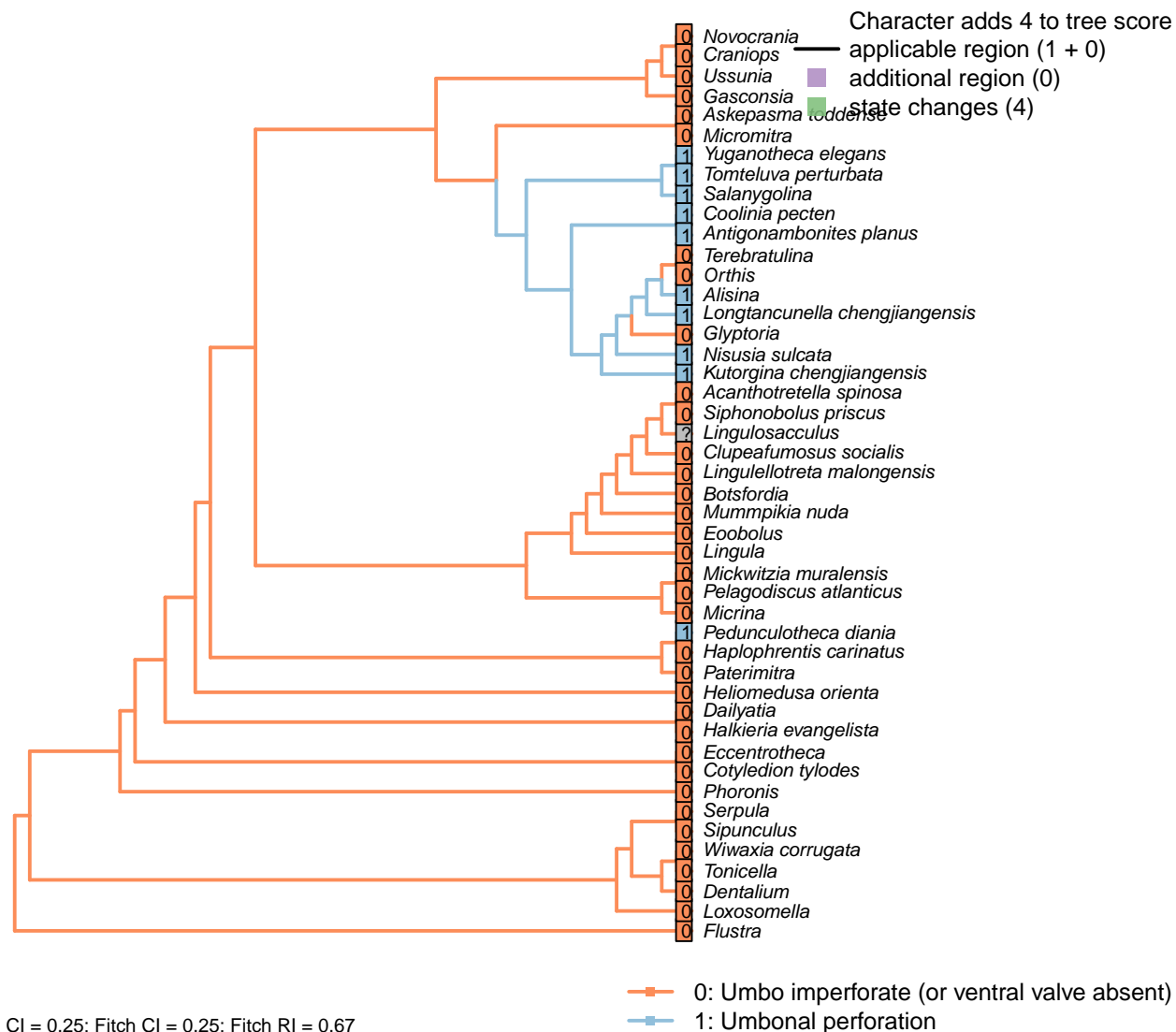
Neomorphic character.

After Bassett *et al.* (2001) character 18, “Hinge furrows on lateral sides of pseudodeltidium”.

Acanthotretella spinosa, *Askepasma toddense*, *Clupeafumosus socialis*, *Dailyatia*, *Eccentrotheca*, *Glyptoria*, *Haplophrentis carinatus*, *Heliomedusa orienta*, *Lingula*, *Lingulellotreta malongensis*, *Lingulosacculus*, *Micrina*, *Micromitra*, *Mummpikia nuda*, *Novocrania*, *Orthis*, *Paterimitra*, *Pedunculotheca diania*, *Pelagodiscus atlanticus*, *Phoronis*, *Terebratulina*: Absent due to inapplicability of neomorphic character.

Salanygolina: The presence of this feature is impossible to determine based on the available material.

[101] Umbonal perforation

**Character 101: Sclerites: Ventral valve: Umbonal perforation**

0: Umbo imperforate (or ventral valve absent)

1: Umbonal perforation

Neomorphic character.

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.

Clupeafumosus socialis: 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.

Dailyatia: 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.

Eccentrotheca: 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.

Heliomedusa orientalis: 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).

Lingulosacculus: The apical termination of the fossil is unknown.

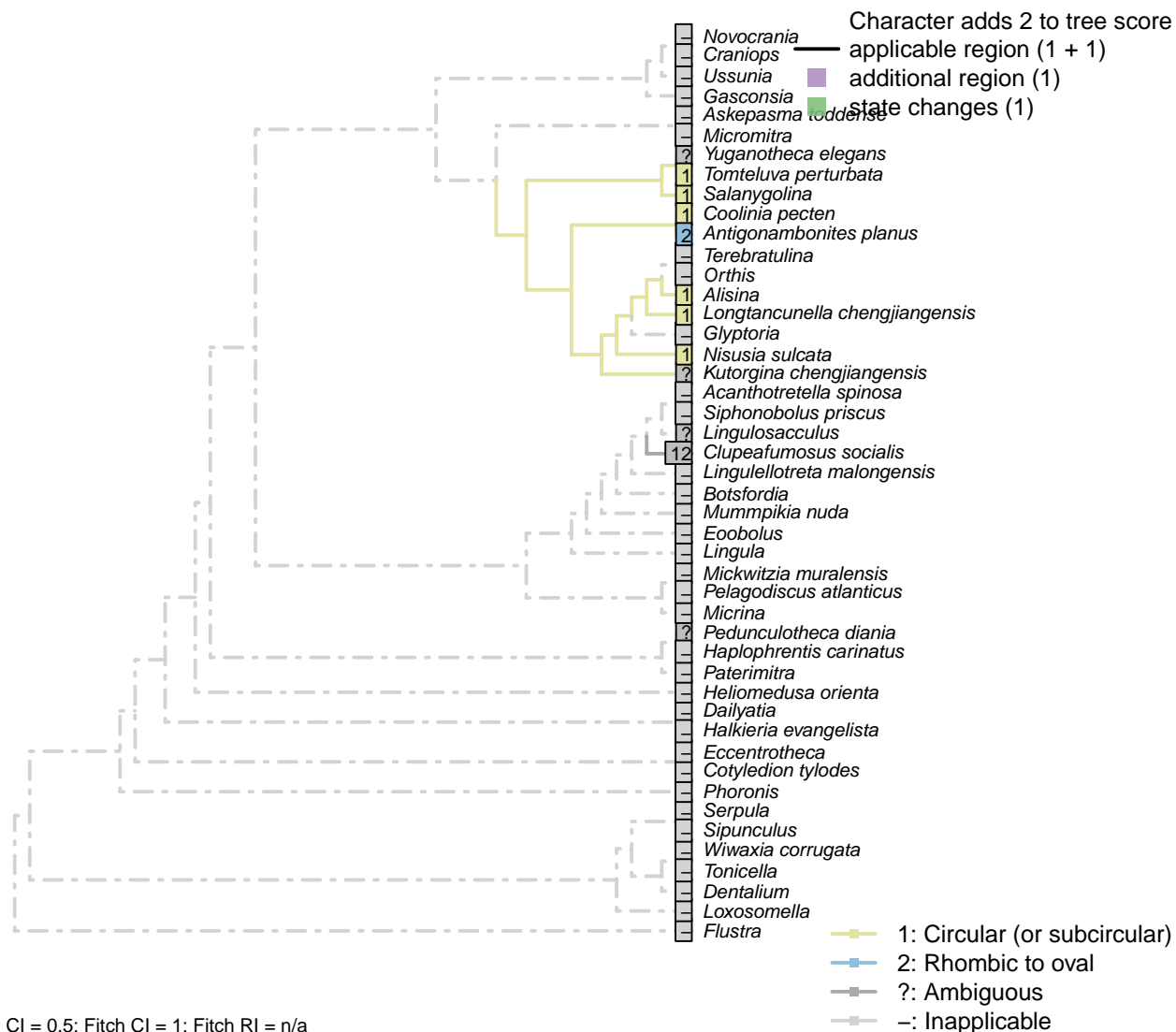
Mickwitzia muralensis: The umbo itself is imperforate (Balthasar, 2004).

Paterimitra: The presumed pedicle foramen is an opening between the S1 and S2 sclerites, neither of which are perforated (Skovsted et al., 2009).

Siphonobolus priscus: 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.

Tomteluva perturbata: 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 tomteividu to be homologous with the pedicle tube of acrotretids and their ilk, stating (p. 274) that it appears to be unique within Brachiopoda.

[102] Umbonal perforation: Shape

**Character 102: Sclerites: Ventral valve: Umbonal perforation: Shape**

1: Circular (or subcircular)

2: Rhombic to oval

Transformational character.

Acanthotretella spinosa: Too small to observe given quality of preservation (Holmer and Caron, 2006).*Alisina*: Seemingly circular (Zhang et al., 2011b).*Antigonambonites planus*: Based on p.92, fig.4B.*Clupeafumosus socialis*: Taller than wide in some cases, but very nearly circular in others; see Topper *et al.* (2013a).*Coolinia pecten*: Bassett and Popov write “a dominant feature of the ventral umbo is a sub-oval perforation about 270 μ m long and 250 μ m wide”: the width and height of this structure are almost identical, and we

score it as (sub) circular.

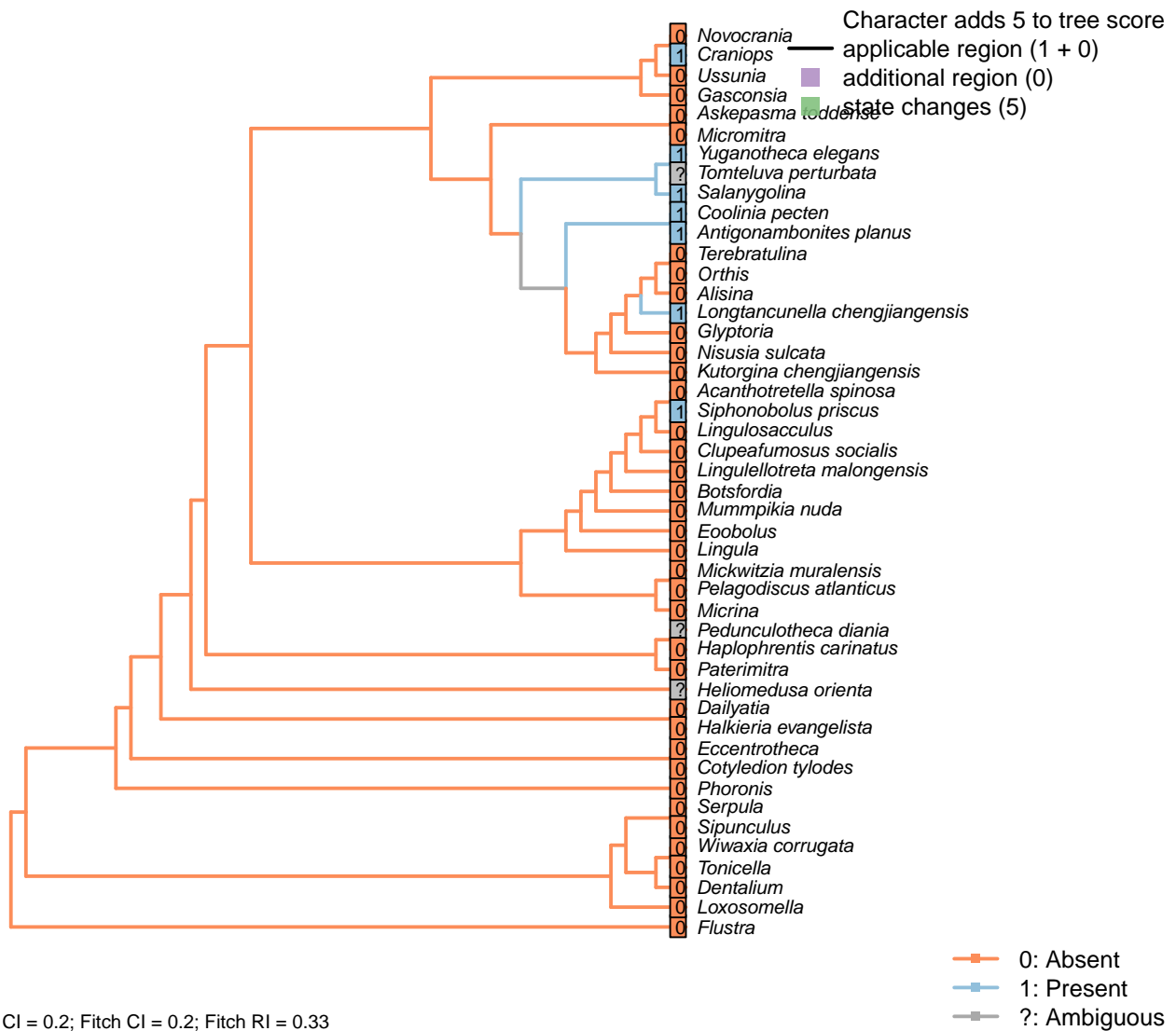
Heliomedusa orientata: Rhombic to oval – seen as evidence for a discinid affinity (Chen et al., 2007).

Kutorgina chengjiangensis: The exact size and shape of the apical perforation is obscured by the emerging pedicle.

Nisusia sulcata: “close to circular” (Holmer et al., 2018a).

Salanygolina: Essentially circular (Holmer et al., 2009, fig. 4).

[103] Colleplax, cicatrix or pedicle sheath



Character 103: 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.

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

Clupeafumosus socialis: Not reported by Topper *et al.* (2013a).

Craniops: *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.

Heliomedusa orientalis: 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.

Kutorgina chengjiangensis: The umbonal region of kutorginides “clearly lacks a pedicle sheath” (Holmer *et al.*, 2018b).

Lingulellotrema malongensis: The pedicle is identified as such (rather than a pedicle sheath) by the internal pedicle tube.

Longtancunella chengjiangensis: 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).

Micrina: Absent in *Micrina* (Holmer *et al.*, 2011).

Pedunculotheca diania: 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.

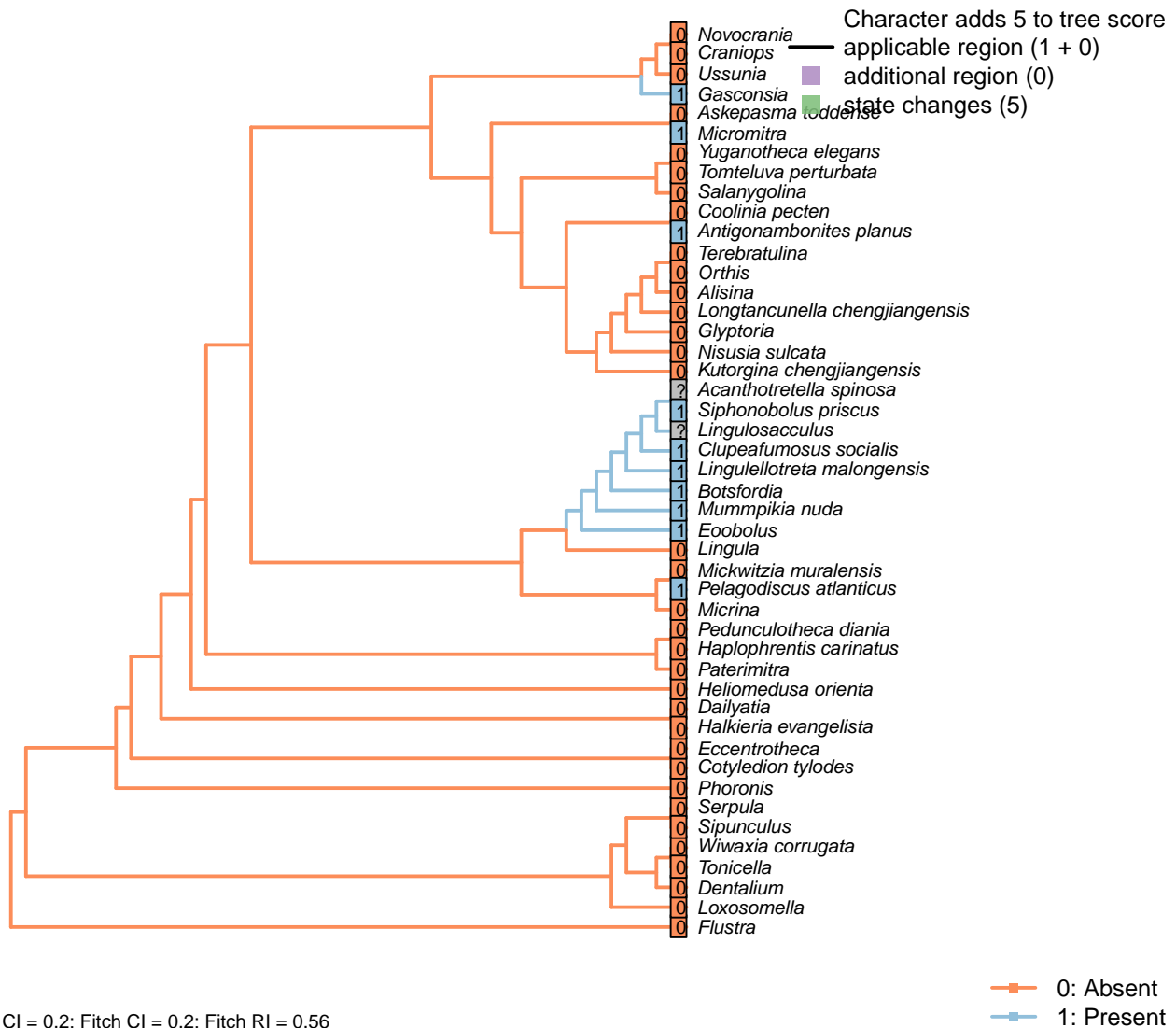
Siphonobolus priscus: Coded as present in view of the attachment scar, which has been considered homologous with the “adult colleplax and foramen with attachment pad” in *Salanygolina* (Popov *et al.*, 2009).

Tomteluva perturbata: 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.

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

Yuganotheca elegans: The median collar or conical tube is conceivably homologous with the pedicle sheath.

[104] Median septum



it is possible that this feature is present, but not observable in the Burgess Shale material.

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

Clupeafumosus socialis: A short medial ridge (septum) is present in the ventral valve (Topper et al., 2013a).

Eoobolus: Prominent median septum (fig. 4d, e in Balthasar, 2009).

Gasconsia: Evident in moulds of ventral valve; see Watkins (2002).

Glyptoria: Neither evident nor reported in Williams et al. (2000).

Haplophrentis carinatus: 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.

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

Lingulellotreta malongensis: Medial septum visible in ventral valve in Williams et al. (2000), fig. 34.1c.

Micromitra: Ventral ridge characteristic of *Micromitra* (Skovsted and Peel, 2010).

Mummpikia nuda: “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).

Novocrania: Valve thin and often unmineralized.

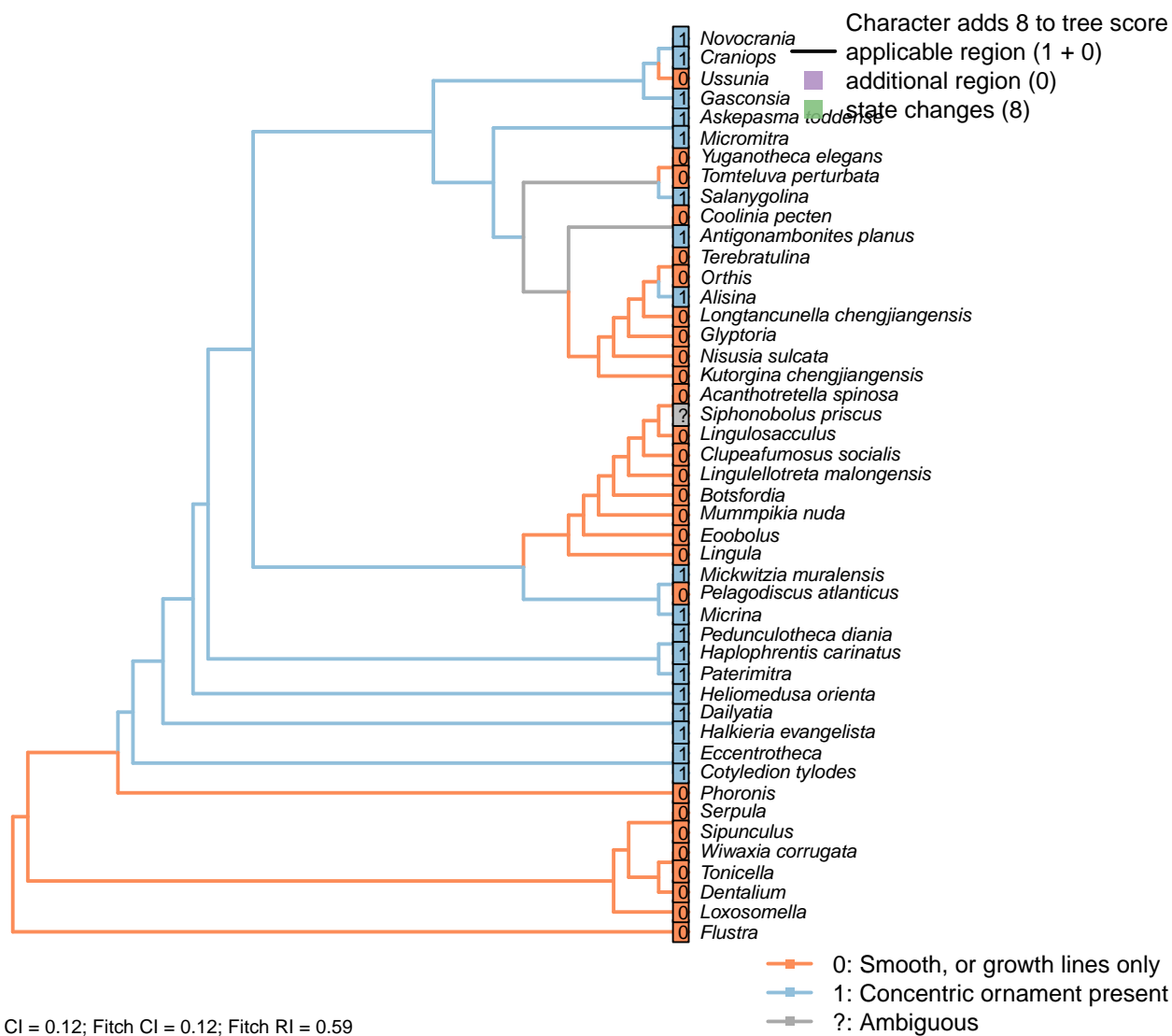
Pelagodiscus atlanticus: Described as present in *Discinisca* by Chen et al. (2007); assumed present also in *Pelagodiscus*.

Siphonobolus priscus: Present; see Popov et al. (2009), fig. 5J.

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

3.18 Sclerites: Ornament

[105] Concentric ornament



CI = 0.12; Fitch CI = 0.12; Fitch RI = 0.59

Character 105: Sclerites: Ornament: Concentric ornament

0: Smooth, or growth lines only
 1: Concentric ornament present
 Neomorphic character.

After character 11 in Williams *et al.* (1998).

Askepasma toddense, *Glyptoria*, *Kutorgina chengjiangensis*, *Micromitra*, *Salanygolina*: Following appendix 2 in Williams *et al.* (1998).

Botsfordia: 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.

Cotyledion tylodes: Zhang et al. (2013).

Eccentrotheca: More or less concentric ridges occur on *Eccentrotheca* sclerites (Skovsted et al., 2011).

Halkieria evangelista: Ridges in shell parallel, but are more prominent than, growth lines.

Haplophrentis carinatus: A series of regularly spaced concentric ridges adorn both valves (Moysiuk et al., 2017); these are more pronounced than mere growth lines.

Heliomedusa orientalis: 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).

Mickwitzia muralensis: Symmetric fila.

Novocrania: Irregular ridges externally (Williams et al., 2000).

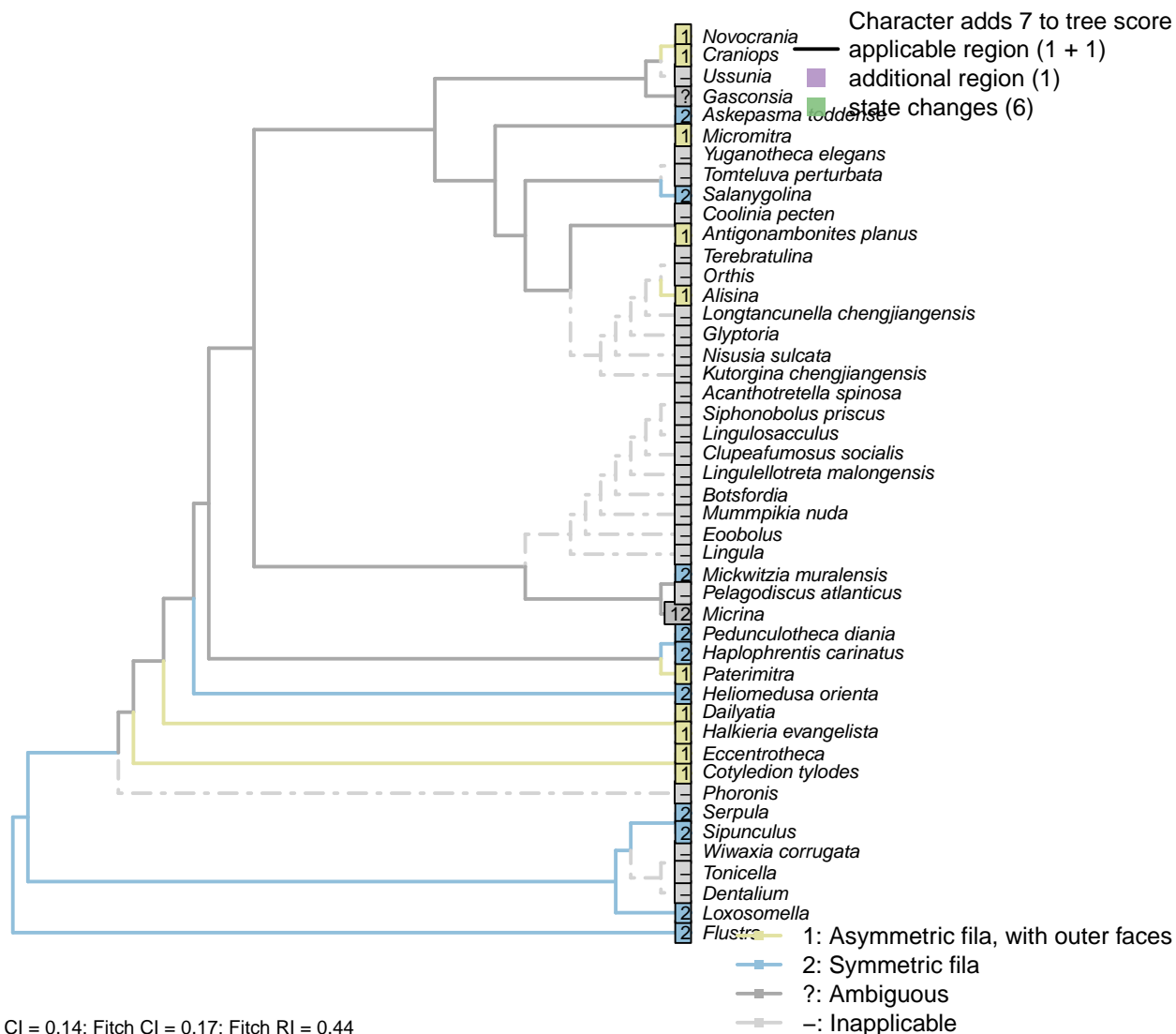
Pedunculotheca diania: A series of regularly spaced concentric ridges adorn the ventral valve; comparatively less regular lines ornament the operculum.

Pelagodiscus atlanticus: Only growth lines evident (Williams et al., 2000).

Terebratulina: 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).

Tonicella: No prominent ornamentat in *Tonicella* (Connors et al., 2012).

[106] Concentric ornament: Symmetry

**Character 106: Sclerites: Ornament: Concentric ornament: Symmetry**

1: Asymmetric fila, with outer faces

2: Symmetric fila

Transformational character.

After character 11 in Williams *et al.* (1998).*Alisina*: Seemingly asymmetric (Williams *et al.*, 2000, fig. 122.3c; Zhang *et al.*, 2011b, Fig. 1).*Askepasma toddense*, *Glyptoria*, *Kutorgina chengjiangensis*, *Micromitra*, *Salanygolina*: Following appendix 2

in Williams *et al.* (1998).

Dailyatia: Clear asymmetry (Skovsted *et al.*, 2015).

Eccentrotheca: Ornament, such as it is, is asymmetric, with prominent outer faces (Skovsted *et al.*, 2011).

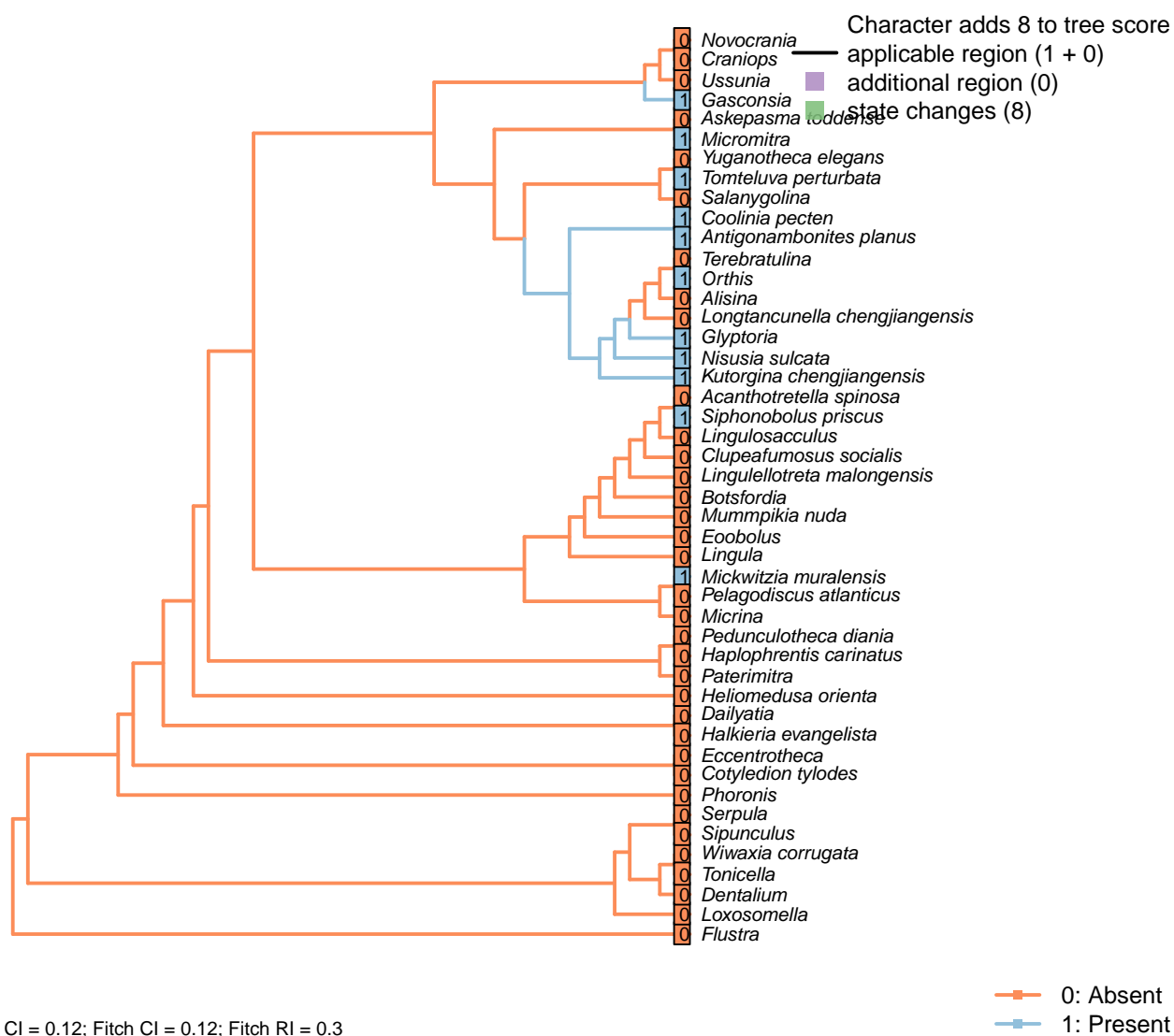
Heliomedusa orientata: See fig. 1715 in Williams *et al.* (2007).

Mickwitzia muralensis: Symmetric fila (Balthasar, 2004).

Micrina: No obvious asymmetry, even if not obviously symmetric either (Holmer *et al.*, 2008). Coded as ambiguous.

Novocrania: Clear outer faces (Williams *et al.*, 2000, fig. 100.2b).

[107] Radial ornament



Character 107: Sclerites: Ornament: Radial ornament

0: Absent

1: Present

Neomorphic character.

Ridges radiating from umbo, i.e. ribs.

Askepasma toddense: “Ornament of irregularly developed, concentric growth lamellae; microornament of irregularly arranged, polygonal pits” – Williams et al. (2000), p153; figs on p.155.

Botsfordia: Following Williams et al. (1998), Appendix 2.

Eoobolus: Very faint costellae in some specimens but coded absent.

Gasconsia: “Ornament of indistinct low radial ribs” – Williams et al. (2000, p167).

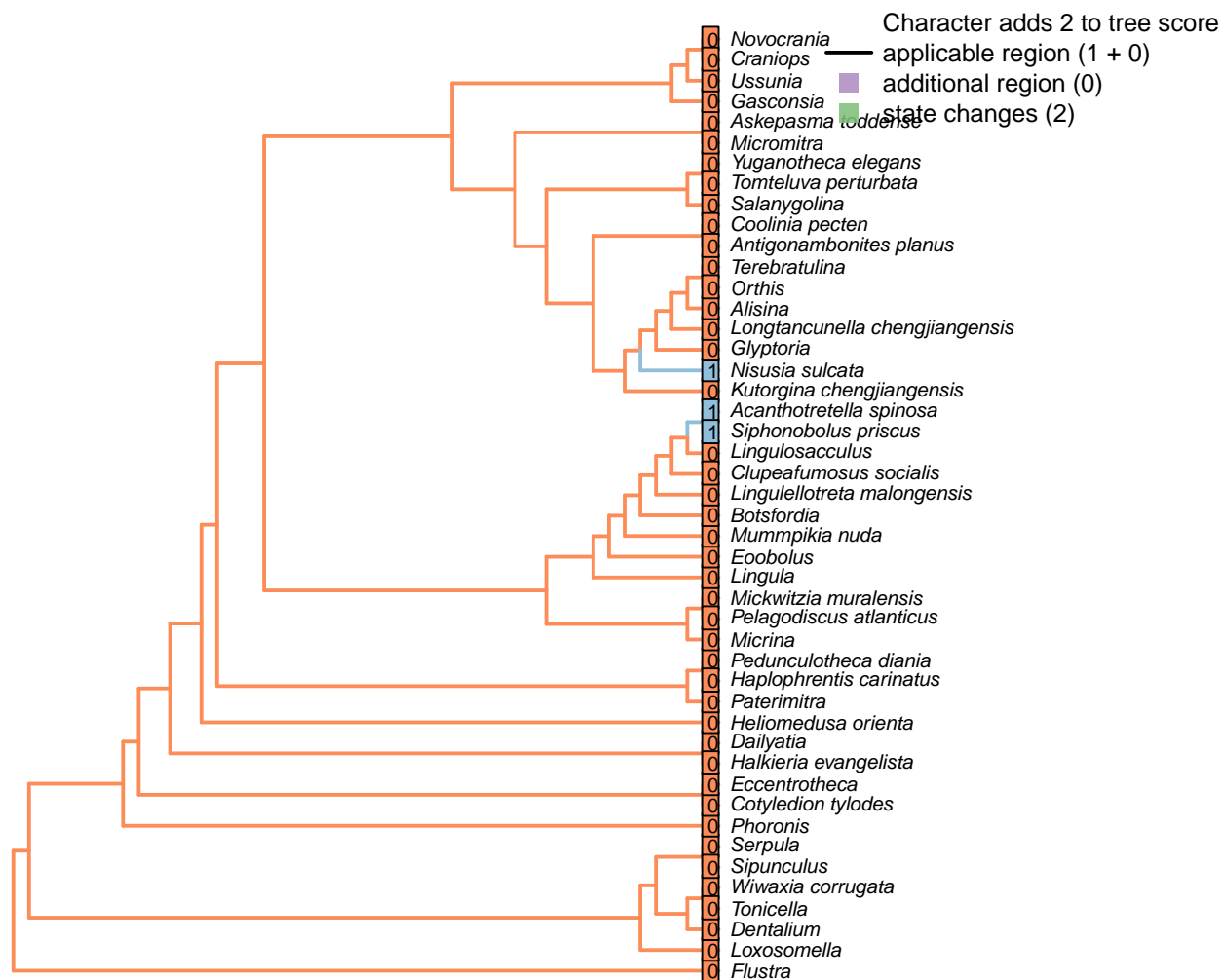
Glyptoria: “Coarsely costate” – Williams et al. (2000, p710).

Heliomedusa orienta: See fig. 1715 in Williams et al. (2007).

Siphonobolus priscus: “Indistinct radial ribs accentuated by radial rows of tubercles” – Popov et al. (2009).

Ussunia: Unornamented.

[108] Shell-penetrating spines



CI = 0.5; Fitch CI = 0.5; Fitch RI = 0.5

0: Absent
1: Present

Character 108: Sclerites: Ornament: Shell-penetrating spines

0: Absent

1: Present

Neomorphic character.

Mineralized or partly mineralized spines are observed in *Heliomedusa* and *Acanthotretella*.

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

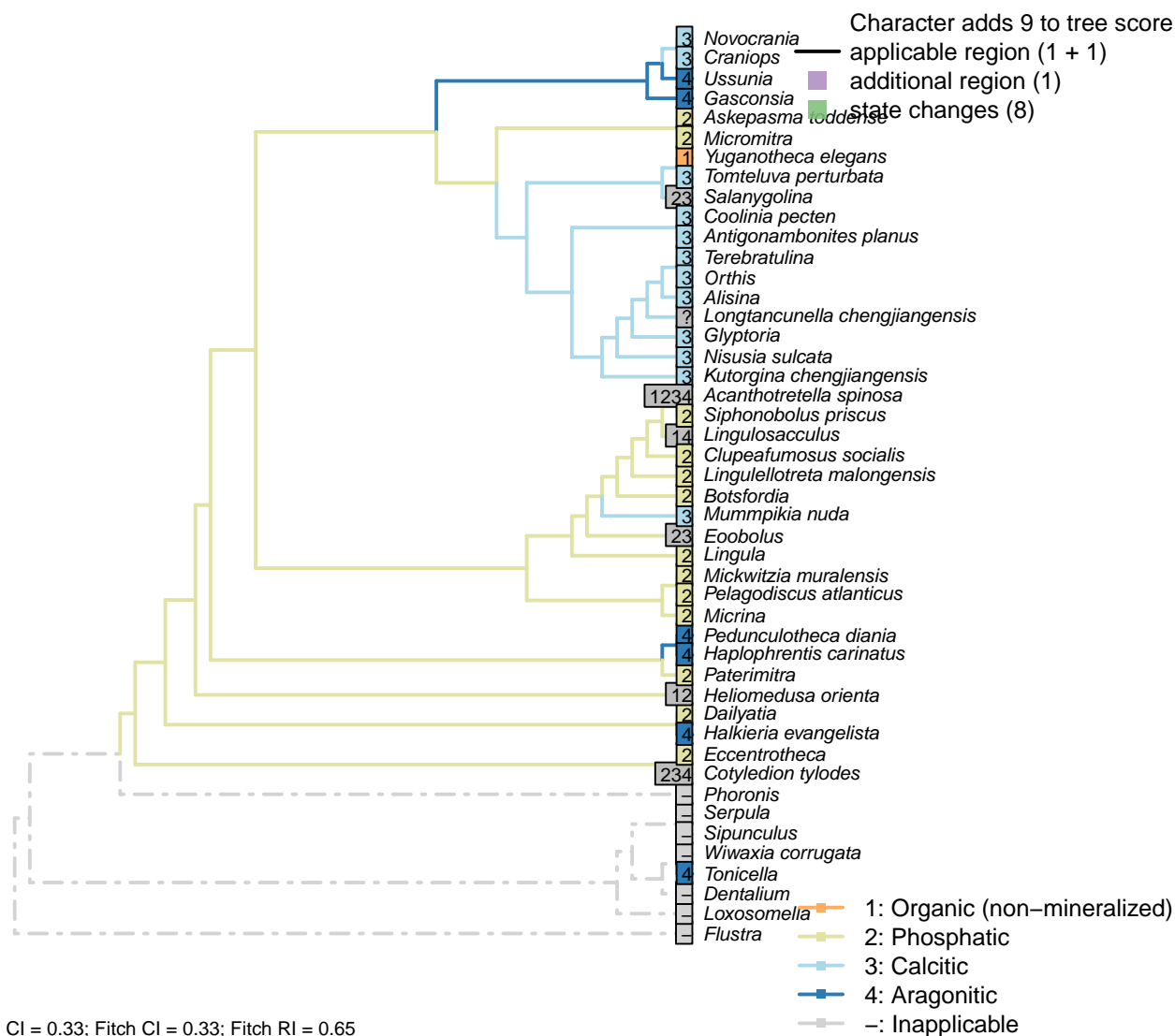
Heliomedusa orientalis: The ‘spines’ reported by Chen *et al.* (2007) are pyritized spinelike setae – see pp. 2580–2590 in Williams *et al.* (2007).

Nisusia sulcata: Bears numerous small, hollow spines (Williams *et al.*, 2000).

Tonicella: Aesthete canals penetrate the main valves of certain chitons, but are not equivalent to the shell-penetrating spines of brachiopods.

3.19 Sclerites: Composition

[109] Mineralogy



than that it was not, though without providing an uncontested rationale. To be as conservative as possible, we therefore code this taxon as ambiguous.

Clupeafumosus socialis: Phosphatic – hence the conventional placement within Linguliformea.

Cotyledion tylodes: The extensive relief and association with pyrite framboids indicates original mineralization, but the identity of the biomineral remains uncertain (Zhang et al., 2013).

Craniops: Shell calcitic.

Eoobolus: “the original shell of *Eoobolus* contained small calcareous grains that were incorporated into organic-rich layers alongside apatite” (Balthasar, 2007).

Gasconsia: Confirmed in Trimerella by Balthasar et al. (2011).

Heliomedusa orienta: “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.”

Lingulellotreta malongensis: 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.

Lingulosacculus: 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).

Longtancunella chengjiangensis: “The original composition of the shell cannot be determined with certainty”, though it was “most probably entirely soft and organic” – Zhang et al. (2011a).

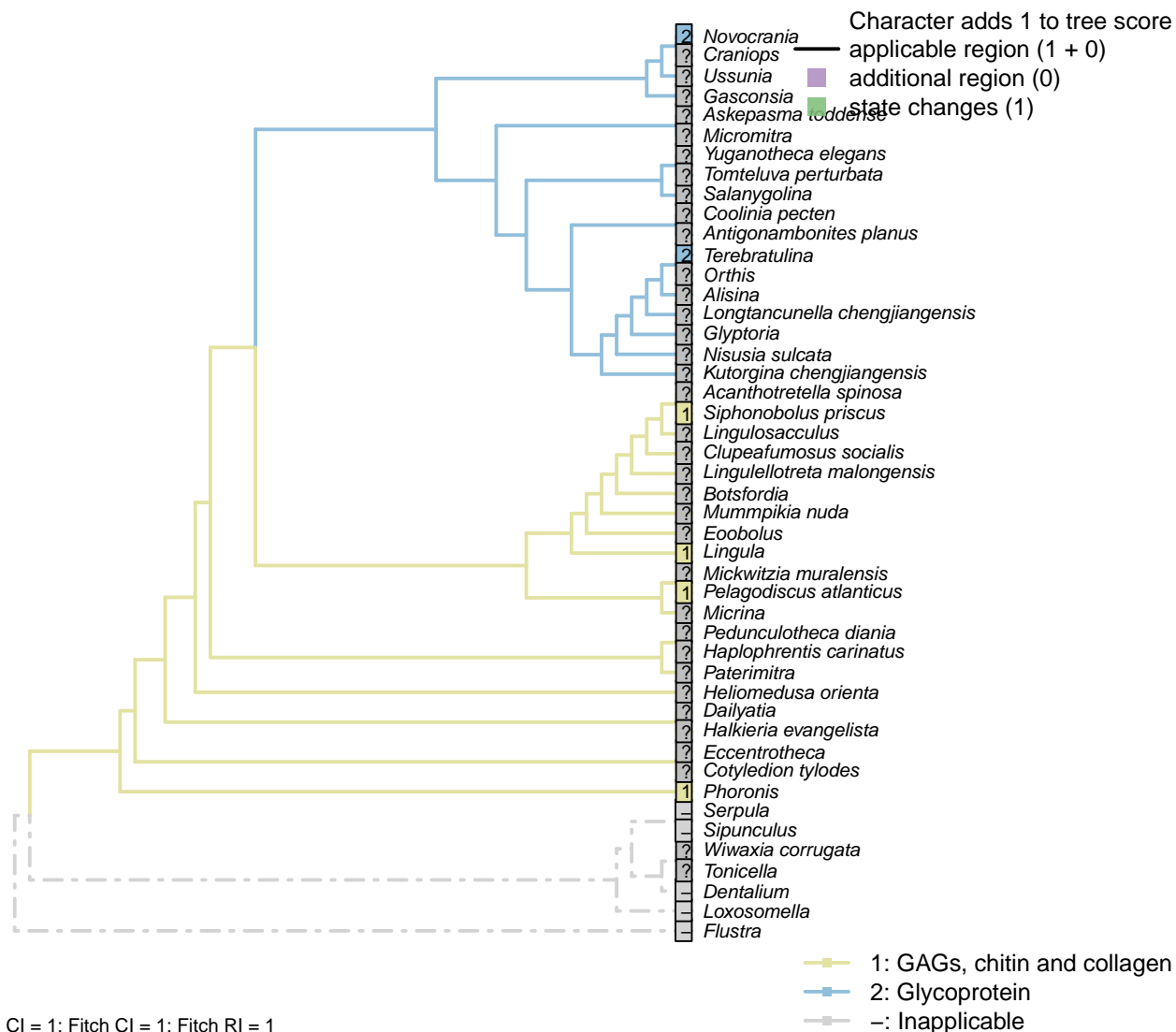
Mickwitzia muralensis: Calcite and silica deemed diagenetic by Balthasar (2004).

Mummpikia nuda: Identified as calcareous by preservational criteria, and description “primary calcitic shells of *M. nuda*” (Balthasar, 2008).

Novocrania: Ventral valve uncalcified in extant forms or sometimes thin (Williams et al., 2000), but coded as calcitic as calcite-mineralizing pathways are present.

Salanygolina: Original mineralogy unknown, but known to be mineralised and anticipated to be phosphatic (Holmer et al., 2009).

[110] Cuticle or organic matrix

**Character 110: 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.

Lingula: Coded as GAGs, chitin and collagen in lingulids by Williams *et al.* (1996).

Novocrania: Coded as glycoprotein for craniids by Williams *et al.* (1996).

Pelagodiscus atlanticus: Coded as GAGs, chitin and collagen in discinids by Williams *et al.* (1996).

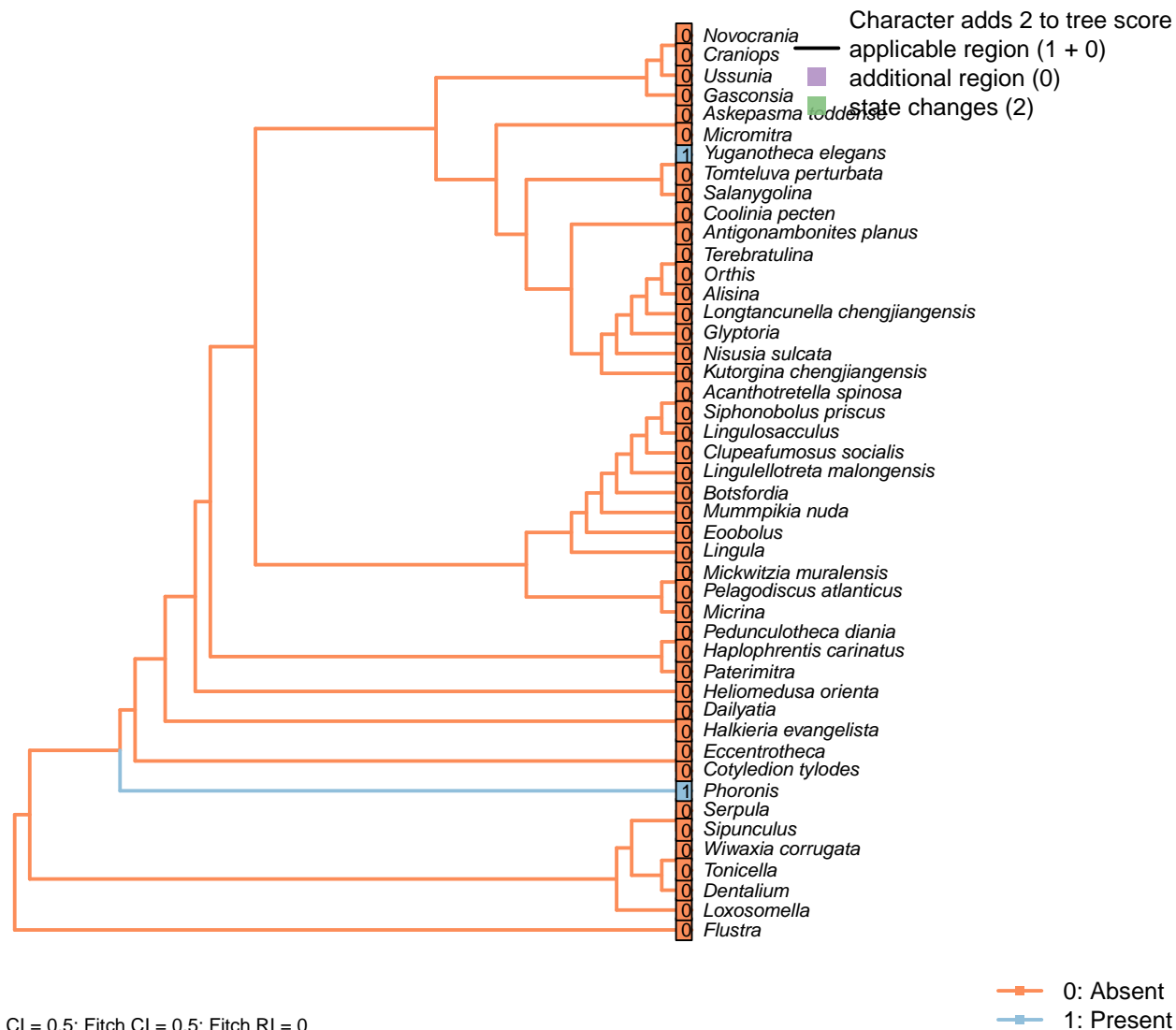
Phoronis: “The presence of sulphated glycosaminoglycans (GAGs) in the chitinous cuticle of *Phoronis* (Herzmann, 1997, p. 215) would suggest a link with linguliforms, as GAGs are unknown in rhynchonelliform shells (Fig. 1891, 1896)” – Williams *et al.* (2007), p. 2830.

Siphonobolus priscus: Lenticular chambers in siphonotretid shells interpreted as degraded GAG residue

(Williams et al., 2004).

Terebratulina: Coded as glycoprotein for terebratulids by Williams *et al.* (1996).

[111] Incorporation of sedimentary particles



Character 111: Sclerites: Composition: Incorporation of sedimentary particles

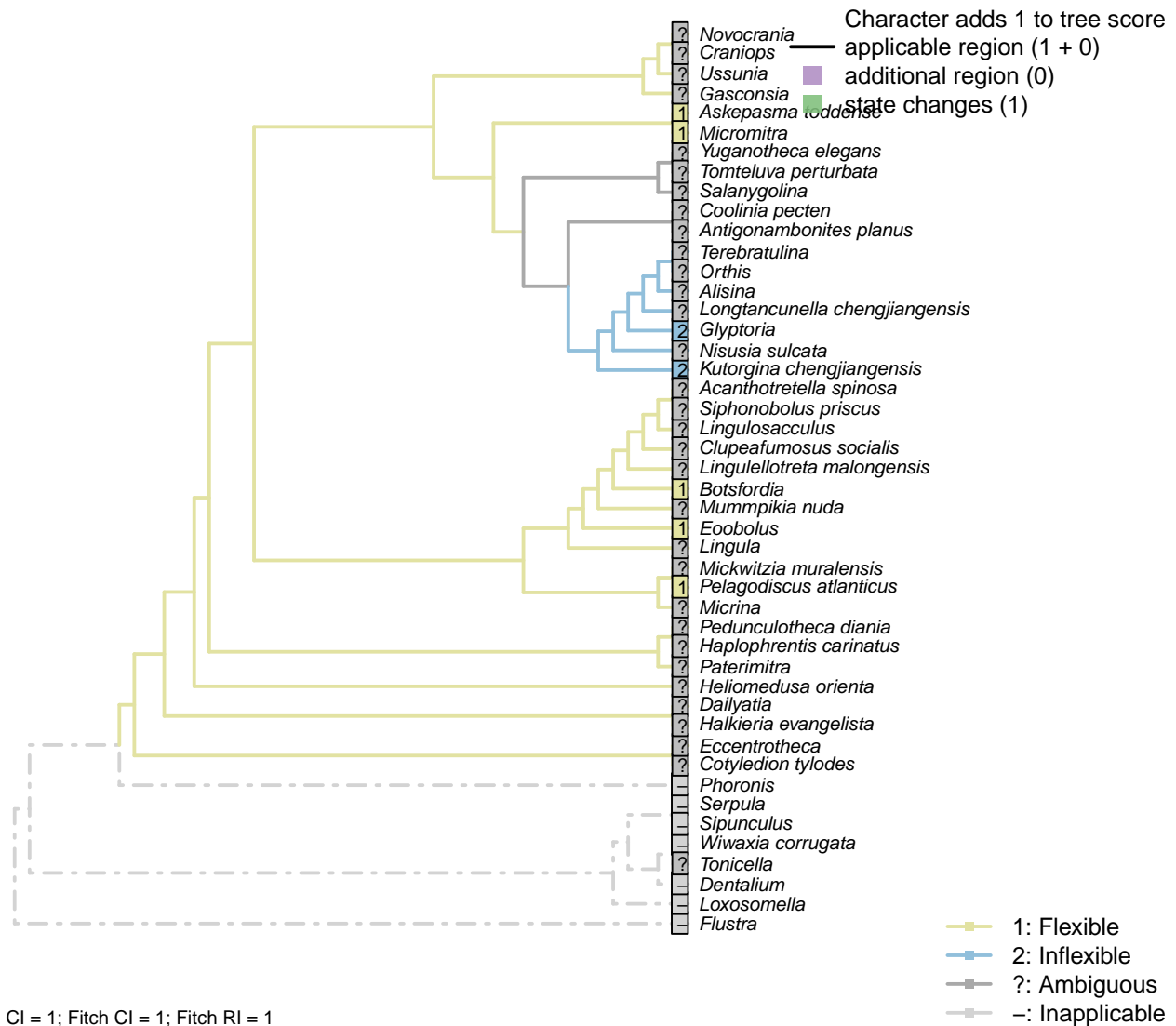
0: Absent

1: Present

Neomorphic character.

Phoronids and *Yoganotherca* agglutinate particles into their sclerites.

[112] Periostracum: Flexibility

**Character 112: 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.

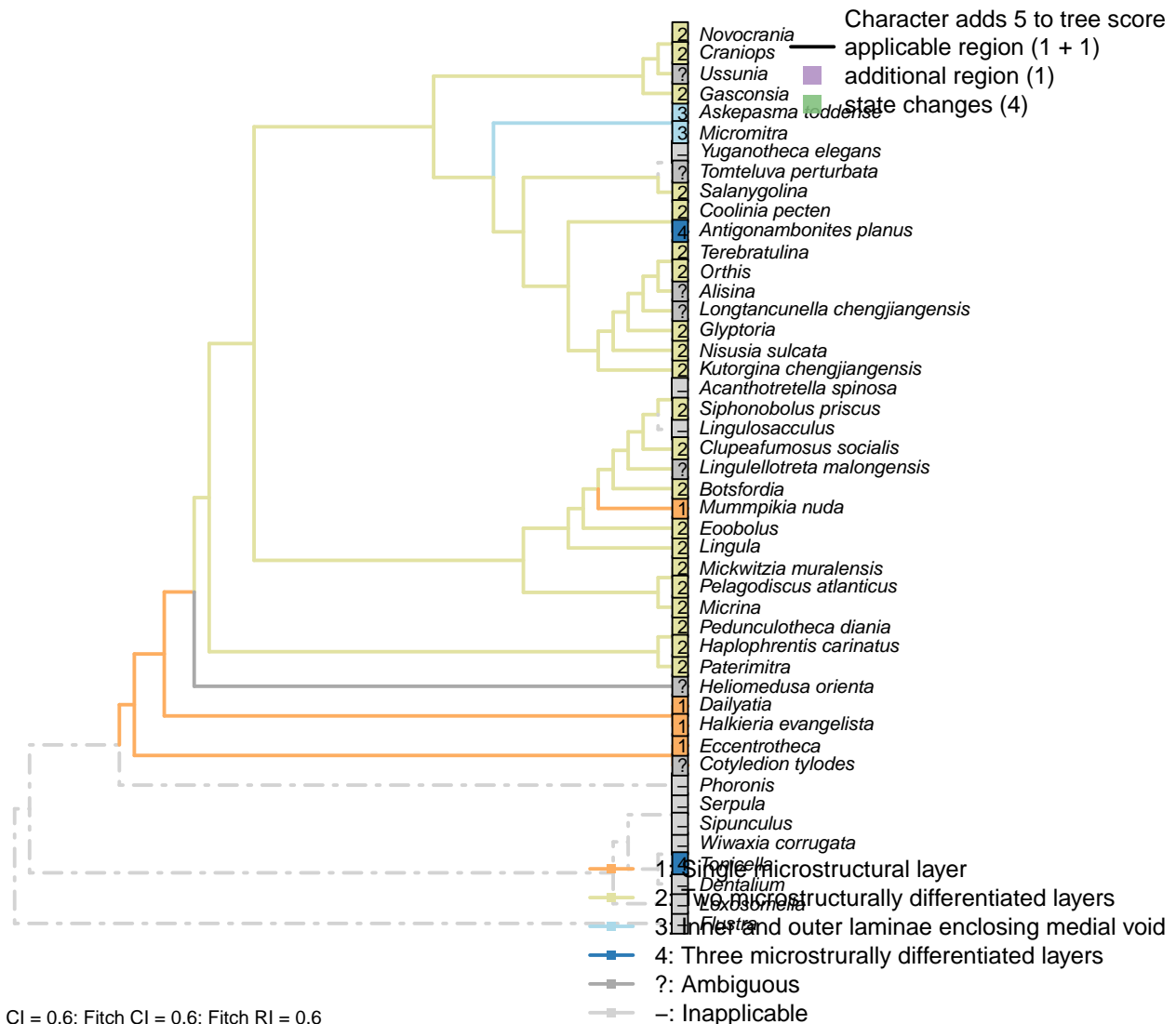
Askepasma toddense, *Glyptoria*, *Kutorgina chengjiangensis*, *Micromitra*: Following appendix 2 in Williams *et al.* (1998).

Botsfordia, *Eoobolus*: Coded as flexible in Williams *et al.* (1998), Appendix 2.

Pelagodiscus atlanticus: Flexible (Williams *et al.*, 1998).

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

[113] Microstructure: Layers

**Character 113: Sclerites: Composition: Microstructure: Layers**

- 1: Single microstructural layer
 - 2: Two microstructurally differentiated layers
 - 3: Inner and outer laminae enclosing medial void
 - 4: Three microstrurally 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.

Botsfordia: “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).

Clupeafumusus socialis: General acrotretid structure taken from Zhang *et al.* (2016).

Eoobolus: “*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).

Halkieria evangelista: Single layer of fibrous aragonite (Porter, 2008).

Haplophrentis carinatus: Assumed to be equivalent to the hyoliths described by Kouchinsky (2000).

Mickwitzia muralensis: “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).

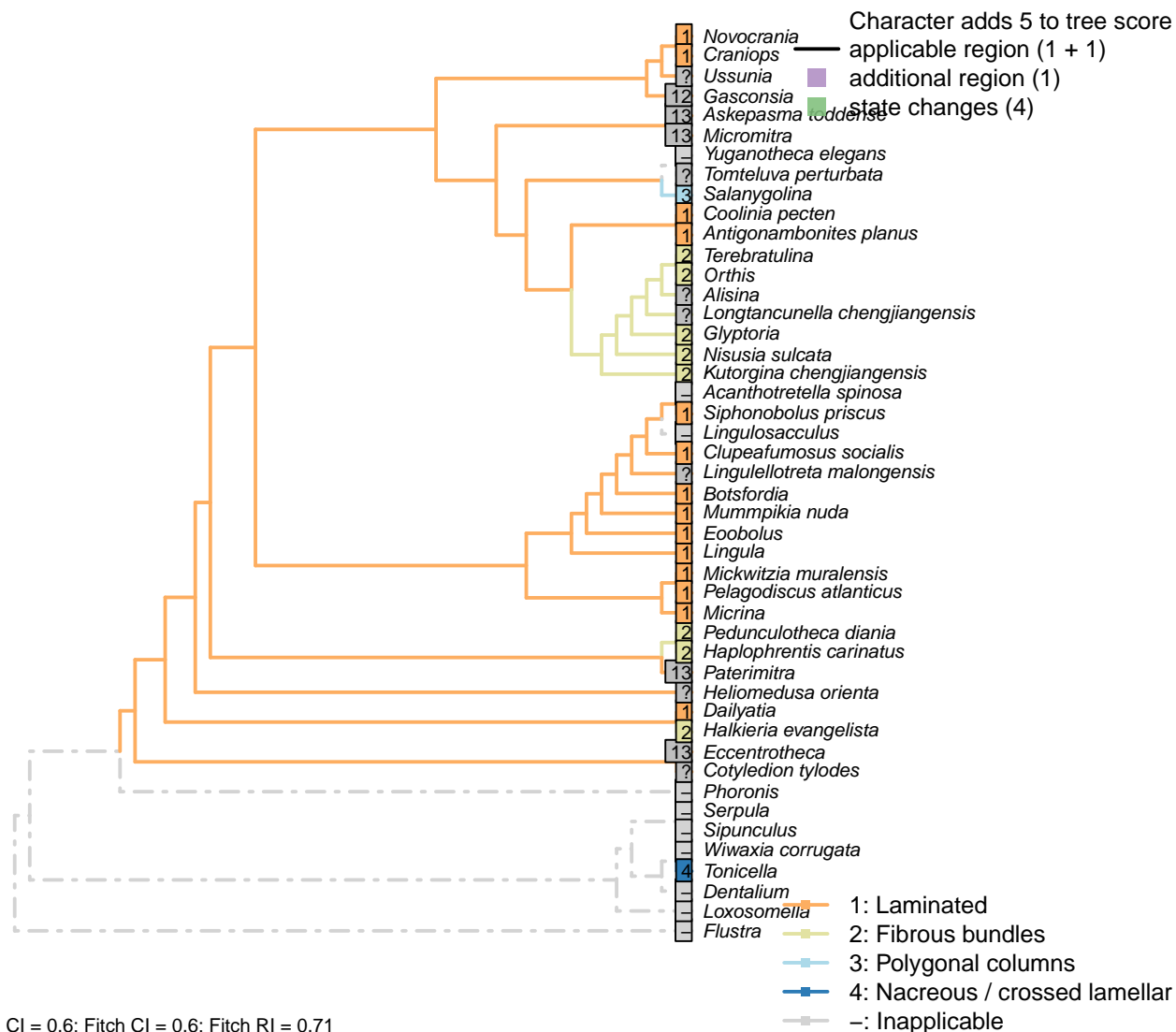
Micrina: Identical to *Mickwitzia* and more derived linguliforms (Holmer *et al.*, 2011).

Namacalathus: *Namacalathus* exhibits three layers, none of which have any obvious correspondence with those of brachiopods.

Siphonobolus priscus: “Orthodoxly secreted primary and secondary layers” – Williams *et al.* (2004).

Tonicella: From periostracum inwards, Chiton bears three microstructural layers: fine-grained, nacreous, and regular crossed lamellar.

[114] Microstructure: Crystal format

**Character 114: 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.

Antigonambonites planus: Shell structure of this taxon is laminated, rather than fibrous as previously considered.

Botsfordia: “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).

Craniops: “with calcitic or possibly aragonitic inarticulated shells with laminar (tabular) secondary layers” (Williams et al., 2000).

Haplophrentis carinatus: Inferred from other hyolithids (e.g. Moore and Porter, 2018).

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 tommotiids and certain brachiopods, their superficial similarity to strophomenid pseudopunctae notwithstanding.

Pedunculotheca diania: Assumed to be fibrous by analogy with the allothecomorph orthothecid described by Kouchinsky (2000).

Siphonobolus priscus: Prominent laminations; see Williams *et al.* (2004).

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)."

Craniops: "impunctate".

Haplophrentis carinatus: 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 allathecid, so the presence of equivalent structures in hyolithids has never been demonstrated.

Heliomedusa orientalis: 'Identical' to those in *Mickwitzia* – see Williams et al. (2007).

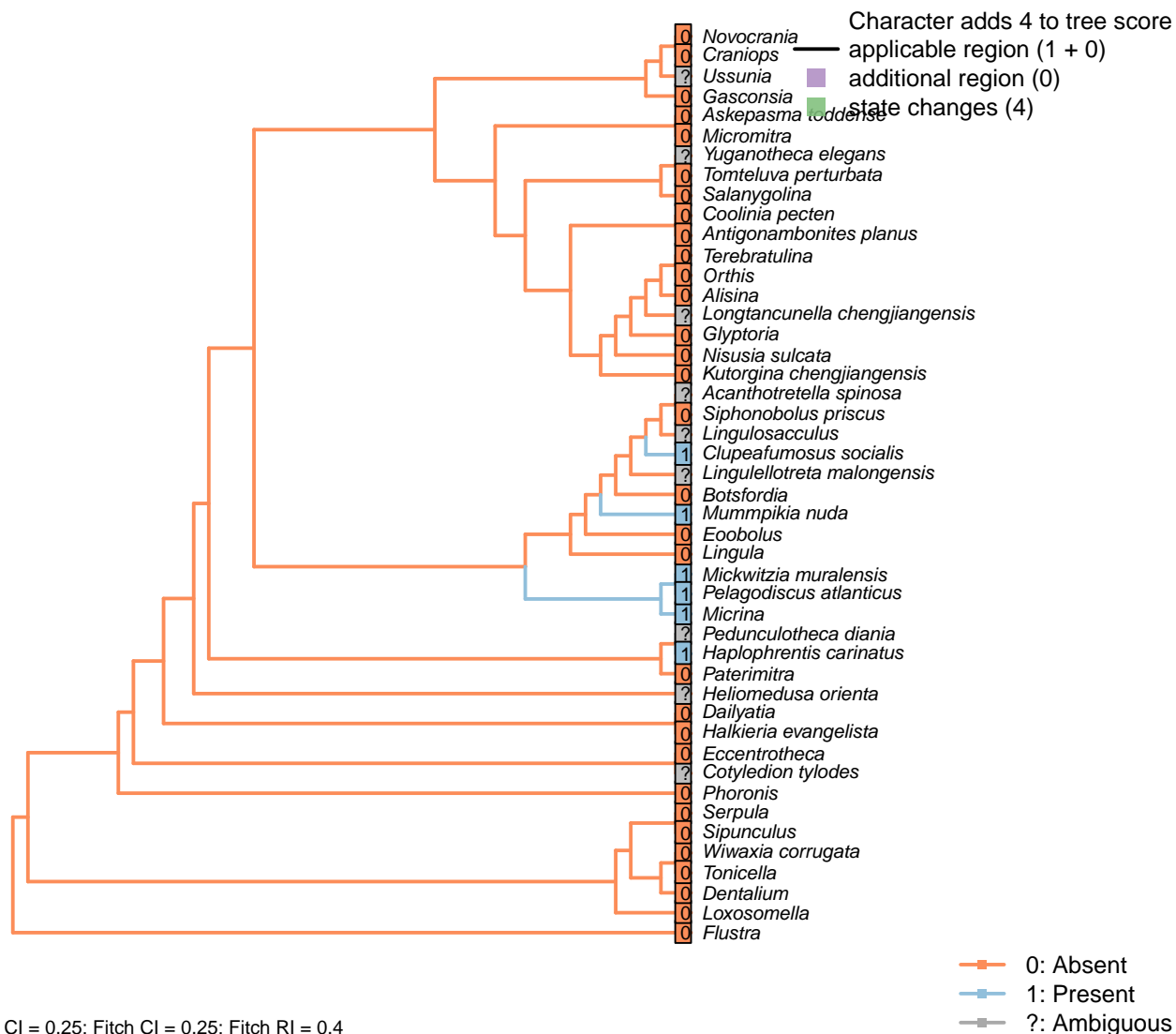
Mickwitzia muralensis: Coded as present to reflect that the chambers contained setae; following Carlson in Williams et al. (2007), the punctae may or may not be homologous as punctae, but are likely homologous as shell perforations; both these perforations and those of *Micrina* were associated with setae, even if their equivalence may be with juvenile vs adult setal structures in modern brachiopods (Balthasar, 2004, p. 397).

Mummpikia nuda: "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 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; Williams et al., 1997)." – Balthasar (2008).

Siphonobolus priscus: 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.

Terebratulina: Endopunctae are relatively large canals, diameter vary greatly from 5–20 μm .

[116] Microstructure: Canals

**Character 116: 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.

Botsfordia: Not evident in section presented by Skovsted & Holmer (2003).

Clupeafumosus socialis: 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.

Halkieria evangelista: The chambers in halkieriid sclerites do not correspond in morphology or dimension to the brachiopod-like canals documented by this character.

Haplophrentis carinatus: 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.

Longtancunella chengjiangensis: Preservational resolution not sufficient to evaluate.

Mickwitzia muralensis: Coded as present to reflect similarity of columnar microstructure remarked on by, among others, Balthasar (2008); Williams et al. (2007); Skovsted & Holmer (2003).

Micrina: 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).

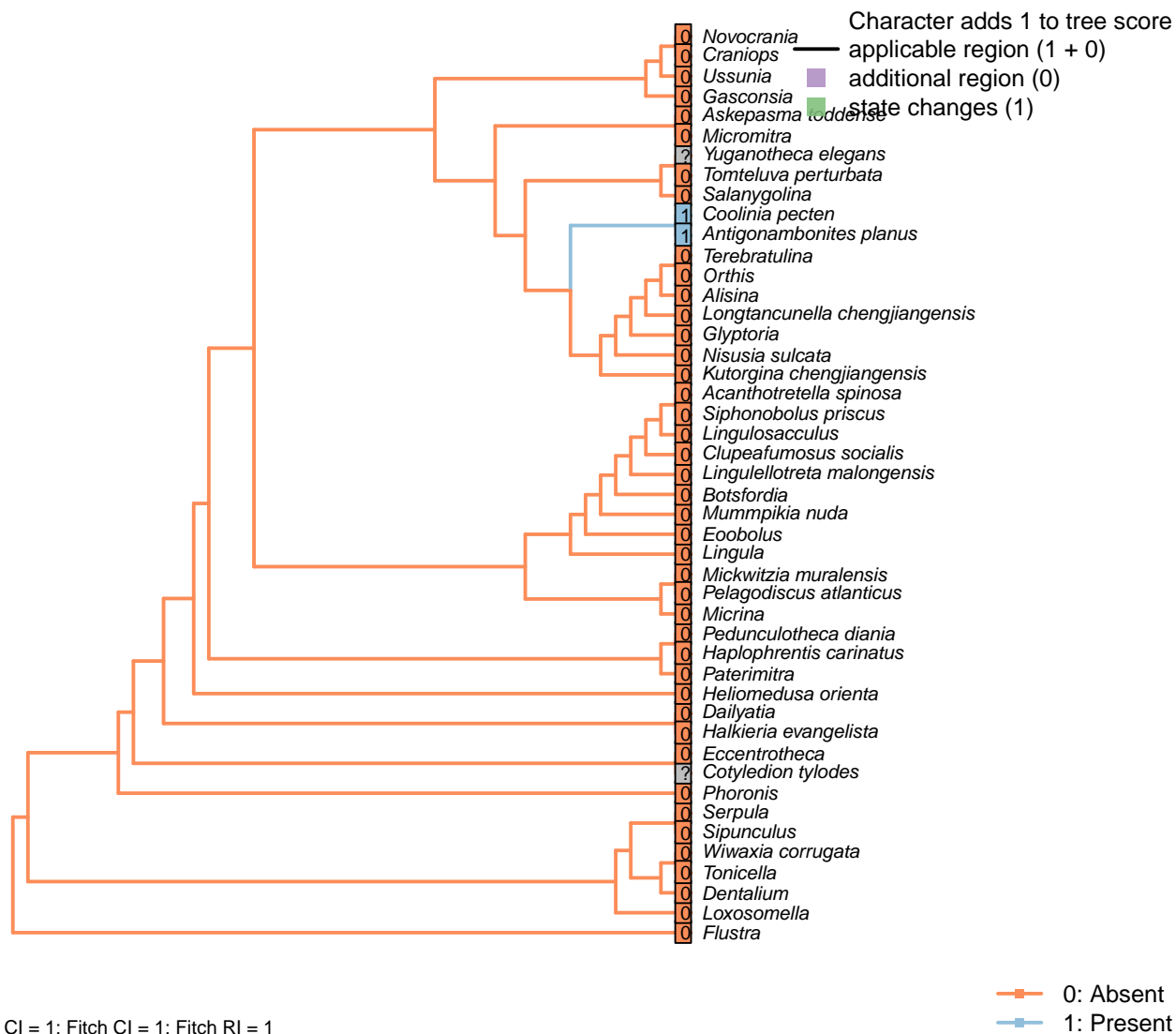
A similar columnar shell microstructure also occurs in the closely related *Mickwitzia* (Balthasar, 2008).

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.

Siphonobolus priscus: 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.

Tonicella: Aesthete canals do not fall within the definition of this character.

[117] Microstructure: Pseudopunctae

**Character 117: Sclerites: Composition: Microstructure: Pseudopunctae**

0: Absent

1: Present

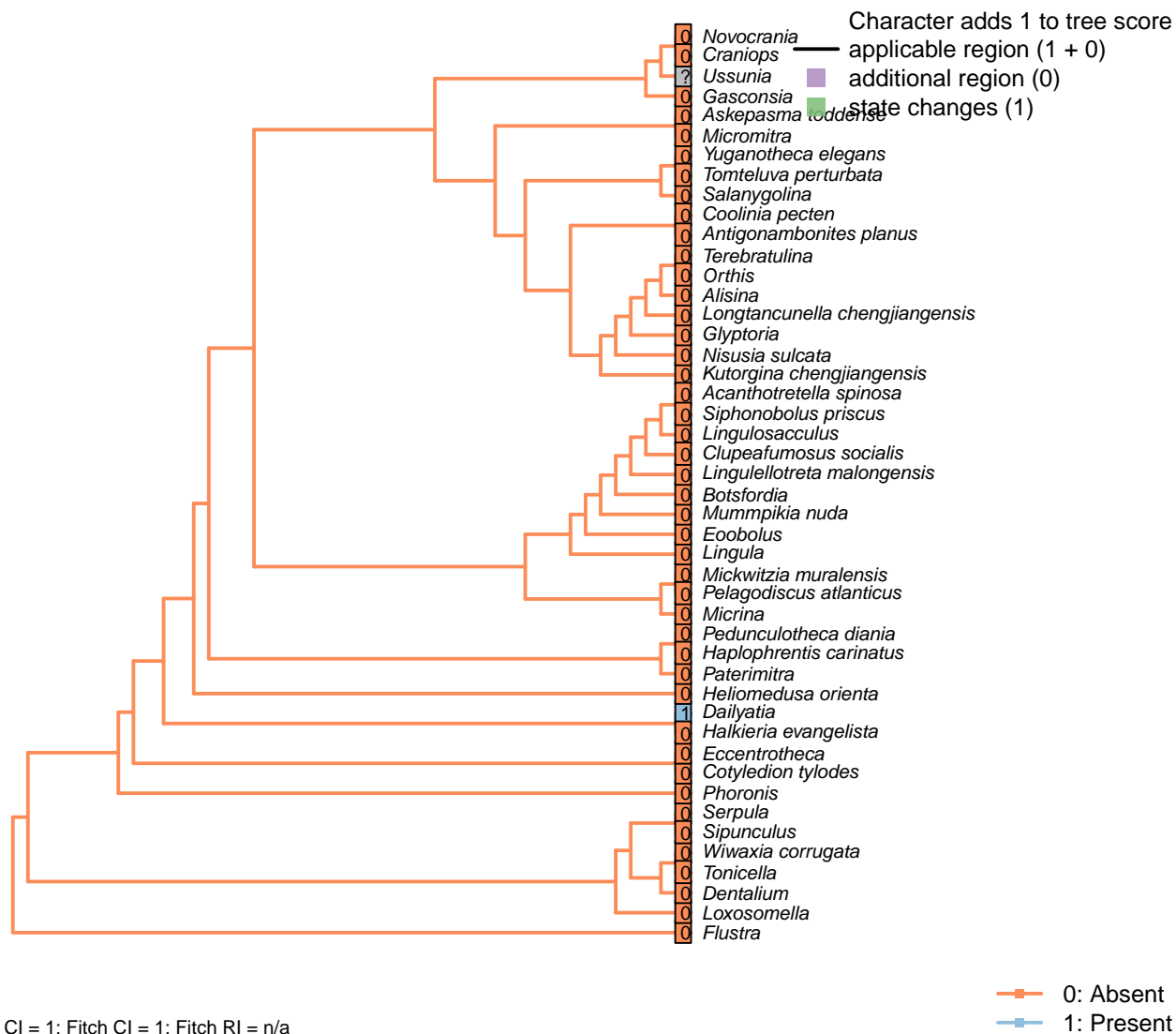
Neomorphic character.

Pseudopunctae are not punctae, but deflections of shell laminae. They characterise Strophomenata in particular.

Antigonambonites planus, *Glyptoria*, *Nisusia sulcata*: Scored absent in data matrix of Benedetto (2009).

Orthis: Scored absent (in *Eoorthis*) in data matrix of Benedetto (2009).

[118] Microstructure: External polygonal ornament

**Character 118: Sclerites: Composition: Microstructure: External polygonal ornament**

0: Absent

1: Present

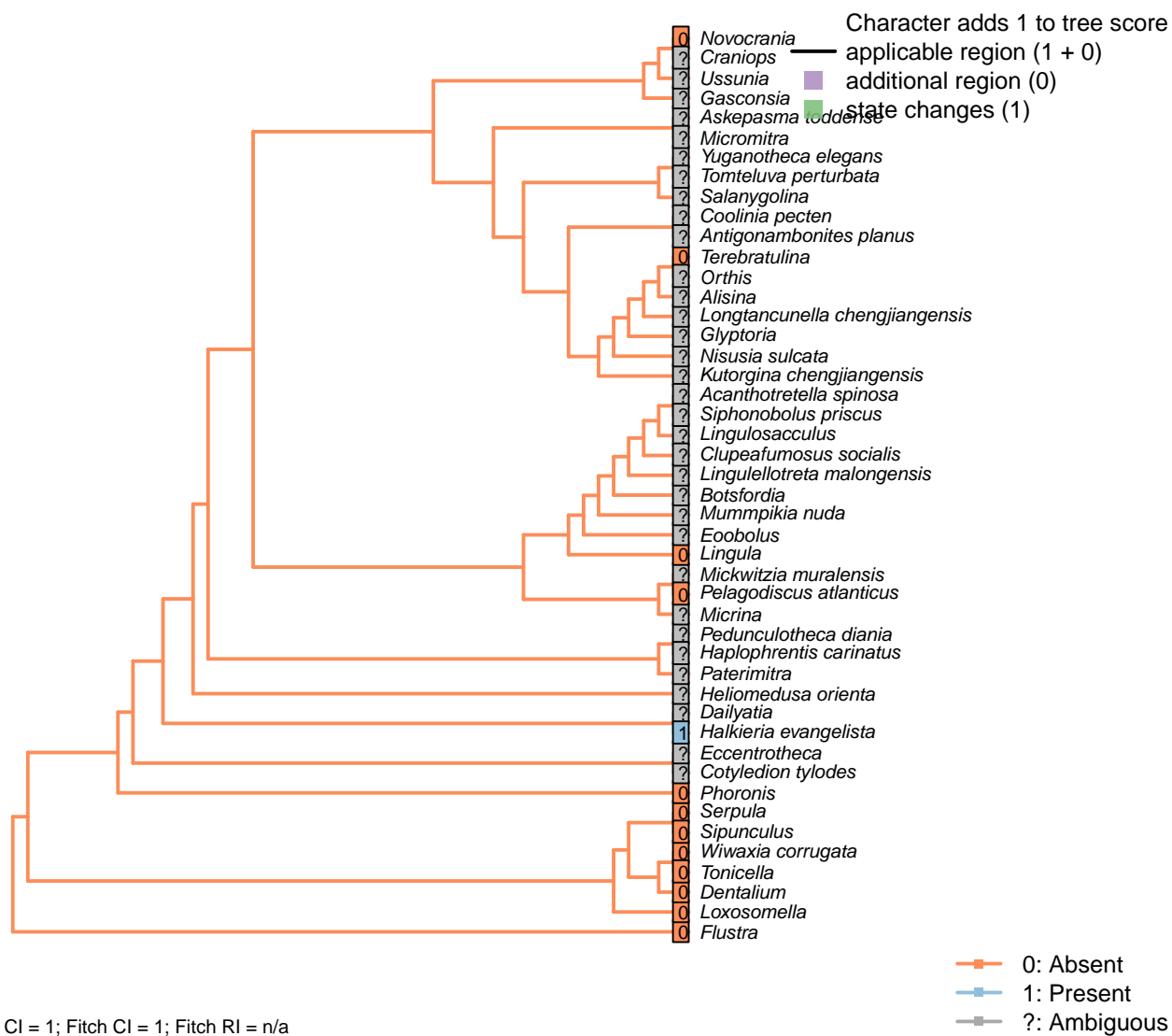
Neomorphic character.

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 *Dailyatia*, but it is a surface pattern, which is different from the polygonal prisms in the body wall of other paterinid-like groups.

Clupeafumosus socialis: The polygonal ornament reported in acrotretids by Zhang *et al.* (2016) is on the internal surface of the shell.

3.20 Sclerites

[119] Periodically shed and replaced



Character 119: Sclerites: Periodically shed and replaced

0: Absent

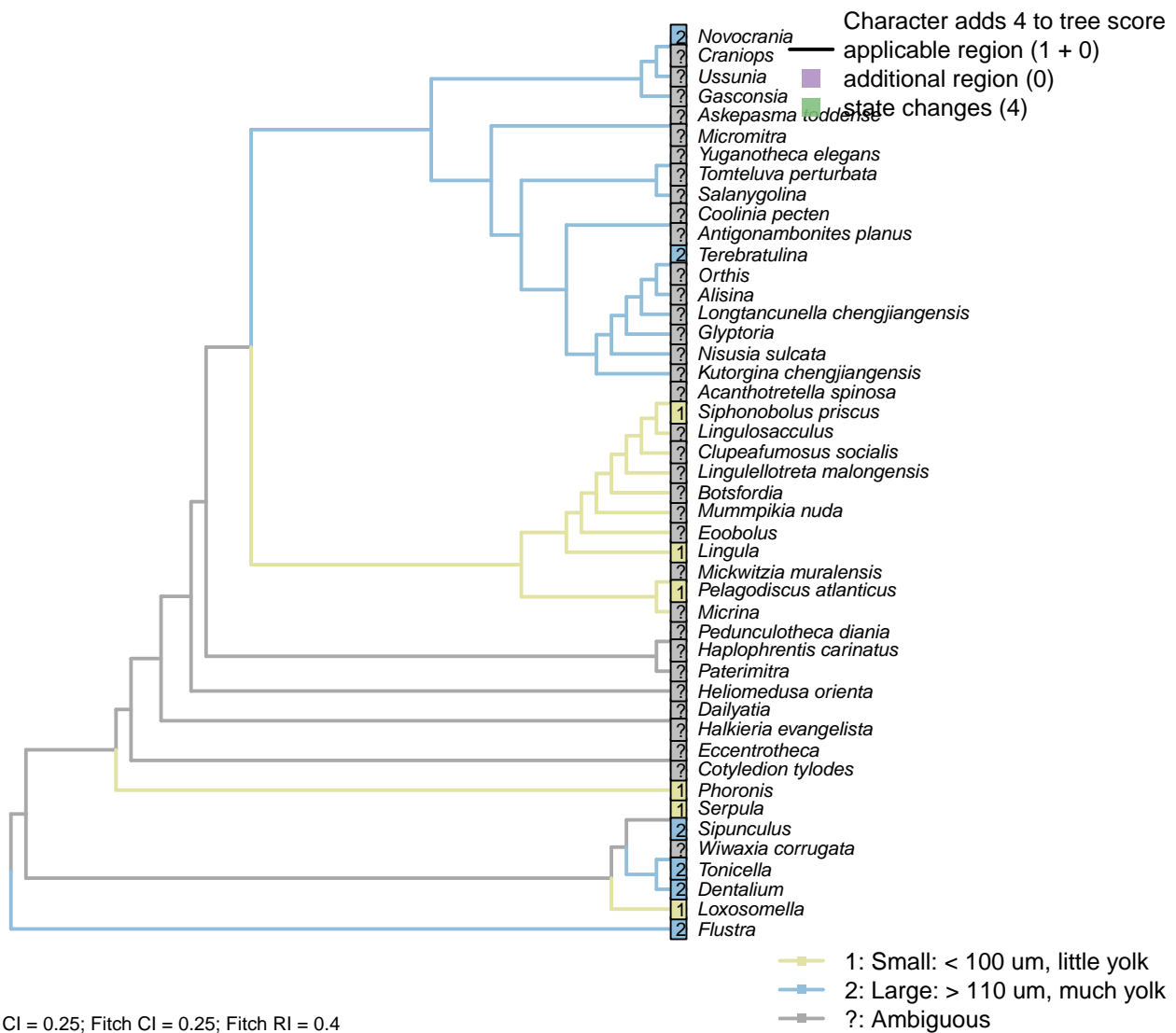
1: Present

Neomorphic character.

Certain taxa periodically slough and replace some of their individual sclerites during growth.

3.21 Gametes

[120] Egg size



Character 120: 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.

Dentalium: Egg size can vary from 60–200 µm in scaphopods, but in *Dentalium* the eggs are large (Dufresne-

Dube et al., 1983).

Flustra: “Mature eggs commonly measure about 200 μm in diameter” –.

Lingula, *Novocrania*, *Pelagodiscus atlanticus*, *Terebratulina*: Following coding for class in Carlson (1995) appendix 1, character 7.

Loxosomella: Tiny (Nielsen, 1966).

Phoronis: *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.

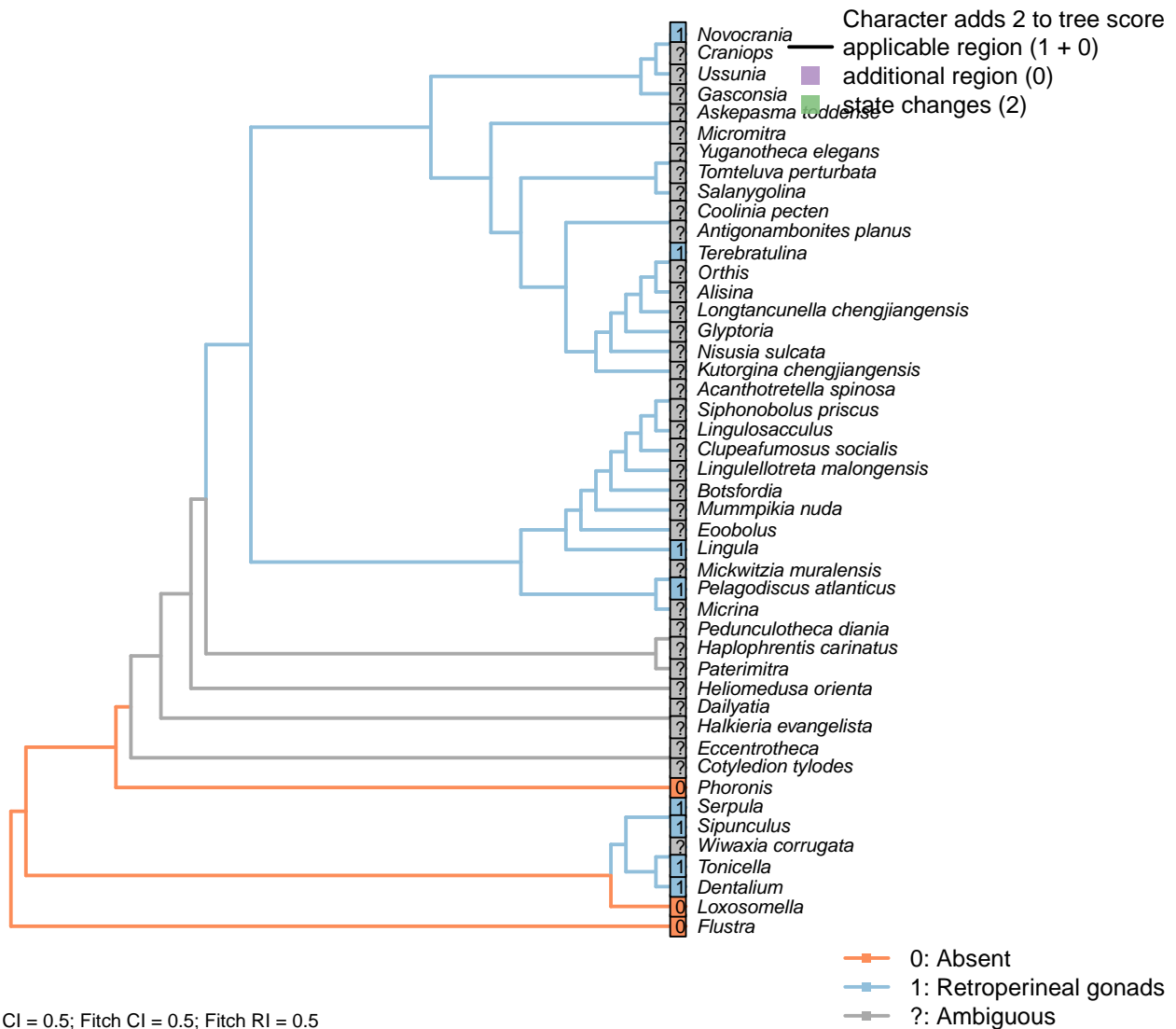
Serpula: c. 50 μm in *Hydroides* (Miles et al., 2007).

Siphonobolus priscus: “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).

Sipunculus: c. 200 μm in diameter (Rice, 1988).

Tonicella: Buckland-Nicks et al. (1988).

[121] Gonocoel



[122] Ovary wall saccular



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

Character 122: Gametes: Ovary wall saccular

0: Plain

1: Saccular

Neomorphic character.

After character 31 in Haszprunar (1996).

[123] Testis wall saccular

Character 123: Gametes: Testis wall saccular

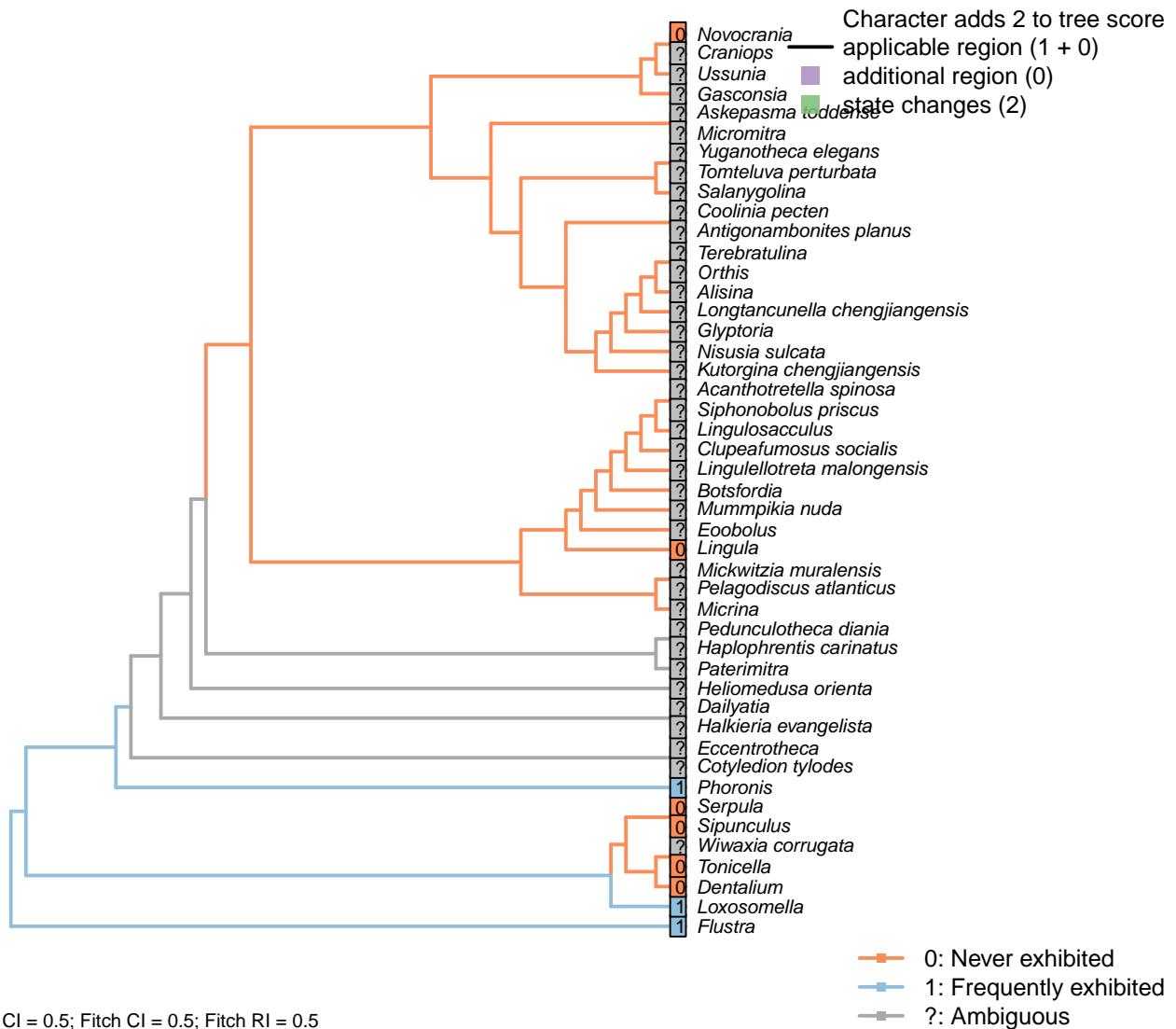
0: Plain

1: Saccular

Neomorphic character.

After character 31 in Haszprunar (1996).

[124] Asexual reproduction



[125] Fertilization

**Character 125: Gametes: Fertilization**

0: External

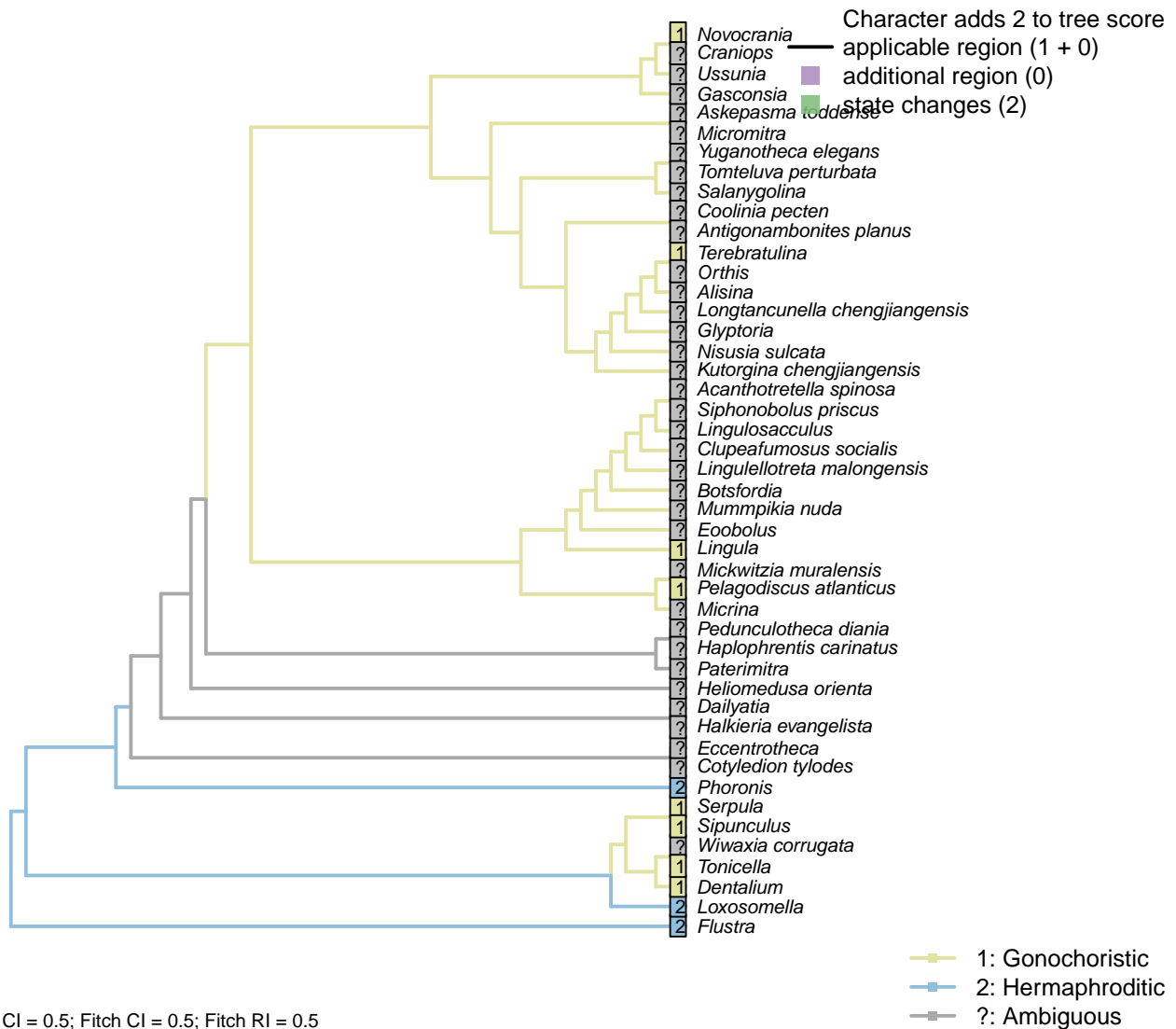
1: Internal

2:

Neomorphic character.

After character 62 in Haszprunar (2000).

[126] Sexes

**Character 126: Gametes: Sexes**

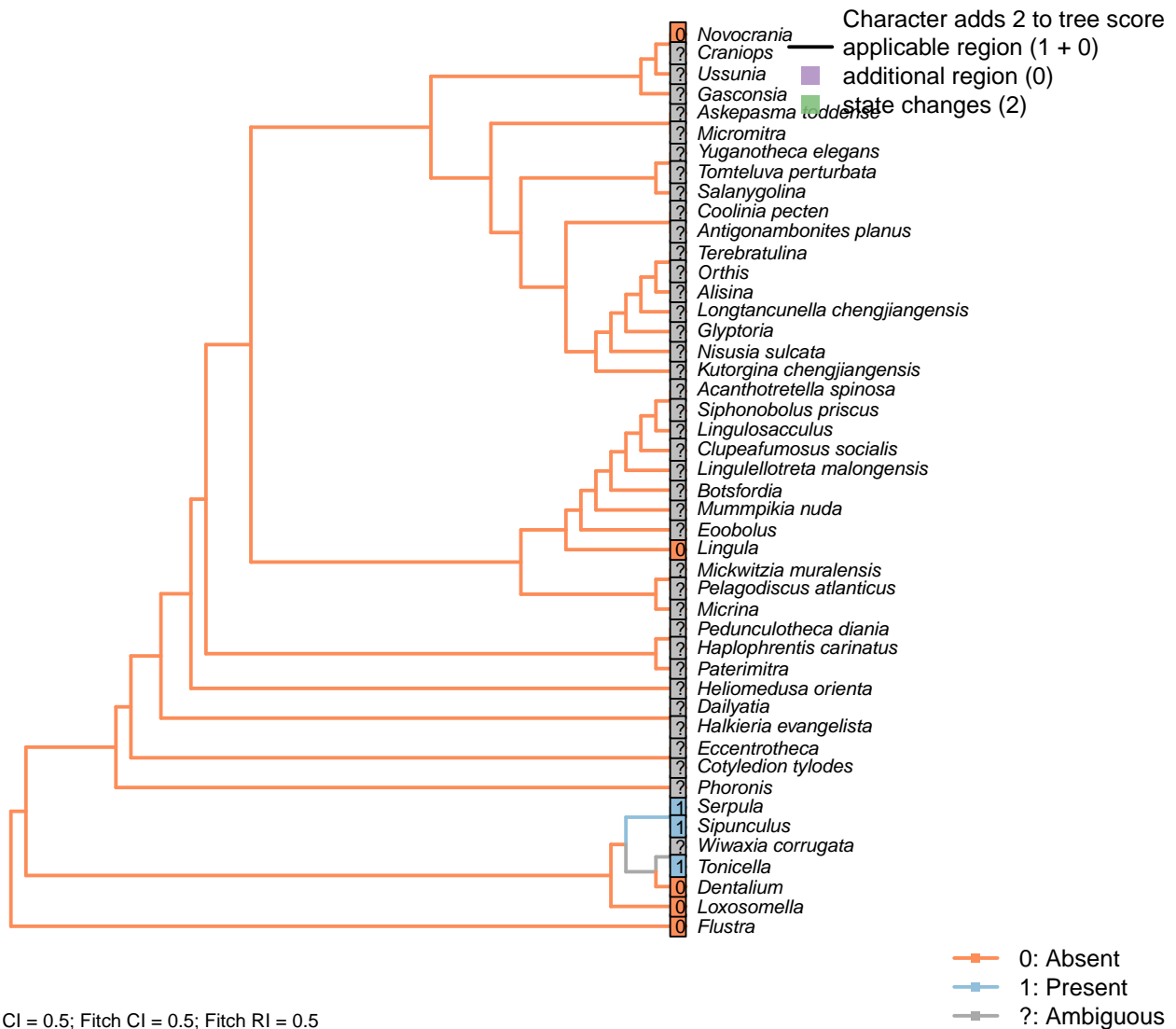
1: Gonochoristic

2: Hermaphroditic

Transformational character.

After characters 1.61 and 2.54 in von Salvini-Plawen and Steiner (1996).

[127] Protective membrane

**Character 127: Gametes: Egg: Protective membrane**

0: Absent

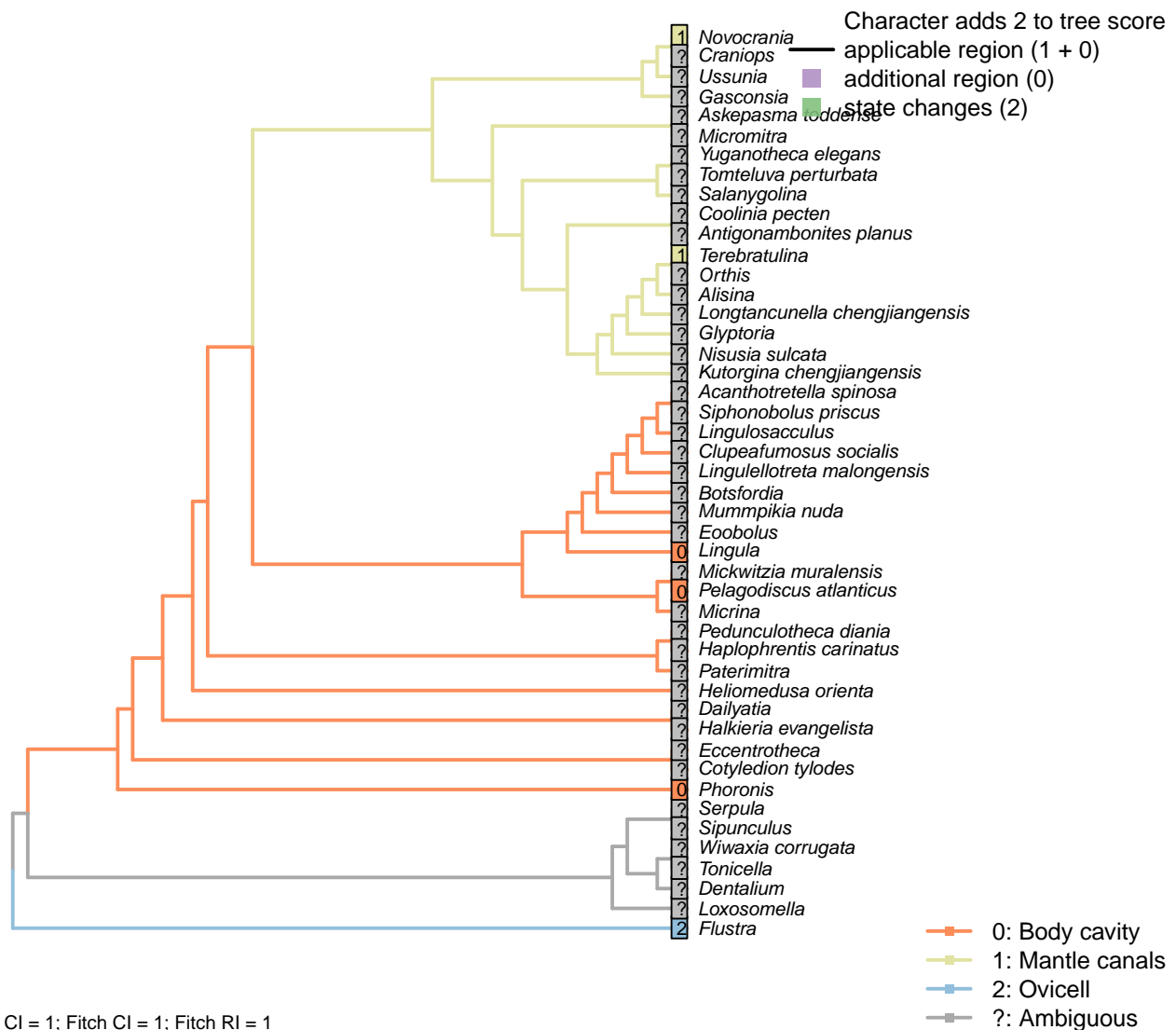
1: Present

Neomorphic character.

After character 4.69 in von Salvini-Plawen and Steiner (1996).

Flustra: “Eggs have a loose consistency and are capable of changing form” (Franzén, 2013).

3.22 Gametes: Site of maturation [128]

**Character 128: 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.

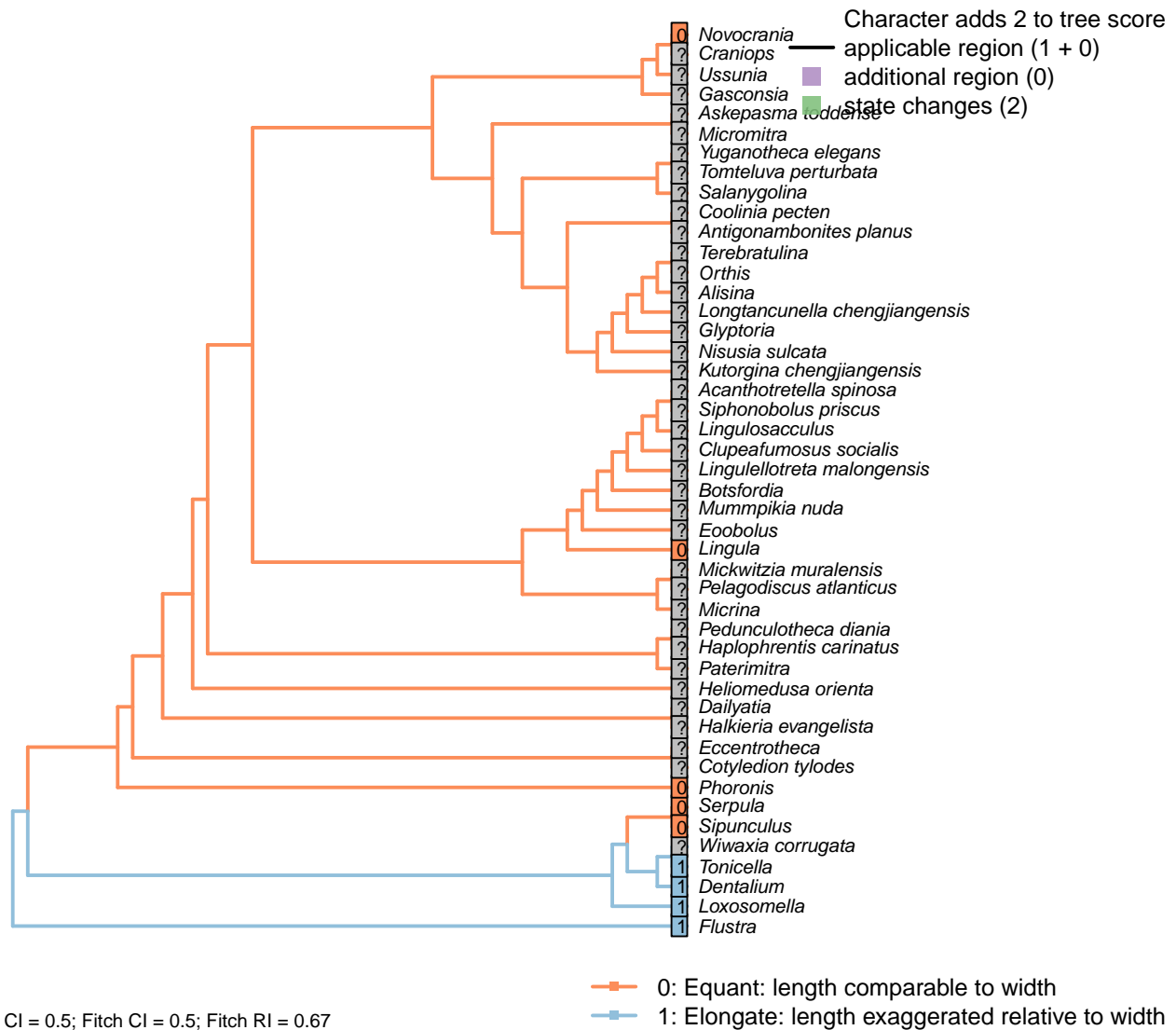
Flustra: Ovicell (Franzén, 2013).

Lingula, *Novocrania*, *Pelagodiscus atlanticus*, *Terebratulina*: Following Hodgson & Reunov (1994).

Phoronis: Following coding for class in Carlson (1995) Appendix 1, character 9.

3.23 Gametes: Spermatozoa

[129] Nucleus: Shape



Character 129: 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).

Dentalium: Elongate nucleus, 4–6 times longer than wide (Dufresne-Dube et al., 1983).

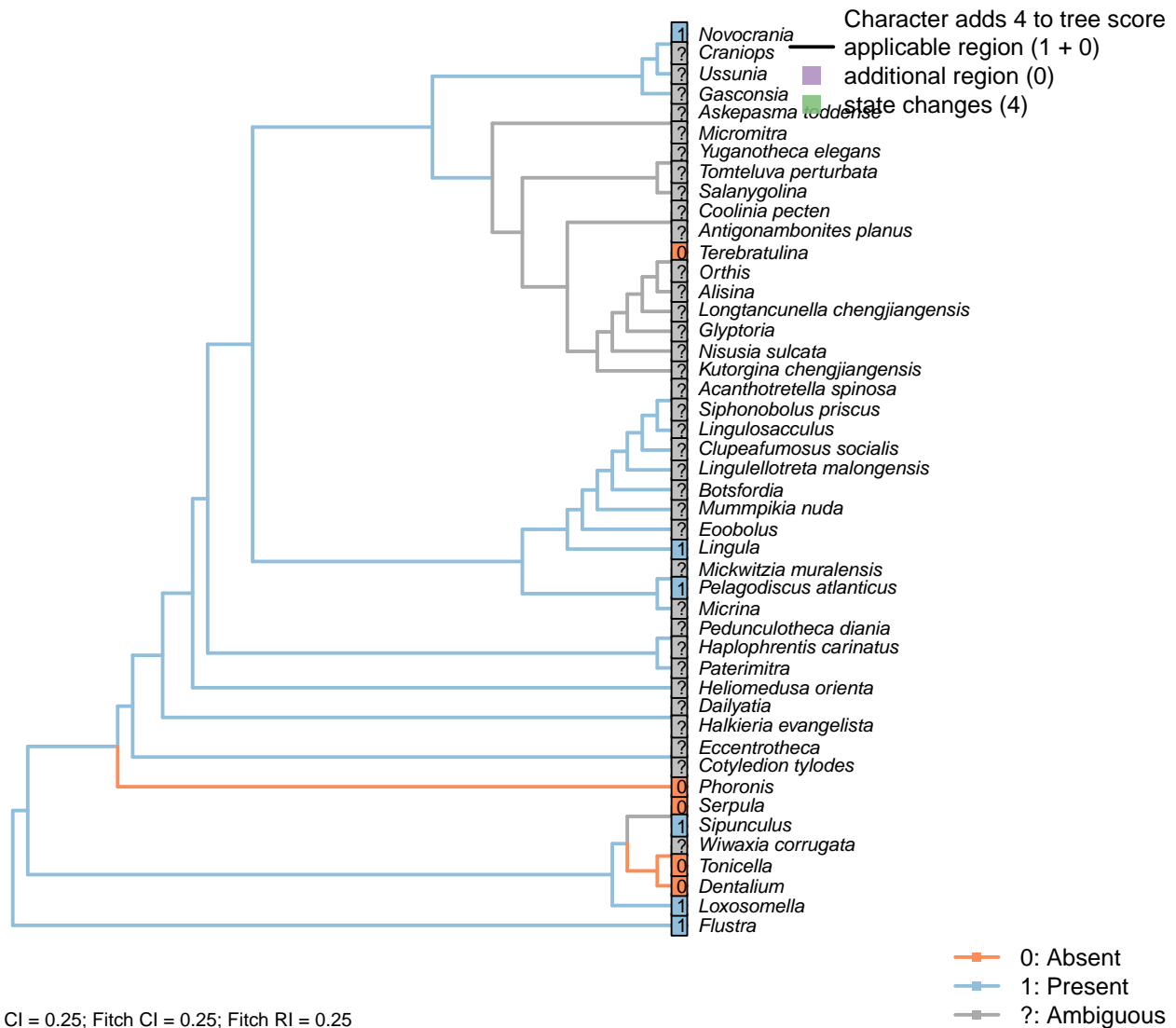
Flustra: Elongate (Franzen, 1981).

Loxosomella: Elongate in *Loxosoma* [Franzen 2000].

Serpula: Gherardi et al. (2011).

Tonicella: Profoundly elongated nucleus (Buckland-Nicks et al., 1988).

[130] Anterior nuclear fossa

**Character 130: Gametes: Spermatozoa: Anterior nuclear fossa**

0: Absent

1: Present

Neomorphic character.

Following Smith (2012a), after character 160 in Giribet and Wheeler (2002). A fossa (latin: ditch) is a dent

or impression.

Dentalium: Dufresne-Dube et al. (1983).

Flustra: Present (in *Tubulipora*; Franzén, 1984).

Loxosomella: Present in *Loxosoma* [Franzen 2000].

Pelagodiscus atlanticus: Present in *Discinisca tenuis* (Hodgson and Reunov, 1994).

Phoronis: Nucleus “almost round” (Reunov and Klepal, 2004).

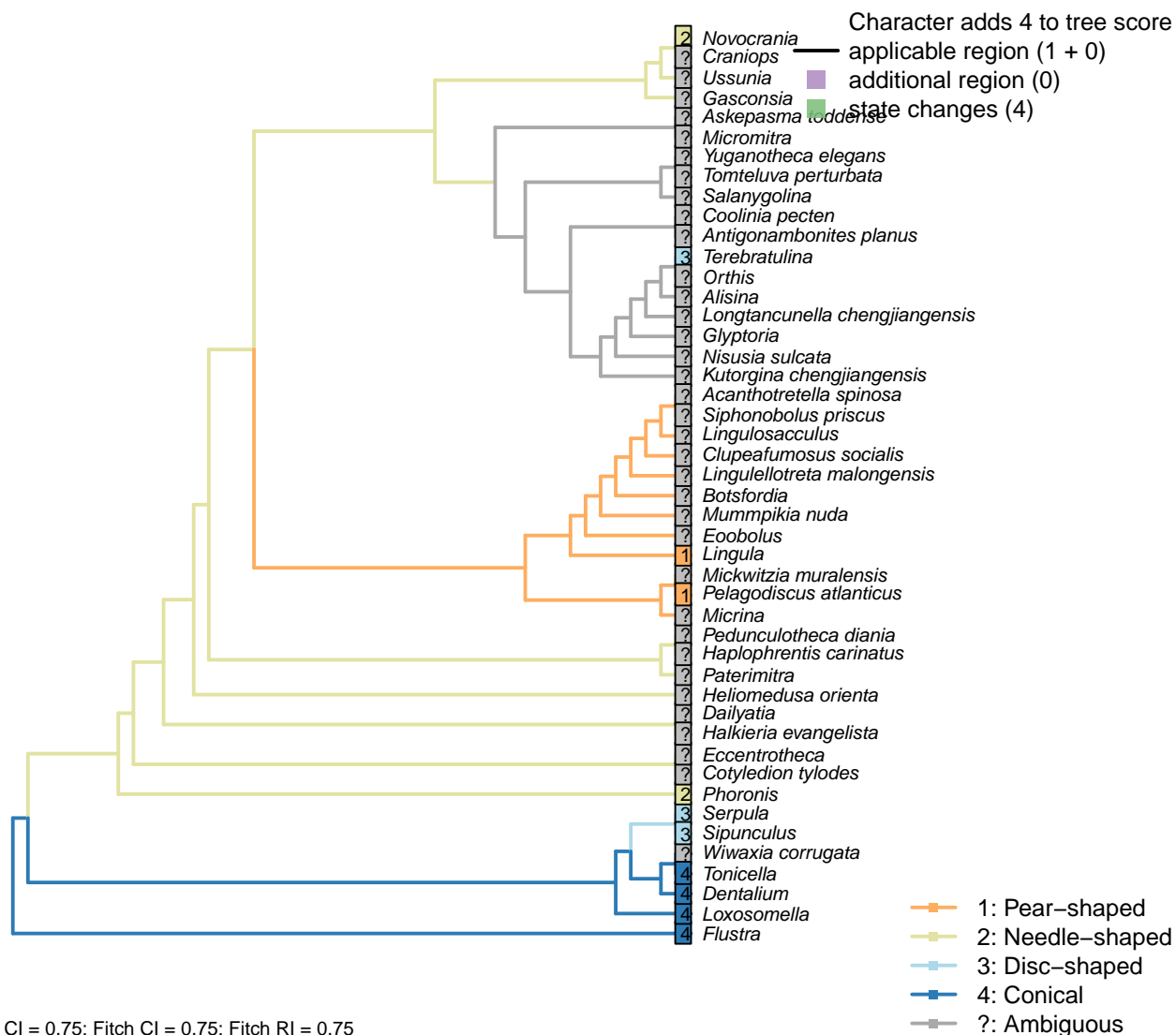
Serpula: Absent: subacrosomal space does not impinge on nuclear envelope (Gherardi et al., 2011).

Sipunculus: Prominent in *Phascolion* (Rice, 1993).

Terebratulina: No anterior invagination (Hodgson and Reunov, 1994).

Tonicella: Buckland-Nicks et al. (1988).

[131] Acrosome: Shape



Character 131: Gametes: Spermatozoa: Acrosome: Shape

- 1: Pear-shaped
- 2: Needle-shaped
- 3: Disc-shaped
- 4: Conical

Transformational character.

Dentalium: Low conical aspect (Dufresne-Dube et al., 1983).

Flustra: Conical (in *Tubulipora*; Franzén, 1984).

Lingula: Pear-shaped (Fukumoto, 2003).

Loxosomella: Conical/cylindrical acrosome-like extension in *Loxosoma* [Franzen 2000].

Novocrania: Needle-shaped (Afzelius and Ferraguti, 1978).

Pelagodiscus atlanticus: Pear-shaped (Hodgson and Reunov, 1994).

Phoronis: Needle-shaped (Reunov and Klepal, 2004).

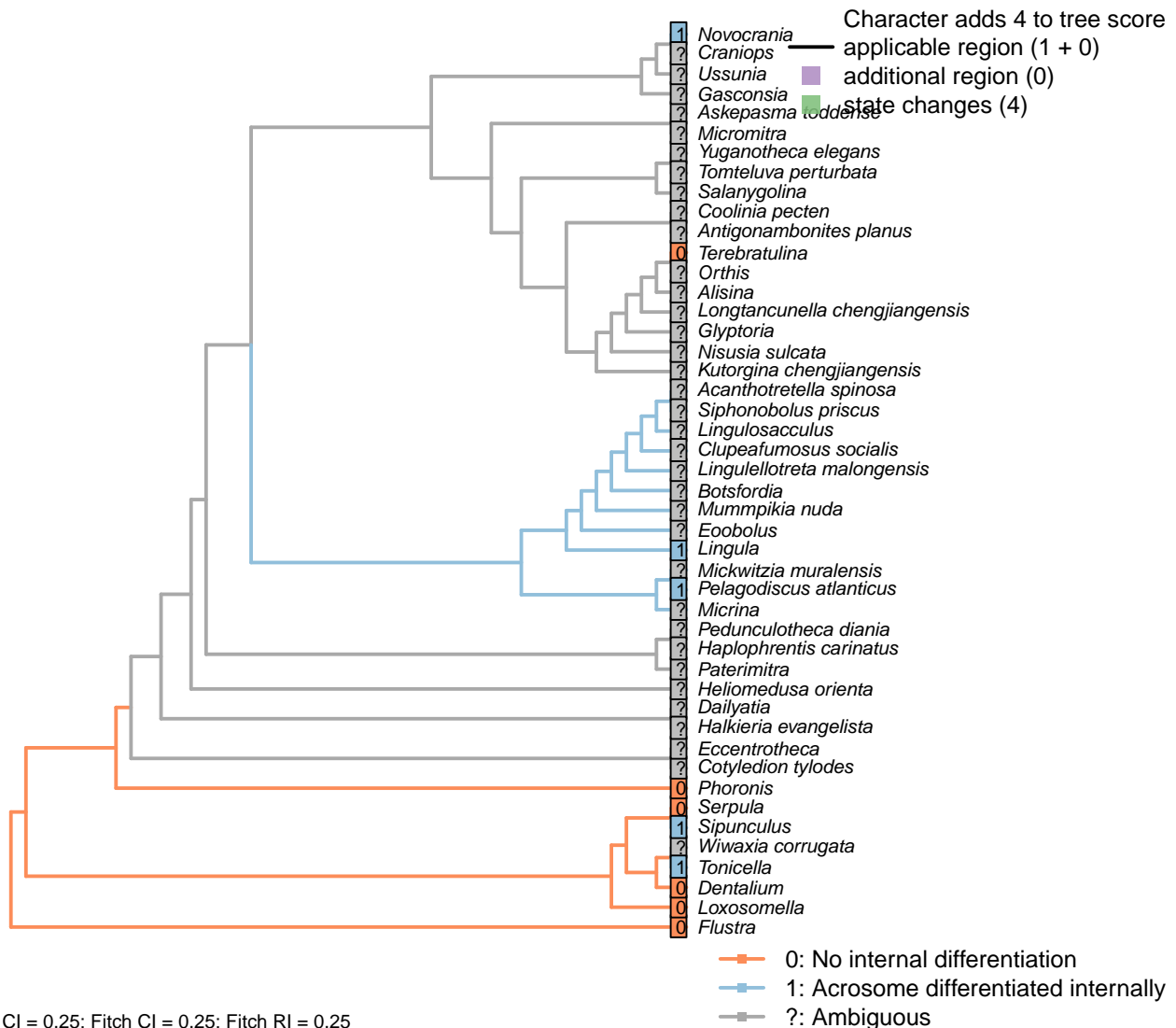
Serpula: Gherardi et al. (2011).

Sipunculus: A peaked disc in *Phascolion* (Rice, 1993).

Terebratulina: Disc-shaped (in *Kraussina*) (Hodgson and Reunov, 1994).

Tonicella: Elongate: cylindrical to conical (Buckland-Nicks et al., 1988).

[132] Acrosome: Differentiated internally

**Character 132: 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.

Dentalium: Differentiated membrane only (Dufresne-Dube et al., 1983).

Flustra: No evidence of internal differentiation (in *Tubulipora*; Franzén, 1984).

Lingula: Clear differentiation of marginal area (Fukumoto, 2003).

Loxosomella: Not evident in *Loxosoma* [©Franzen 2000].

Novocrania: “Along the inner and outer margins there are periodically banded layers, and between them

there is a less dense layer” – Afzelius and Ferraguti (1978).

Pelagodiscus atlanticus: Following *Discinisca tenuis*, described in Hodgson & Reunov (1994).

Phoronis: Acrosome-like structure; no internal division or surrounding membrane, with possibility that much of the acrosome is secondarily lost (Reunov and Klepal, 2004).

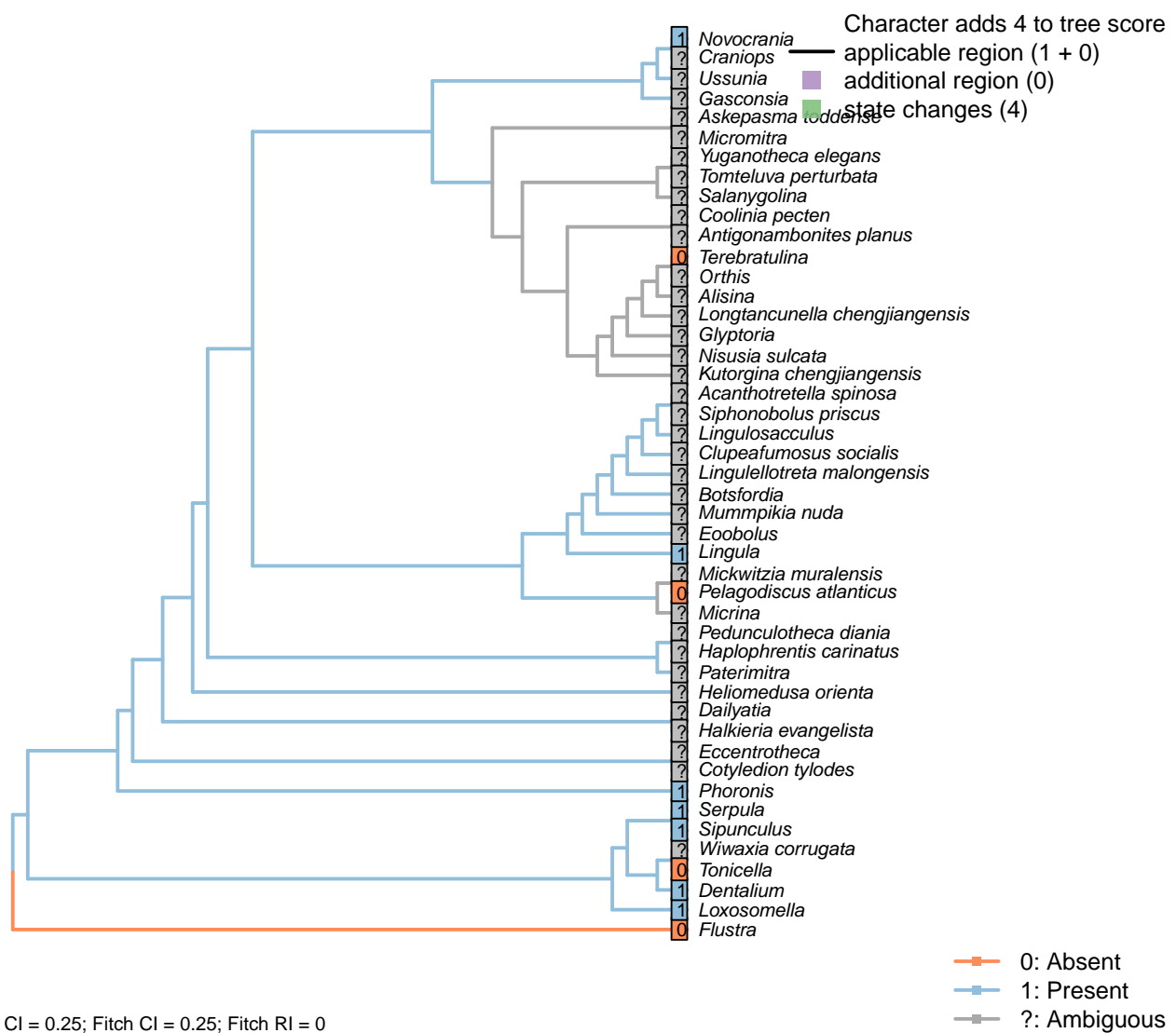
Serpula: Gherardi et al. (2011).

Sipunculus: No differentiation within acrosomal vesicle (Rice, 1993).

Terebratulina: Following Hodgson & Reunov (1994).

Tonicella: “One can distinguish two components in the acrosome, an apical and a basal granule” – Buckland-Nicks et al. (1988).

[133] Acrosome: Sub-acrosomal space



Character 133: Gametes: Spermatozoa: Acrosome: Sub-acrosomal space

0: Absent

1: Present

Neomorphic character.

Dentalium: Dufresne-Dube et al. (1983).

Flustra: No distinct space (in *Tubulipora*; Franzén, 1984).

Lingula: Filled with sub-acrosomal substance (Fukumoto, 2003).

Loxosomella: Present in *Loxosoma* [Franzen 2000].

Novocrania: Prominent (Afzelius and Ferraguti, 1978).

Pelagodiscus atlanticus: Subacrosomal material (in *Discinisca*) but no subacrosomal space (Hodgson and Reunov, 1994).

Phoronis: The filament-like acrosome continues backwards as a tube-like structure (Franzén and Ahlfors, 1980, summarized in Jamieson (1991)).

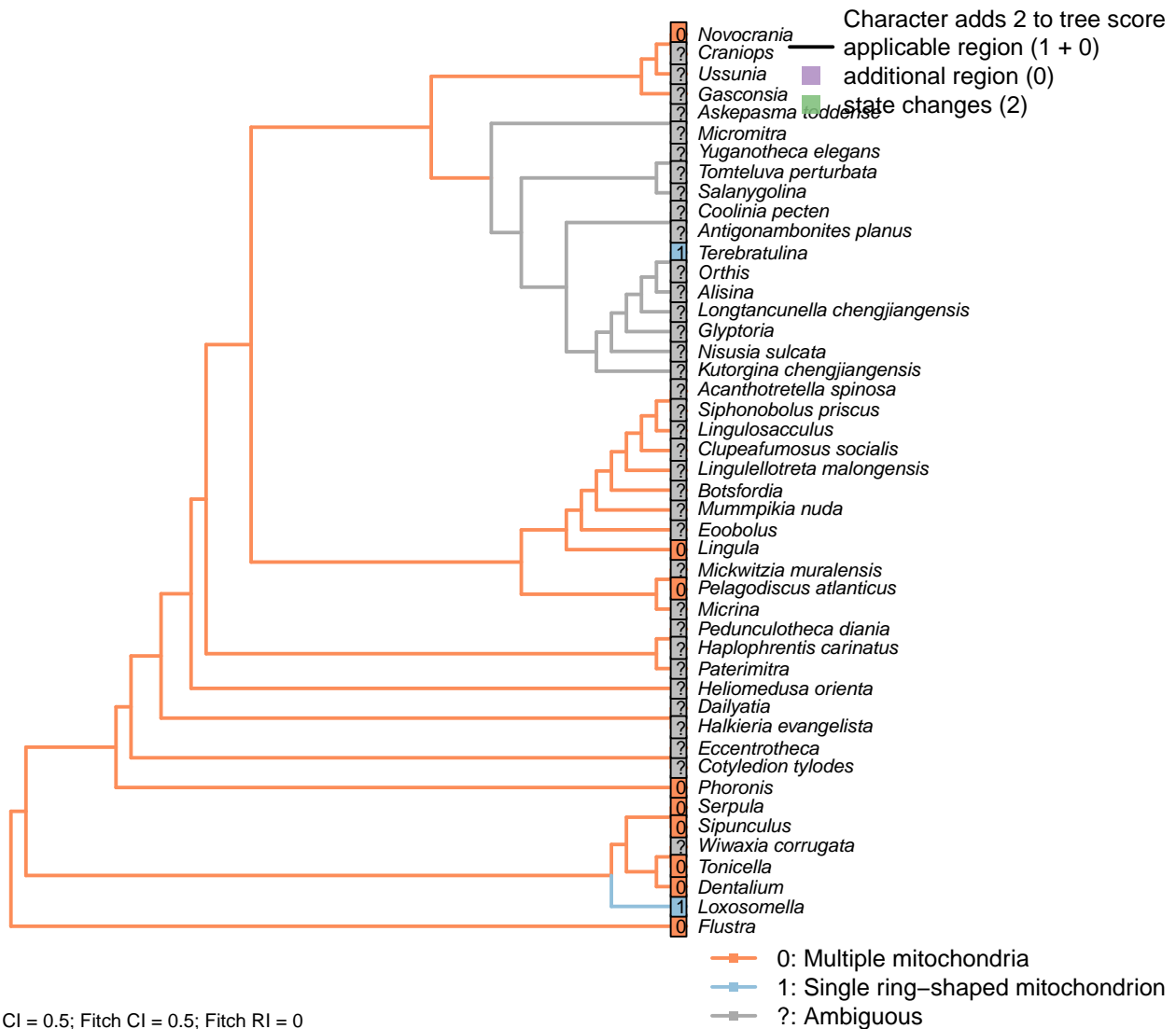
Serpula: Gherardi et al. (2011).

Sipunculus: Rice (1993).

Terebratulina: No subacrosomal material, let alone a subacrosomal space (e.g. Hodgson and Reunov, 1994).

Tonicella: Not evident (Buckland-Nicks et al., 1988).

[134] Mid-piece

**Character 134: Gametes: Spermatozoa: Mid-piece**

0: Multiple mitochondria

1: Single ring-shaped mitochondrion

Neomorphic character.

Following Hodgson & Reunov (1994).

Dentalium: Dufresne-Dube et al. (1983).*Flustra*: Two mitochondrial derivatives in *Flustra* (Franzén, 1981, 2013); four in *Tubulipora* (Franzén, 1984).*Lingula*, *Terebratulina*: Following Hodgson & Reunov (1994).*Loxosomella*: “The midpiece consists of two long mitochondrial rods connected with each other by a thin mitochondrial lamella” (Franzén, 2000, in *Loxosoma*); these are essentially a single organelle surrounding a

central rod of electron-dense material.

Novocrania: Four mitochondria (Afzelius and Ferraguti, 1978).

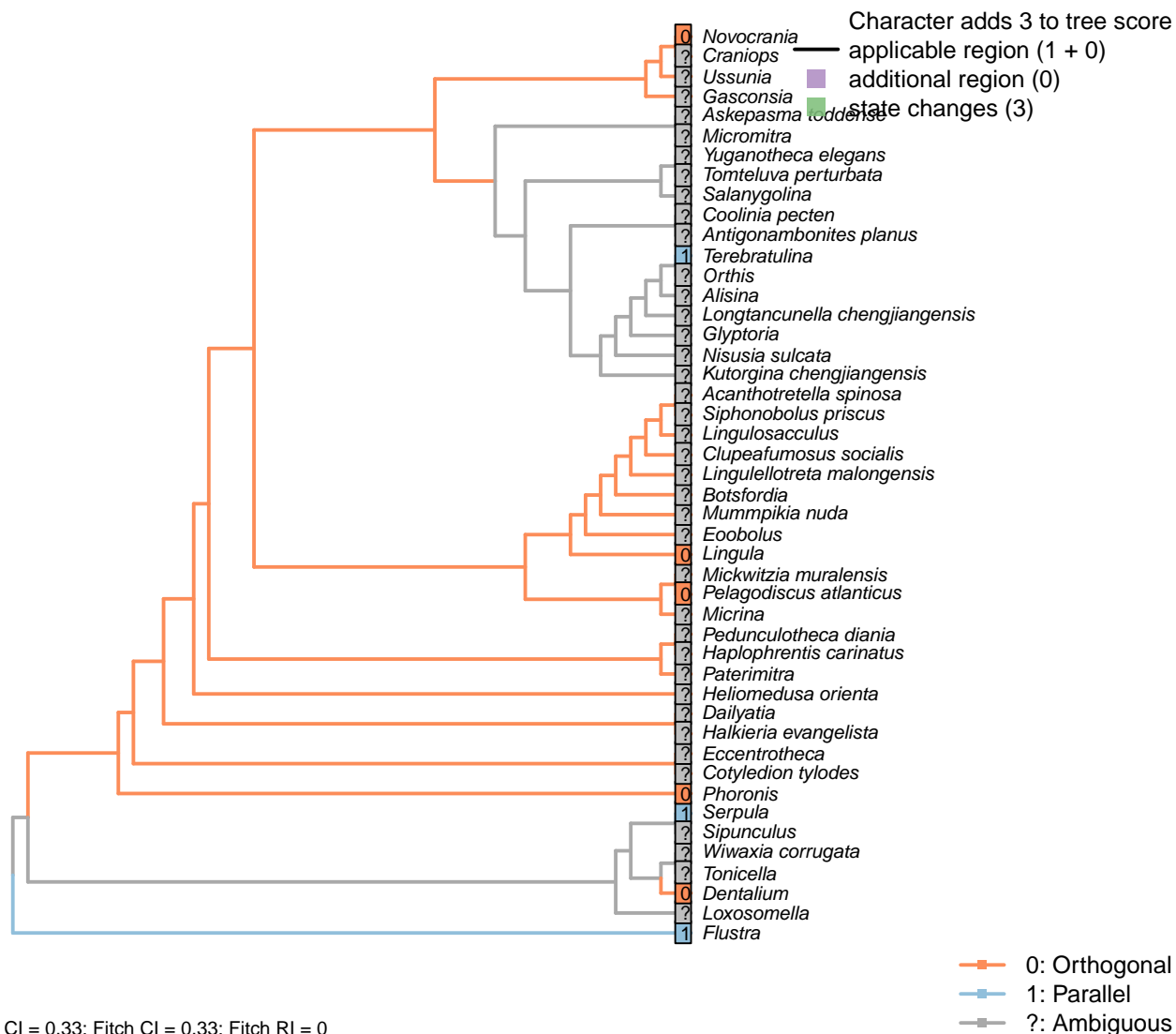
Pelagodiscus atlanticus: Following *Discinisca tenuis*, described in Hodgson & Reunov (1994).

Phoronis: The mitochondria fuse in the middle stage of spermiogenesis to become a pair of mitochondria (Reunov and Klepal, 2004).

Serpula: Five mitochondria in ring (Gherardi et al., 2011).

Sipunculus: Ring of five mitochondria around the central centriole (Rice, 1993).

[135] Centrioles: Orientation



Character 135: Gametes: Spermatozoa: Centrioles: Orientation

0: Orthogonal

1: Parallel

Neomorphic character.

Following Hodgson and Reunov (1994).

Dentalium: Dufresne-Dube et al. (1983).

Flustra: (Franzén, 1981).

Lingula, *Terebratulina*: Following Hodgson & Reunov (1994).

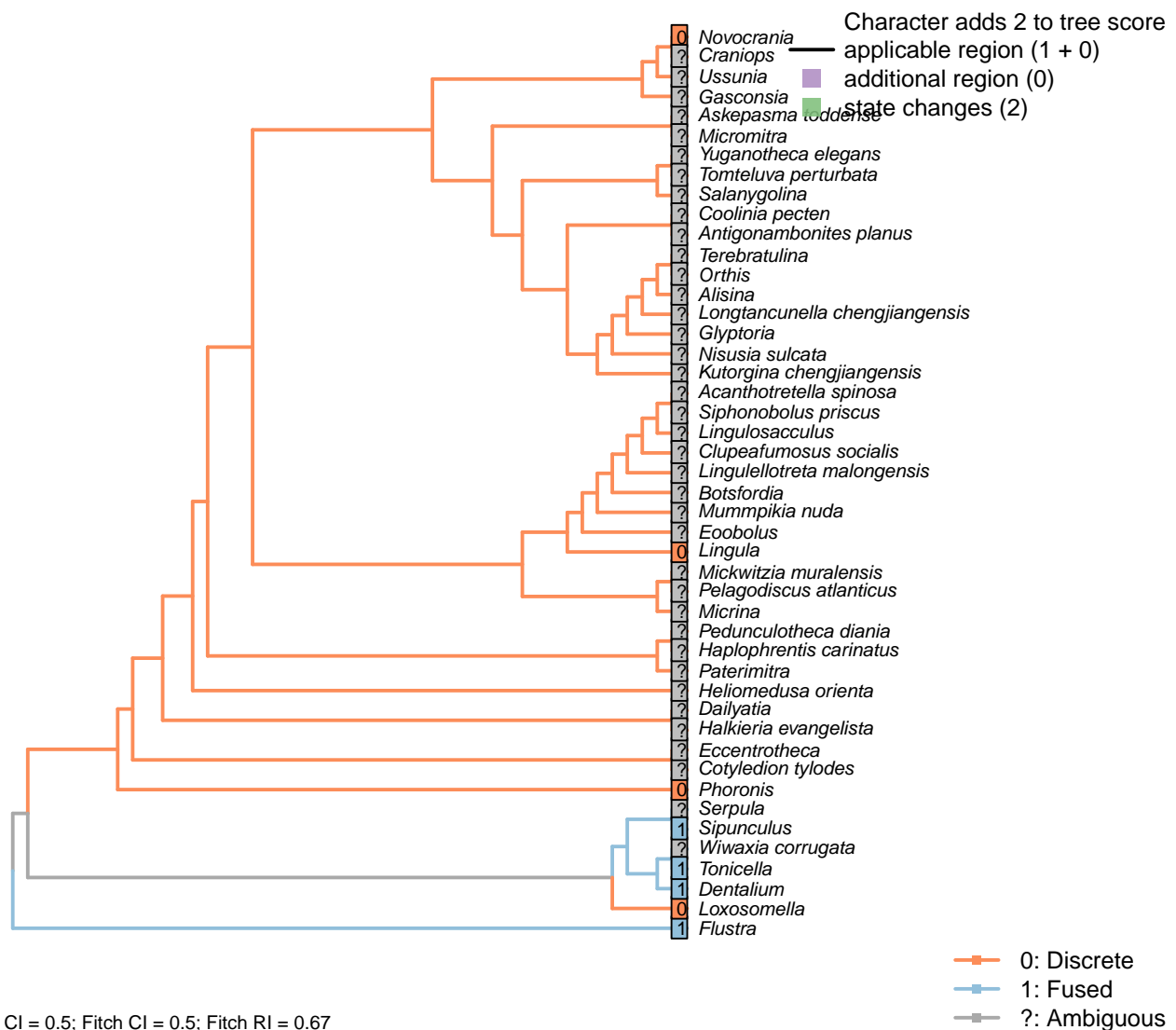
Novocrania: Two orthogonal centrioles (Afzelius and Ferraguti, 1978).

Pelagodiscus atlanticus: Following *Discinisca tenuis*, described in Hodgson & Reunov (1994).

Phoronis: Only one centriole in spermatzoon (Reunov and Klepal, 2004, p. 7), but centrioles are perpendicularly oriented in spermatogonia (ibid., p. 2).

Serpula: The proximal centriole is parallel to the flagellum (Gherardi et al., 2011).

[136] Centrioles: Fusion



0: Discrete

1: Fused

Neomorphic character.

Following Smith (2012a); see Buckland-Nicks (2008).

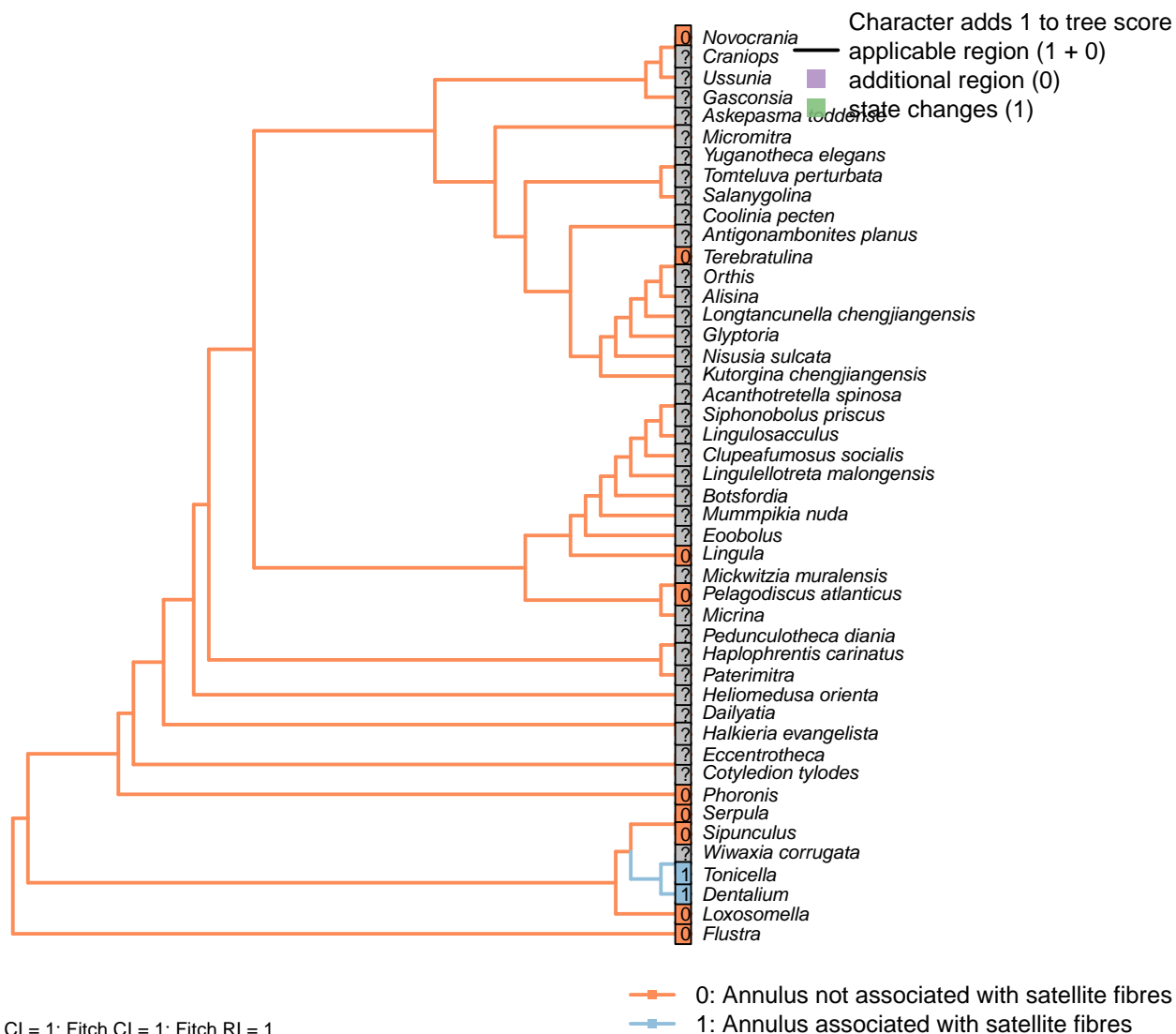
Dentalium: Proximal centriole fused anterior to distal centriole (Dufresne-Dube et al., 1983).

Flustra, *Sipunculus*: Proximal centriole fused anterior to distal centriole.

Lingula, *Loxosomella*, *Novocrania*, *Phoronis*: Basal body in deep nuclear fossa.

Tonicella: Proximal centriole fused lateral to distal centriole and offset.

[137] Satellite fibre complex



Character 137: Gametes: Spermatozoa: Satellite fibre complex

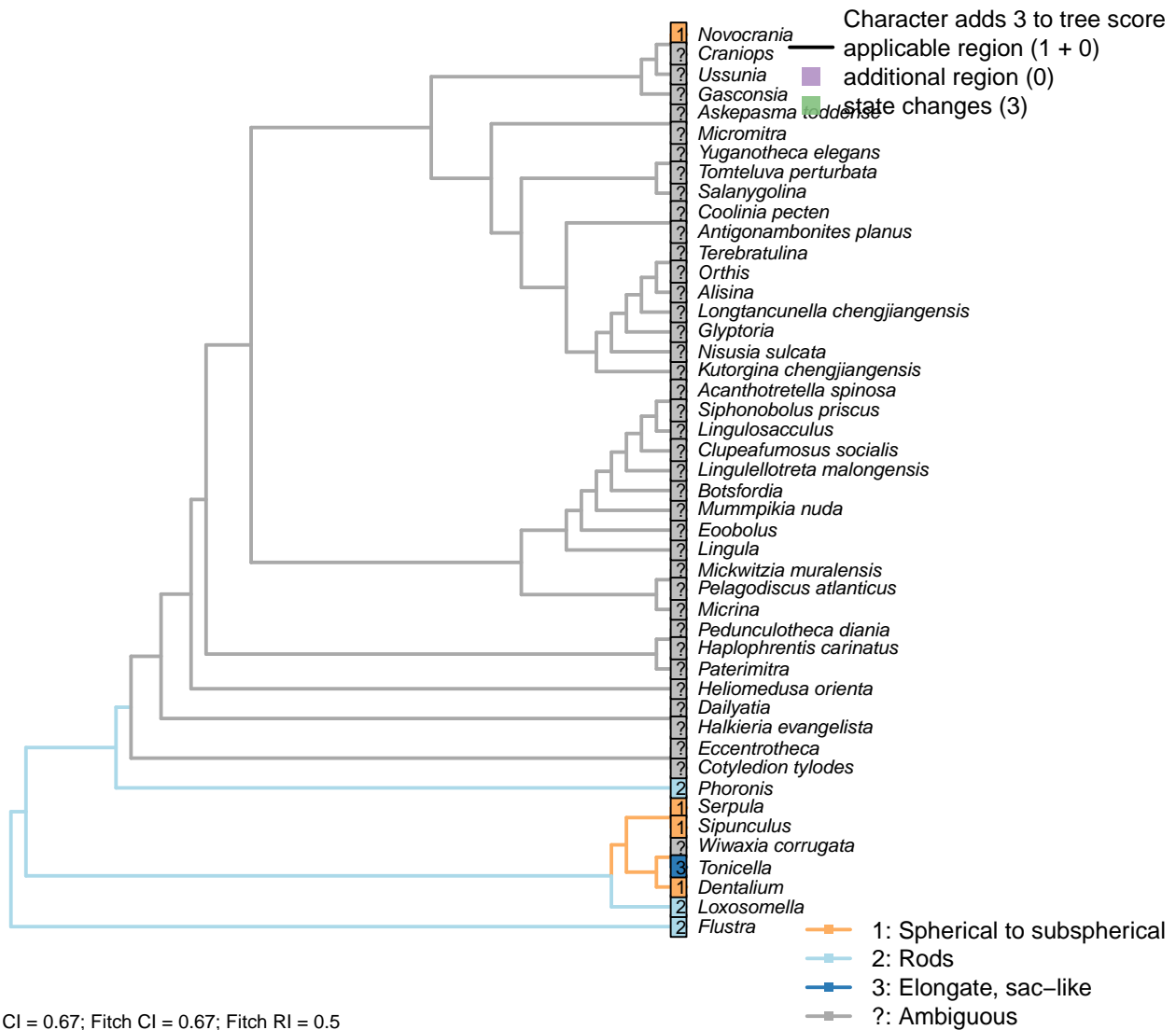
0: Annulus not associated with satellite fibres

1: Annulus associated with satellite fibres

Neomorphic character.

Following Smith (2012a), after character 48 in Ponder and Lindberg (1997).

[138] Mitochondria: Shape



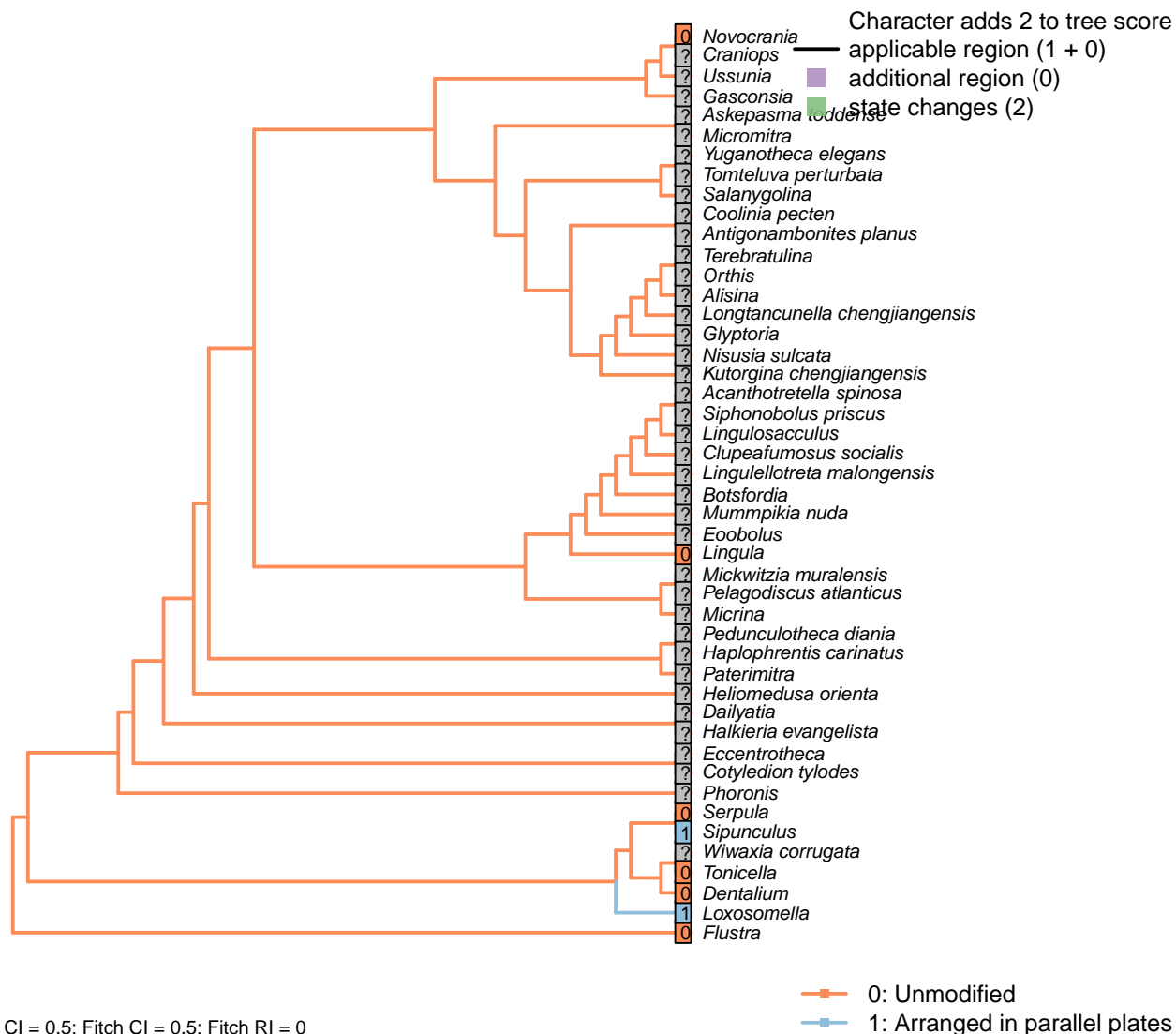
After character 5 in Buckland-Nicks (2008); see also character 43 in Ponder and Lindberg (1997).

Flustra: Rods (Franzén, 1981).

Loxosomella: Elongate rods in *Loxosoma* (Franzén, 2000).

Tonicella: See Buckland-Nicks et al. (1988).

[139] Mitochondria: Cristae: Configuration

**Character 139: Gametes: Spermatozoa: Mitochondria: Cristae: Configuration**

0: Unmodified

1: Arranged in parallel plates

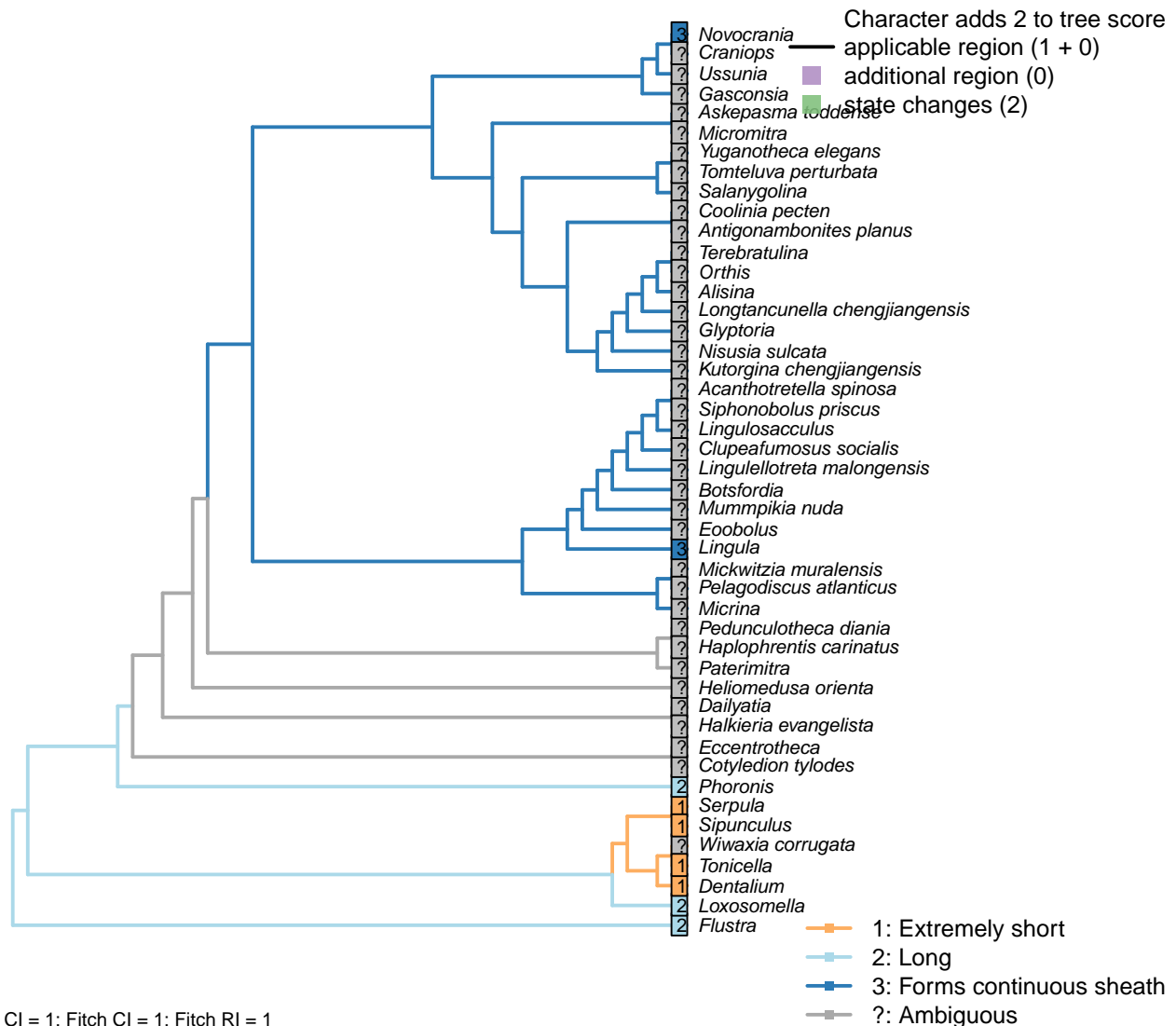
Neomorphic character.

After character 44 in Ponder and Lindberg (1997). Cristae are internal compartments formed by inner mitochondrial membranes.

Flustra: “Typical cristae”; “Randomly oriented” – Franzén (1984) (in *Tubulipora*).

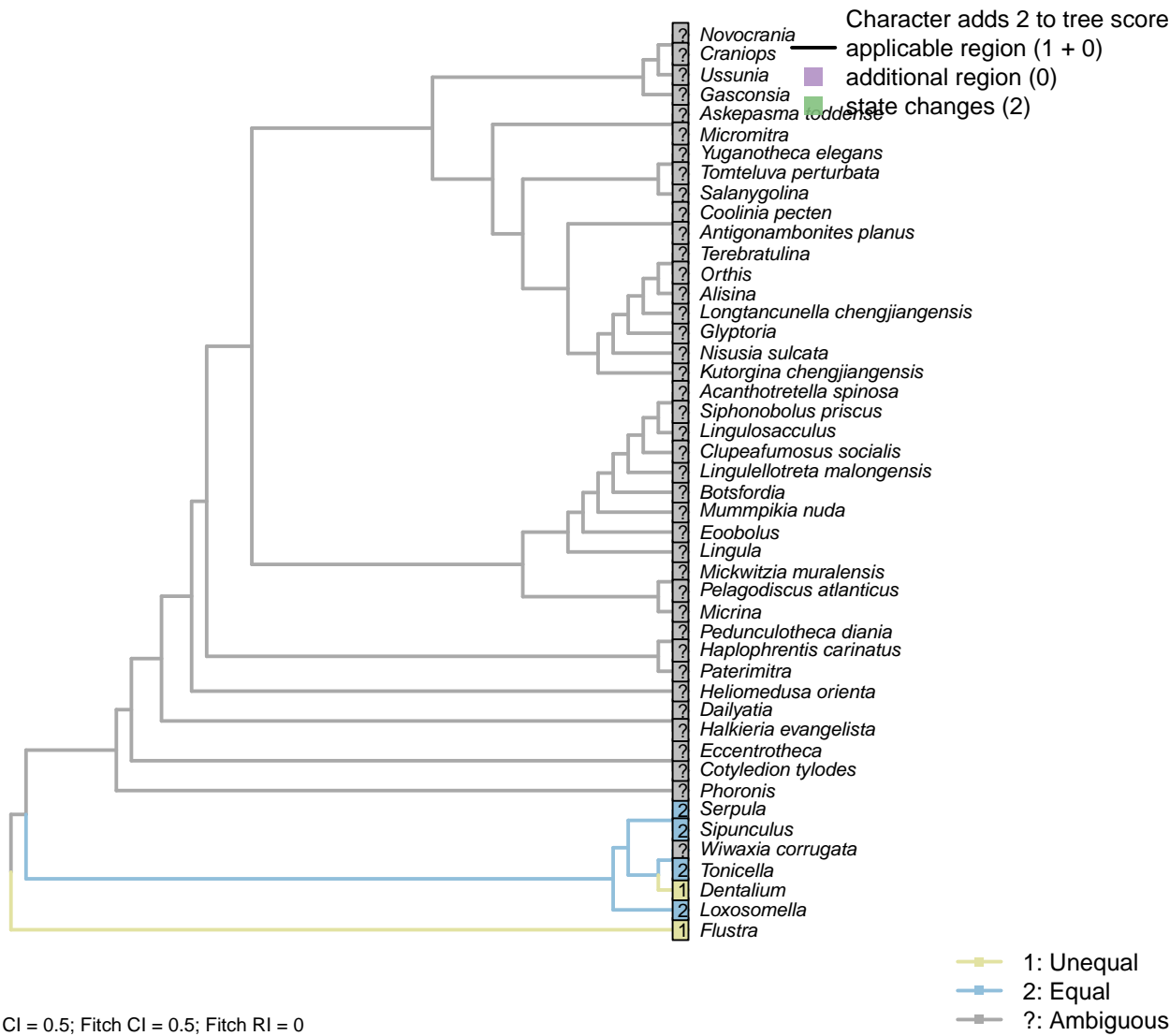
Loxosomella: in *Loxosoma* (Franzén, 2000).

[140] Mitochondria: Midpiece

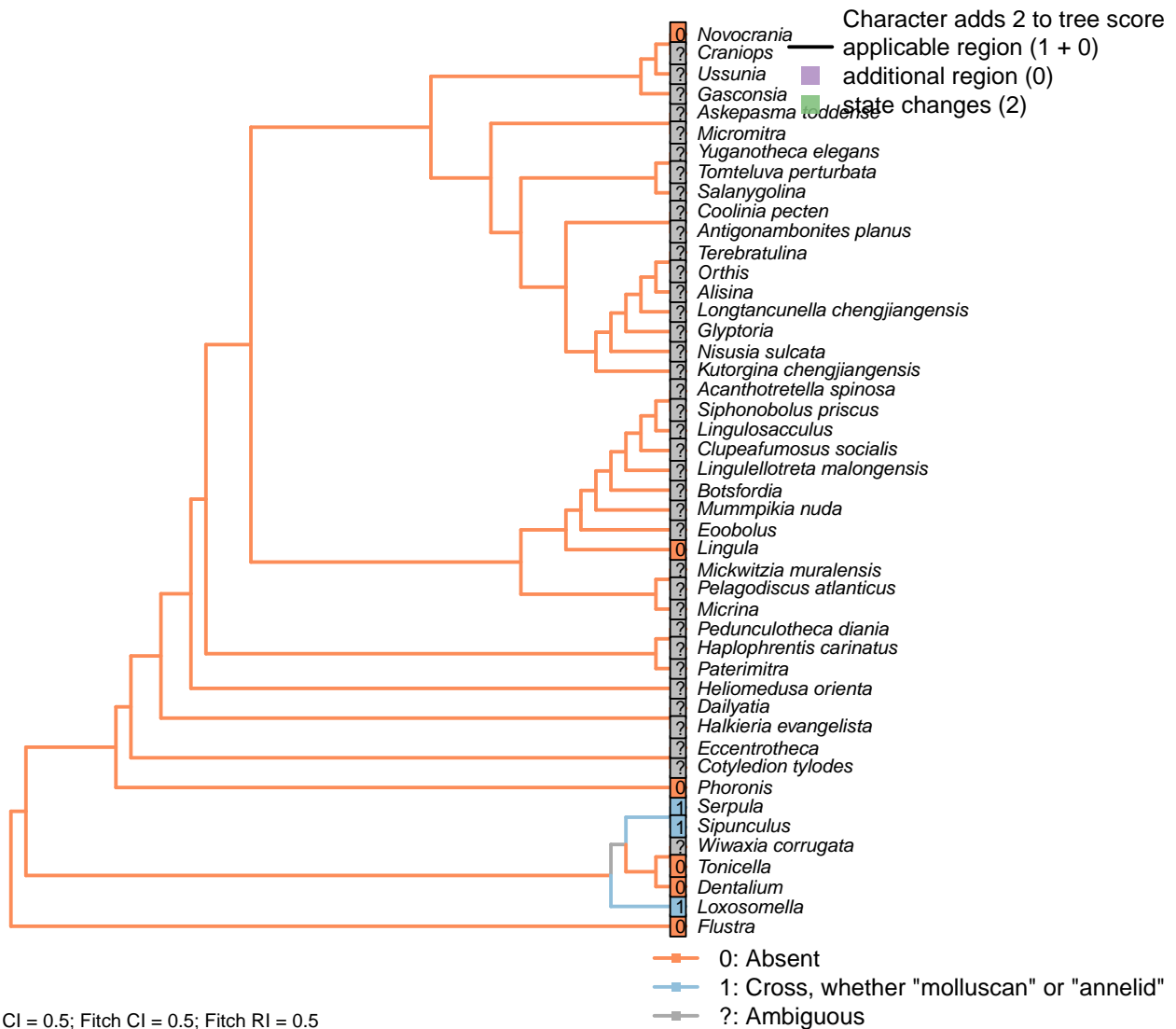


3.24 Embryo: Cleavage

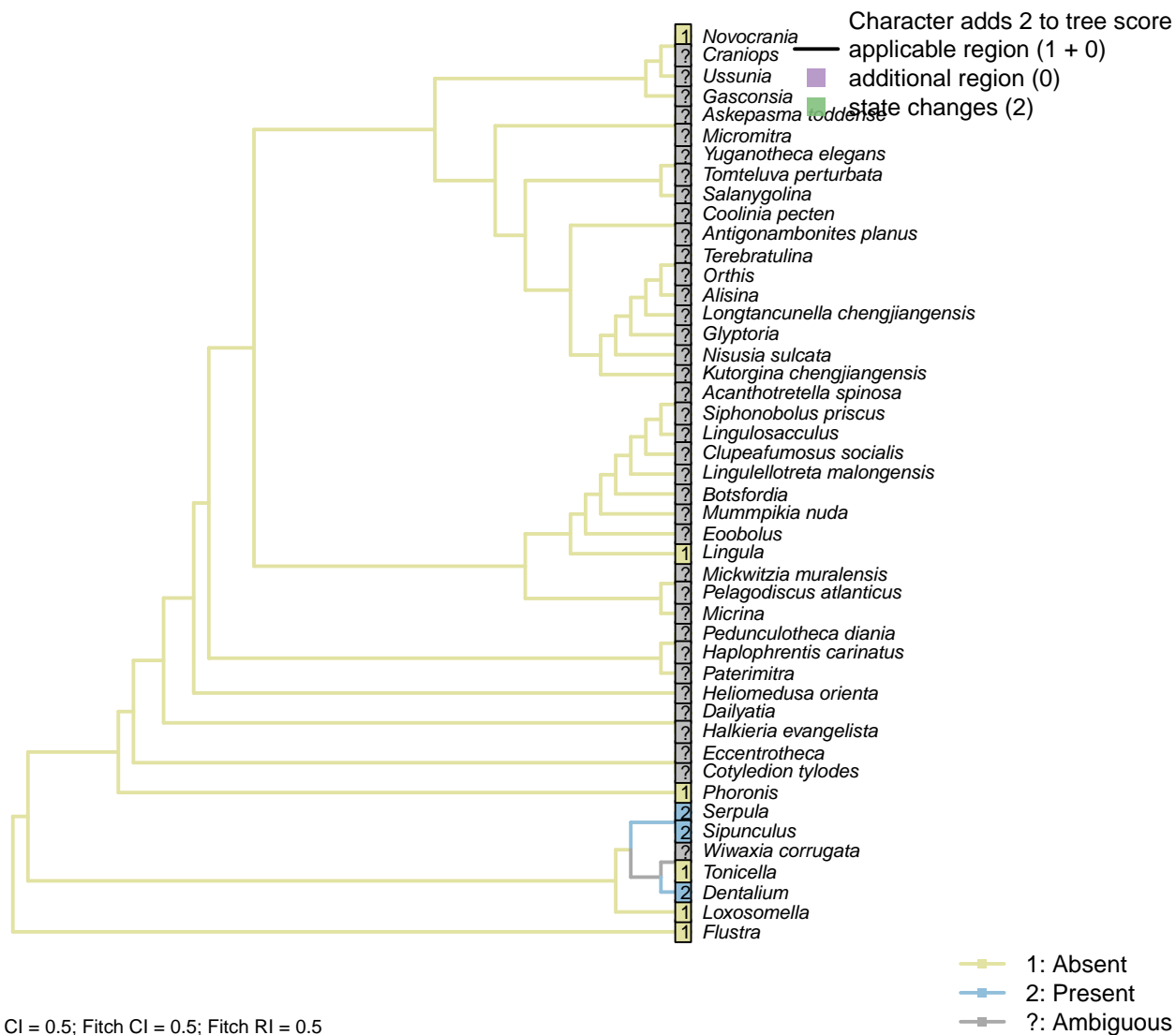
[141] Equal



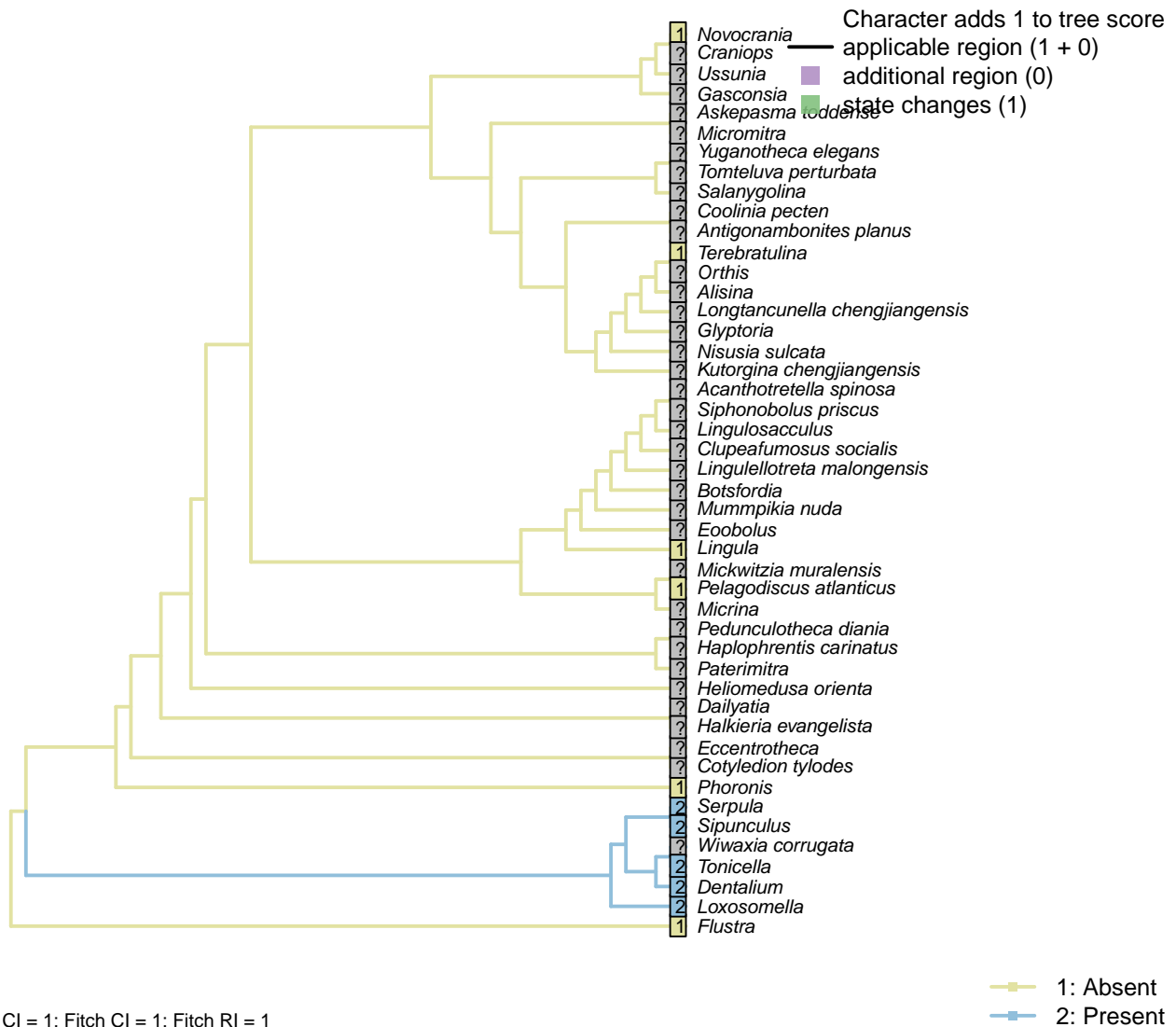
[142] Cross pattern



[143] Polar lobe formation



[144] Spiral

**Character 144: Embryo: Cleavage: Spiral**

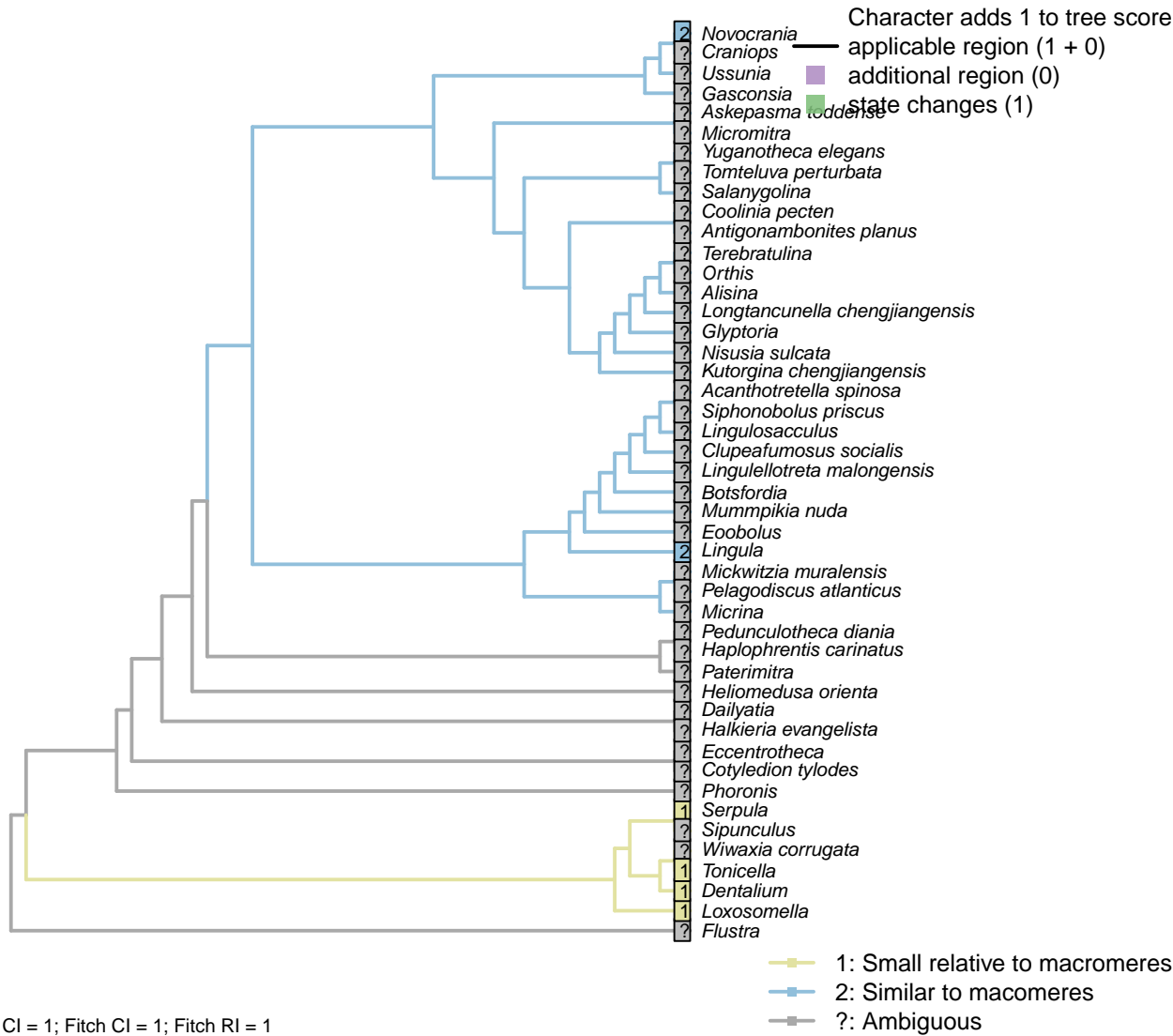
1: Absent

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).

3.25 Embryo: Micromere size [145]

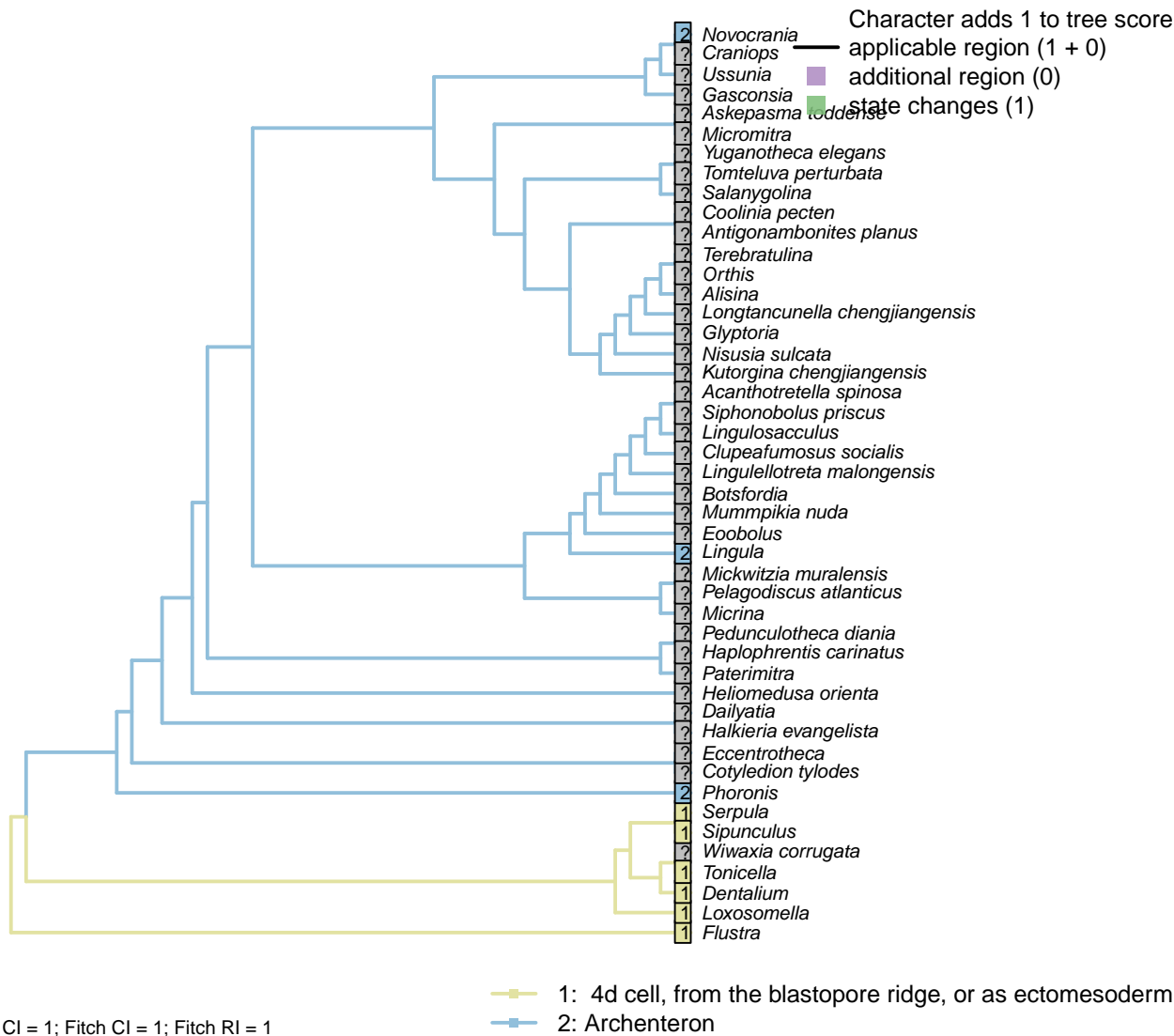


Character 145: Embryo: Micromere size

- 1: Small relative to macromeres
 - 2: Similar to macomeres
- Transformational character.

1.

[146] Origin of mesoderm



Character 146: Embryo: Origin of mesoderm

1: 4d cell, from the blastopore ridge, or as ectomesoderm

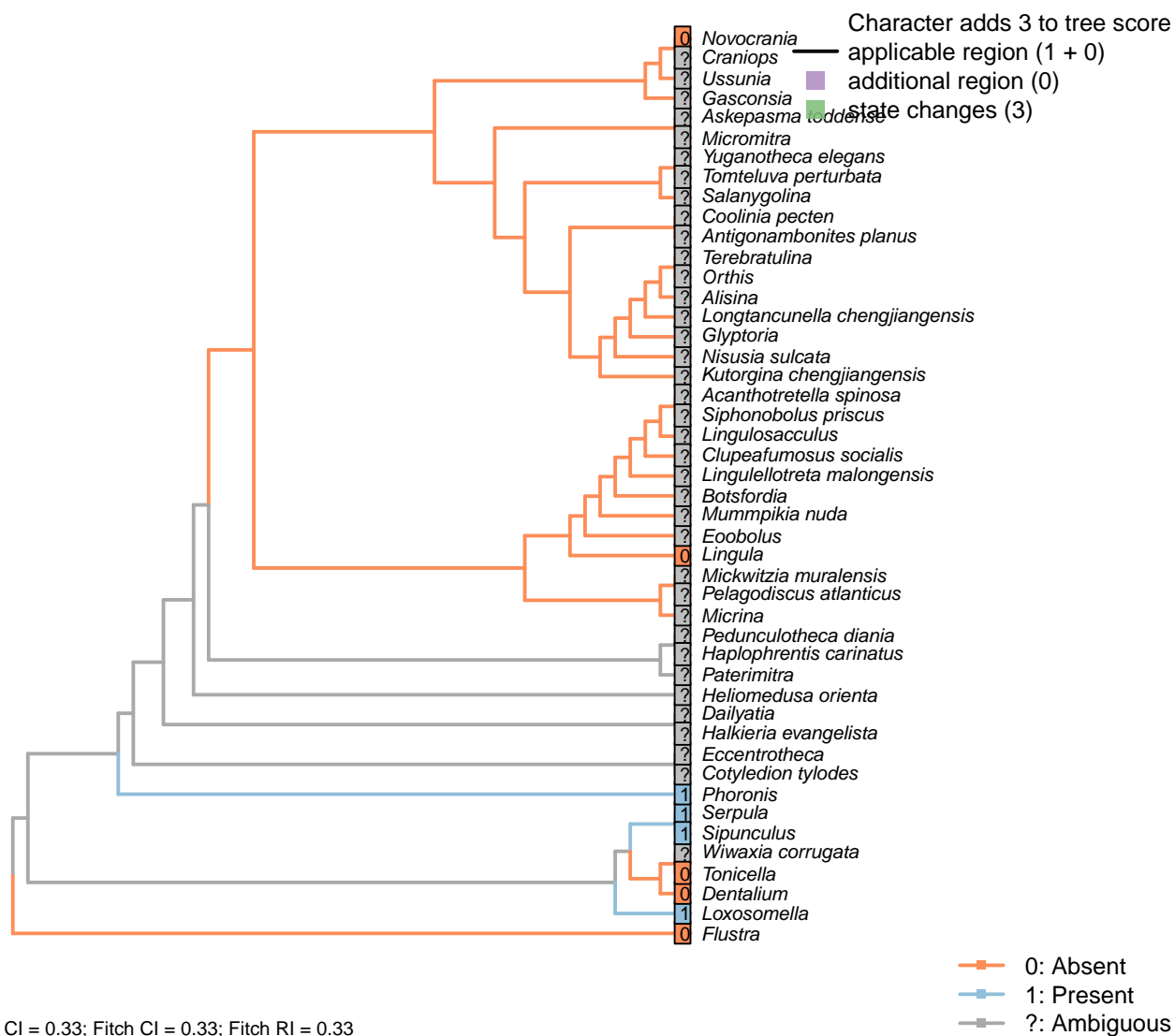
2: Archenteron

Transformational character.

After characters 32 in Grobe (2007) and 36–37 in Glenner et al. (2004).

3.26 Larva

[147] Metatroch



Character 147: Larva: Metatroch

0: Absent

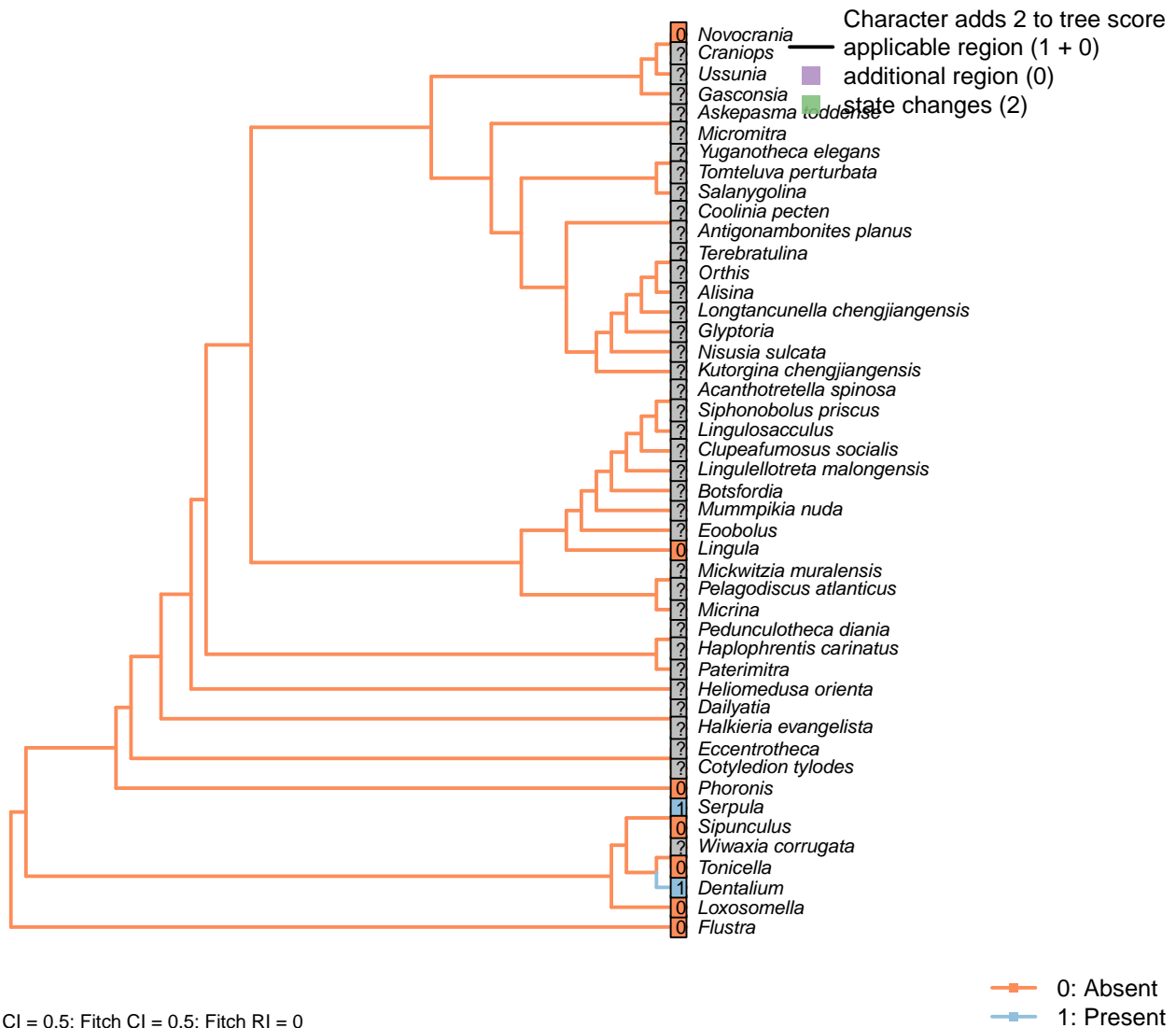
1: Present

Neomorphic character.

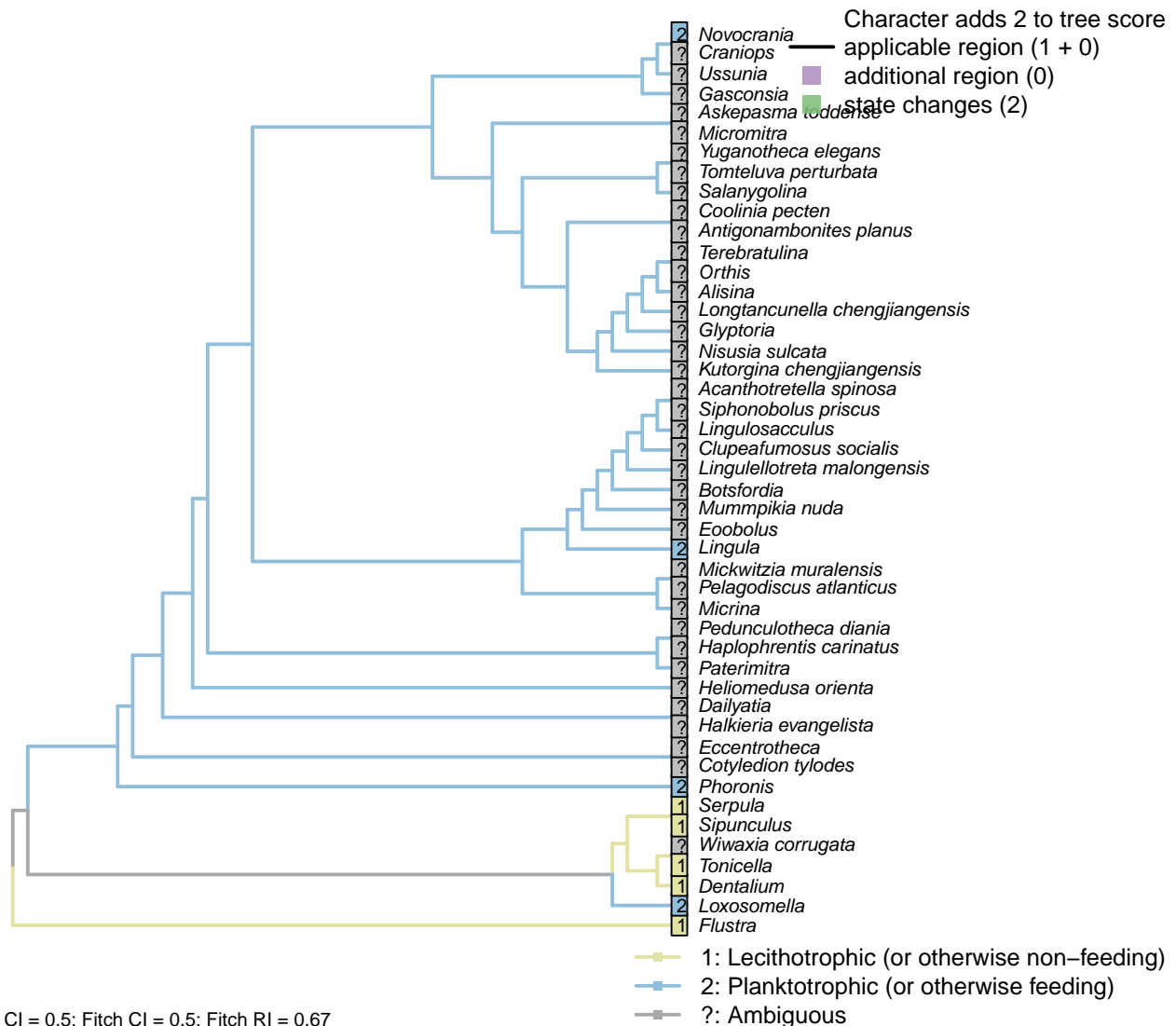
See characters 129 and 131 in Rouse (1999); 40 in Haszprunar (1996).

A prototroch is the defining character of a trochophore larva; a metatroch is a secondary ciliary ring (Rouse, 1999).

[148] Telotroch



[149] Feeding

**Character 149: Larva: Feeding**

1: Lecithotrophic (or otherwise non-feeding)

2: Planktotrophic (or otherwise feeding)

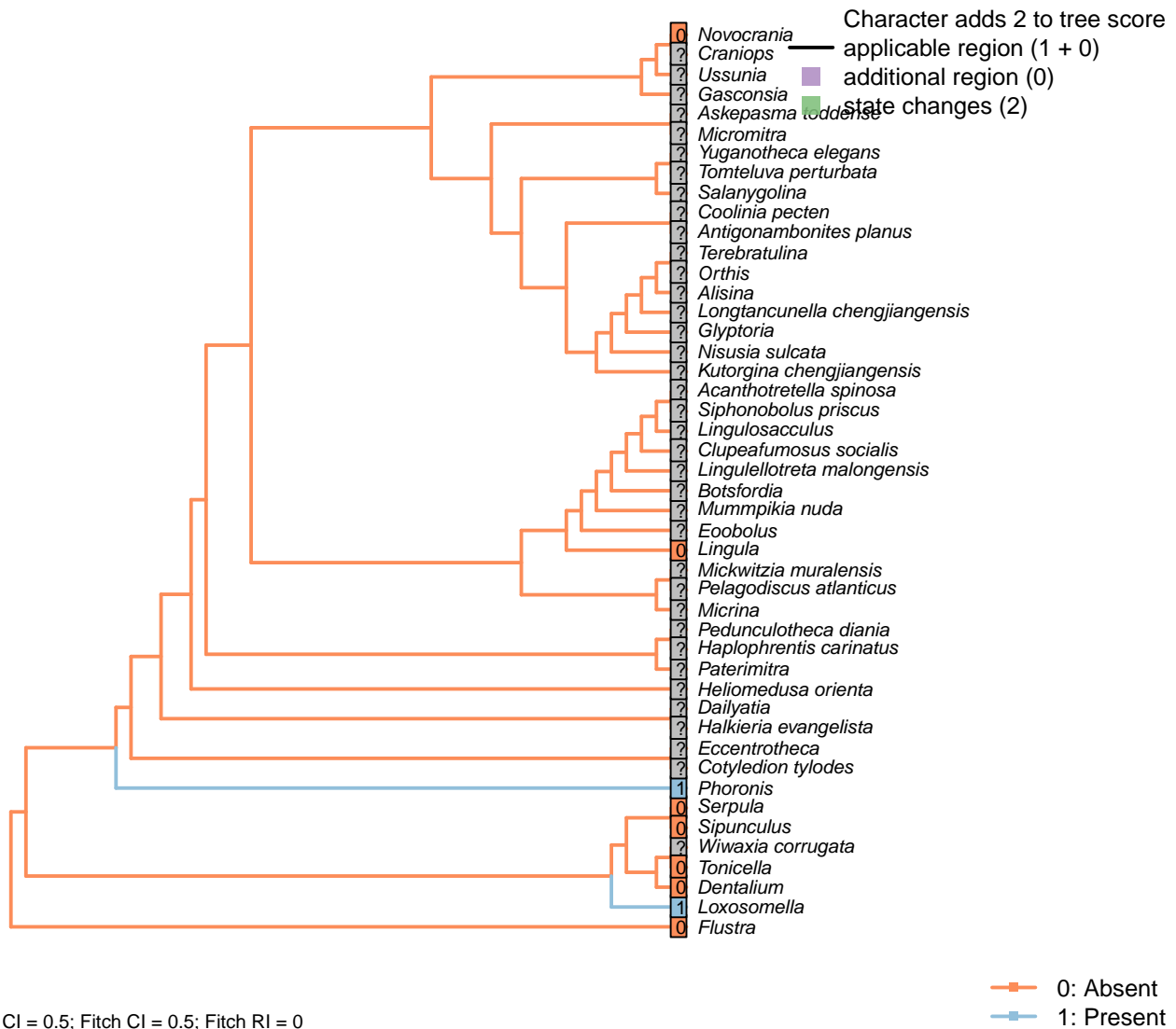
Transformational character.

Character 140 in Rouse (1999). See also Collin (1997); character 2.66 in von Salvini-Plawen and Steiner (1996); 153 in Giribet and Wheeler (2002).

Flustra: Metamorphose almost immediately after release from gonozooid (Zimmer and Woollacott, 2013).

3.27 Larva: Cilia

[150] Ciliated food groove



Character 150: Larva: Cilia: Ciliated food groove

0: Absent

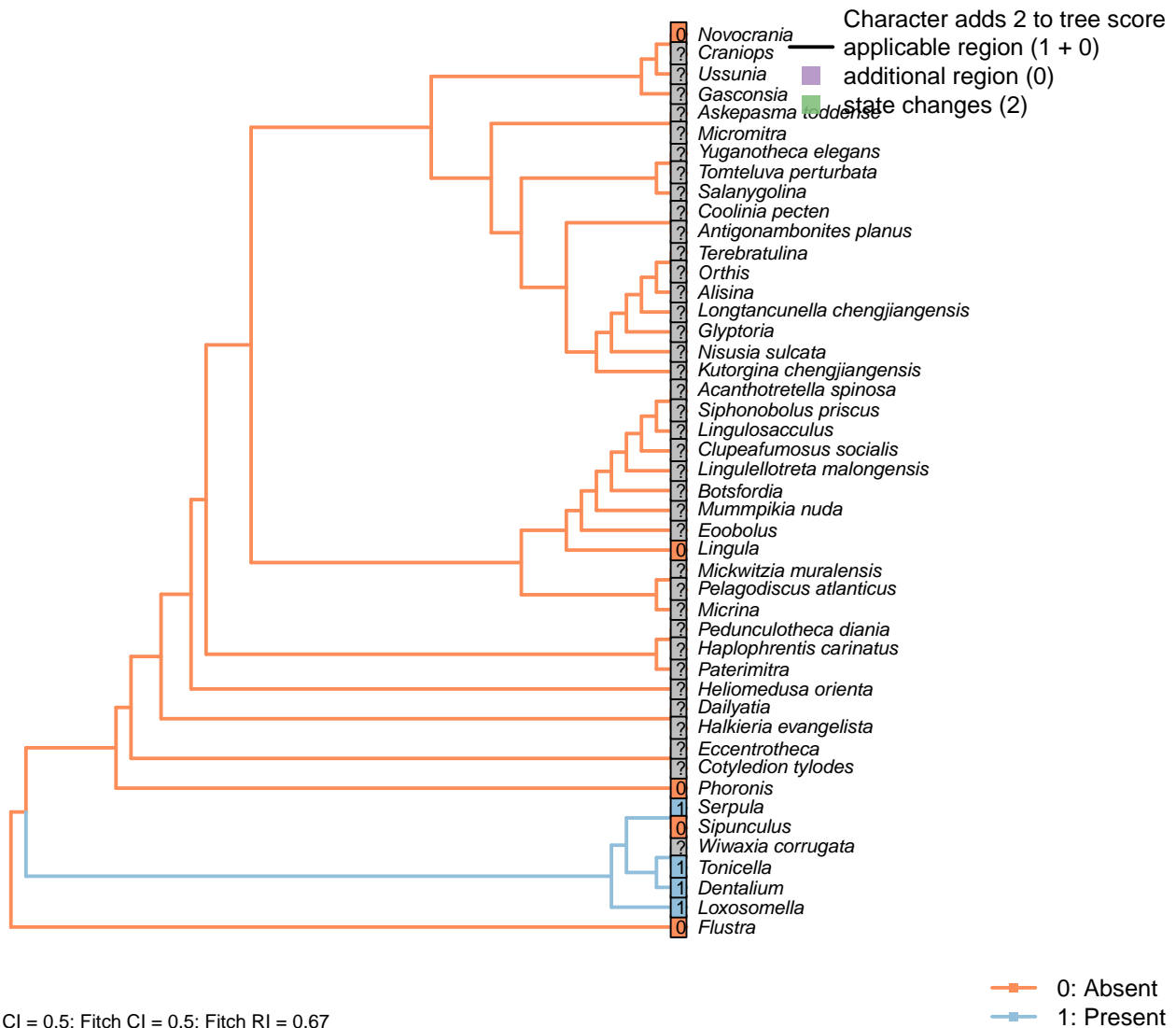
1: Present

Neomorphic character.

Character 132 in Rouse (1999).

Flustra: Cyclostomes are covered in cilia but not arranged in food groove.

[151] Ciliary bands: Downstream

**Character 151: Larva: Cilia: Ciliary bands: Downstream**

0: Absent

1: Present

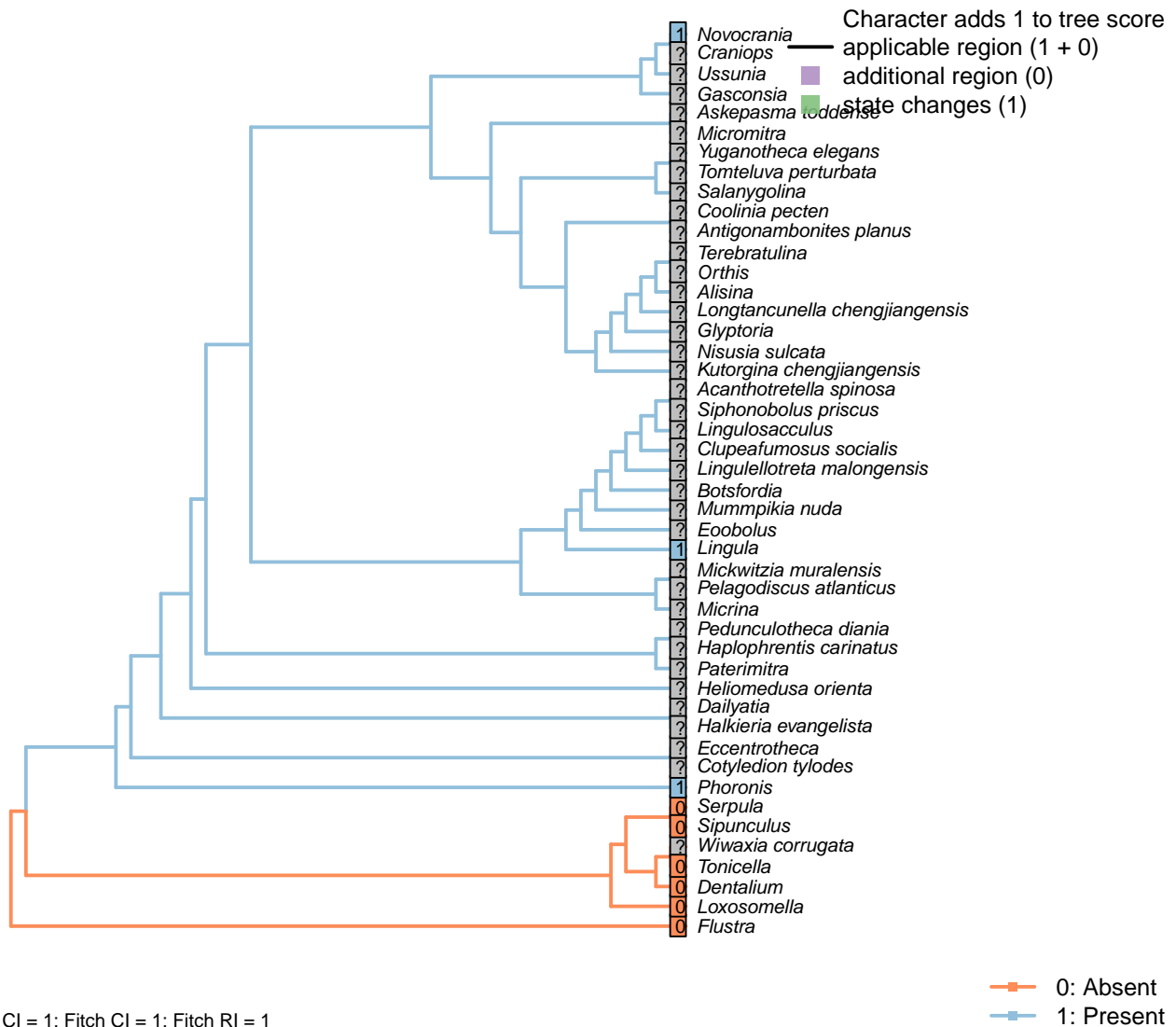
Neomorphic character.

Downstream-collecting ciliary bands of compound cilia on multiciliated cells. See character 32 in Glenner et al. (2004).

Serpula: “Groups such as Sabellariidae [...] have evolved downstream-feeding without the aid of a metatroch” – (Rouse, 2000).

Sipunculus: “Taxa such as Sipuncula [...] have a metatroch and do not have downstream larval-feeding” – Rouse (2000).

[152] Ciliary bands: Upstream

**Character 152: Larva: Cilia: Ciliary bands: Upstream**

0: Absent

1: Present

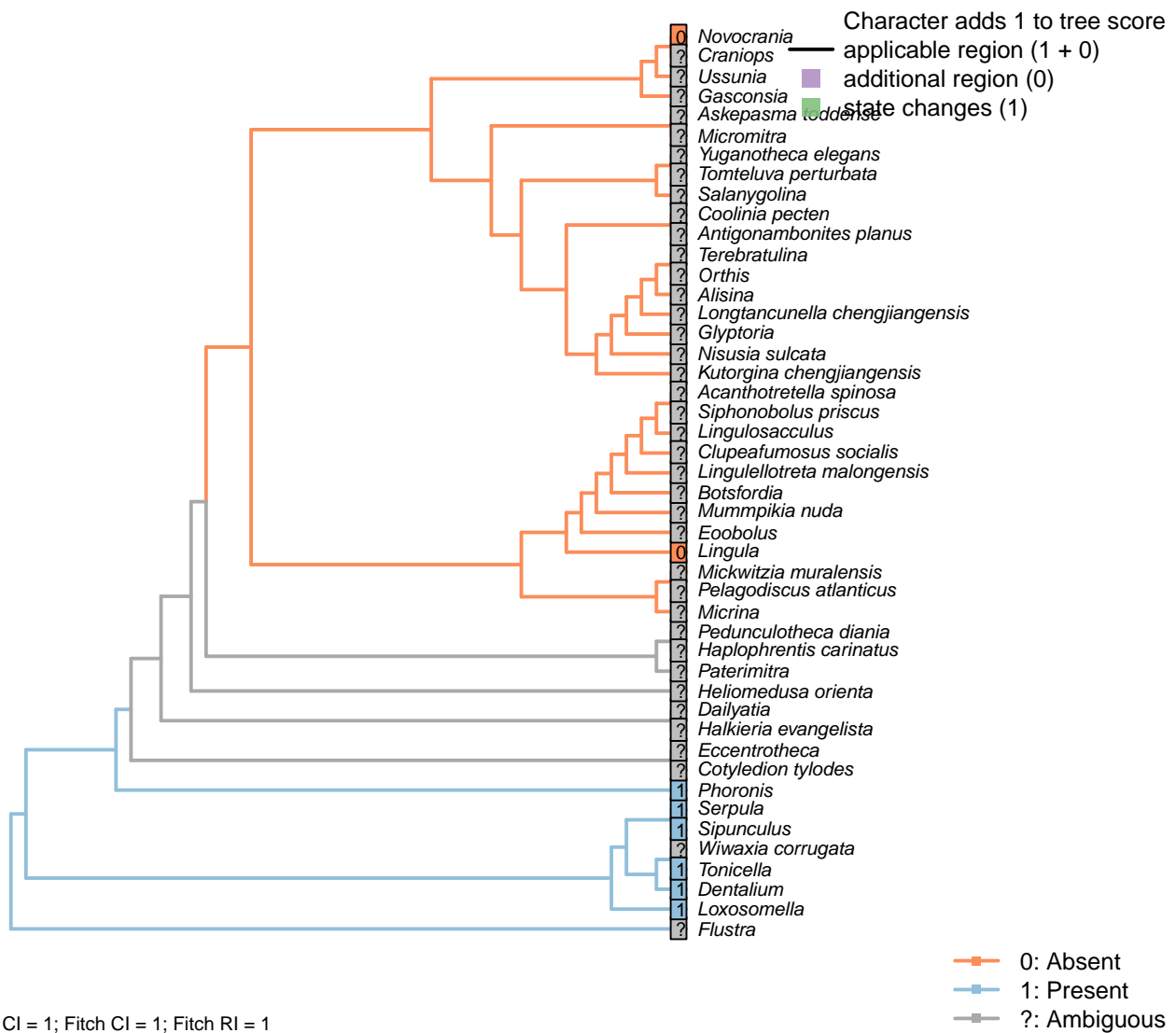
Neomorphic character.

Upstream-collecting ciliary bands with single cilia on monociliated cells. See character 32 in Glenner et al. (2004).

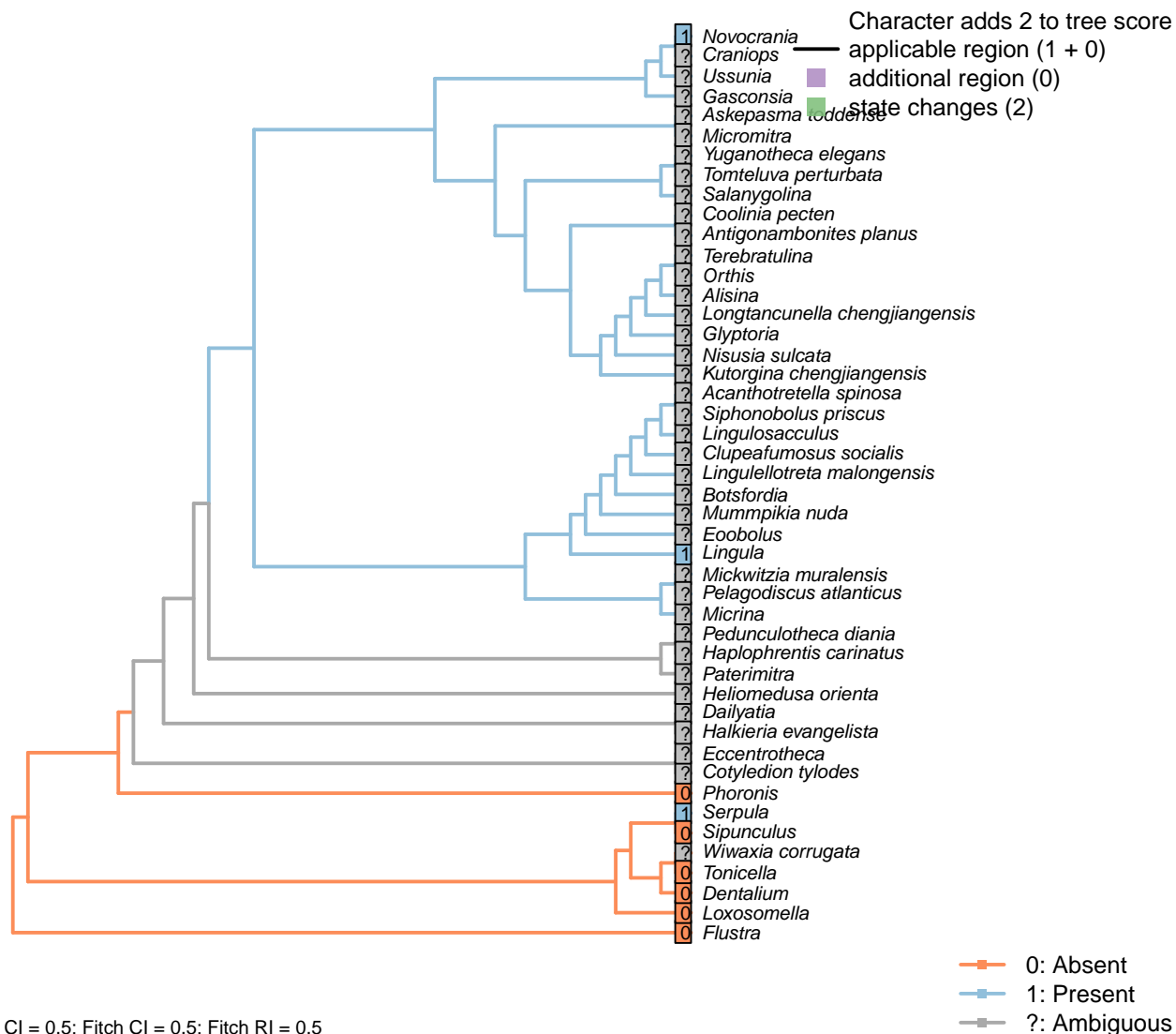
[153] Adoral ciliary band



3.28 Larva: Nerve ring underlying ciliated larval swimming organ [154]



[155] Paired dorsal setal bundles

**Character 155: Larva: Paired dorsal setal bundles**

0: Absent

1: Present

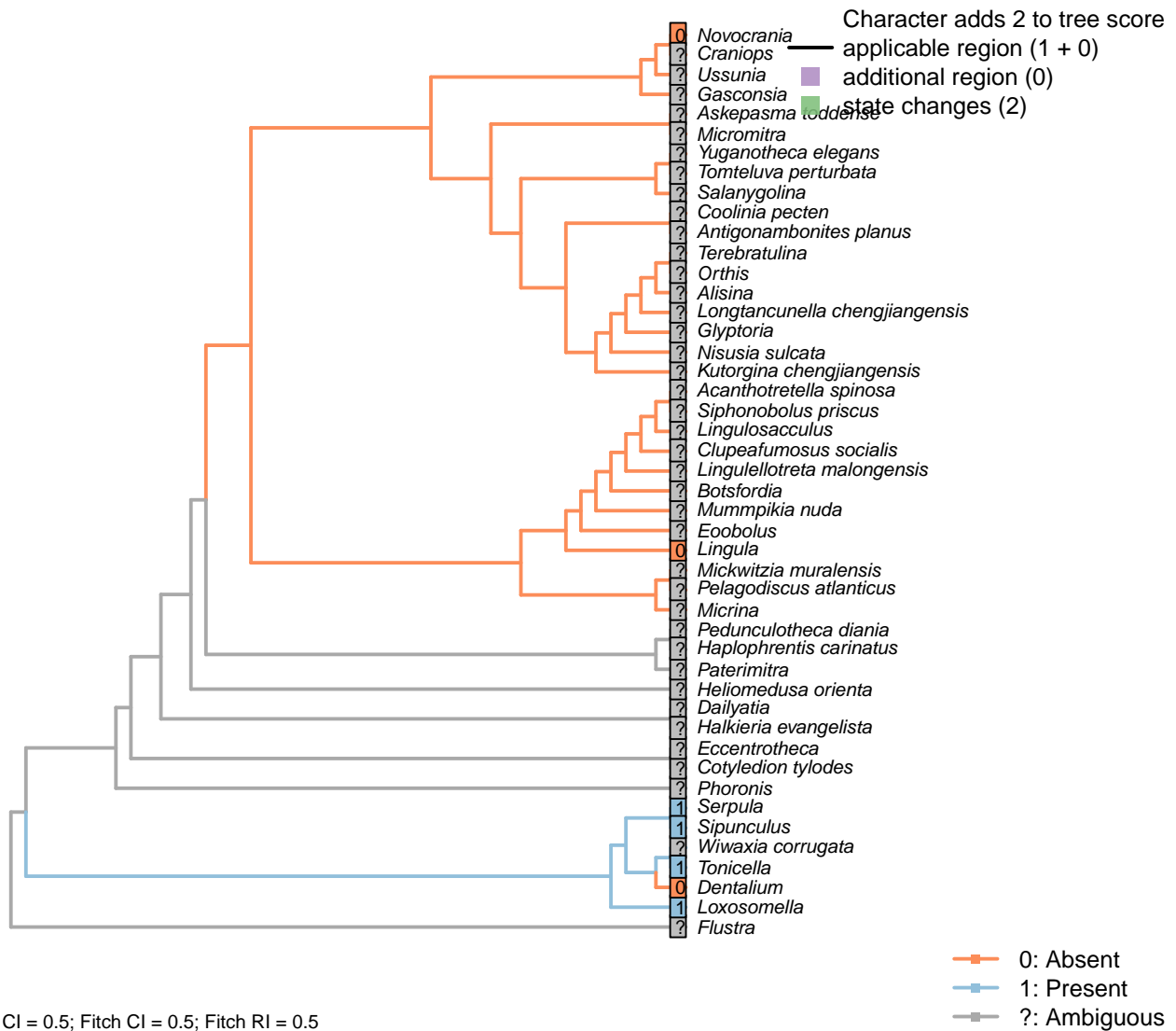
Neomorphic character.

Annelid chaetae are equivalent to the bundled setae expressed in certain brachiopod larvae. See character 12 in Vinther et al. (2008).

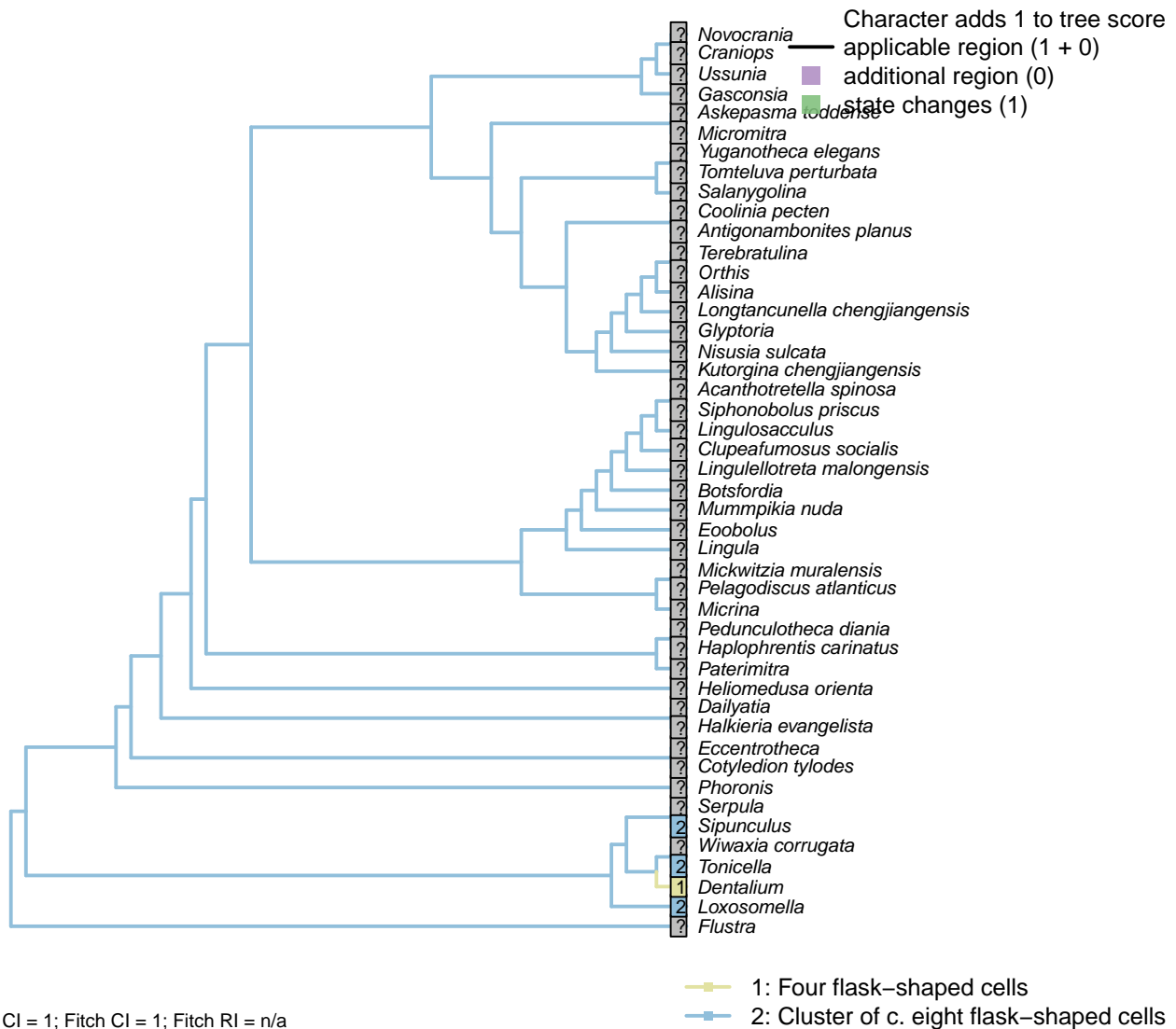
Flustra: Absent (Zimmer and Woollacott, 2013).

3.29 Larva: Apical organ

[156] Muscles extending to the hyposphere



[157] Serotonergic cells

**Character 157: Larva: Apical organ: Serotonergic cells**

- 0: Two flask-shaped cells
 - 1: Four flask-shaped cells
 - 2: Cluster of c. eight flask-shaped cells
- Neomorphic character.

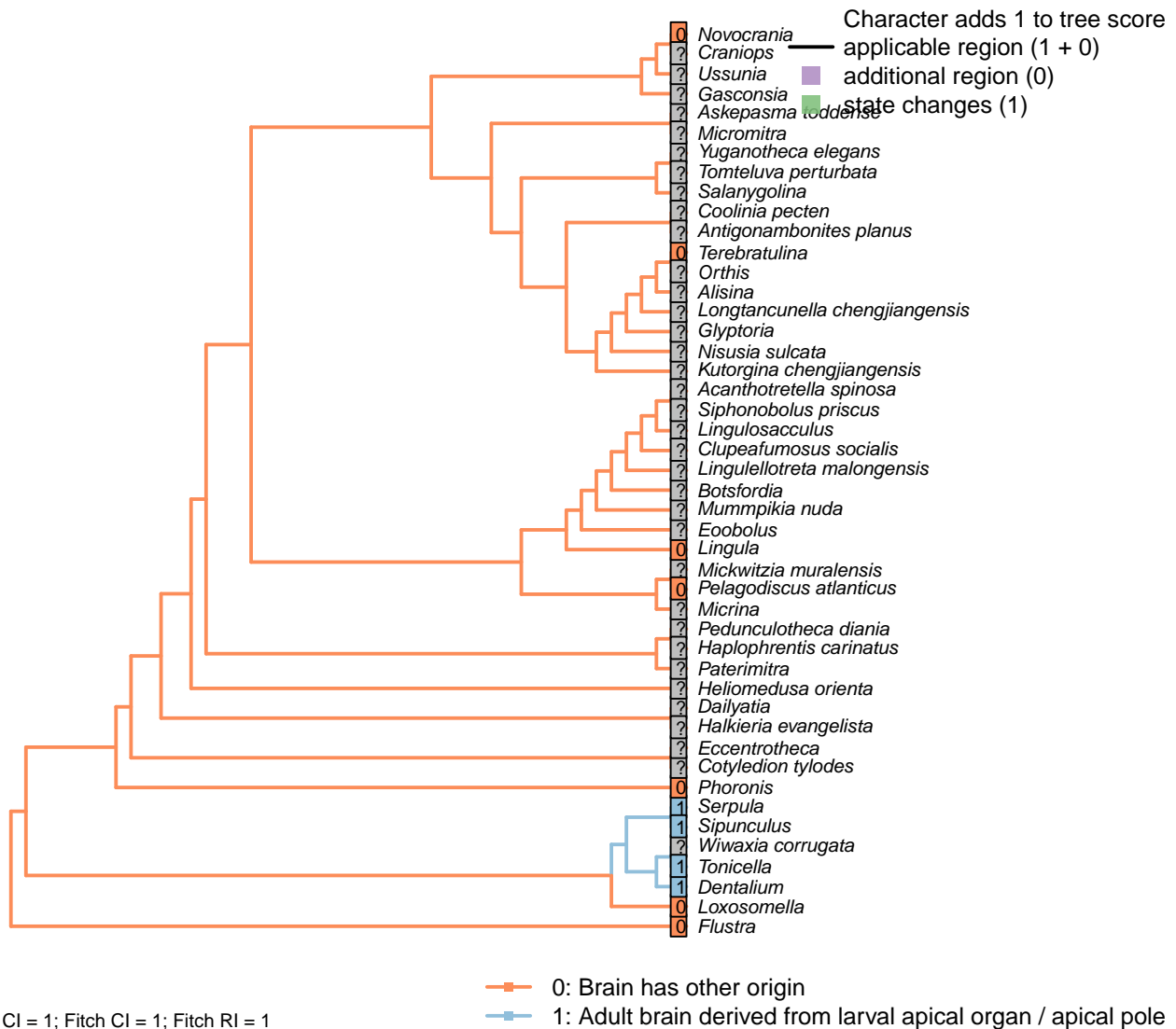
Character 8 in Haszprunar and Wanninger (2008).

Loxosomella: Six to eight apical cells; eight peripheral cells (Wanninger et al., 2007), indicating a probable equivalence to polyplacophorans (Haszprunar and Wanninger, 2008).

Sipunculus: Cluster of around eight cells, though not quite countable (Wanninger et al., 2005).

Tonicella: Eight in *Ischnochiton* and *Mopalia* (Wanninger et al., 2007).

[158] Develops into adult brain

**Character 158: Larva: Apical organ: Develops into adult brain**

0: Brain has other origin

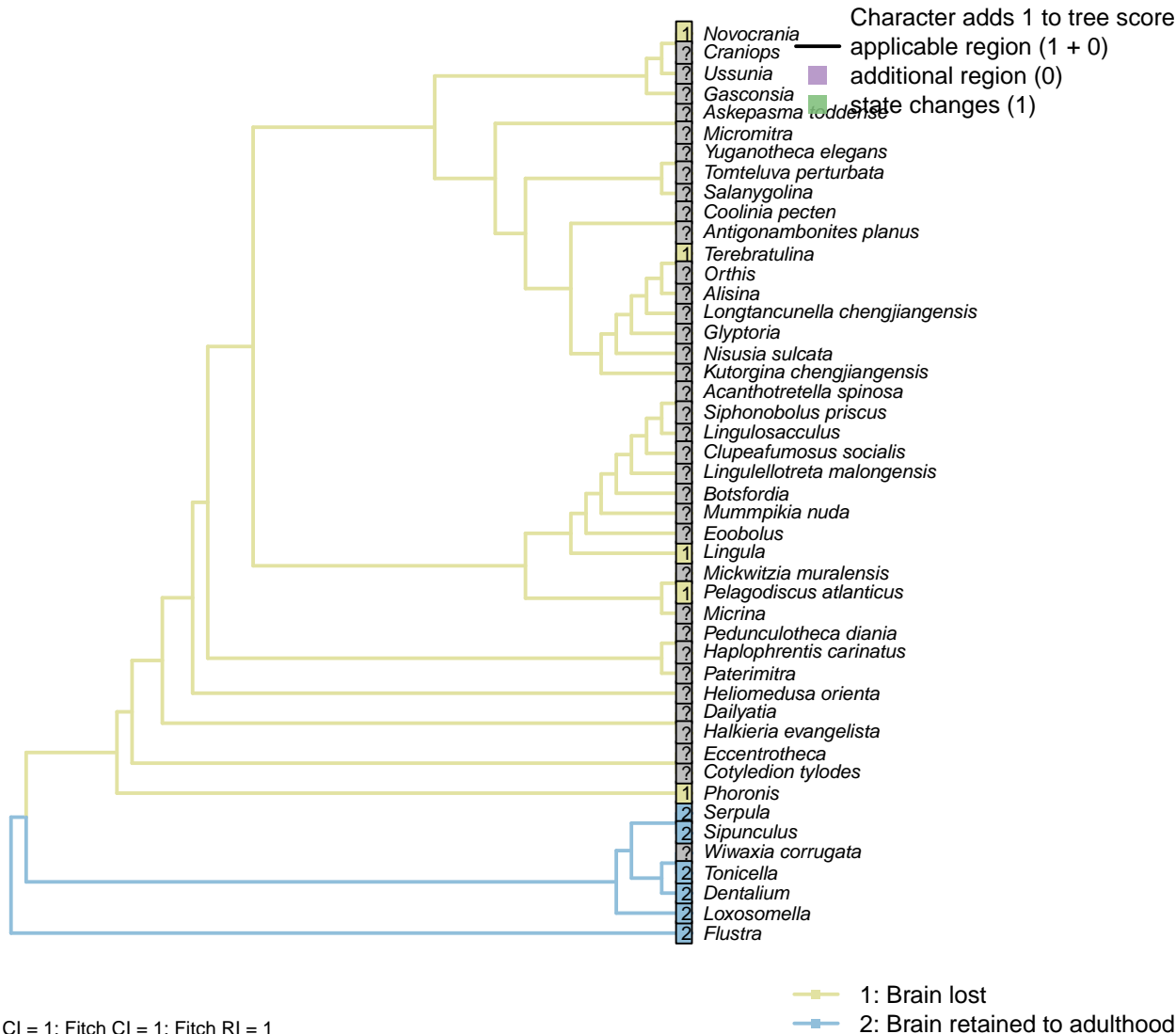
1: Adult brain derived from larval apical organ / apical pole

2:

Neomorphic character.

Character 79 in Glenner et al. (2004).

3.30 Larva: Brain persists into adulthood [159]

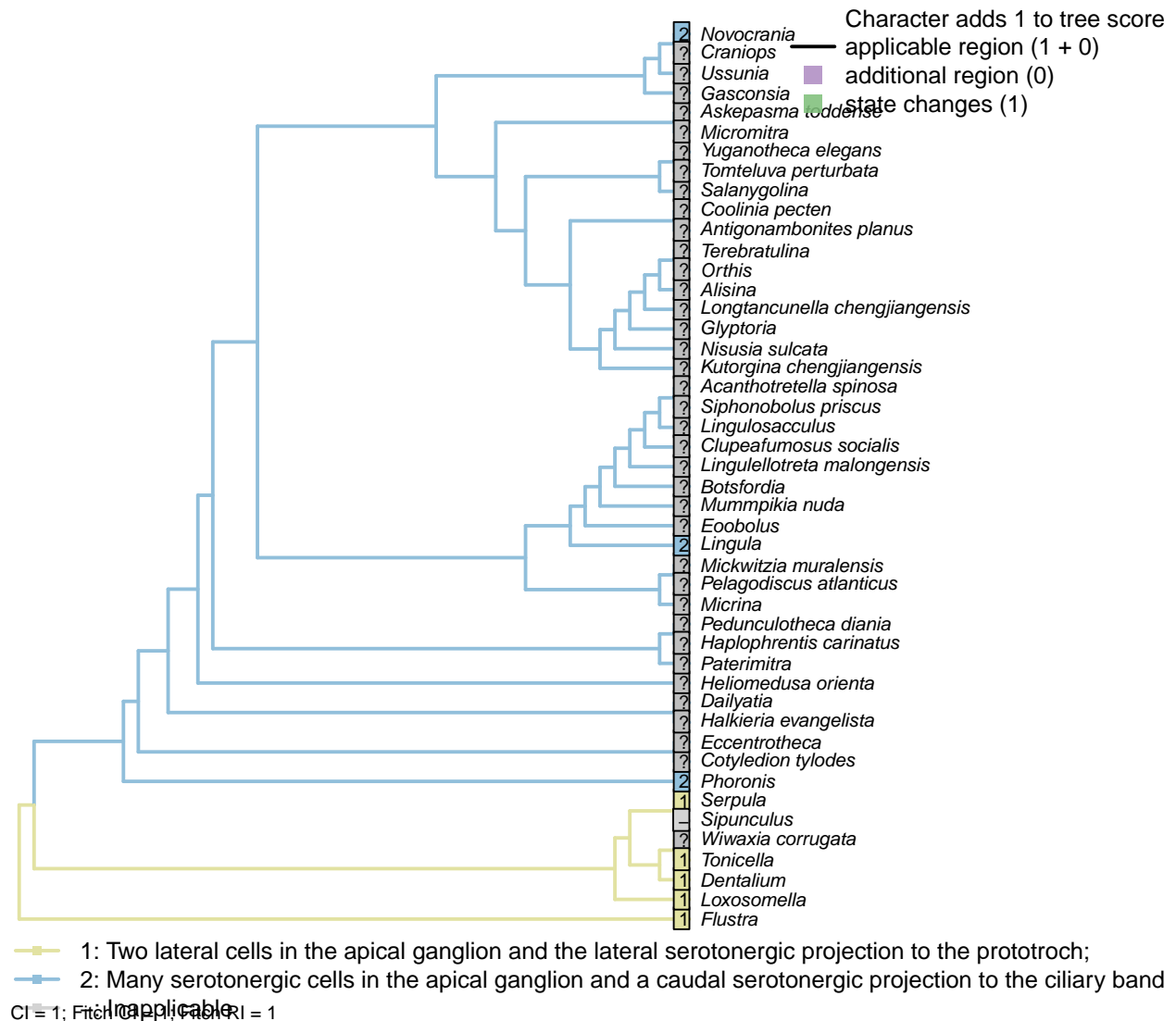


Character 159: Larva: Brain persists into adulthood

- 1: Brain lost
 - 2: Brain retained to adulthood
- Transformational character.

After character 3 in Richter et al. (2010).

[160] Serotonin-like immunoreactivity in apical organ

**Character 160: Larva: Serotonin-like immunoreactivity in apical organ**

- 1: Two lateral cells in the apical ganglion and the lateral serotonergic projection to the prototroch;
2: Many serotonergic cells in the apical ganglion and a caudal serotonergic projection to the ciliary band

Transformational character.

(SLI) See Haszprunar (2000); Richter et al. (2010)

Absent (or faint) in *Phascolion* only, so this character only details the location in taxa in which SLR is readily evident.

Phylogenetic tree showing relationships among Aplousobranchia and related taxa. The tree is rooted on the left and branches to the right. Taxa names are listed on the right, with a small colored box next to each name indicating character state changes (2) and applicable regions (1 + 0). The legend indicates:

- Character adds 2 to tree score
- applicable region (1 + 0)
- additional region (0)
- state changes (2)

Taxa listed (from top to bottom):

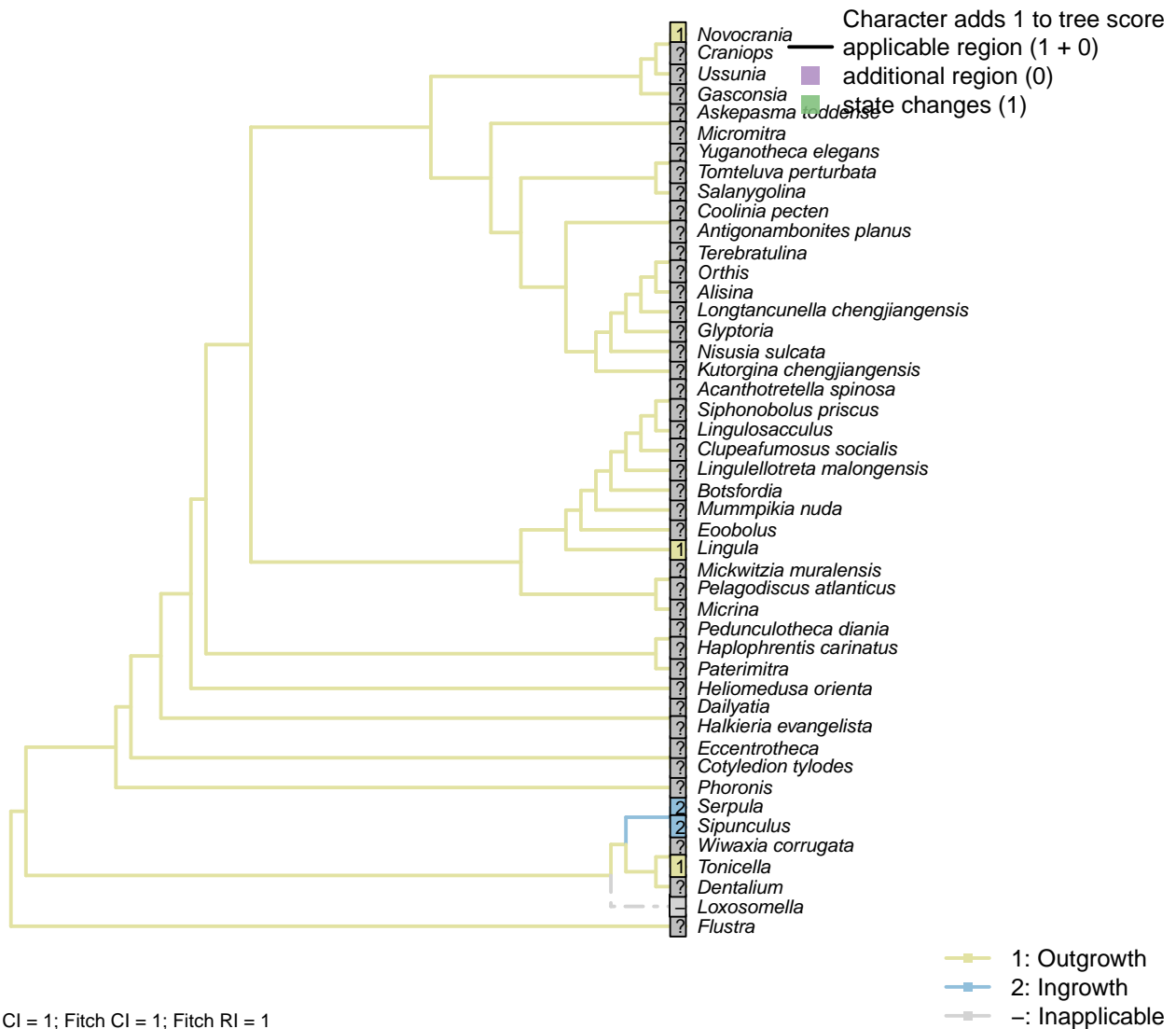
- Novocrania
- Craniops
- Ussunia
- Gasconsia
- Askepasma
- Micromitra
- Yuganotheca elegans
- Tomteluva perturbata
- Salanygolina
- Coolinia pecten
- Antigonambonites planus
- Terebratulina
- Orthis
- Alisina
- Longtancunella chengjiangensis
- Glyptoria
- Nisusia sulcata
- Kutorgina chengjiangensis
- Acanthotretella spinosa
- Siphonobolus priscus
- Lingulosacculus
- Clupeafumusus socialis
- Lingulellotreta malongensis
- Botsfordia
- Mummpikia nuda
- Eoobolus
- Lingula
- Mickwitzia muralensis
- Pelagodiscus atlanticus
- Micrina
- Pedunculotheca diania
- Haplophrentis carinatus
- Paterimitra
- Heliomedusa orienta
- Dailyatia
- Halkieria evangelista
- Eccentrotheca
- Cotyledion tylodes
- Phoronis
- Serpula
- Sipunculus
- Wiwaxia corrugata
- Tonicella
- Dentalium
- Loxosomella
- Flustra

 1: Mesenchyme
 2: Coelom

- 1: Mesenchyme
- 2: Coelom
- Transformational character.

Character 1.43 in@SPS1996.

[162] Formation of coelomoducts

**Character 162: Larva: Formation of coelomoducts**

1: Outgrowth

2: Ingrowth

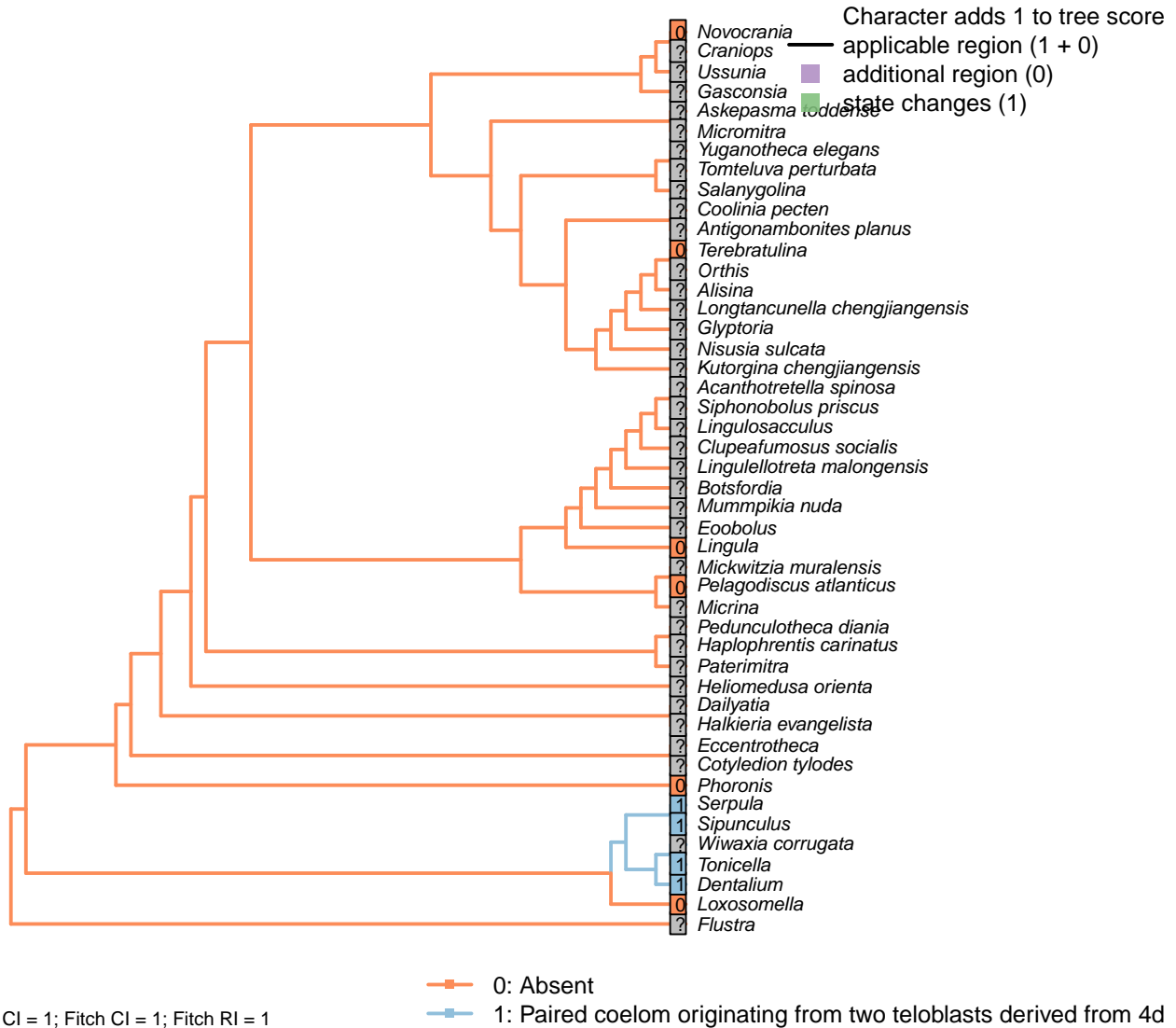
Transformational character.

Character 26 in Haszprunar (2000).

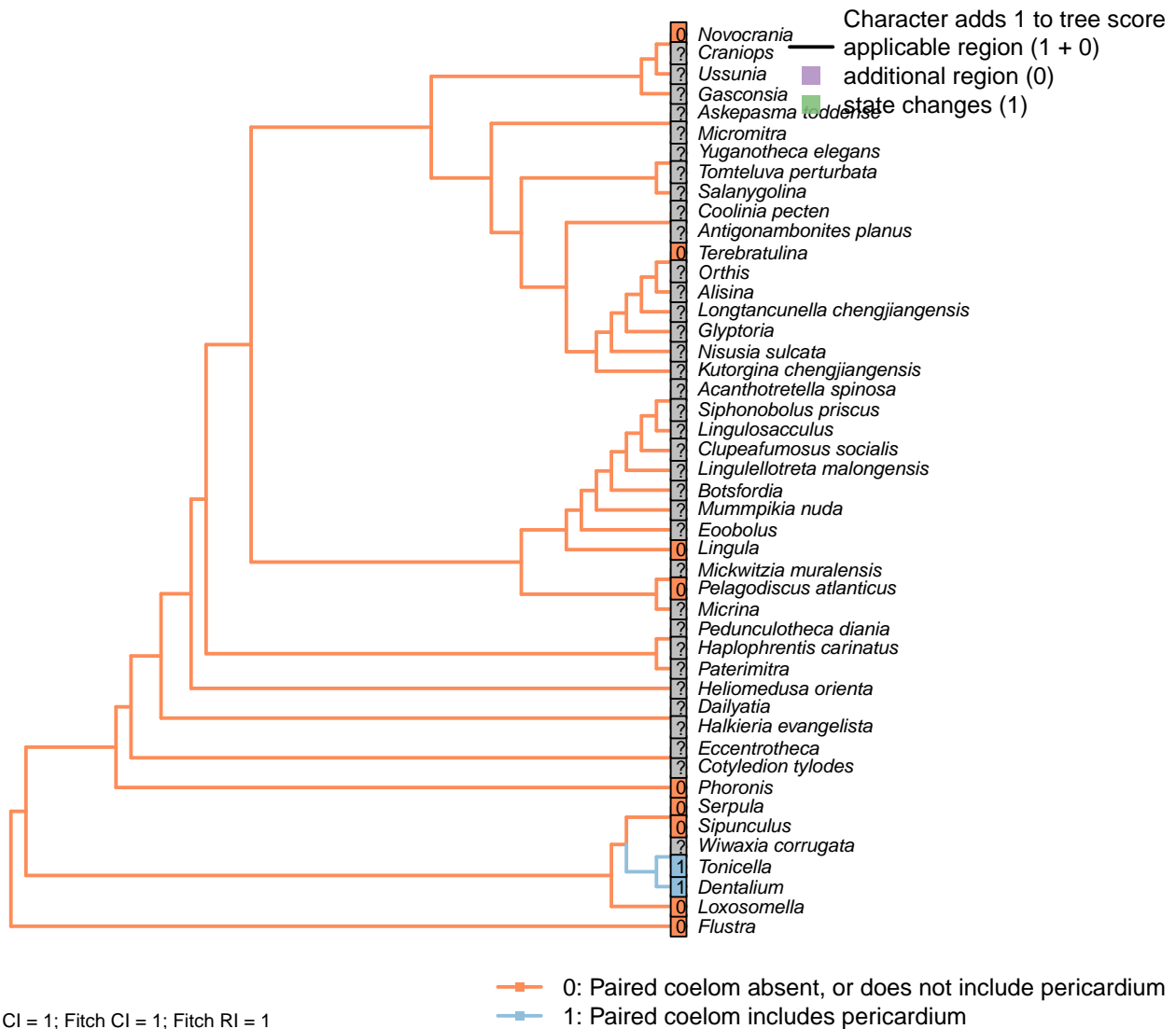
Loxosomella: Coelomoducts absent (Haszprunar, 2000).

3.31 Larva: Coelom

[163] Paired



[164] Paried: Includes pericardium

**Character 164: Larva: Coelom: Paried: Includes pericardium**

0: Paired coelom absent, or does not include pericardium

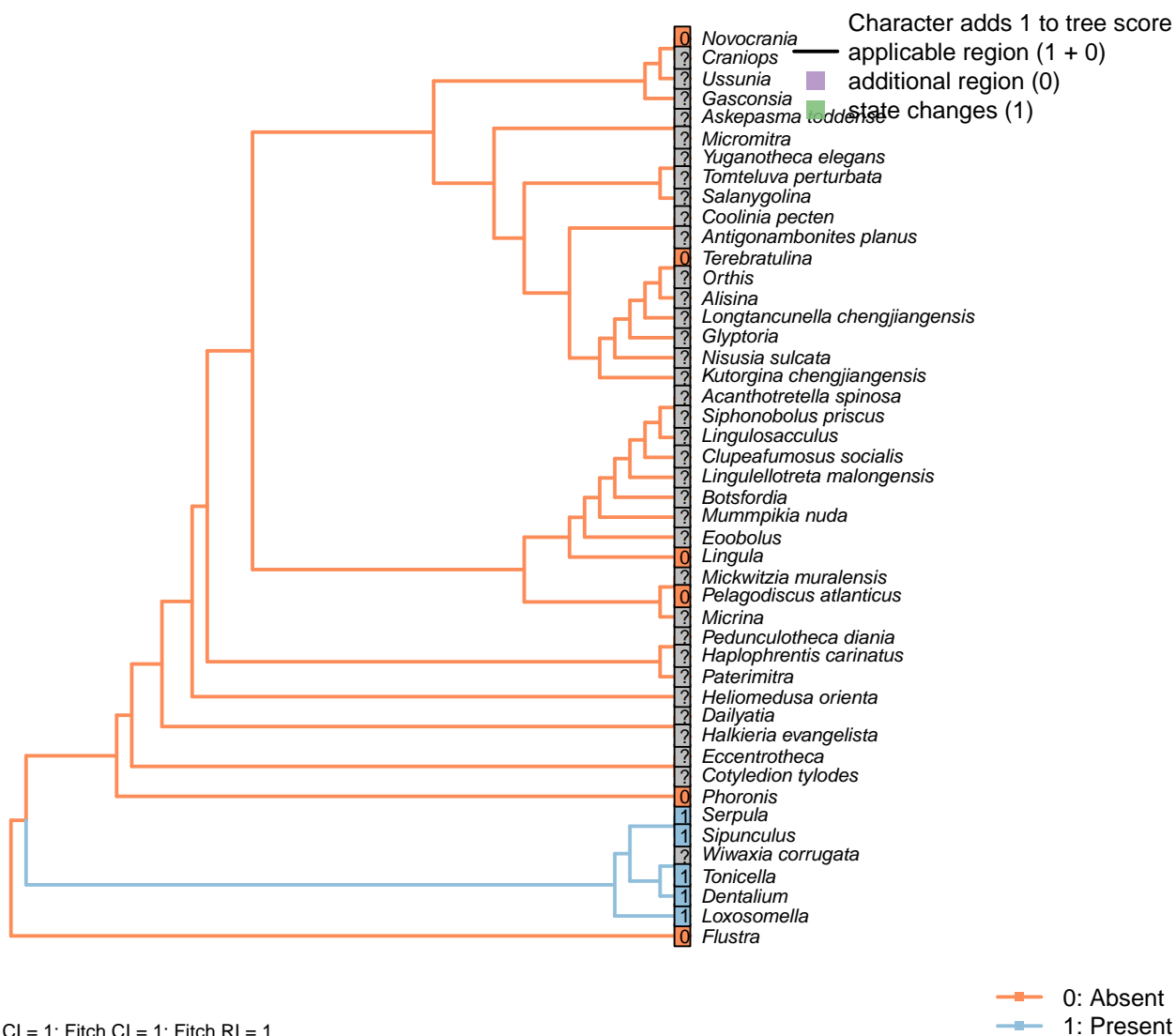
1: Paired coelom includes pericardium

Neomorphic character.

Character 1.03 in Scheltema (1993).

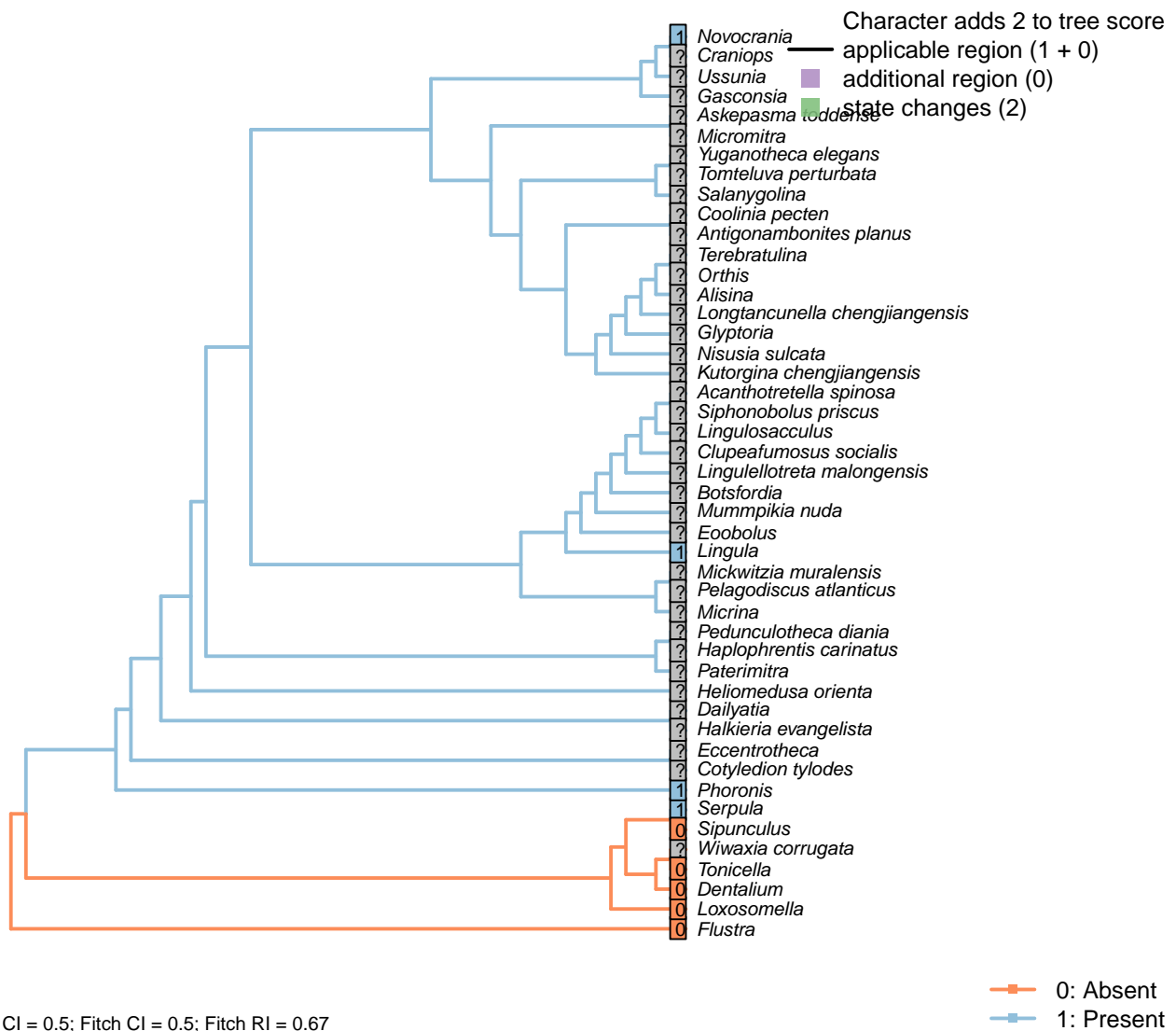
3.32 Larva

[165] Foot

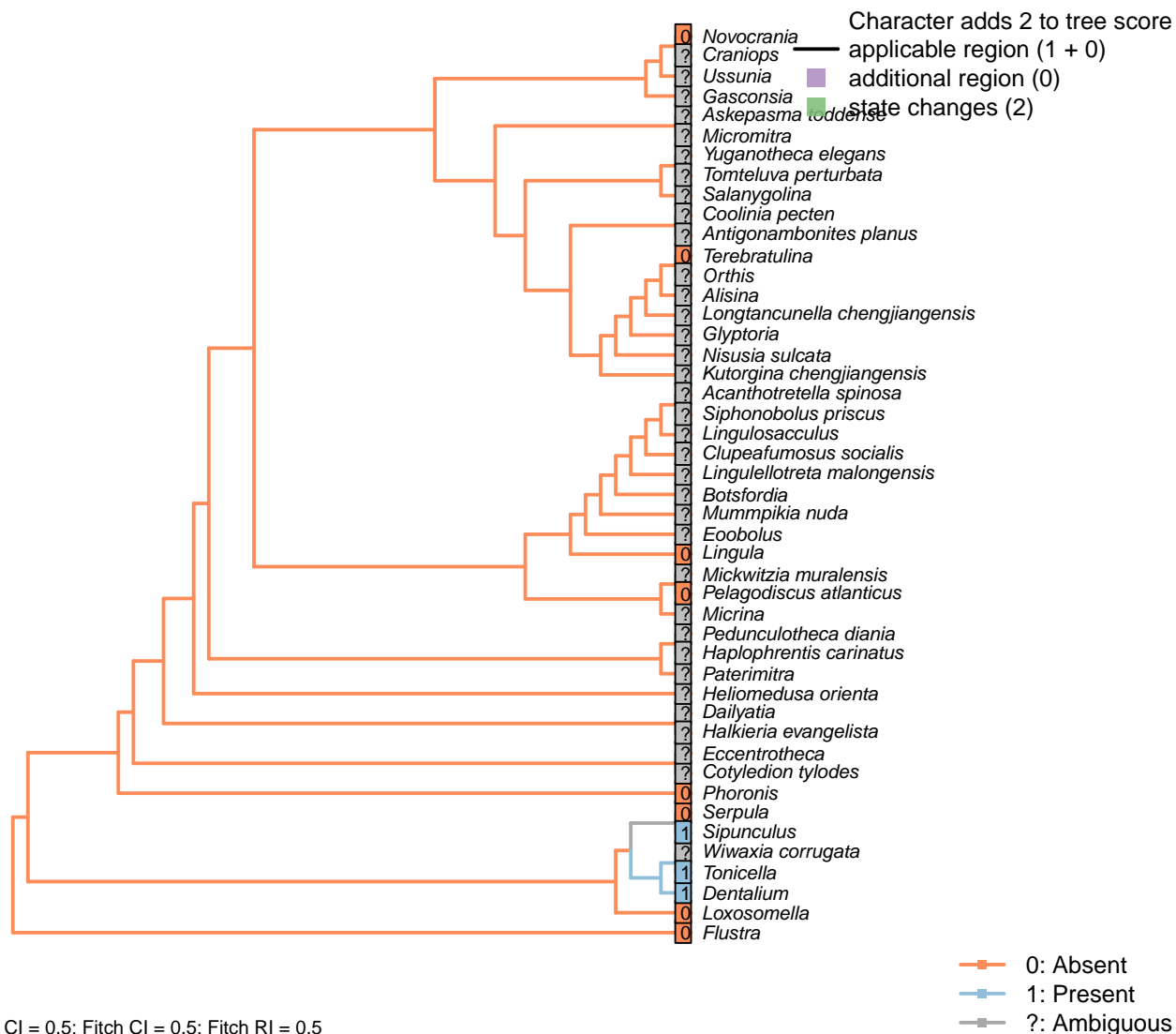


3.33 Ciliary ultrastructure

[166] Accessory centriole



[167] Aggregation of granules below basal plate

**Character 167: Ciliary ultrastructure: Aggregation of granules below basal plate**

0: Absent

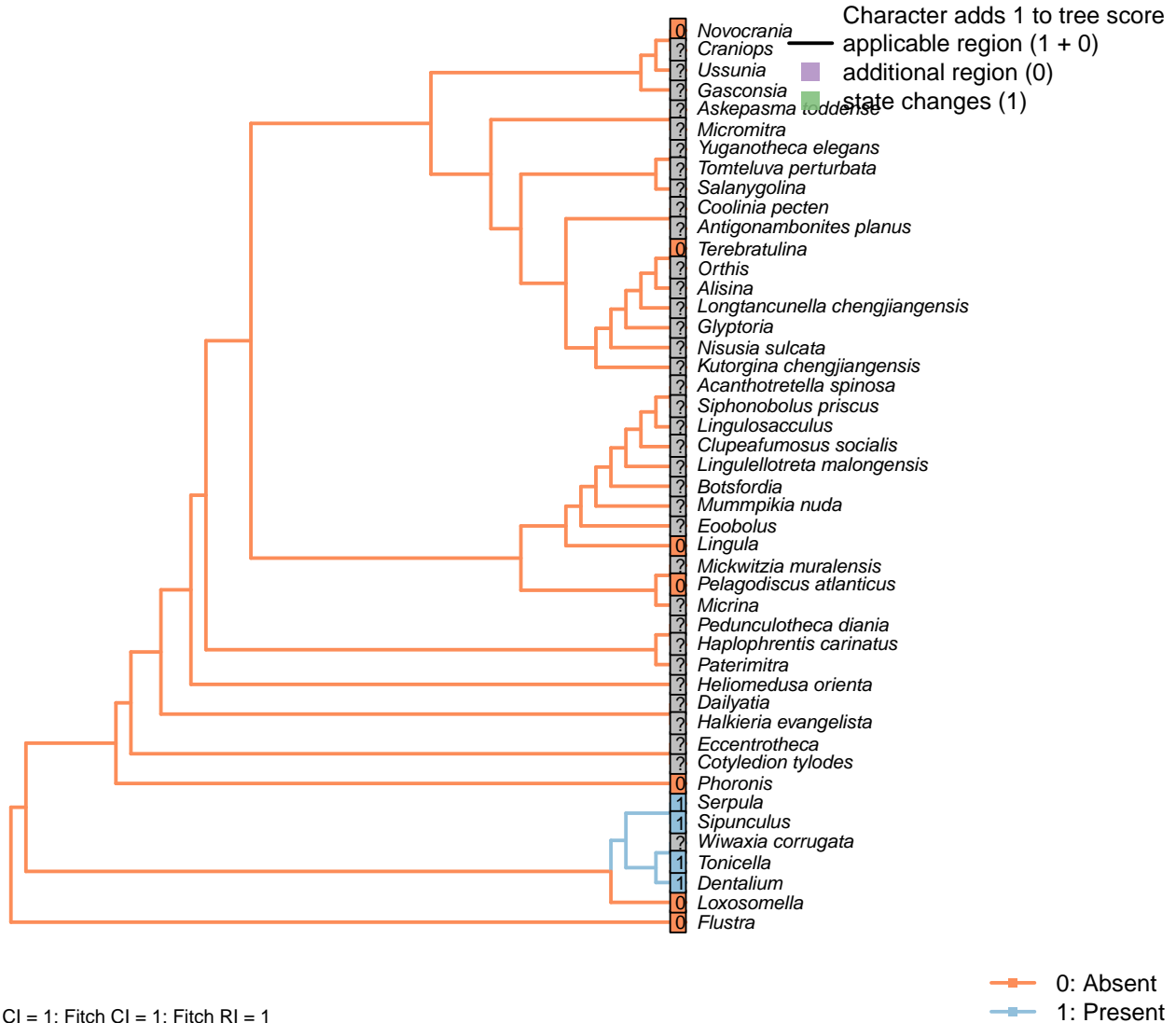
1: Present

Neomorphic character.

After Lundin et al. (2009).

Serpula: Following *Harmothoe* (Holborow et al., 1969).

[168] Radiating tubular fibres

**Character 168: Ciliary ultrastructure: Basal foot: Radiating tubular fibres**

0: Absent

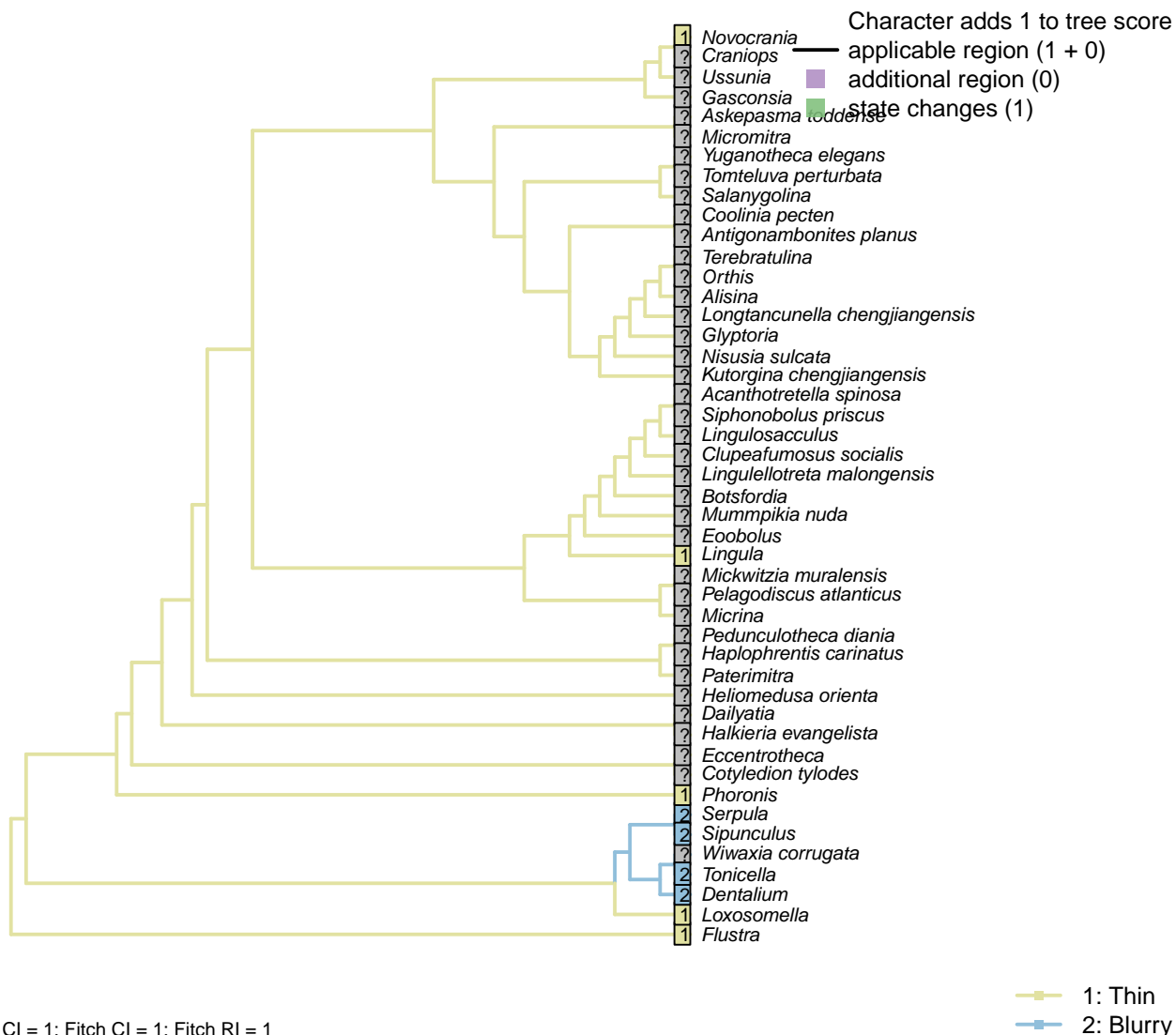
1: Present

Neomorphic character.

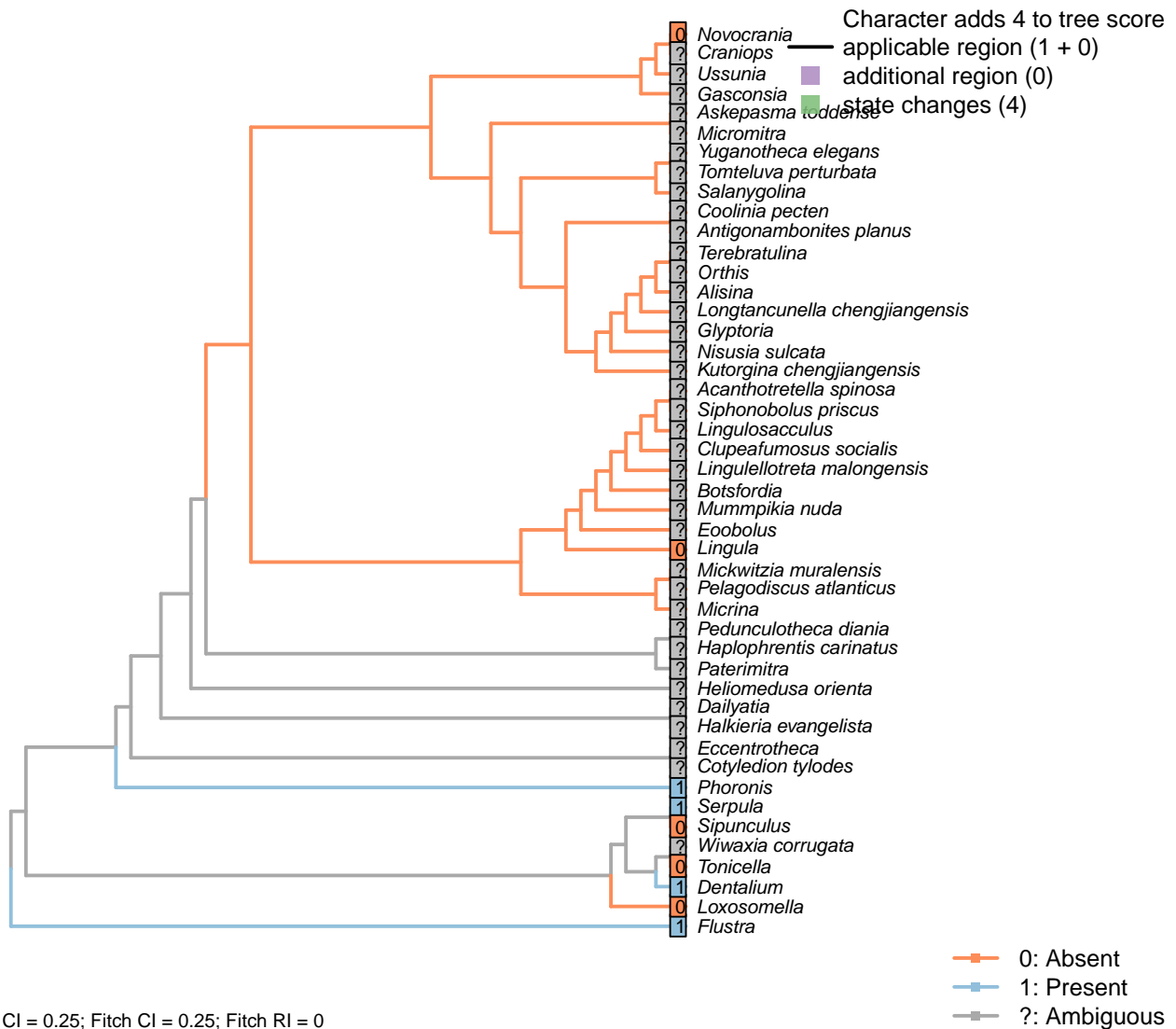
After Lundin et al. (2009). Fibres radiate from the distal end of the basal foot of the cilia in certain taxa.

Serpula: Basal foot in *Magelona* is connected to cytoplasmic microtubules (Bartolomaeus, 1995).

3.34 Ciliary ultrastructure: Basal plate [169]



[170] Brushborder of microvilli

**Character 170: Ciliary ultrastructure: Brushborder of microvilli**

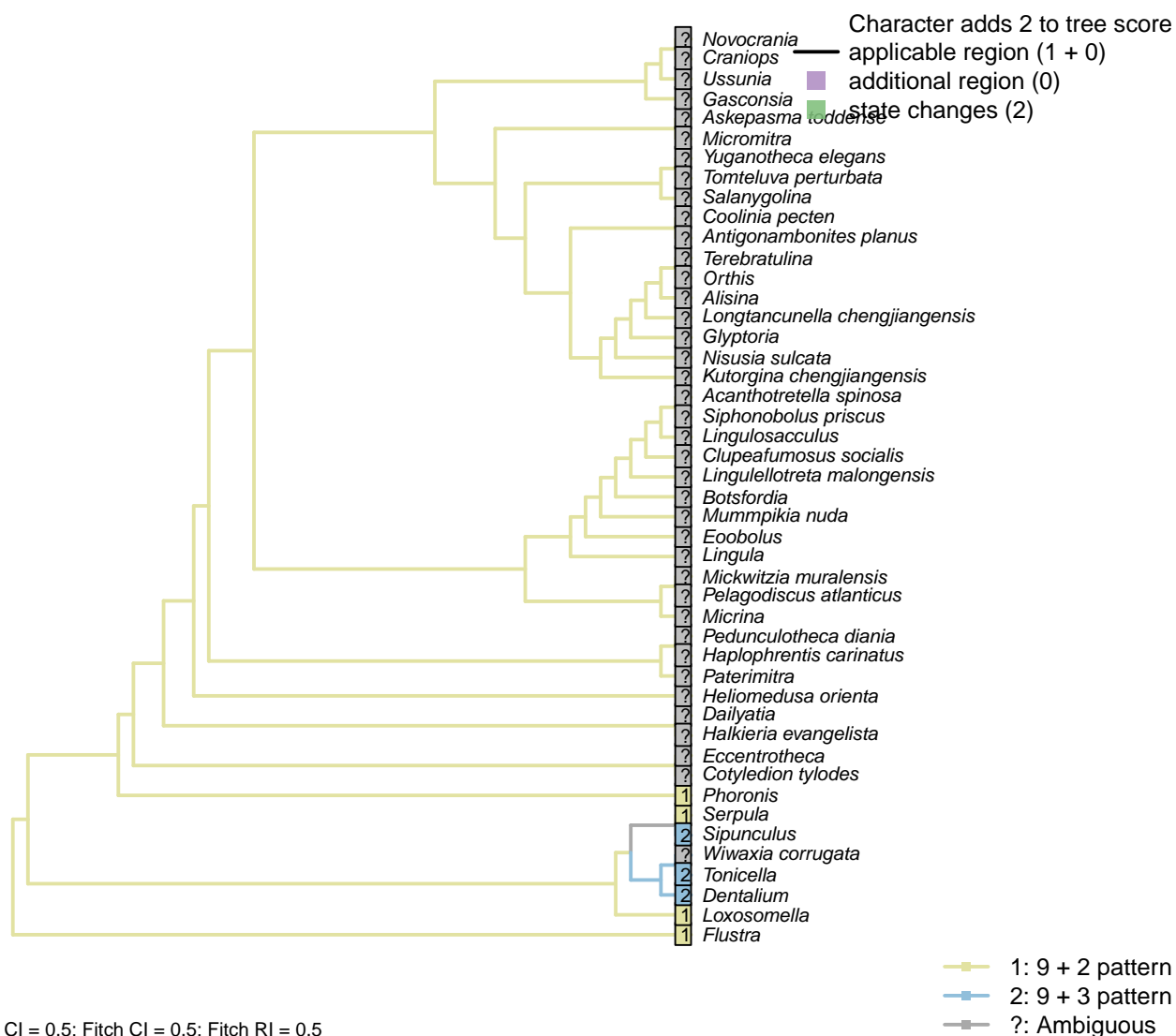
0: Absent

1: Present

Neomorphic character.

After Lundin et al. (2009); coded following Smith (2012a).

[171] Centriolar triplet derivative in basal body

**Character 171: Ciliary ultrastructure: Centriolar triplet derivative in basal body**

1: 9 + 2 pattern

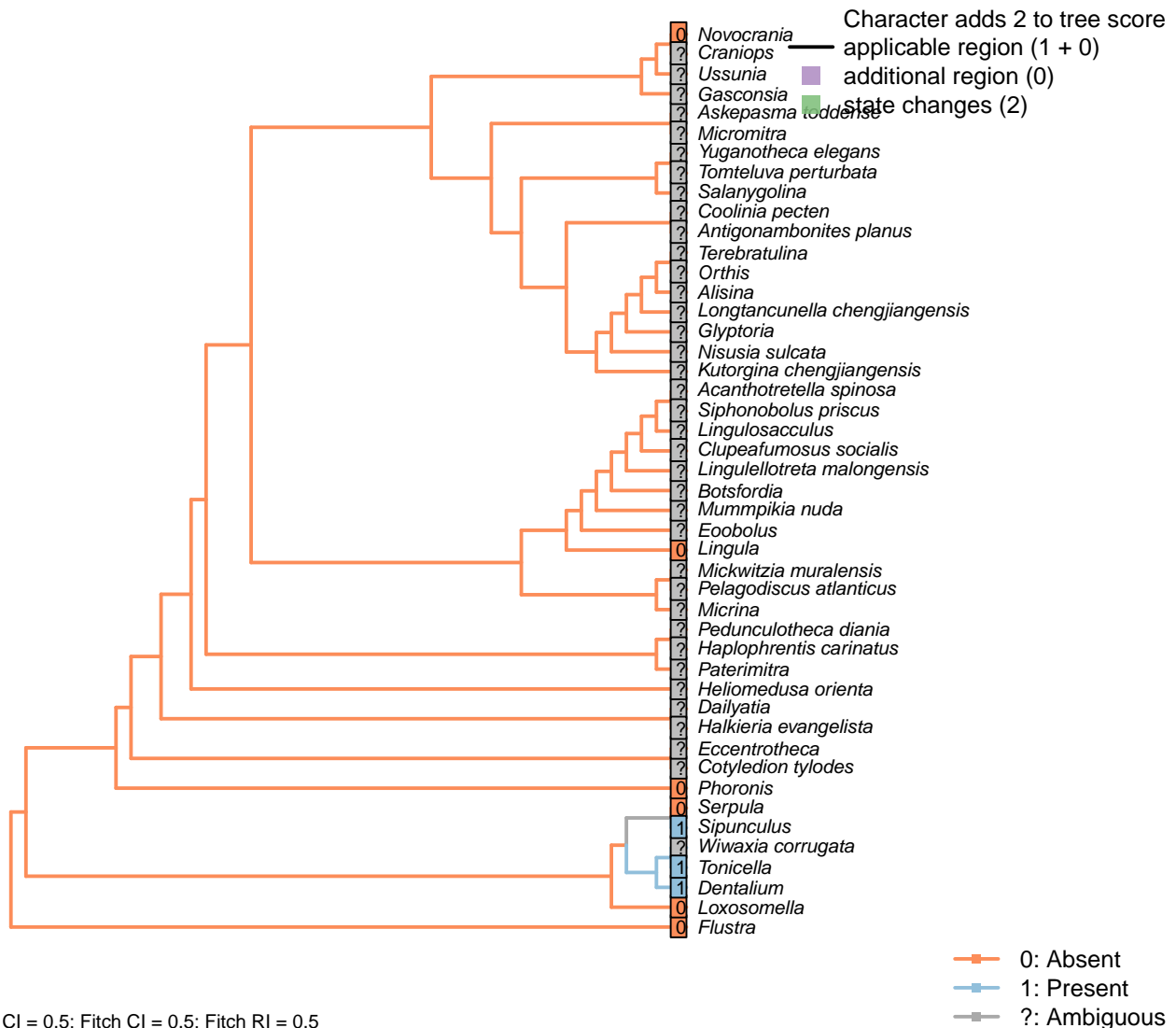
2: 9 + 3 pattern

Transformational character.

After Lundin et al. (2009).

Serpula: Following *Enchytraeus* (Reger, 1967), *Magelona* (Bartolomaeus, 1995) and *Harmothoe* (Holborow et al., 1969).

[172] Ciliary necklace with connecting strands

**Character 172: Ciliary ultrastructure: Ciliary necklace with connecting strands**

0: Absent

1: Present

Neomorphic character.

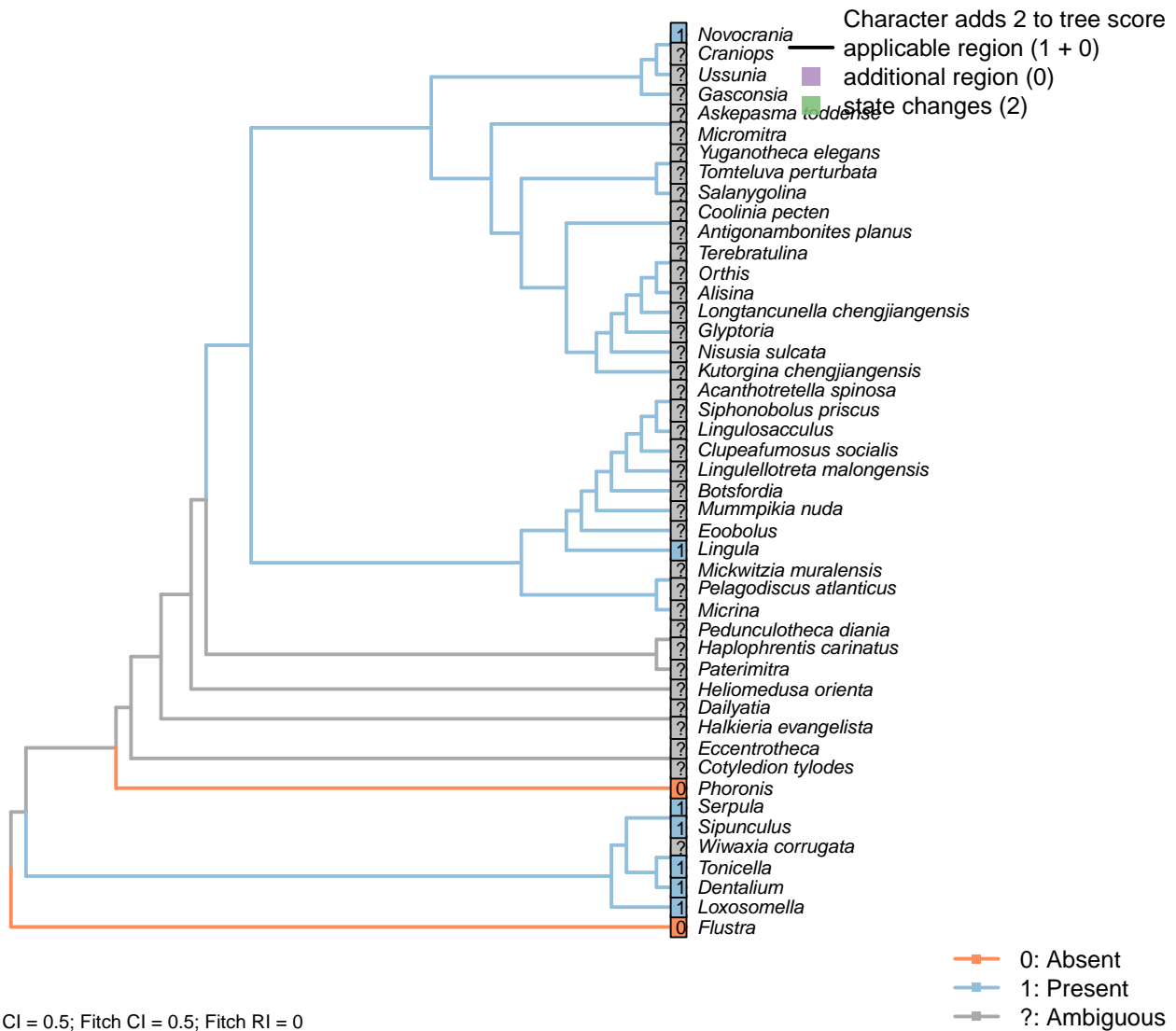
After Lundin et al. (2009).

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.

Serpula: Not evident in *Enchytraeus* (Reger, 1967), *Magelona* (Bartolomaeus, 1995) or *Harmothoe* (Holborow et al., 1969).

3.35 Ciliary ultrastructure: Compound cilia

[173] Presence



Character 173: Ciliary ultrastructure: Compound cilia: Presence

0: Absent

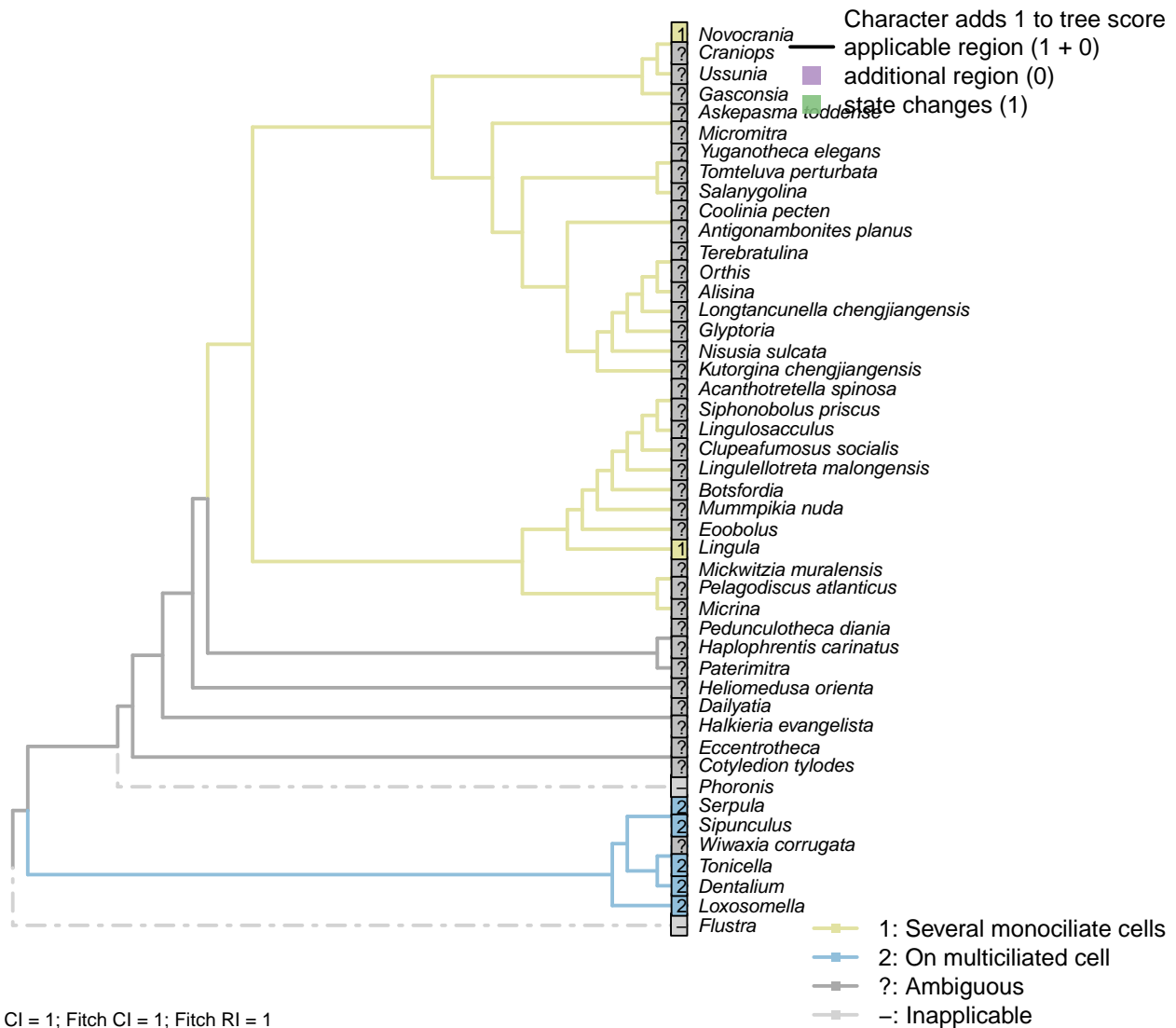
1: Present

Neomorphic character.

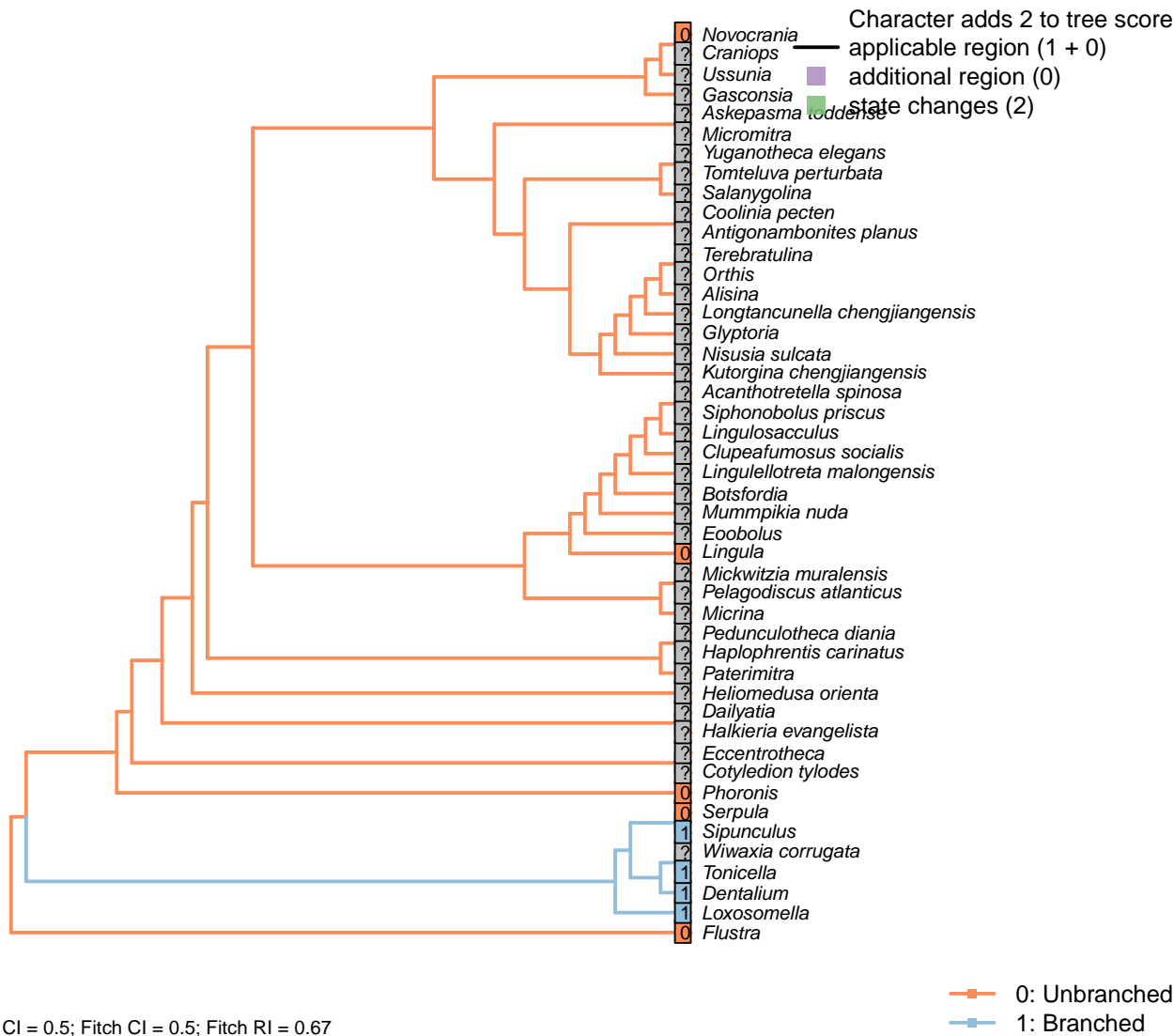
After Lundin et al. (2009). Compound cilia are motile structures composed of 10–100 regular cilia used in locomotion or feeding.

Serpula: Nielsen (1987).

[174] Origin



[176] Branched



Character 176: Ciliary ultrastructure: Microvilli on epidermal surface: Branched

0: Unbranched

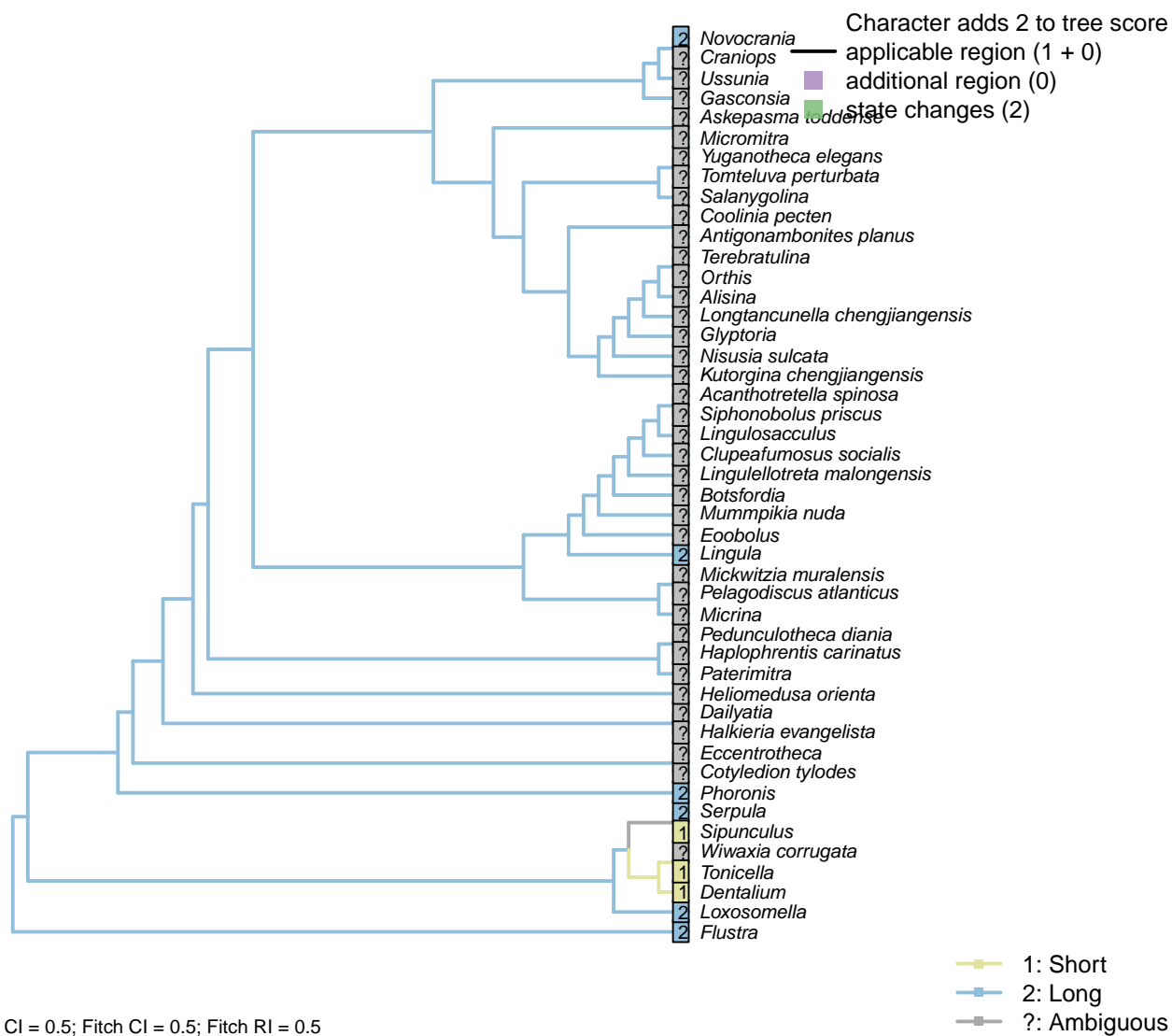
1: Branched

Neomorphic character.

After Lundin et al. (2009).

3.37 Ciliary ultrastructure: Vertical ciliary rootlet

[177] Length



Character 177: Ciliary ultrastructure: Vertical ciliary rootlet: Length

1: Short

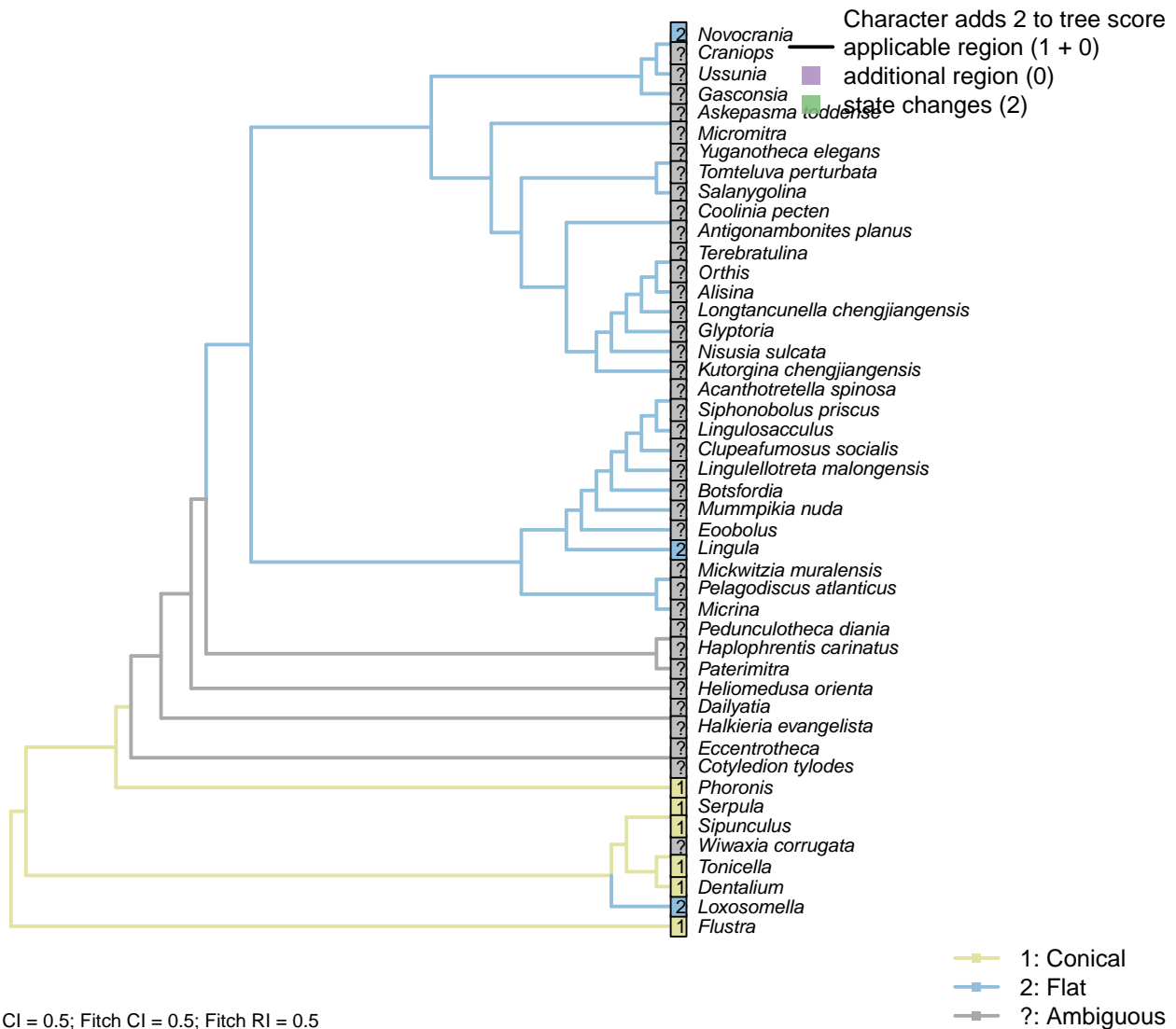
2: Long

Transformational character.

After Lundin et al. (2009). The vertical ciliary rootlet is also termed the posterior rootlet.

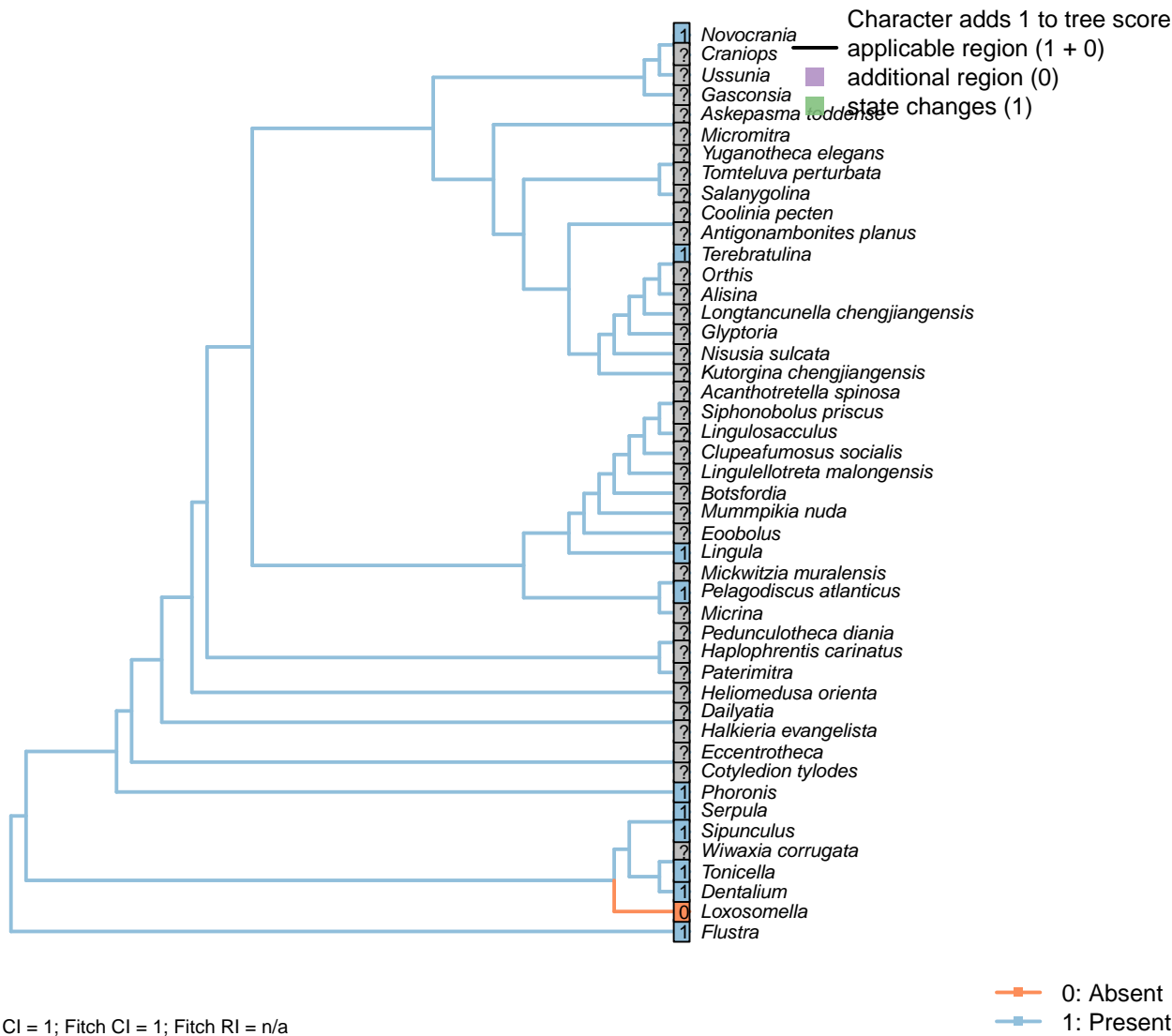
Loxosomella: Details of ciliary ultrastructure are illustrated in Nielsen and Rostgaard (1976).

[178] Shape



3.38 Ciliary ultrastructure: Secondary ciliary rootlet

[179] Presence

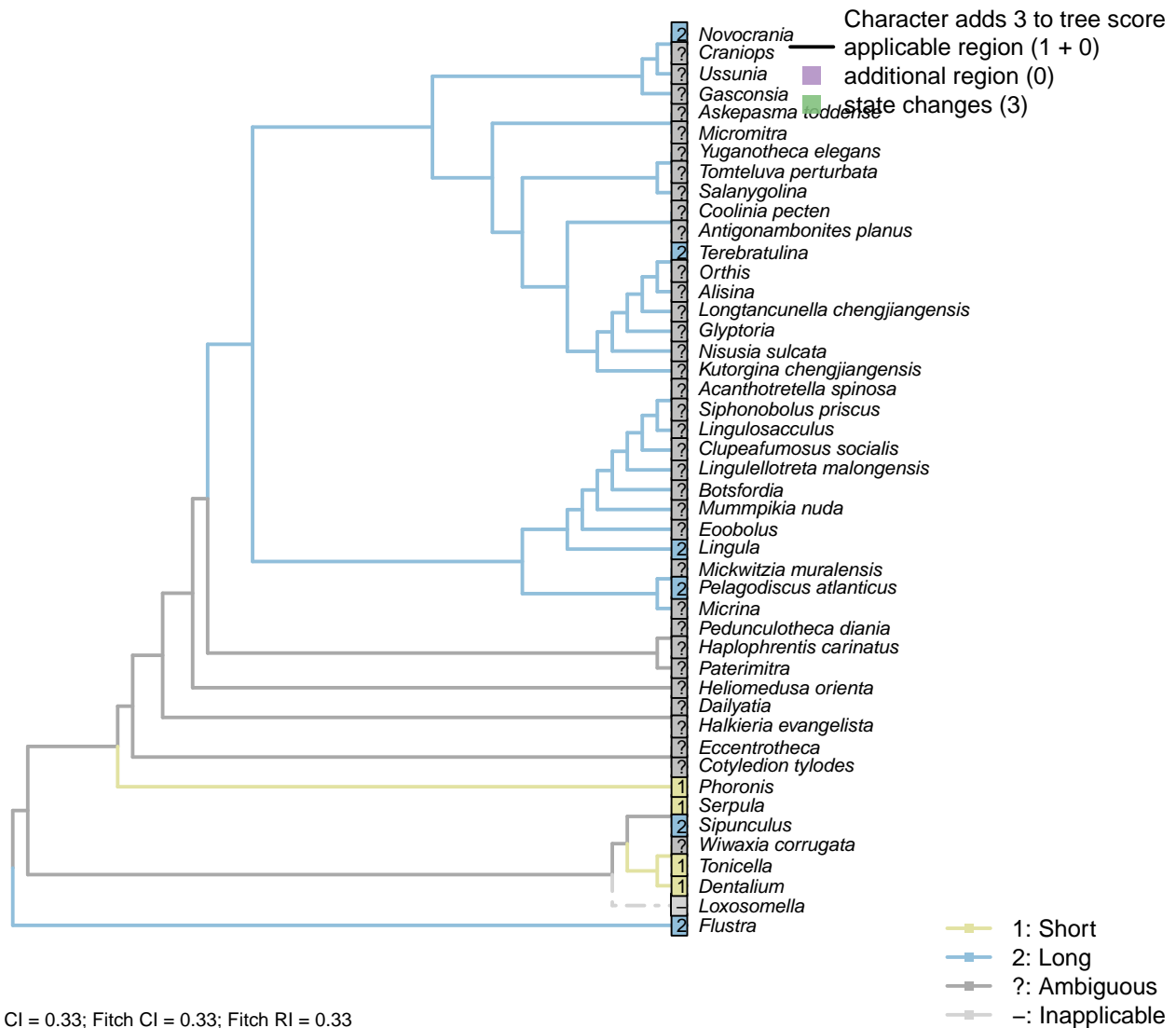


Character 179: Ciliary ultrastructure: Secondary ciliary rootlet: Presence

0: Absent
1: Present
Neomorphic character.

After Lundin et al. (2009). The secondary ciliary rootlet is also termed the anterior ciliary rootlet.

[180] Length

**Character 180: Ciliary ultrastructure: Secondary ciliary rootlet: Length**

1: Short

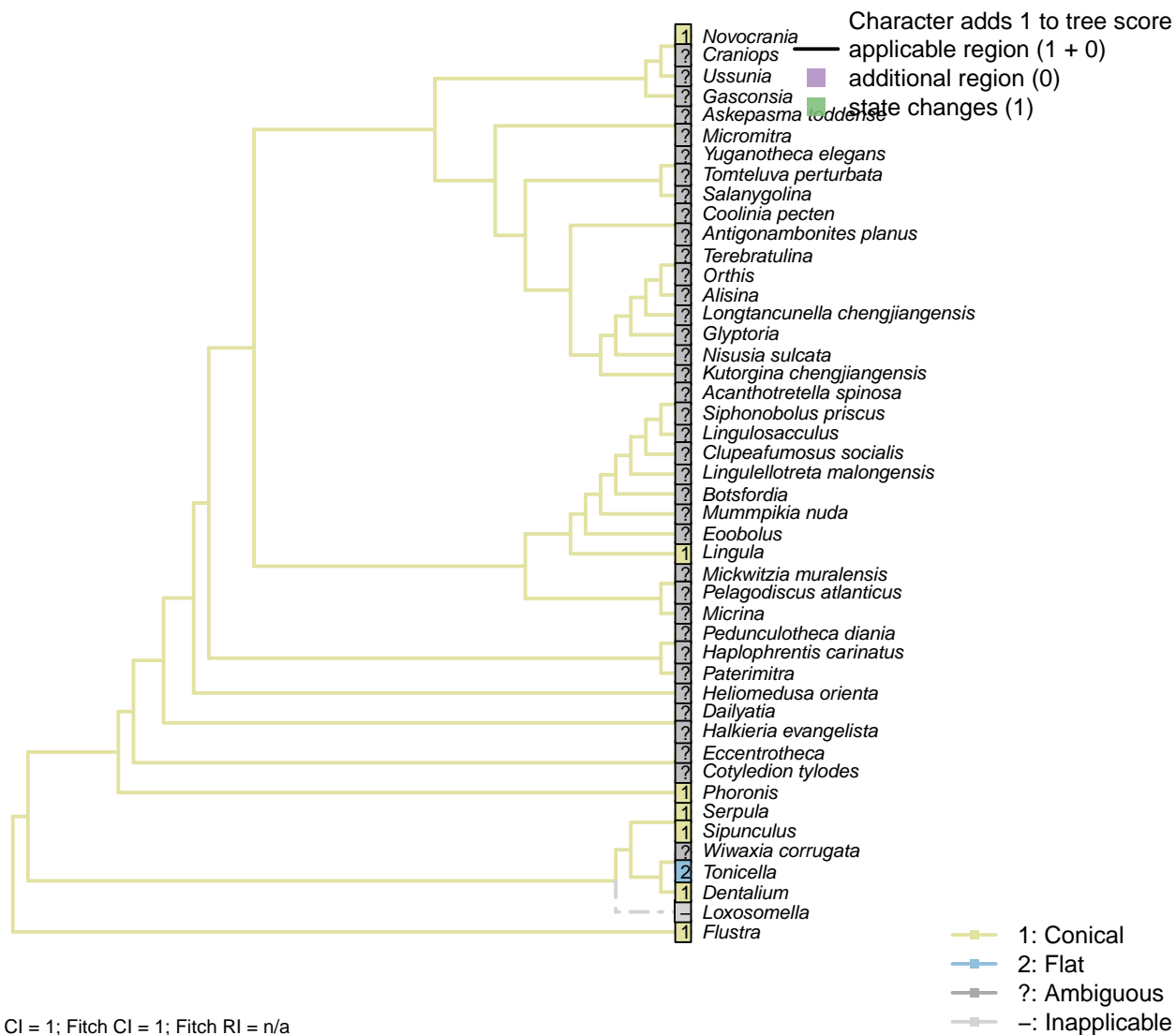
2: Long

Transformational character.

After Lundin et al. (2009). The secondary ciliary rootlet is also termed the anterior ciliary rootlet.

Serpula: Short in *Enchytraeus* (Reger, 1967), *Magelona* (Bartolomaeus, 1995) and *Harmothoe* (Holborow et al., 1969).

[181] Shape

**Character 181: Ciliary ultrastructure: Secondary ciliary rootlet: Shape**

1: Conical

2: Flat

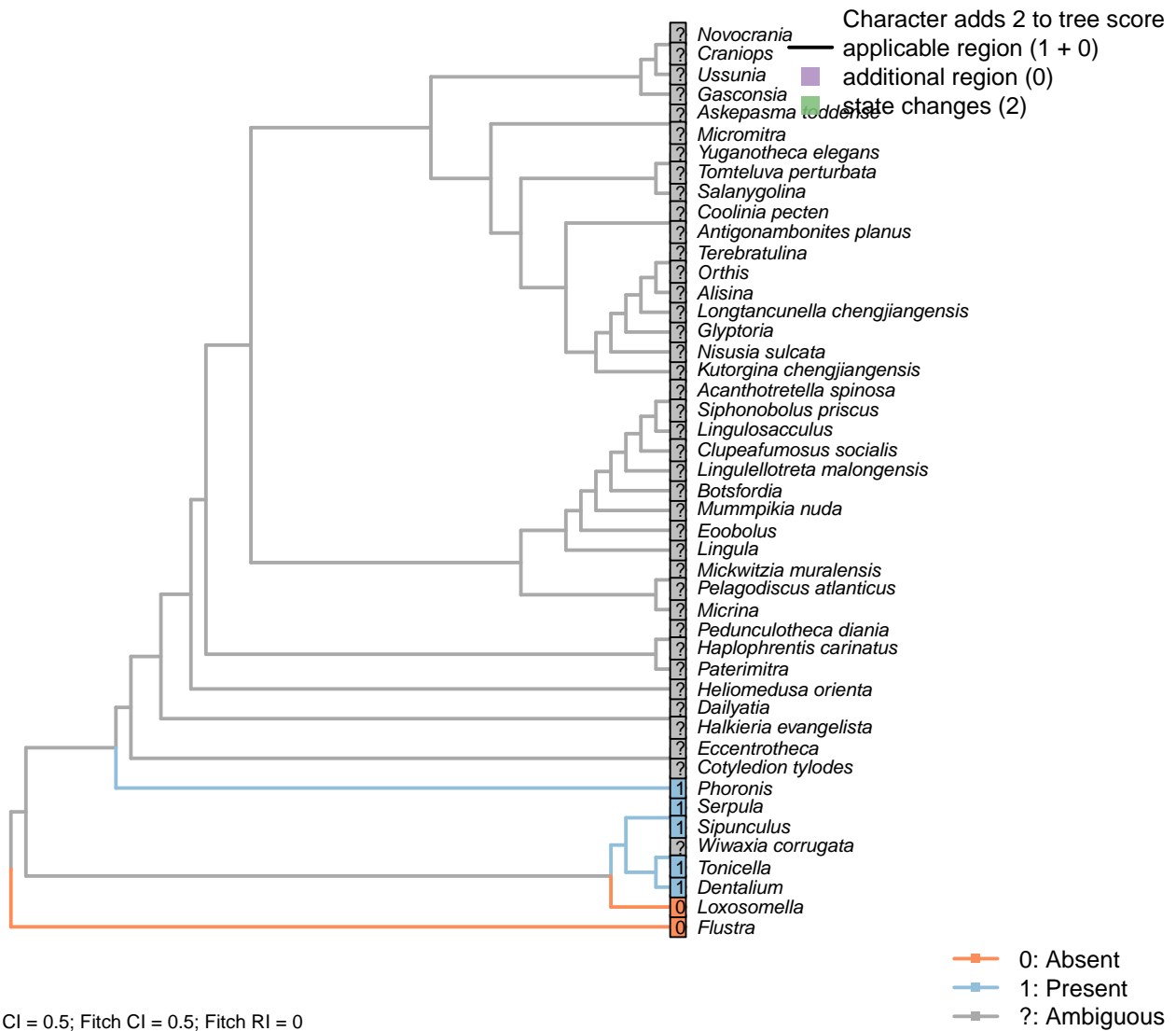
Transformational character.

After Lundin et al. (2009). The secondary ciliary rootlet is also termed the anterior ciliary rootlet.

Serpula: Conical in *Magelona* (Bartolomaeus, 1995).

3.39 Nephridia

[182] Podocytes



Character 182: Nephridia: Podocytes

0: Absent

1: Present

Neomorphic character.

See characters 21 and 28 in Haszprunar (2000); 1.12 in Scheltema (1993).

Serpula: Present in serpulids (Bartolomaeus and Quast, 2005).

[183] Rhogocytes



Character 183: Nephridia: Rhogocytes

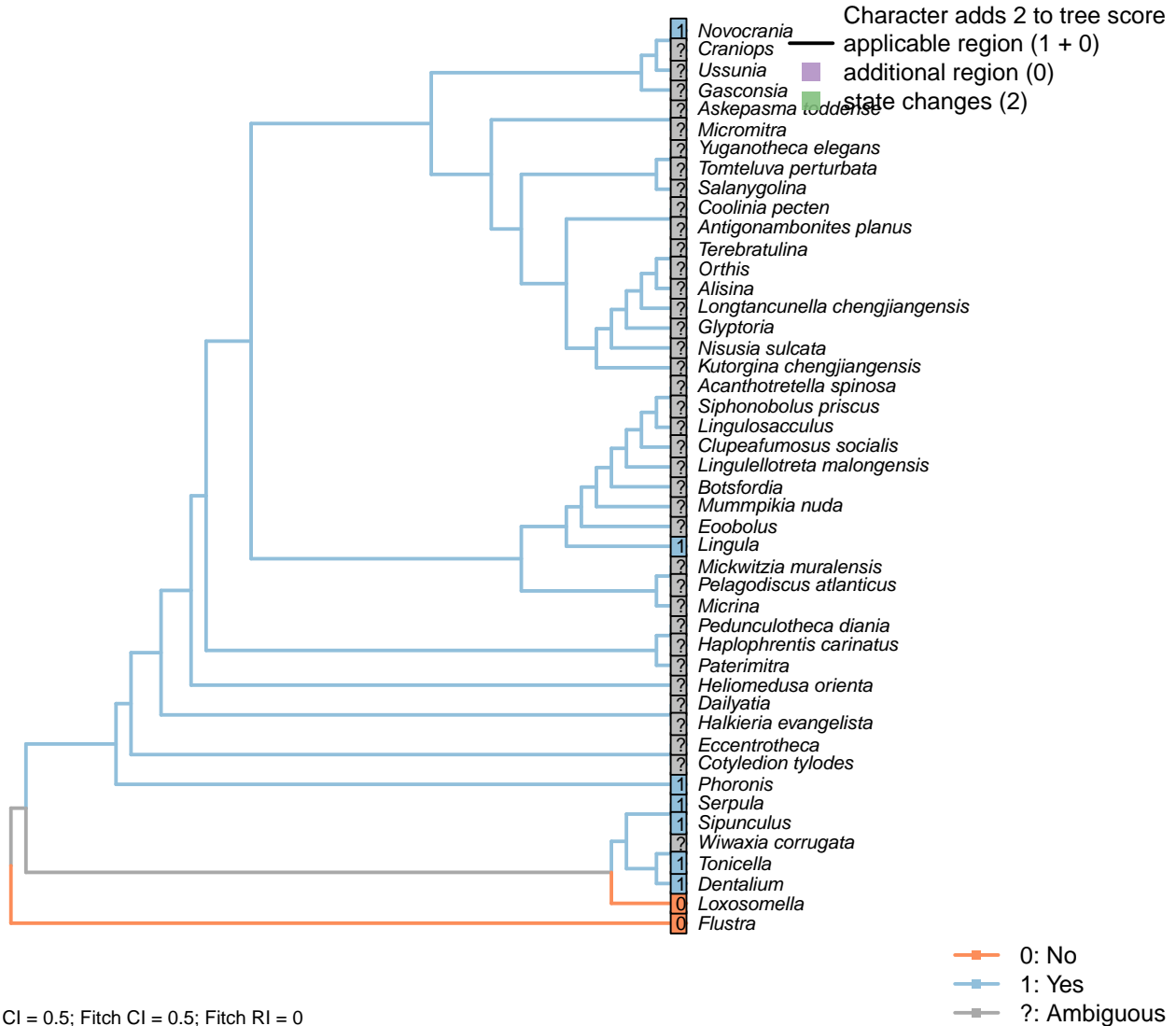
0: Absent

1: Present

Neomorphic character.

Pore cells. Character 20 in Haszprunar (2000).

[184] Serve as excretory organs

**Character 184: Nephridia: Serve as excretory organs**

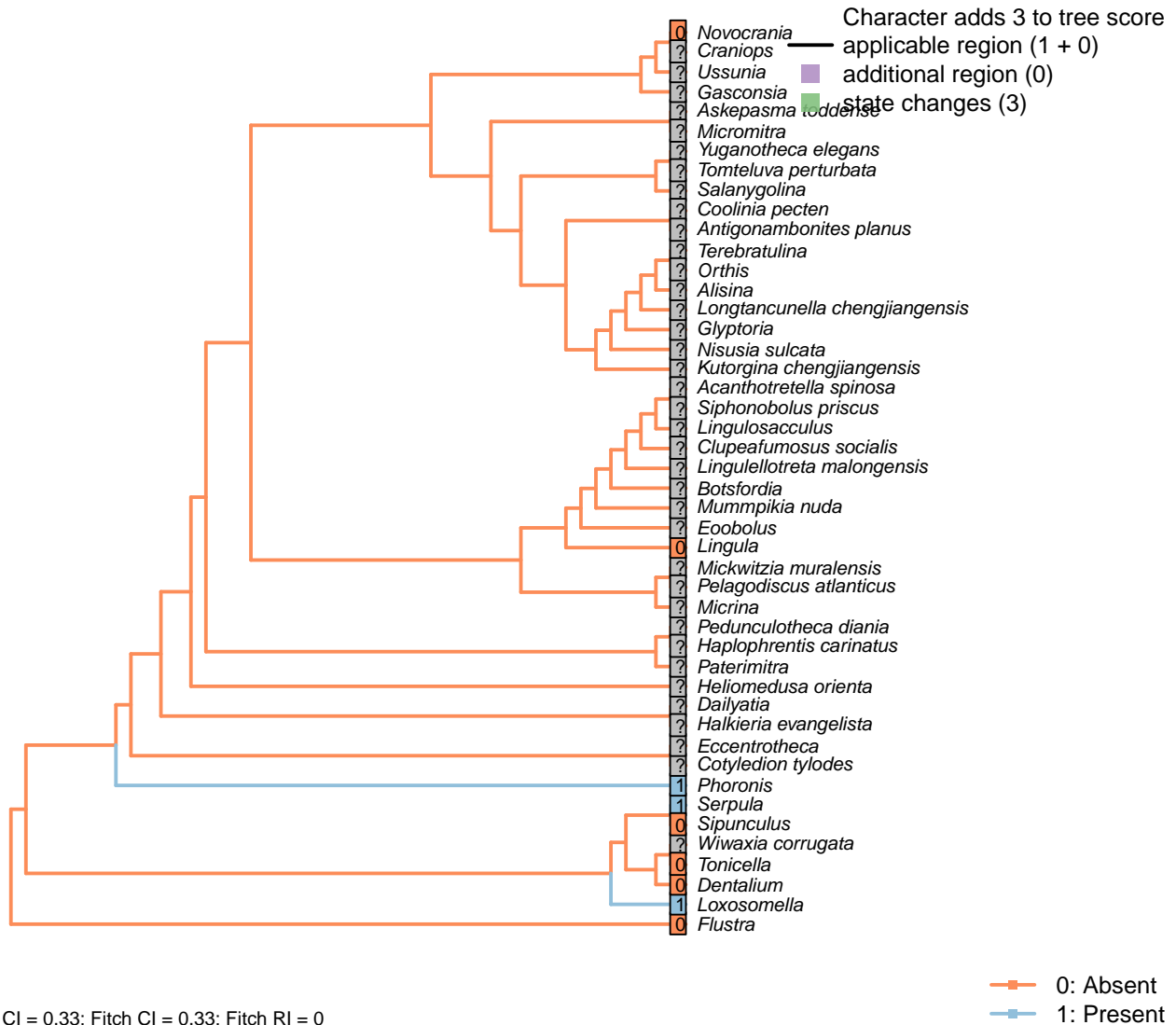
0: No

1: Yes

Neomorphic character.

See character 4.46 in von Salvini-Plawen and Steiner (1996).

[185] Protonephridia

**Character 185: Nephridia: Protonephridia**

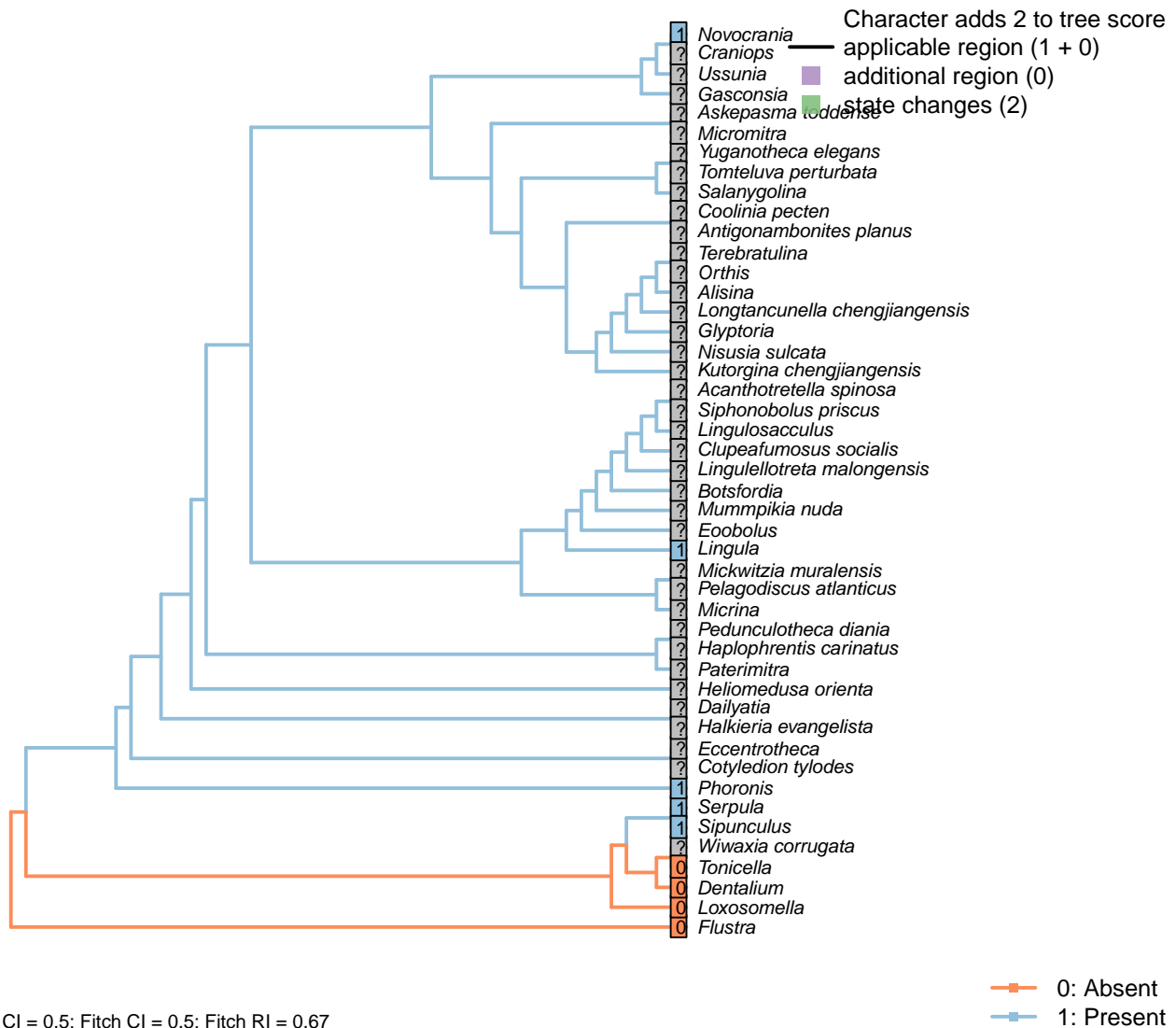
0: Absent

1: Present

Neomorphic character.

Also termed cyrtocytes. Character 21 in Grobe (2007); 1.47 in von Salvini-Plawen and Steiner (1996); 138 in Rouse (1999); 20 in Haszprunar (1996); 90 in Glenner et al. (2004).

[186] Metanephridia

**Character 186: Nephridia: Metanephridia**

0: Absent

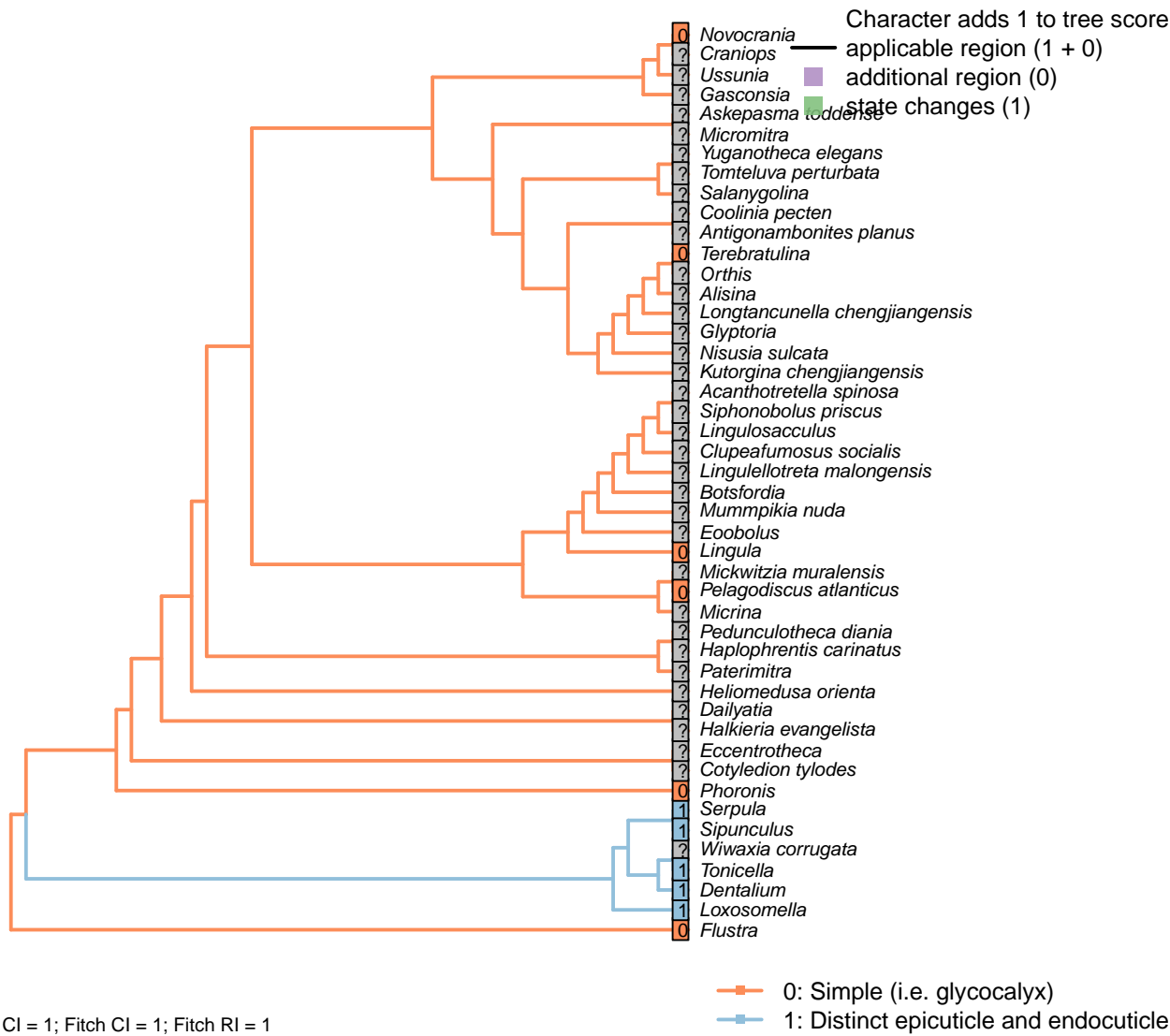
1: Present

Neomorphic character.

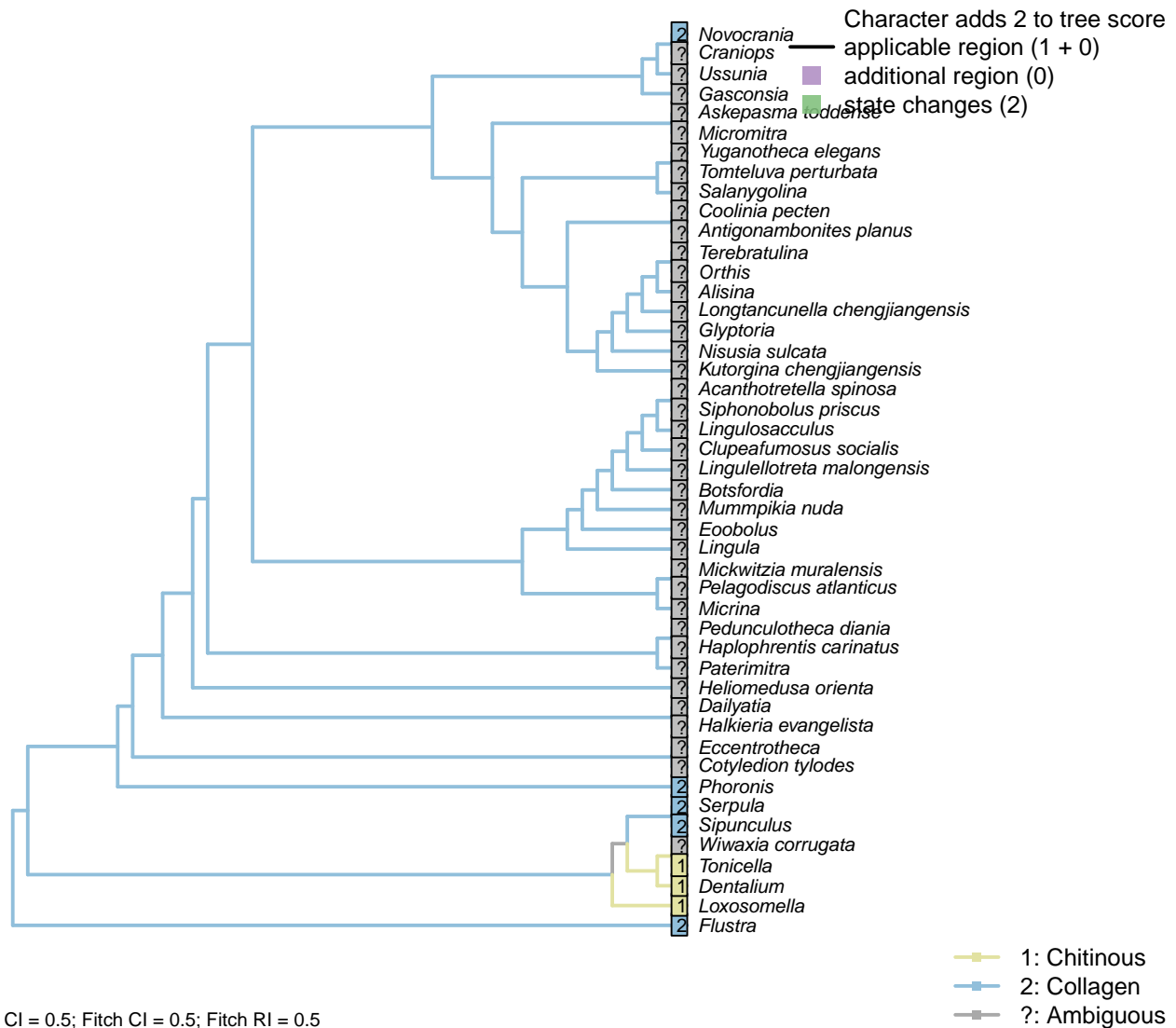
See characters 35 in Rouse (1999); 28 in Haszprunar (2000); 93 in Glenner et al. (2004); 1.47 in von Salvini-Plawen and Steiner (1996); 21 in Grobe (2007); 138 in Rouse (1999); 20 in Haszprunar (1996).

3.40 Cuticle

[187] Layers



[188] Composition



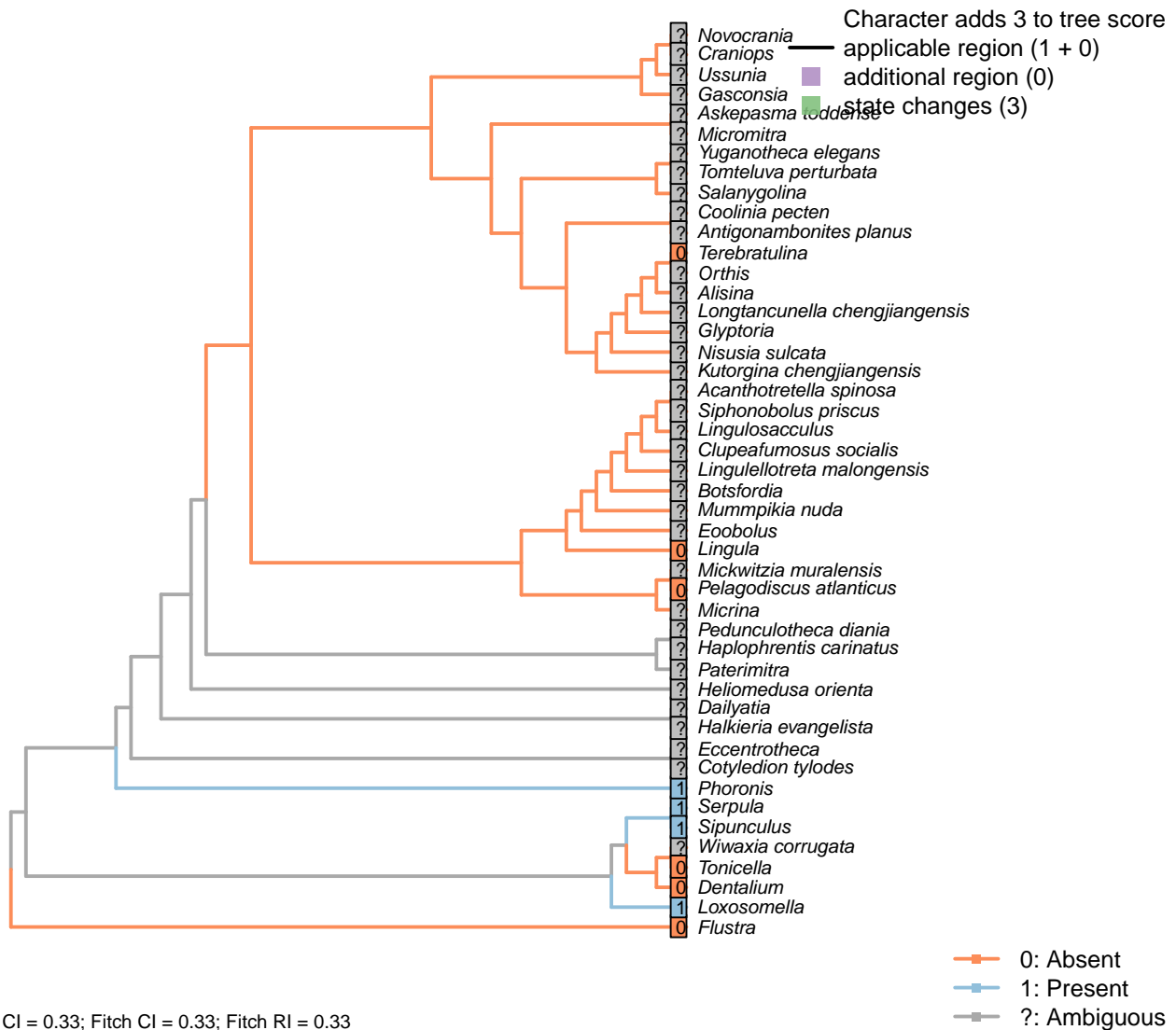
perhaps in regions where rigidity is necessary (Borisanova et al., 2015).

Novocrania: No (chitinous) pedicle, so only collagenous cuticle present (Williams et al., 1997).

Phoronis: Collagen fibres in tentacle cuticle (Bartolomaeus, 2001); chitin only present in tubes (Jeuniaux, 1971).

Sipunculus: Collagenous (Goffinet et al., 1978).

[189] Fibrous layer with thick fibrils



Character 189: Cuticle: Fibrous layer with thick fibrils

0: Absent

1: Present

Neomorphic character.

After Borisanova et al. (2015).

Dentalium, *Flustra*, *Loxosomella*, *Serpula*, *Tonicella*: Following table 2 in Borisanova et al. (2015).

Lingula: Pedicle cuticle entirely homogeneous (Williams et al., 1997).

Pelagodiscus atlanticus: Microvilli in otherwise homogeneous epidermis (Williams et al., 1997).

Phoronis: Outer layer seemingly fibrous (Bereiter-Hahn et al., 1984).

Sipunculus: Fibrous collagen only (Bereiter-Hahn et al., 1984).

Terebratulina: Not evident in *Notosaria* (Bereiter-Hahn et al., 1984; Williams et al., 1997).

[190] Homogeneous layer



CI = 0.33; Fitch CI = 0.33; Fitch RI = 0.5

Character 190: Cuticle: Homogeneous layer

0: Absent

1: Present

Neomorphic character.

After Borisanova et al. (2015).

Dentalium, *Flustra*, *Loxosomella*, *Serpula*, *Tonicella*: Following table 2 in Borisanova et al. (2015).

Lingula: Pedicle cuticle entirely homogeneous (Williams et al., 1997).

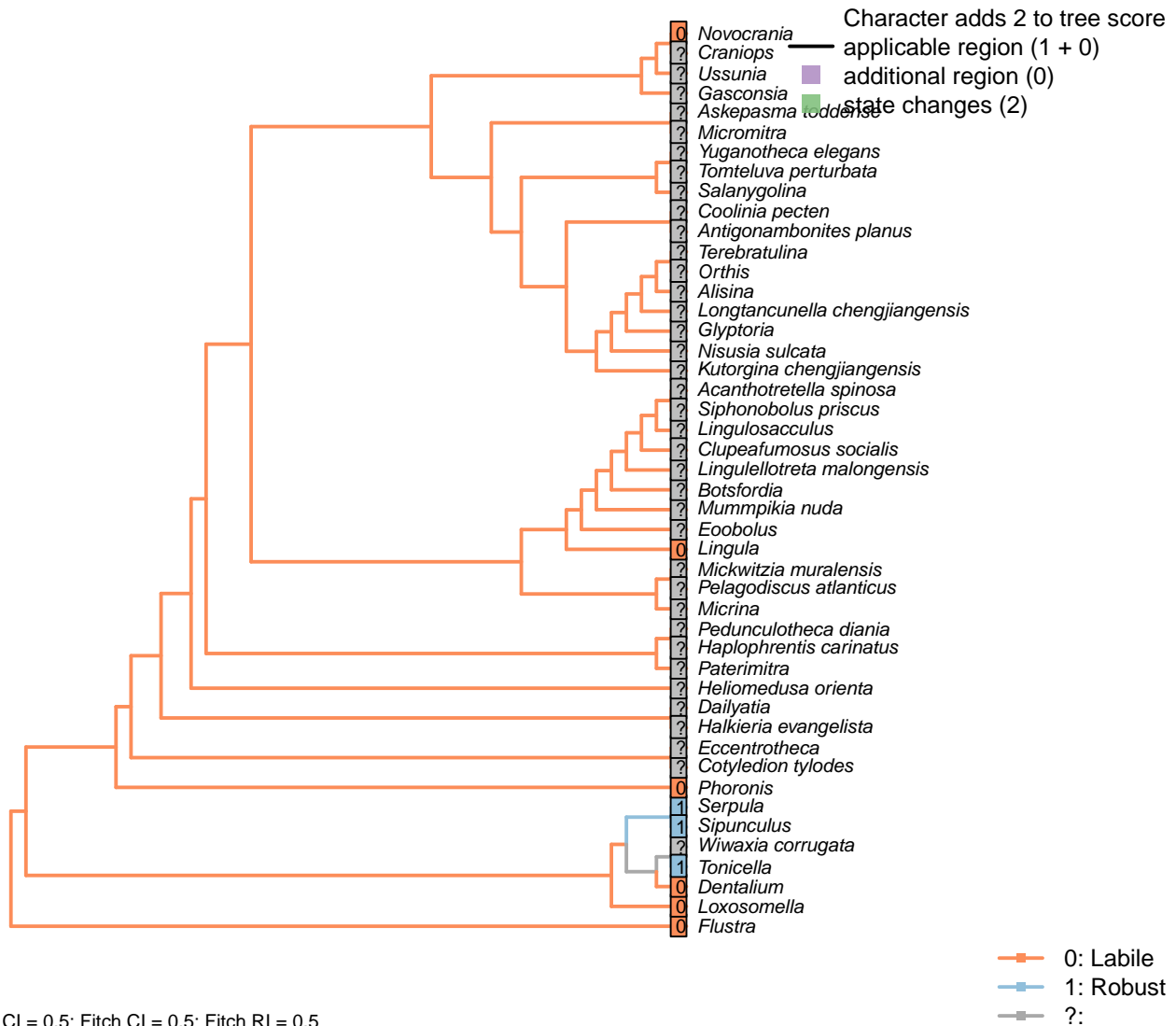
Pelagodiscus atlanticus: Microvilli in otherwise homogeneous epidermis (Williams et al., 1997).

Phoronis: Not evident (Bereiter-Hahn et al., 1984).

Sipunculus: Fibrous collagen only (Bereiter-Hahn et al., 1984).

Terebratulina: Cuticle is homogeneous in *Notosaria* (Bereiter-Hahn et al., 1984; Williams et al., 1997).

[191] Resilience



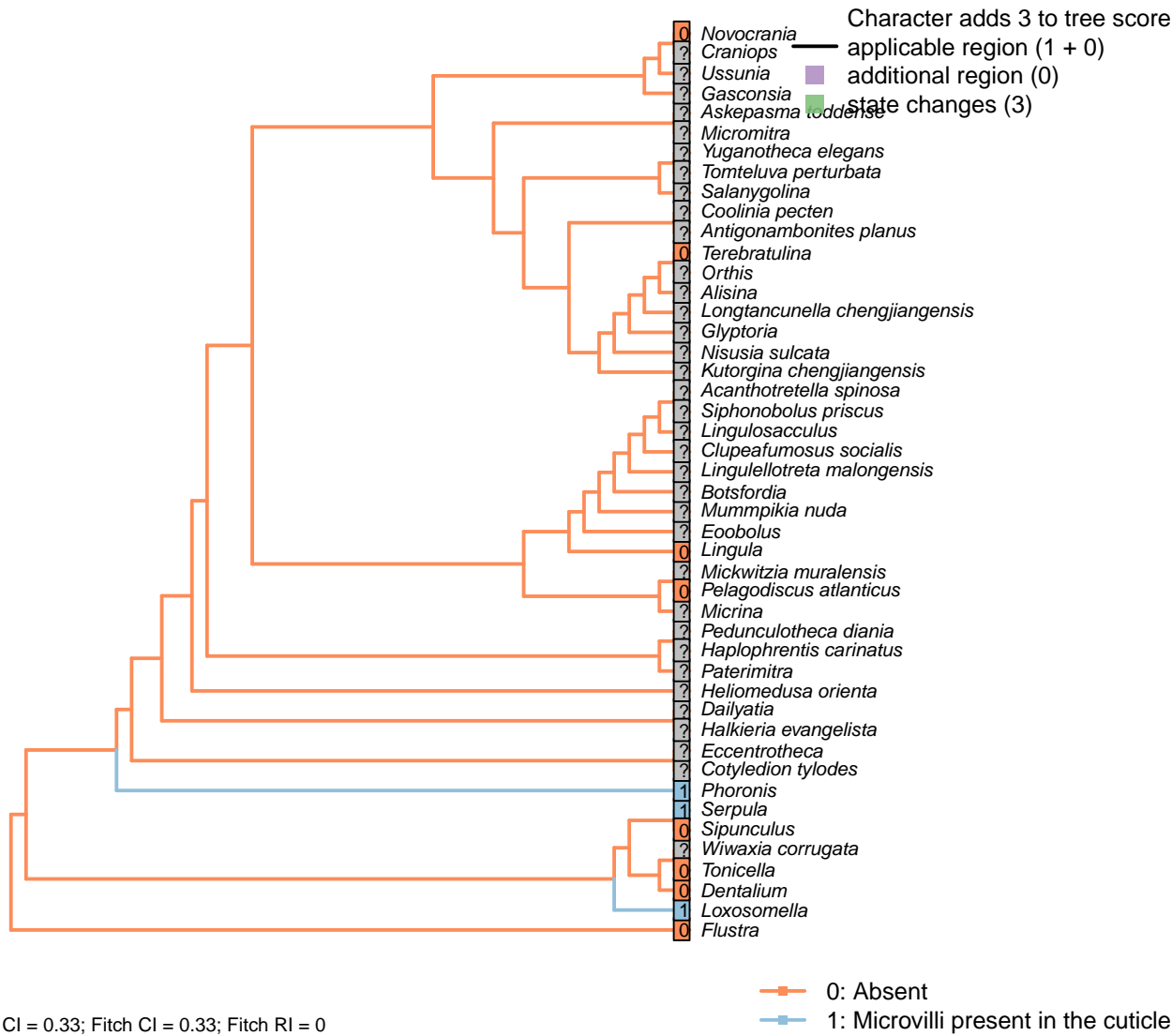
Character 191: Cuticle: Resilience

0: Labile

1: Robust

2:
Neomorphic character.
Character 1 in Haszprunar (2000).

[192] Microvilli



Character 192: Cuticle: Microvilli

0: Absent
1: Microvilli present in the cuticle
Neomorphic character.

After Borisanova et al. (2015).

Dentalium, *Flustra*, *Loxosomella*, *Serpula*, *Tonicella*: Following table 2 in Borisanova et al. (2015).

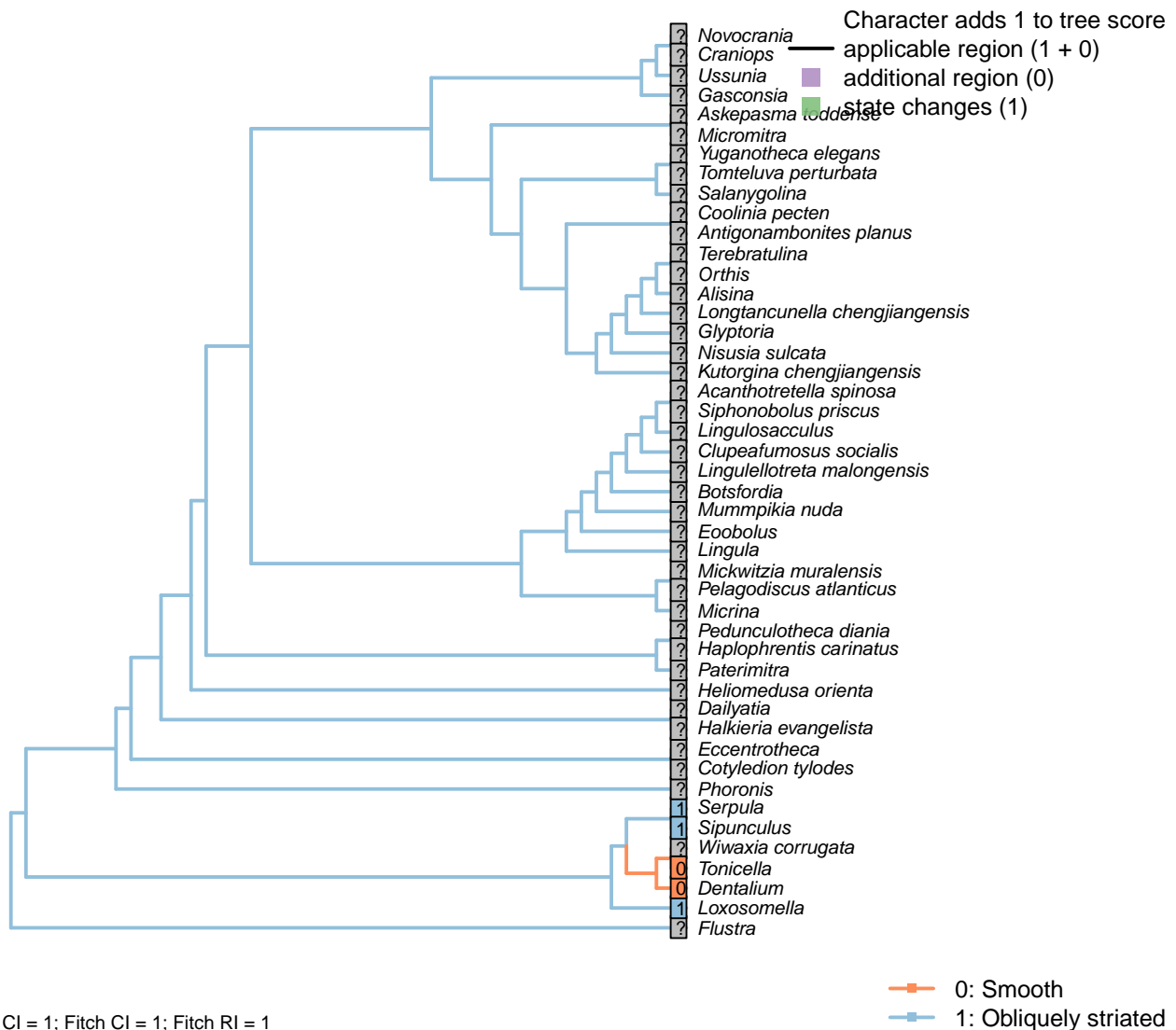
Pelagodiscus atlanticus: Microvillios inner epithelium in Discina (Williams et al., 1997).

Phoronis: Present on outer epithelium (Bereiter-Hahn et al., 1984).

Sipunculus: Fibrous collagen only (Bereiter-Hahn et al., 1984).

3.41 Muscles

[193] Cytology



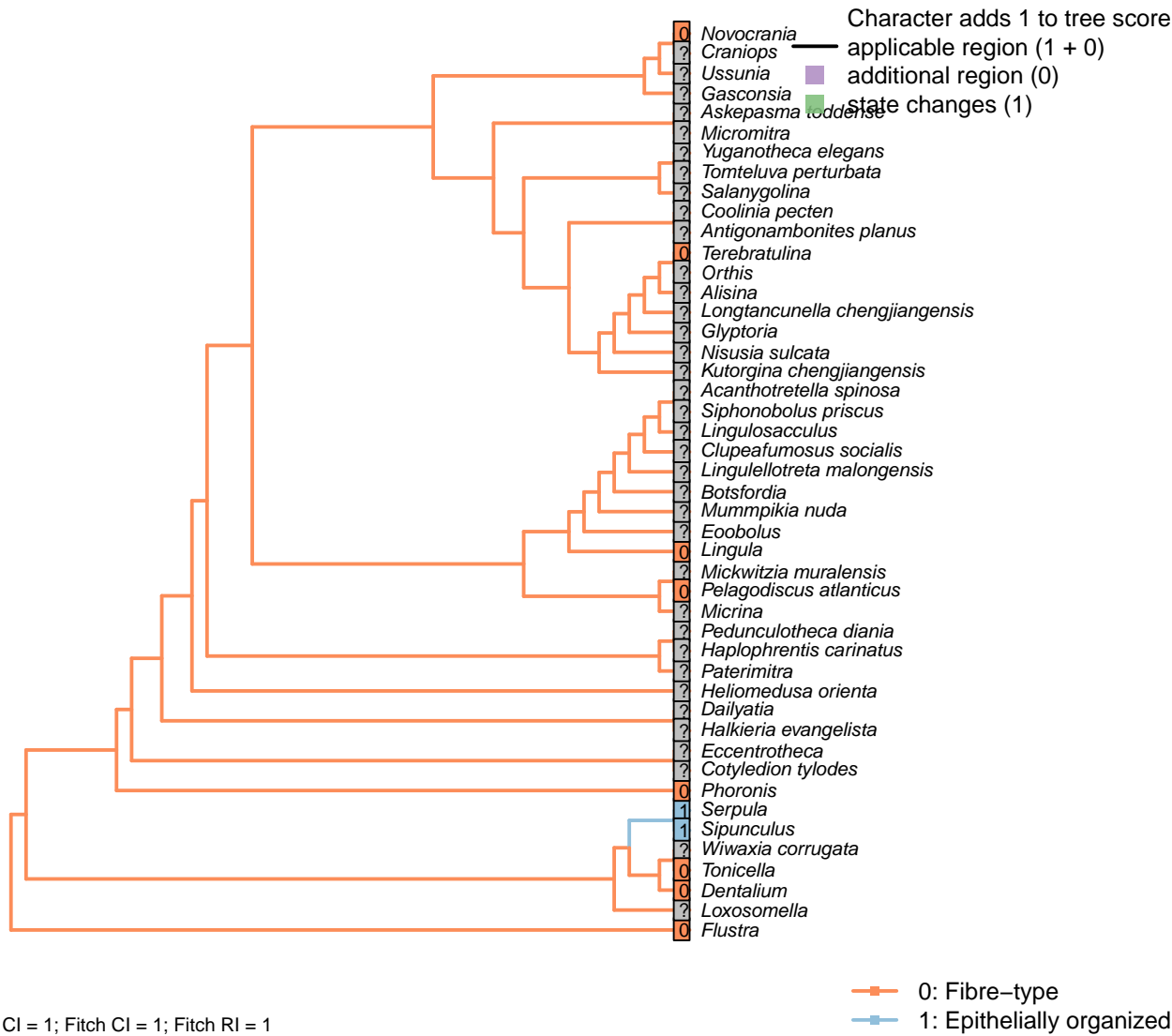
Character 193: Muscles: Cytology

0: Smooth

1: Obliquely striated

2:
Neomorphic character.
Character 19 in Haszprunar (1996); see also character 13 in Haszprunar (2000).

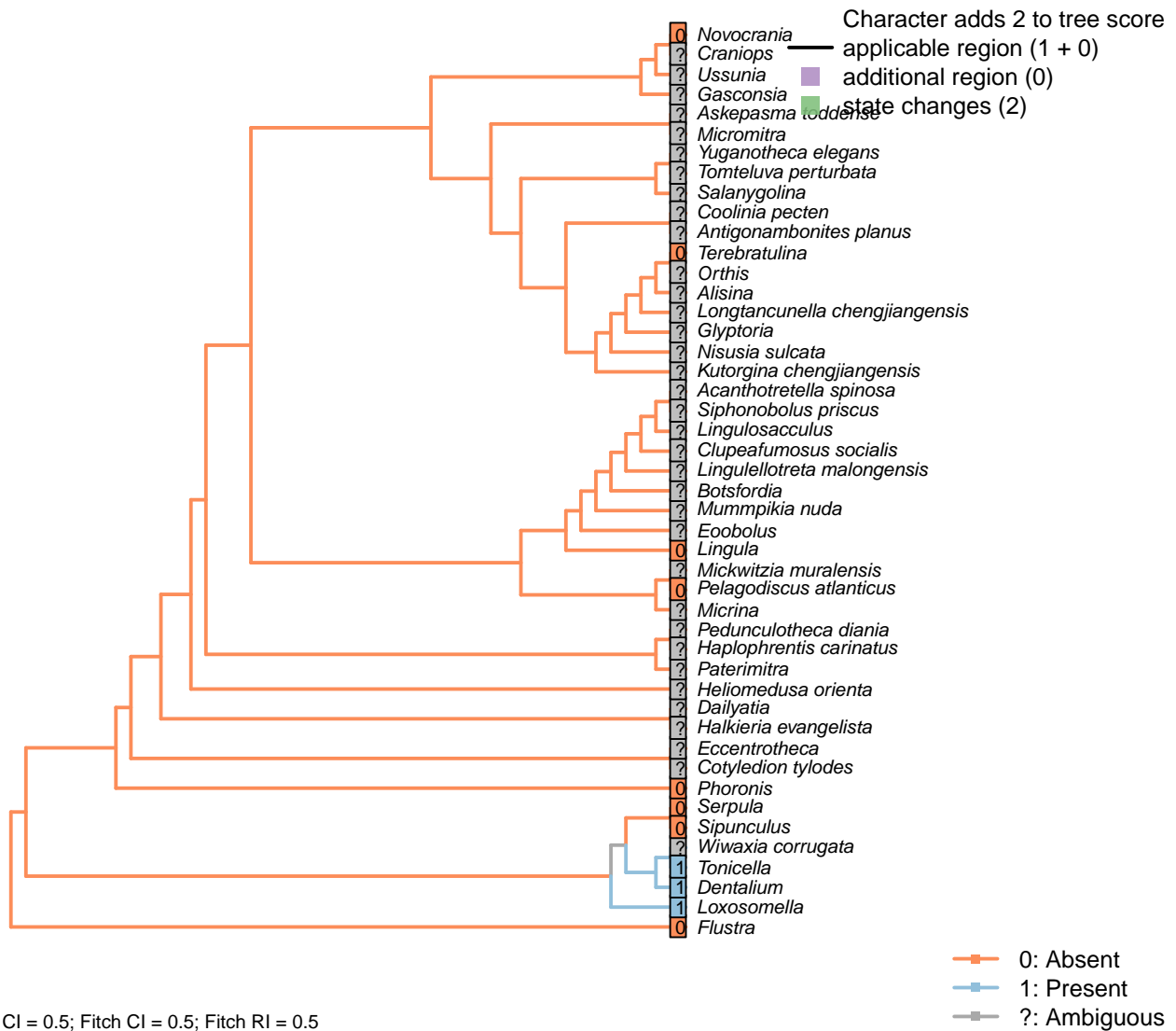
[194] Histology



Character 194: Muscles: Histology
0: Fibre-type
1: Epithelially organized
2:
Neomorphic character.
See character 18 in Haszprunar (1996).

3.42 Glands

[195] Pedal gland



Character 195: Glands: Pedal gland

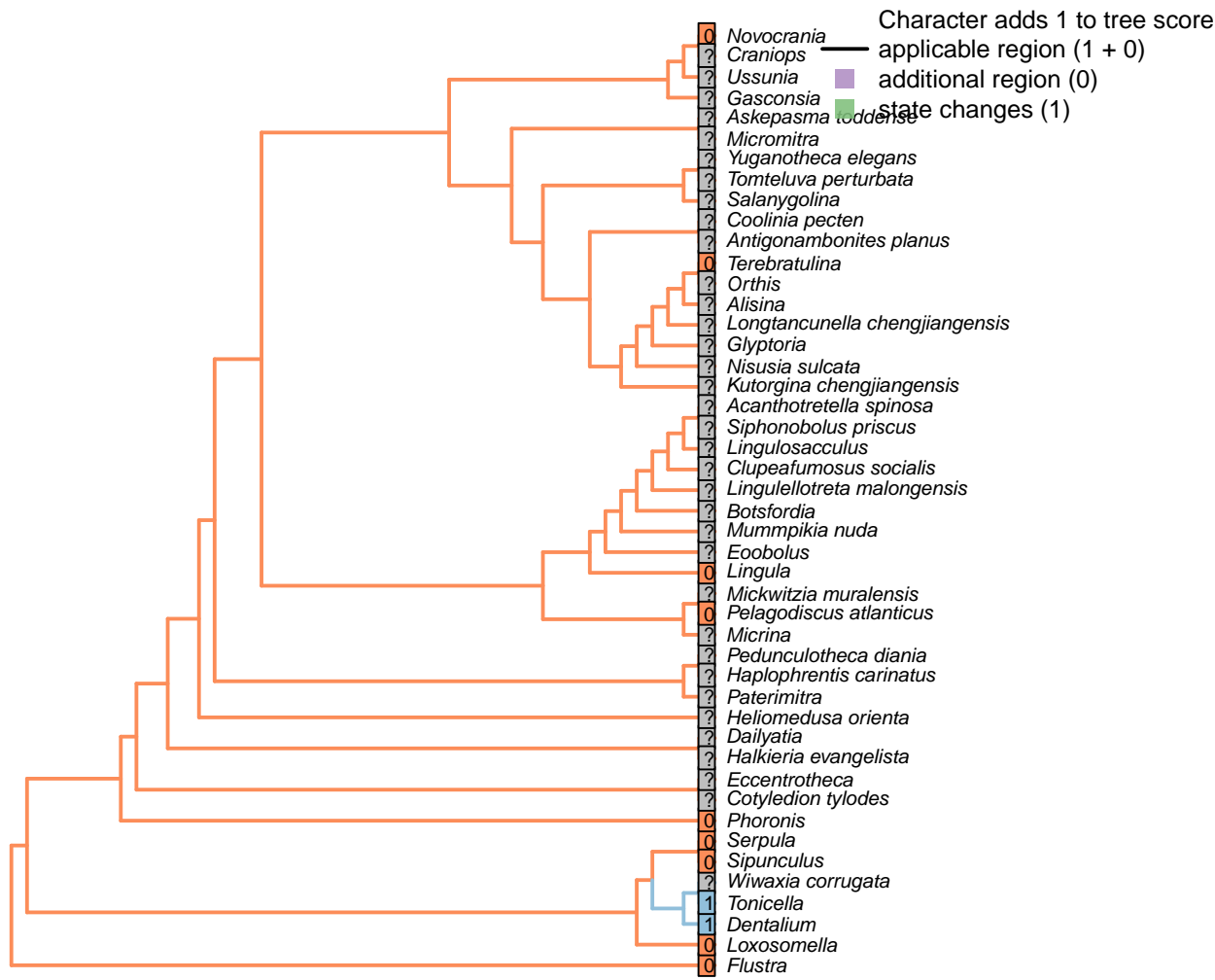
0: Absent

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).

[196] Paired pharyngeal diverticulae



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

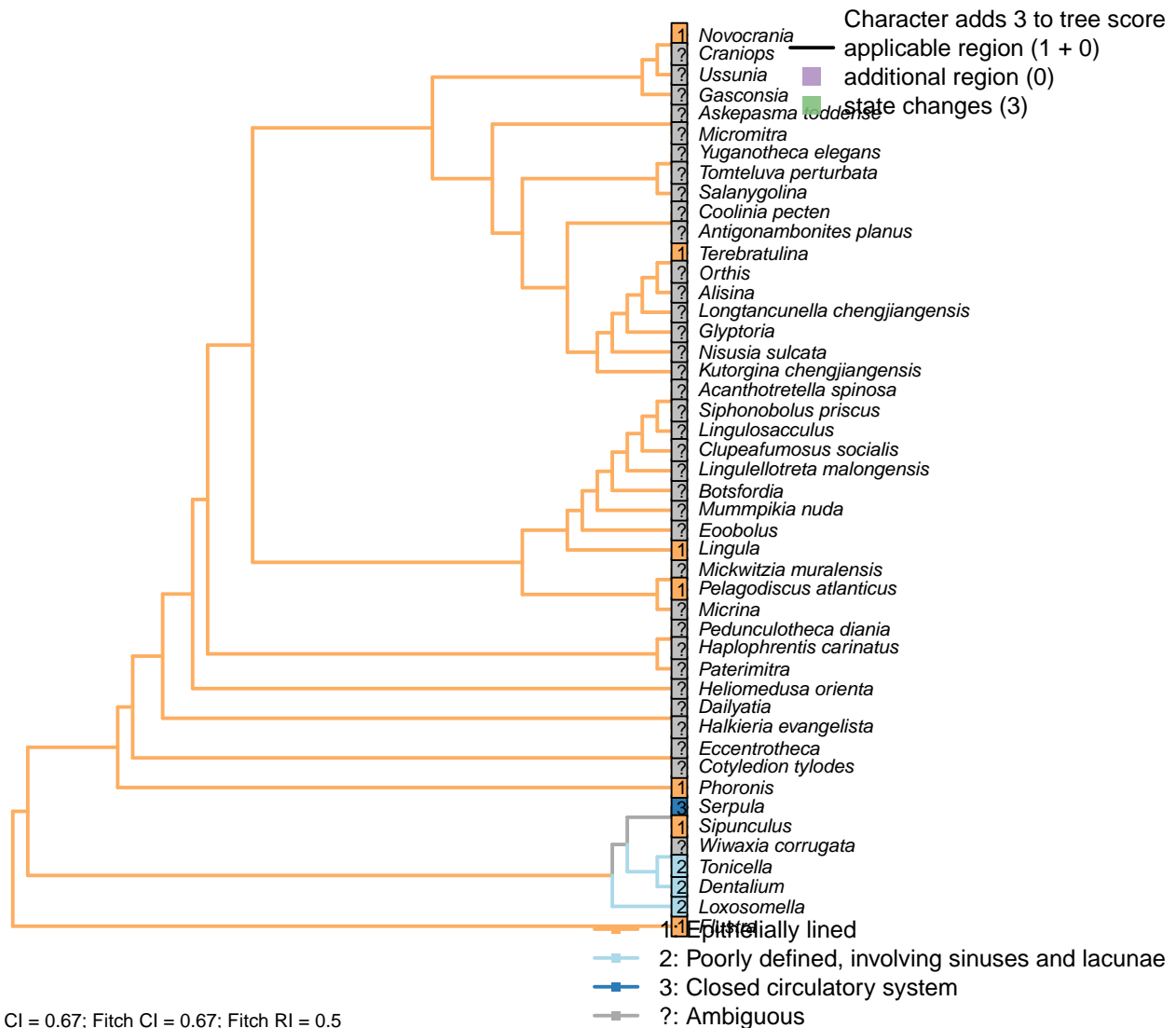
Character 196: Glands: Paired pharyngeal diverticulae

0: Absent

1: Present

Neomorphic character.

3.43 Body organization: Circulatory system [197]



Character 197: Body organization: Circulatory system

- 1: Epithelially lined
 - 2: Poorly defined, involving sinuses and lacunae
 - 3: Closed circulatory system
- Transformational character.

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).

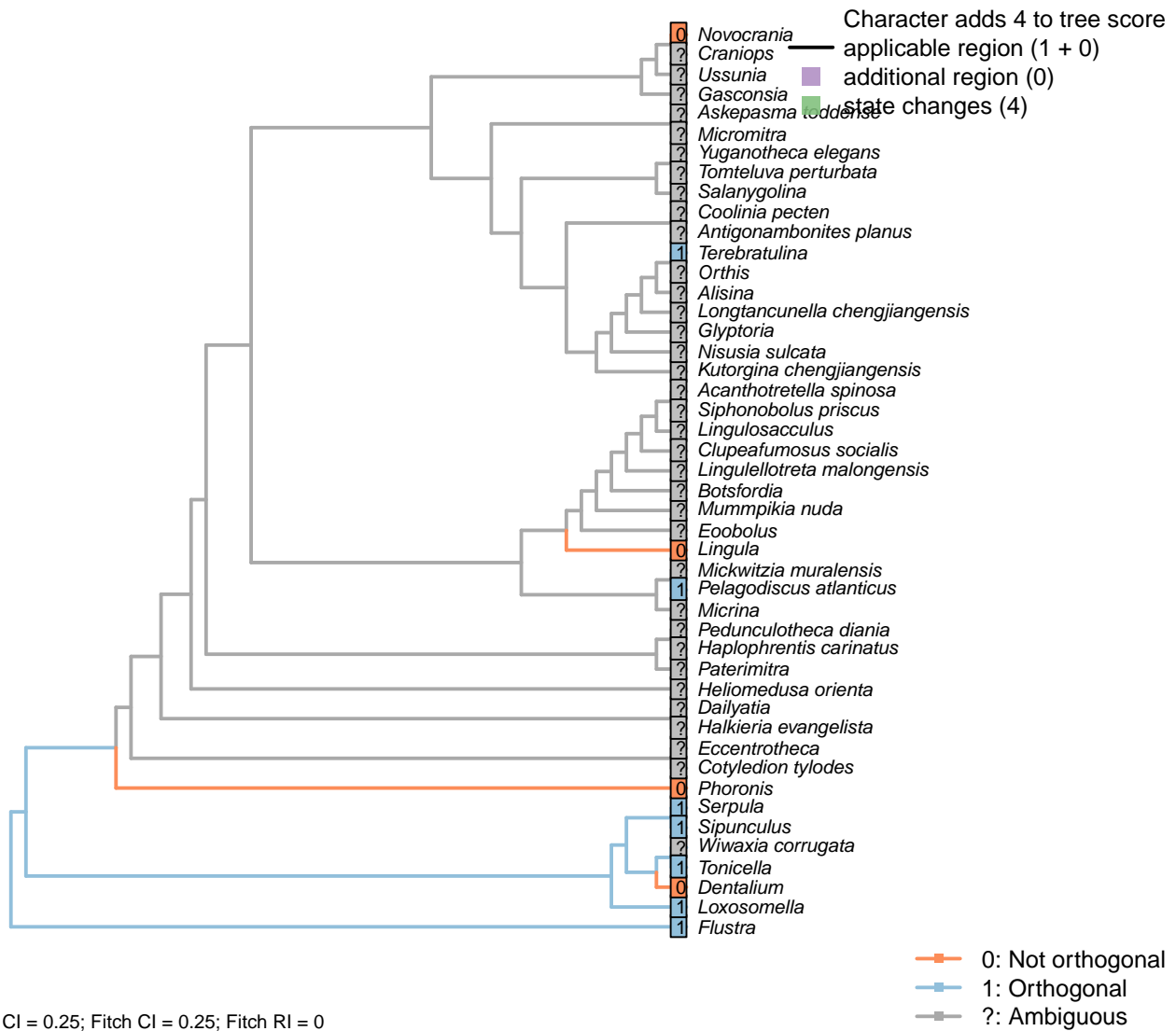
Dentalium, *Loxosomella*, *Tonicella*: See Haszprunar and Wanninger (2008).

Flustra: As Brachiopods, sipunculans and relatives (Ruppert and Carle, 1983).

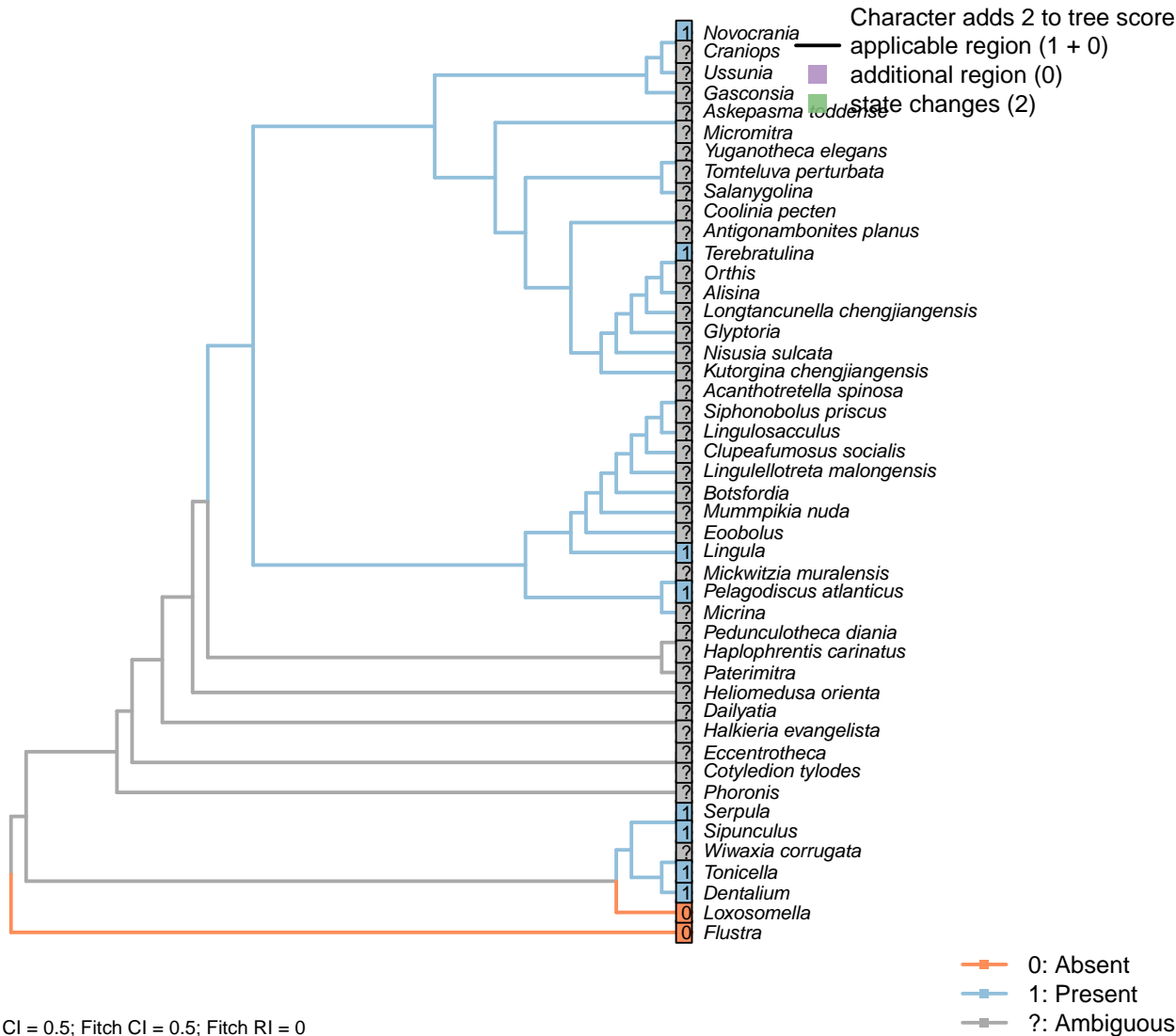
Sipunculus: Open circulatory system.

3.44 Nervous system

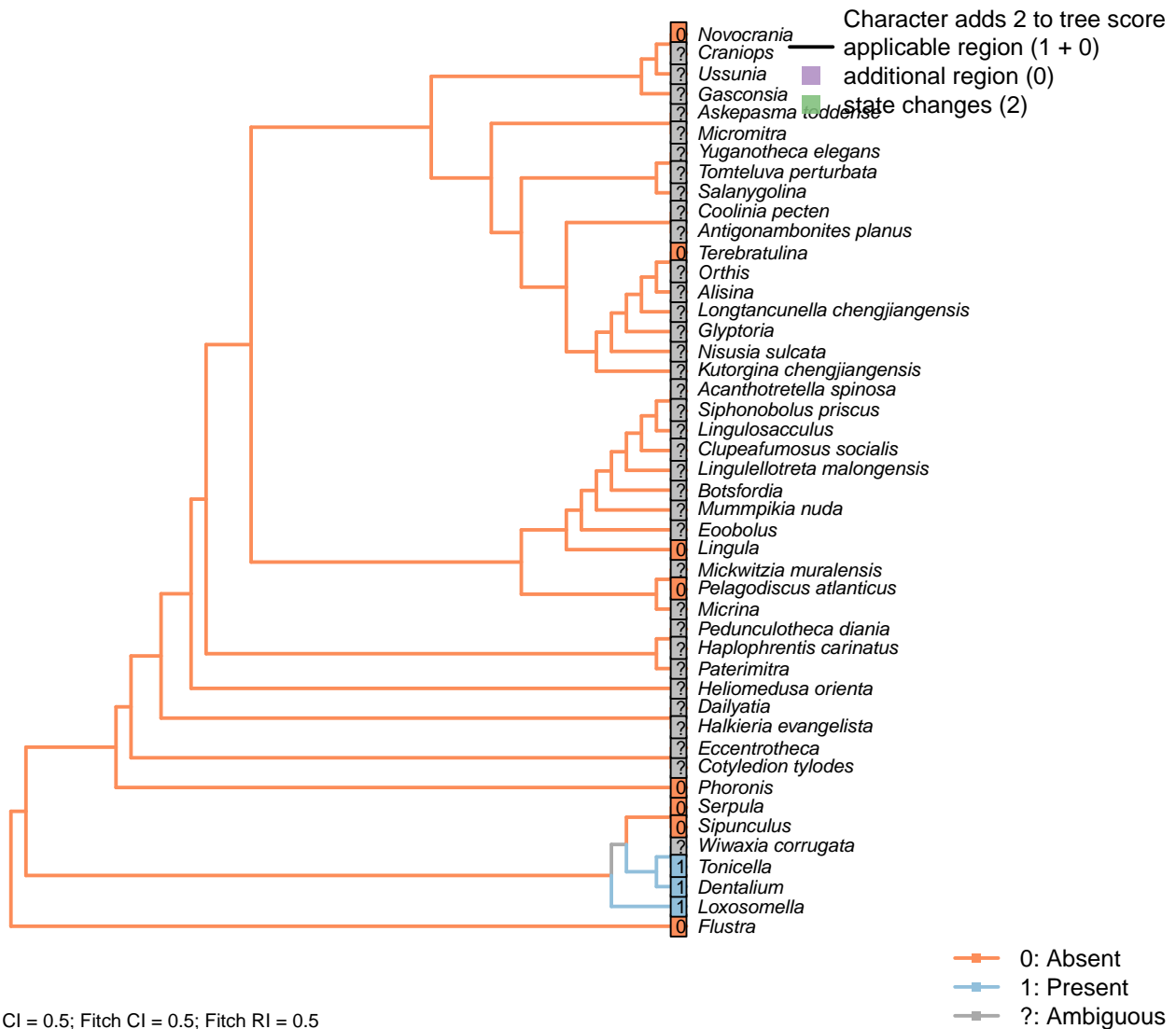
[198] Orthogonal



[199] Glial system



[200] Buccal nerve ring

**Character 200: Nervous system: Buccal nerve ring**

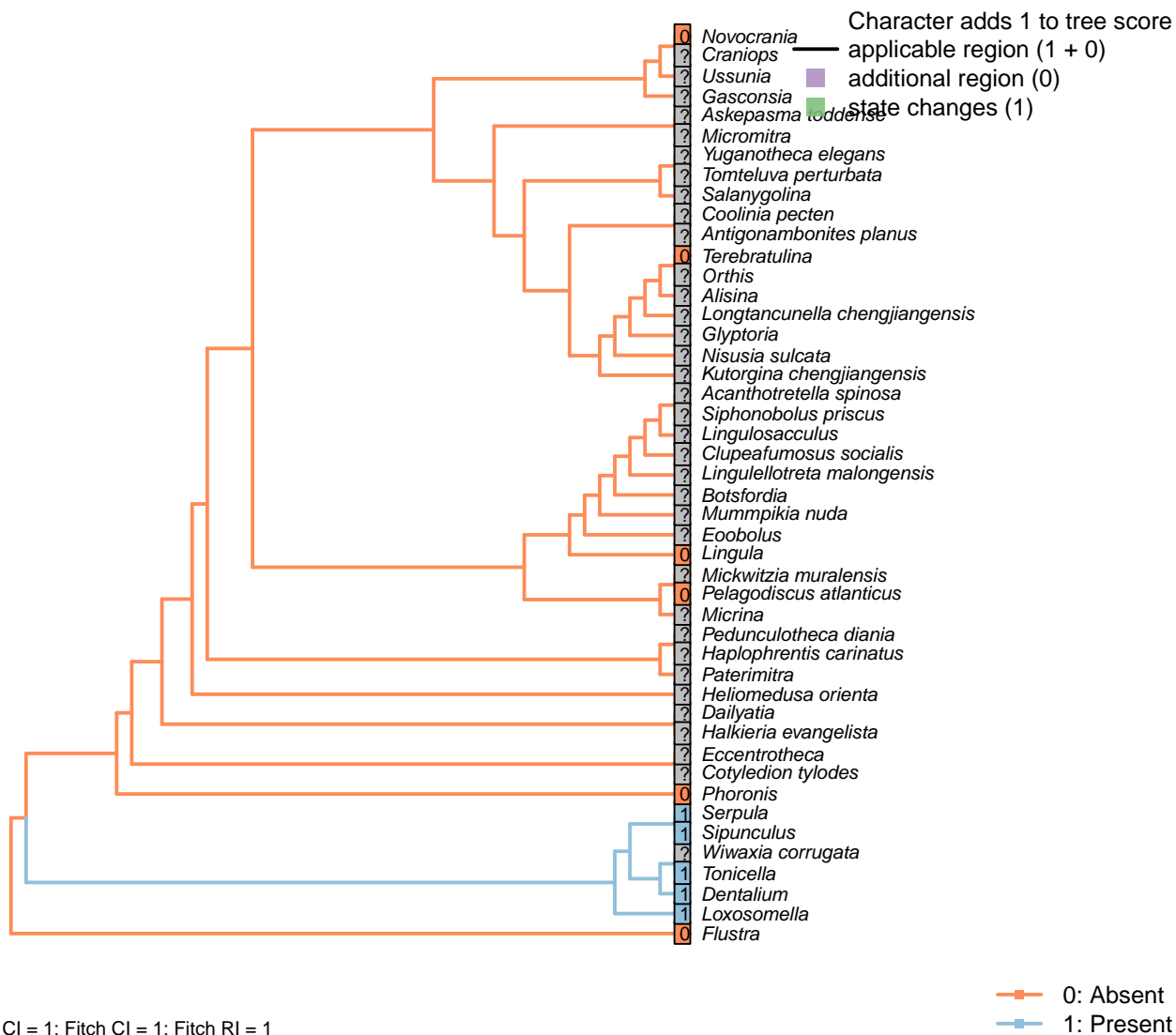
0: Absent

1: Present

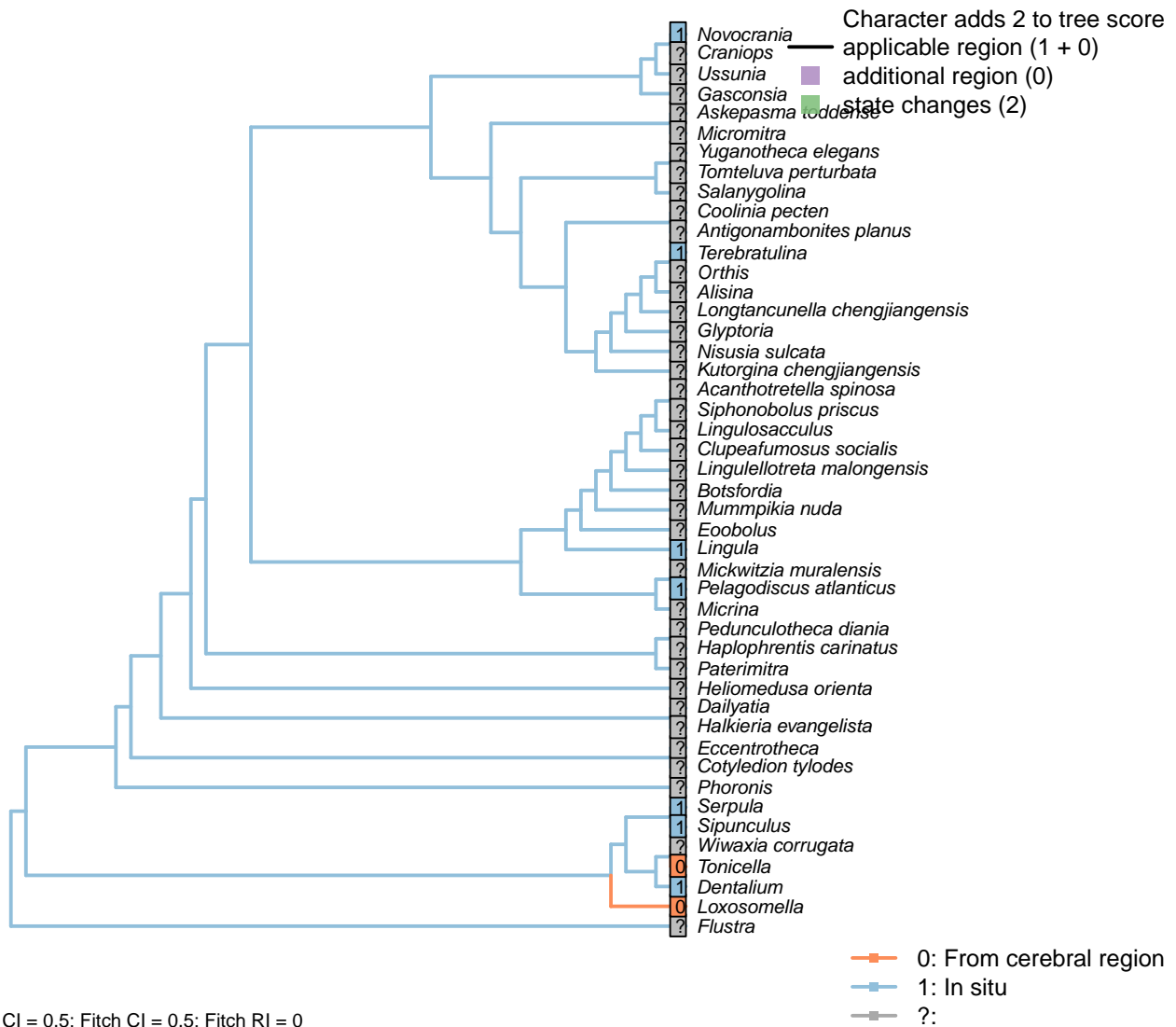
Neomorphic character.

Character 7b in Haszprunar and Wanninger (2008).

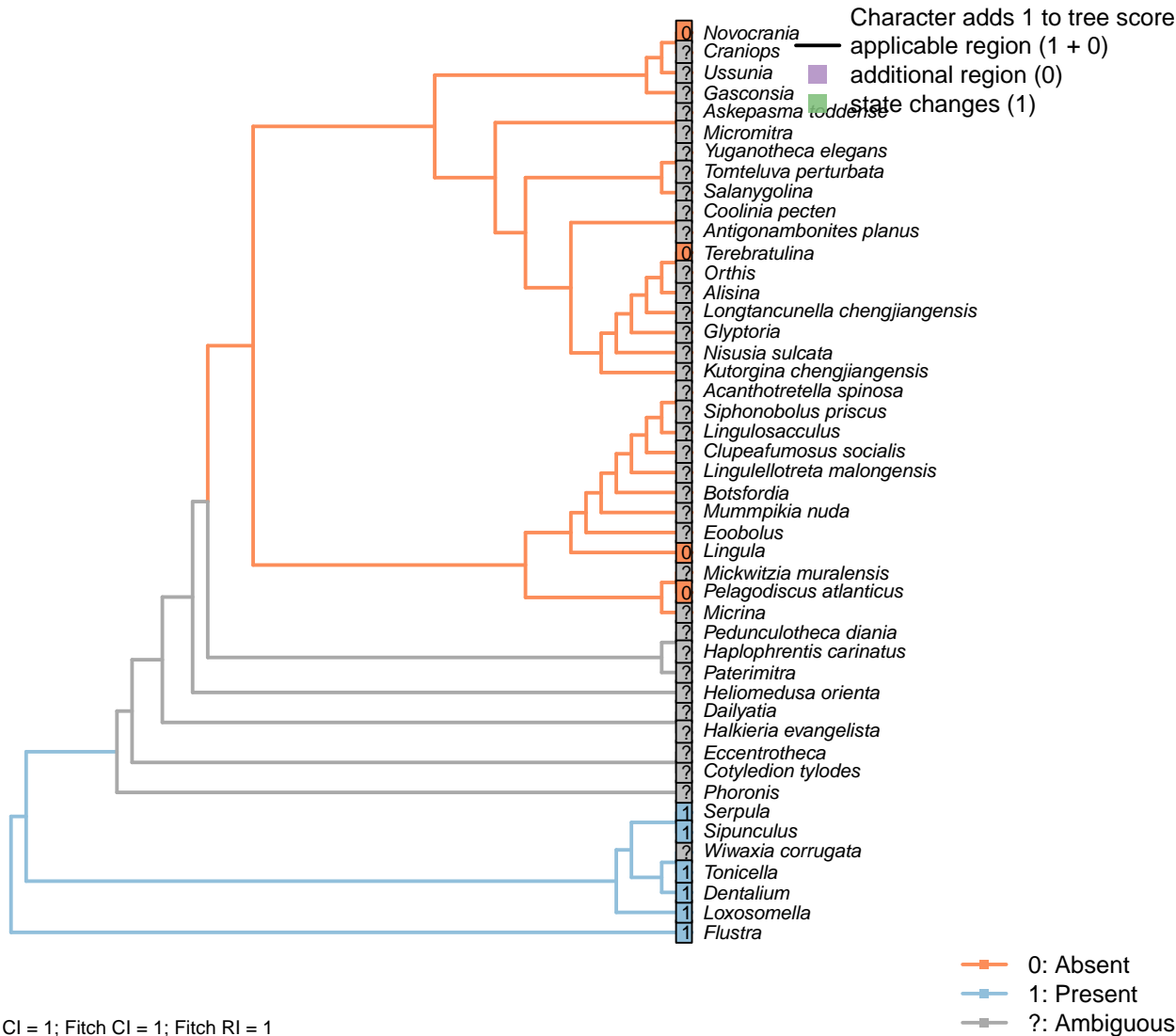
[201] Anterior nerve loop



[202] Formation of ganglia



[203] Presence



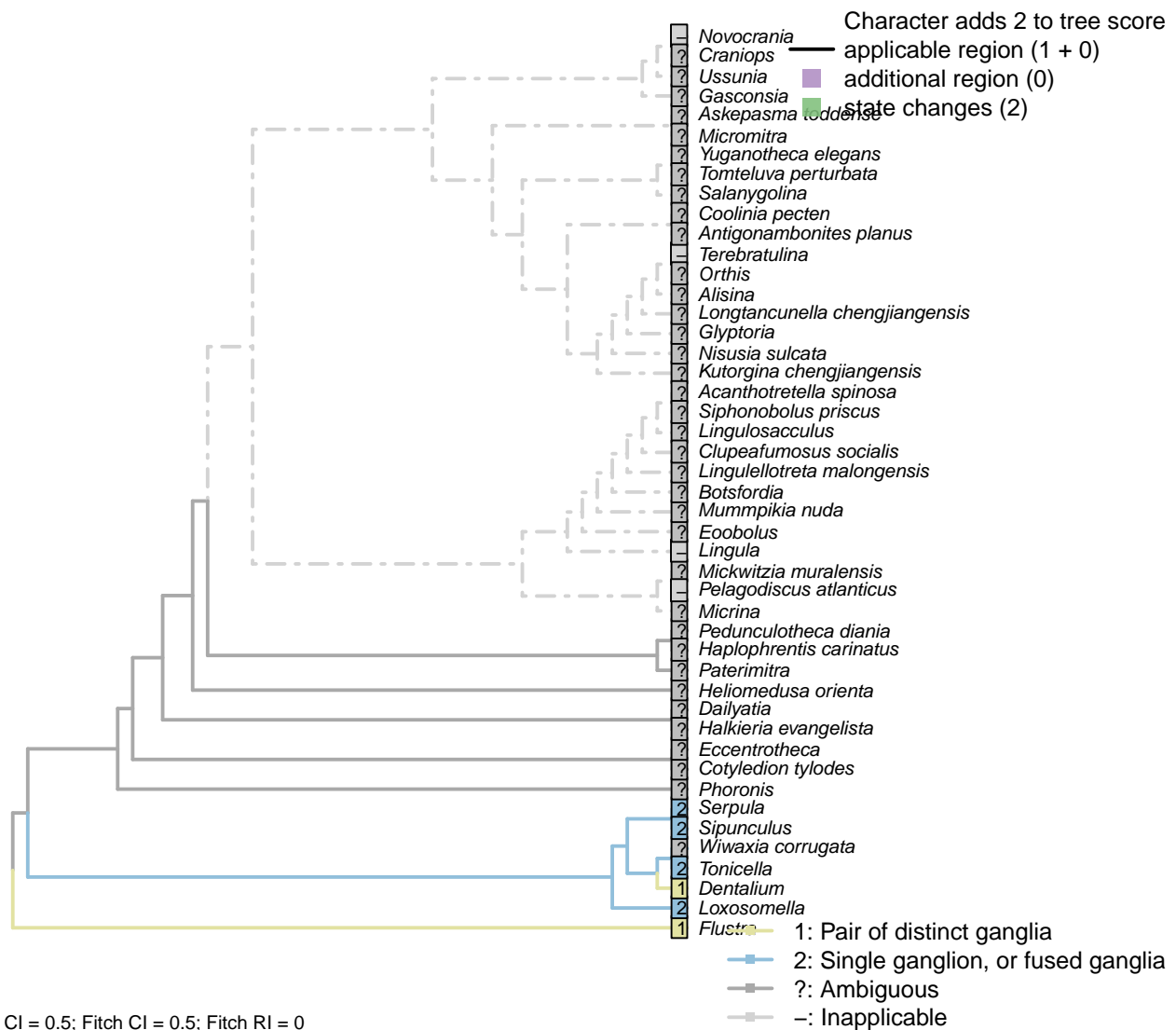
Character 203: Nervous system: Cerebral ganglia: Presence

0: Absent
1: Present
Neomorphic character.

After character 13 in Haszprunar (1996).

3.45 Nervous system

[204] Fused



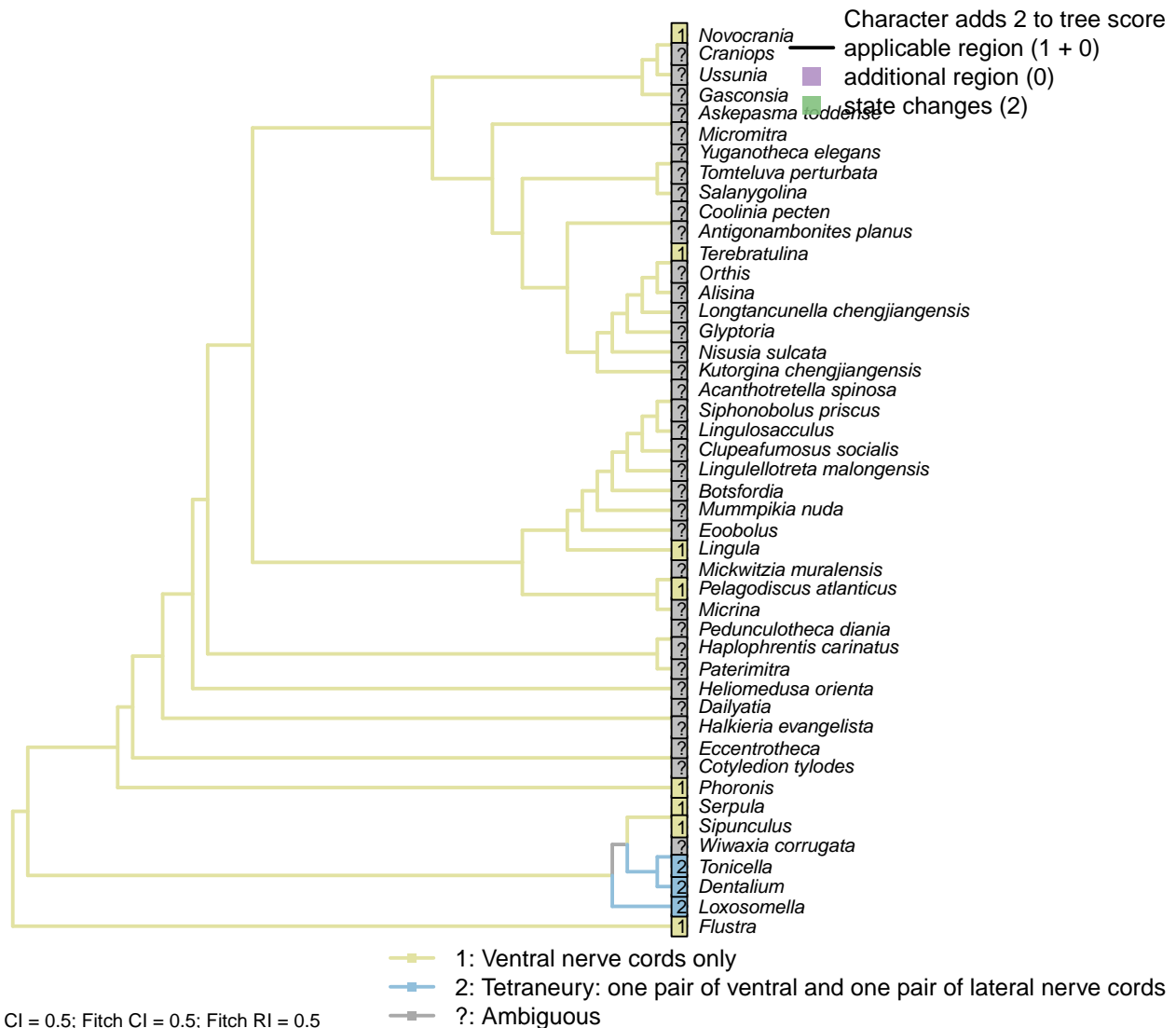
CI = 0.5; Fitch CI = 0.5; Fitch RI = 0

Character 204: Nervous system: Cerebral ganglia: Fused

- 1: Pair of distinct ganglia
 - 2: Single ganglion, or fused ganglia
- Transformational character.

After character 13 in Haszprunar (1996).

3.46 Nervous system: Nerve cords [205]



Character 205: Nervous system: Nerve cords

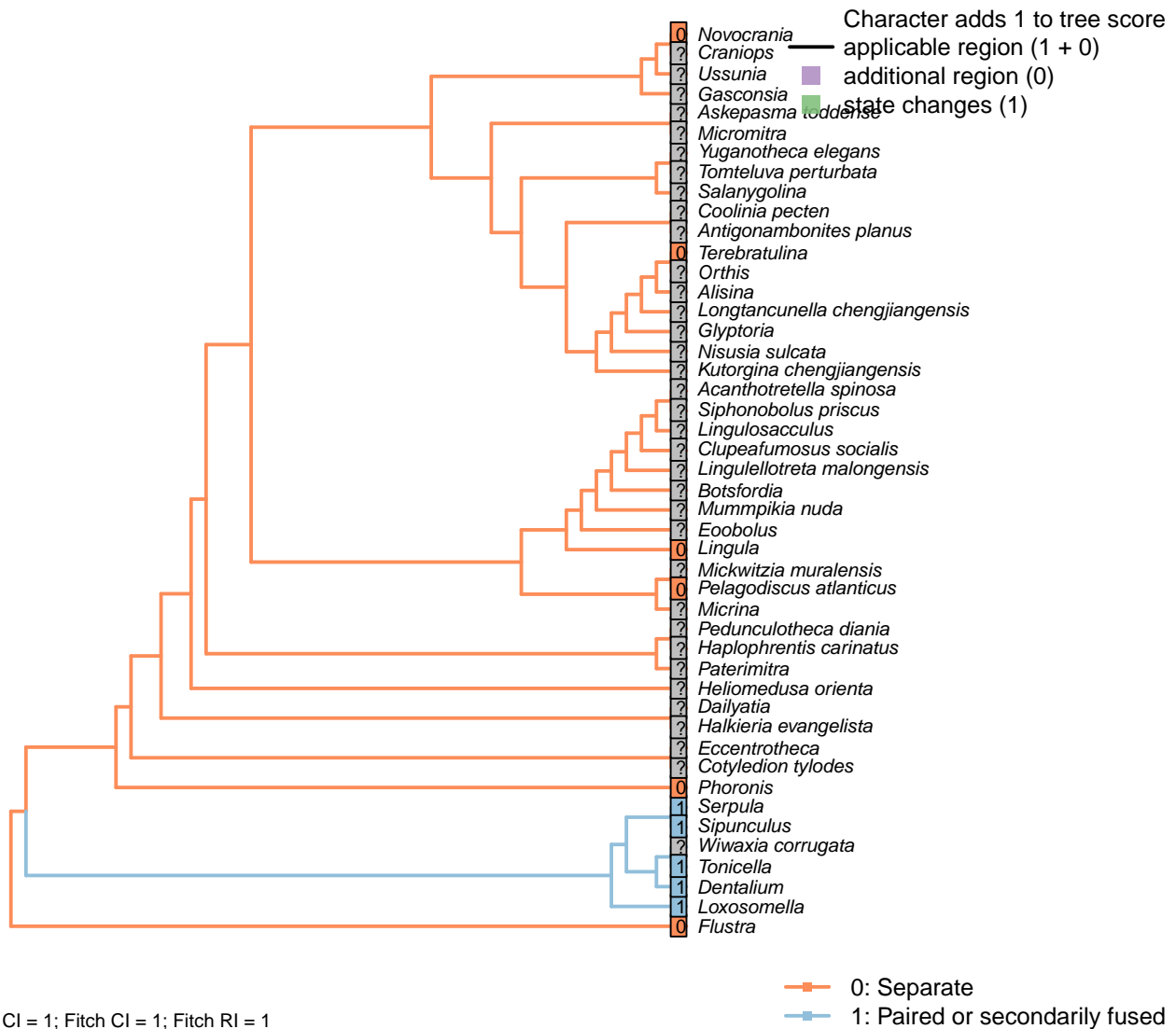
1: Ventral nerve cords only

2: Tetraneury: one pair of ventral and one pair of lateral nerve cords

Transformational character.

See character 7 in Haszprunar and Wanninger (2008).

[206] Ventral longitudinal nerves

**Character 206: Nervous system: Ventral longitudinal nerves**

0: Separate

1: Paired or secondarily fused

Neomorphic character.

Character 80 in Glenner et al. (2004); see also character 6 in Vinther et al. (2008).

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

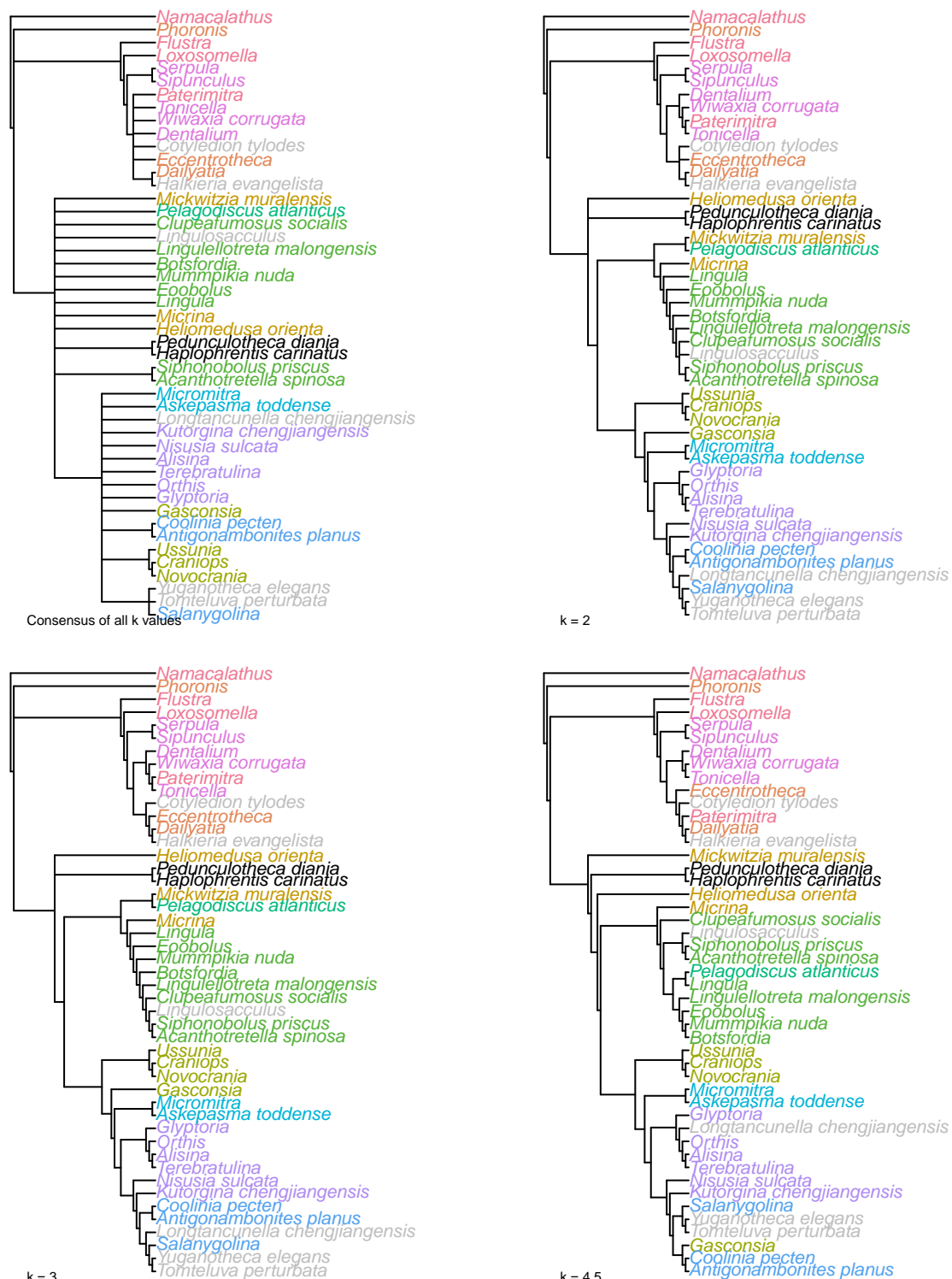


Figure 4.1: Strict consensus of all trees recovered by TNT using Fitch parsimony with implied weighting at all values of k , and at the individual values $k = 2, 3$ and 4.5 . The consensus of all implied weights runs is not very well resolved, largely due to a few wildcard taxa, particularly at $k = 4.5$, which obscures a consistent set of relationships between the remaining taxa.

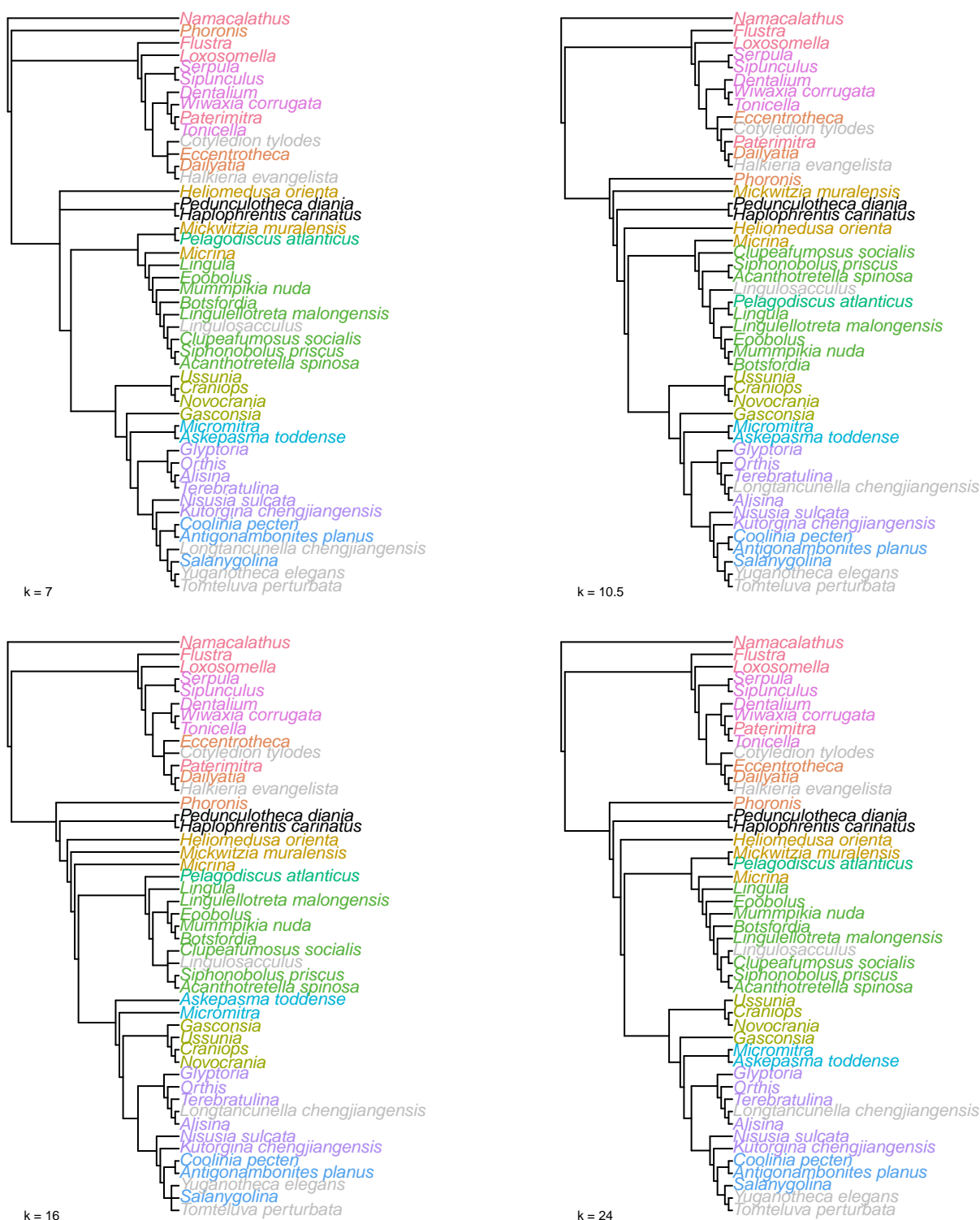


Figure 4.2: Strict consensus of all trees recovered by TNT using Fitch parsimony with implied weighting, at $k = 7, 10.5, 16$ and 24 .

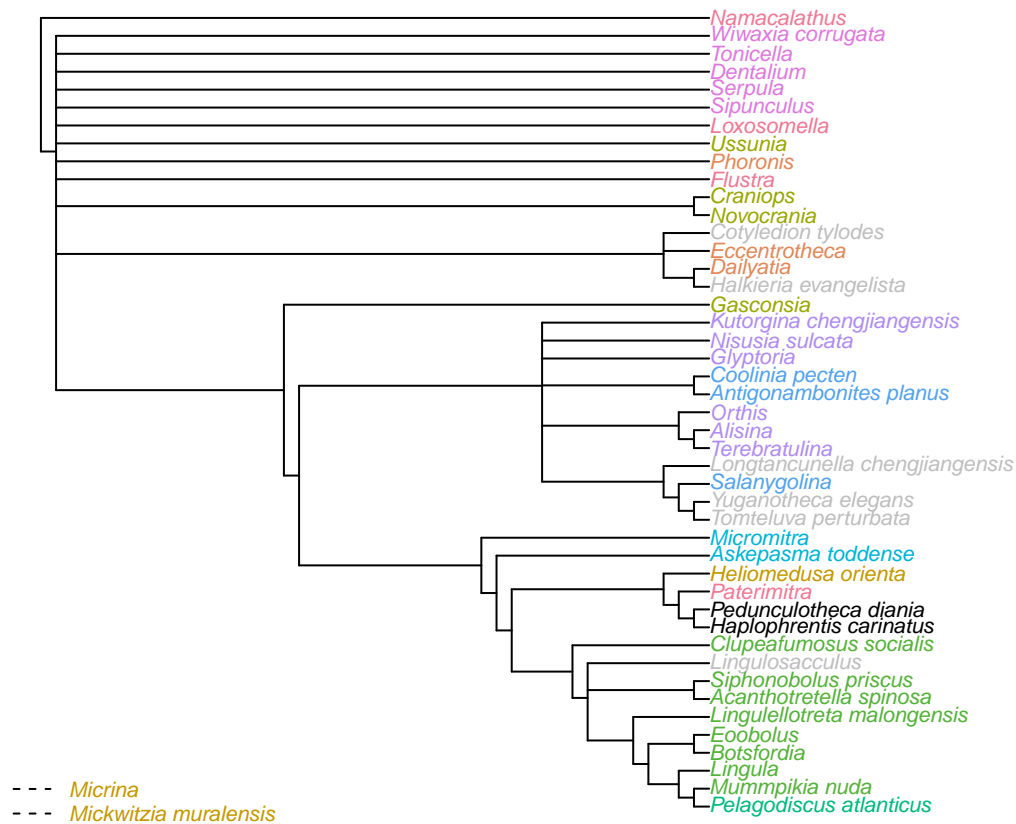


Figure 4.3: Consensus of all trees obtained using equally weighted Fitch parsimony in TNT. *Mickwitzia* and *Micrina* may equally parsimoniously be reconstructed in the basal region of the linguliform or rhynchonel-liform lineages; as such, the inclusion of these taxa in the consensus tree reduces resolution. 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, 0.35, 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 11 12 14 15 18 19 23 24 26 27 29 32 33 34 37 38 41 42 43 44 45 46  
47 48 49 53 54 56 57 59 61 62 63 64 66 68 71 72 73 76 77 78 79 82 83 84 85 86 89 91 93 100 101  
103 104 105 107 108 111 115 116 117 118 119 121 122 123 124 125 127 128 129 130 132 133 134  
135 136 137 139 142 147 148 150 151 152 153 154 155 156 157 158 163 164 165 166 167 168 170  
172 173 176 179 182 183 184 185 186 187 189 190 191 192 193 194 195 196 198 199 200 201 202  
203 206;
```

```
charset Transformational = 2 3 4 5 8 10 13 16 17 20 21 22 25 28 30 31 35 36 39 40 50 51 52 55  
58 60 65 67 69 70 74 75 80 81 87 88 90 92 94 95 96 97 98 99 102 106 109 110 112 113 114 120  
126 131 138 140 141 143 144 145 146 149 159 160 161 162 169 171 174 175 177 178 180 181 188  
197 204 205;
```

```
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

Bibliography

- Adrianov, A. V., Malakhov, V. V., and Maiorova, A. S. (2006). Development of the tentacular apparatus in sipunculans (Sipuncula): I. *Thysanocardia nigra* (Ikeda, 1904) and *Themiste pyroides* (Chamberlin, 1920). *Journal of Morphology*, 267(5):569–583, doi:10.1002/jmor.10423.
- Afzelius, B. A. and Ferraguti, M. (1978). Fine structure of brachiopod spermatozoa. *Journal of Ultrastructure Research*, 63(3):308–315, doi:10.1016/s0022-5320(78)80054-9.
- Altenburger, A., Wanninger, A., and Holmer, L. E. (2013). Metamorphosis in Craniiformea revisited: *Novocrania anomala* shows delayed development of the ventral valve. *Zoomorphology*, 132(4):379–387, doi:10.1007/s00435-013-0194-3.
- Balthasar, U. (2004). Shell structure, ontogeny, and affinities of the Lower Cambrian bivalved problematic fossil *Mickwitzia muralensis* Walcott, 1913. *Lethaia*, 37(4):381–400, doi:10.1080/00241160410002090.
- Balthasar, U. (2007). An early Cambrian organophosphatic brachiopod with calcitic granules. *Palaeontology*, 50(6):1319–1325, doi:10.1111/j.1475-4983.2007.00729.x.
- Balthasar, U. (2008). *Mummpikia* gen. nov. and the origin of calcitic-shelled brachiopods. *Palaeontology*, 51(2):263–279, doi:10.1111/j.1475-4983.2008.00754.x.
- Balthasar, U. (2009). The brachiopod *Eoobolus* from the early Cambrian Mural Formation (Canadian Rocky Mountains). *Paläontologische Zeitschrift*, 83(3):407–417, doi:10.1007/s12542-009-0026-4.
- Balthasar, U. and Butterfield, N. J. (2009). Early Cambrian soft-shelled brachiopods as possible stem-group phoronids. *Acta Palaeontologica Polonica*, 54(2):307–314, doi:10.4202/app.2008.0042.
- Balthasar, U., Cusack, M., Faryma, L., Chung, P., Holmer, L. E., Jin, J., Percival, I. G., and Popov, L. E. (2011). Relic aragonite from Ordovician–Silurian brachiopods: Implications for the evolution of calcification. *Geology*, 39(10):967–970, doi:10.1130/g32269.1.
- Bartolomaeus, T. (1995). Secondary monociliarity in the Annelida: monociliated epidermal cells in larvae of *Magelona mirabilis* (Magelonida). *Microfauna Marina*, 10(January 1995):327–332.
- Bartolomaeus, T. (2001). Ultrastructure and formation of the body cavity lining in *Phoronis muelleri* (Phoronida, Lophophorata). *Zoomorphology*, 120(3):135–148, doi:10.1007/s004350000030.
- Bartolomaeus, T. and Quast, B. (2005). Structure and development of nephridia in Annelida and related taxa. *Hydrobiologia*, 535:139–165, doi:10.1007/s10750-004-1840-z.
- Bassett, M. G. and Popov, L. E. (2017). Earliest ontogeny of the Silurian orthotetide brachiopod *Coolinia* and its significance for interpreting strophomenate phylogeny. *Lethaia*, 50(4):504–510, doi:10.1111/let.12204.
- Bassett, M. G., Popov, L. E., and Egerquist, E. (2008). Early ontogeny of some Ordovician–Silurian strophomenate brachiopods: Significance for interpreting evolutionary relationships within early Rhynchonelliformea. *Fossils and Strata*, 54:13–20.

- Bassett, M. G., Popov, L. E., and Holmer, L. E. (2001). Functional morphology of articulatory structures and implications for patterns of musculature in Cambrian rhynchonelliform brachiopods. In Brunton, H., Cocks, R. M., and Long, S. L., editors, *Brachiopods, Past and Present*, pages 163–176.
- Benedetto, J. L. (2009). *Chaniella*, a new lower Tremadocian (Ordovician) brachiopod from northwestern Argentina and its phylogenetic relationships within basal rhynchonelliforms. *Paläontologische Zeitschrift*, 83(3):393–405, doi:10.1007/s12542-009-0023-7.
- Bereiter-Hahn, J., Matoltsy, A. G., and Sylvia Richards, K. (1984). *Biology of the Integument*.
- Borisanova, A. O., Yushin, V. V., Malakhov, V. V., and Temereva, E. N. (2015). The fine structure of the cuticle of kamptozoans is similar to that of annelids. *Zoomorphology*, 134(2):165–181, doi:10.1007/s00435-015-0261-z.
- Brazeau, M. D., Guillerme, T., and Smith, M. R. (2018). An algorithm for morphological phylogenetic analysis with inapplicable data. *Systematic Biology*, doi:10.1101/209775.
- Brazeau, M. D., Smith, M. R., and Guillerme, T. (2017). MorphyLib: a library for phylogenetic analysis of categorical trait data with inapplicability. doi:10.5281/zenodo.815371.
- Buckland-Nicks, J. A. (2008). Fertilization biology and the evolution of chitons. *American Malacological Bulletin*, 25(1):97–111.
- Buckland-Nicks, J., Koss, R., and Chia, F. . (1988). Fertilization in a chiton: Acrosome-mediated sperm-egg fusion. *Gamete Research*, 21(3):199–212, doi:10.1002/mrd.1120210302.
- Butler, A. D., Streng, M., Garwood, R., Lowe, T., and Holmer, L. E. (2012). Constructing Cambrian body-plans: critical evaluation of tommotiid and stem-brachiopod character homologies [Exceptional preservation of *Micrina* setae and 3D MicroCT reconstruction confirm the tommotiid stem-group brachiopod link]. In *Palaeontological Association Annual Meeting*, volume 56, page 61. The Palaeontological Association.
- Butler, A. D., Streng, M., Holmer, L. E., and Babcock, L. E. (2015). Exceptionally preserved *Mickwitzia* from the Indian Springs Lagerstätte (Cambrian Stage 3), Nevada. *Journal of Paleontology*, 89(6):933–955, doi:10.1017/jpa.2016.8.
- Butterfield, N. J. (1990). A reassessment of the enigmatic Burgess Shale fossil *Wiwaxia corrugata* (Matthew) and its relationship to the polychaete *Canadia spinosa* Walcott. *Paleobiology*, 16(3):287–303, doi:10.2307/2400789.
- Carlson, S. J. (1995). Phylogenetic relationships among extant brachiopods. *Cladistics*, 11:131–197, doi:10.1111/j.1096-0031.1995.tb00084.x.
- Chen, J.-Y., Huang, D.-Y., and Chuang, S.-H. (2007). Reinterpretation of the Lower Cambrian brachiopod *Heliomedusa orientalis* Sun and Hou, 1987a as a discinid. *Journal of Paleontology*, 81(1):38–47, doi:10.1666/0022-3360(2007)81[38:rotlcb]2.0.co;2.
- Collin, R. (1997). Hydrophobic larval shells: Another character for higher level systematics of gastropods. *Journal of Molluscan Studies*, 63(3):425.
- Connors, M. J., Ehrlich, H., Hog, M., Godeffroy, C., Araya, S., Kallai, I., Gazit, D., Boyce, M., and Ortiz, C. (2012). Three-dimensional structure of the shell plate assembly of the chiton *Tonicella marmorea* and its biomechanical consequences. *Journal of Structural Biology*, 177(2):314–328, doi:10.1016/j.jsb.2011.12.019.
- Cooper, G. A. (1976). Lower Cambrian brachiopods from the Rift Valley (Israel and Jordan). *Journal of Paleontology*, 50(2):269–289.
- Cusack, M., Williams, A., and Buckman, J. O. (1999). Chemico-structural evolution of linguloid brachiopod shells. *Palaeontology*, 42(5):799–840, doi:10.1111/1475-4983.00098.

- Dewing, K. (2001). Hinge modifications and musculature of strophomenoid brachiopods: examples across the Ordovician–Silurian boundary, Anticosti Island, Quebec. *Canadian Journal of Earth Sciences*, 38:125–141, doi:10.1139/e00-027.
- Dufresne-Dube, L., Picheral, B., and Guerrier, P. (1983). An ultrastructural analysis of *Dentalium vulgare* (Mollusca, Scaphopoda) gametes with special reference to early events at fertilization. *Journal of Ultrastructure Research*, 83(3):242–257, doi:10.1016/S0022-5320(83)90132-6.
- Dzik, J. (1980). Ontogeny of *Bactrotheca* and related hyoliths. *Geologiska Föreningen i Stockholm Förhandlingar*, 102(3):223–233, doi:10.1080/11035898009455162.
- Emig, C. C. (1992). Functional disposition of the lophophore in living Brachiopoda. *Lethaia*, 25(3):291–302, doi:10.1111/j.1502-3931.1992.tb01398.x.
- Fischer, F. P., Maile, W., and Renner, M. (1980). Die Mantelpapillen und Stacheln von *Acanthochiton fascicularis* L. (Mollusca, Polyplacophora). *Zoomorphologie*, 94(2):121–131, doi:10.1007/BF01081929.
- Franzén, Å. (1981). Comparative ultrastructural studies of spermatids and spermatozoa in Bryozoa and Entoprocta. In Larwood, G. P. and Nielsen, C., editors, *Recent and Fossil Bryozoans*, pages 83–92. Olsen & Olsen.
- Franzén, Å. (1984). Ultrastructure of spermatids and spermatozoa in the cyclostomatous bryozoan *Tubulipora* (Bryozoa, Cyclostomata). *Zoomorphology*, 104(3):140–146, doi:10.1007/BF00312132.
- Franzén, Å. (2000). Spermiogenesis, sperm ultrastructure and sperm transport in *Loxosoma pectinaricola* (Entoprocta). *Invertebrate Reproduction and Development*, 37(2):129–136, doi:10.1080/07924259.2000.9652411.
- Franzén, Å. (2013). Gametogenesis of Bryozoans. In Woollacott, R. M. and Zimmer, R. L., editors, *Biology of Bryozoans*, pages 1–22. Elsevier.
- Franzén, Å. and Ahlfors, K. (1980). Ultrastructure of spermatids and spermatozoa in *Phoronis*, Phylum Phoronida. *Journal of Submicroscopic Cytology*, 12(4):585–597.
- Freeman, G. and Lundelius, J. W. (1999). Changes in the timing of mantle formation and larval life history traits in linguliform and craniiform brachiopods. *Lethaia*, 32:197–217, doi:10.1111/j.1502-3931.1999.tb00539.x.
- Fukumoto, M. (2003). The acrosome reaction of the spermatozoa of the inarticulate brachiopod *Lingula anatina*. In Brunton, H., Cocks, R. M., and Long, S. L., editors, *Brachiopods, Past and Present*, pages 40–45. Taylor & Francis.
- Gherardi, M., Lepore, E., Sciscioli, M., Mercurio, M., Licciano, M., and Giangrande, A. (2011). A study on spermatogenesis of three Mediterranean serpulid species. *Italian Journal of Zoology*, 78(2):174–181, doi:10.1080/11250003.2010.529468.
- Gilula, N. B. and Satir, P. (1972). The ciliary necklace. *The Journal of Cell Biology*, 53(2):494–509, doi:10.1083/jcb.53.2.494.
- Giribet, G. and Wheeler, W. C. (2002). On bivalve phylogeny: a high-level analysis of the Bivalvia (Mollusca) based on combined morphology and DNA sequence data. *Invertebrate Biology*, 121(4):271–324.
- Glenner, H., Hansen, A. J., Sørensen, M. V., Ronquist, F., Huelsenbeck, J. P., and Willerslev, E. (2004). Bayesian inference of the metazoan phylogeny; a combined molecular and morphological approach. *Current Biology*, 14(18):1644–9, doi:10.1016/j.cub.2004.09.027.
- Goffinet, G., Voss-Foucart, M.-F., and Barzin, S. (1978). Ultrastructure of the cuticle of the sipunculans *Golfingia vulgaris* and *Sipunculus nudus*. *Transactions of the American Microscopical Society*, 97(4):512–523.

- Goloboff, P. A. (1997). Self-weighted optimization: tree searches and character state reconstructions under implied transformation costs. *Cladistics*, 13(3):225–245, doi:10.1111/j.1096-0031.1997.tb00317.x.
- Goloboff, P. A. (1999). Analyzing large data sets in reasonable times: solutions for composite optima. *Cladistics*, 15(4):415–428, doi:10.1006/clad.1999.0122.
- Goloboff, P. A. (2014). Extended implied weighting. *Cladistics*, 30(3):260–272, doi:10.1111/cla.12047.
- Goloboff, P. A. and Catalano, S. A. (2016). TNT version 1.5, including a full implementation of phylogenetic morphometrics. *Cladistics*, 32(3):221–238, doi:10.1111/cla.12160.
- Goodrich, E. S. (1945). The study of nephridia and genital ducts since 1895. *The Quarterly Journal of Microscopical Science*, 86(344):113–392.
- Gordon, D. P. (1975). The resemblance of bryozoan gizzard teeth to "annelid-like" setae. *Acta Zoologica*, 56(4):283–289, doi:10.1111/j.1463-6395.1975.tb00105.x.
- Gorjansky, V. Y. and Popov, L. E. (1986). On the origin and systematic position of the calcareous-shelled inarticulate brachiopods. *Lethaia*, 19:223–240, doi:10.1111/j.1502-3931.1986.tb00737.x.
- Grobe, P. (2007). *Larval development, the origin of the coelom and the phylogenetic relationships of the Phoronida*. PhD thesis, Berlin.
- Hanken, N.-M. and Harper, D. A. T. (1985). The taxonomy, shell structure, and palaeoecology of the trimerellid brachiopod *Gasconsia* Northrop. *Palaeontology*, 28(2):243–254.
- Harper, D. A. T., Popov, L. E., and Holmer, L. E. (2017). Brachiopods: origin and early history. *Palaeontology*, 60:609–631, doi:10.1111/pala.12307.
- Haszprunar, G. (1996). The Mollusca: coelomate turbellarians or mesenchymate annelids? In Taylor, J. D., editor, *Origin and Evolutionary Radiation of the Mollusca*, pages 29–51. The Malacological Society of London, London.
- Haszprunar, G. (2000). Is the Aplacophora monophyletic? A cladistic point of view. *American Malacological Bulletin*, 15:115–130.
- Haszprunar, G. and Wanninger, A. (2008). On the fine structure of the creeping larva of *Loxosomella murmanica*: additional evidence for a clade of Kamptozoa (Entoprocta) and Mollusca. *Acta Zoologica*, 89(2), doi:10.1111/j.1463-6395.2007.00301.x.
- Havlicek, M. (1982). Lingulacea, Paterinacea, and Siphonotretacea (Brachiopoda) in the Lower Ordovician sequence of Bohemia. *Sborník geologických věd, Paleontologie*, 25:9–82, pl. 1–16.
- Herrmann, K. (1997). Phoronida. In Harrison, F. W. and Woollacott, R. M., editors, *Microscopic Anatomy of Invertebrates*, 13: Lophophorates, Entoprocta, and Cyclophora, pages 207–236. Wiley-Blackwell.
- Hodgson, A. N. and Reunov, A. A. (1994). Ultrastructure of the spermatozoon and spermatogenesis of the brachiopods *Disciniscus tenuis* (Inarticulata) and *Kraussina rubra* (Articulata). *Invertebrate Reproduction & Development*, 25(1):23–31, doi:10.1080/07924259.1994.9672365.
- Holborow, P. L., Laverack, M. S., and Barber, V. C. (1969). Cilia and other surface structures of the trochophore of *Harmothoe imbricata* (Polychaeta). *Zeitschrift für Zellforschung und Mikroskopische Anatomie*, 98(2):246–261, doi:10.1007/BF00338328.
- Holmer, L. E. (1989). Middle Ordovician phosphatic inarticulate brachiopods from Västergötland and Dalarna, Sweden. *Fossils and Strata*, 26:1–172.
- Holmer, L. E. and Caron, J.-B. (2006). A spinose stem group brachiopod with pedicle from the Middle Cambrian Burgess Shale. *Acta Zoologica*, 87:273–290, doi:10.1111/j.1463-6395.2006.00241.x.

- Holmer, L. E., Pettersson Stolk, P. S., Skovsted, C. B., Balthasar, U., and Popov, L. E. (2009). The enigmatic early Cambrian *Salanygolina* – A stem group of rhynchonelliform chileate brachiopods? *Palaeontology*, 52(1):1–10, doi:10.1111/j.1475-4983.2008.00831.x.
- Holmer, L. E., Popov, L. E., Koneva, S. P., and Rong, J.-Y. (1997). Early Cambrian Lingulellotreta (Lingulata, Brachiopoda) from south Kazakhstan (Malyi Karatau Range) and South China (eastern Yunnan). *Journal of Paleontology*, 71(4):577–584, doi:10.1017/s0022336000040063.
- Holmer, L. E., Popov, L. E., Pour, M. G., Claybourn, T., Zhang, Z.-L., Brock, G. A., and Zhang, Z.-F. (2018a). Evolutionary significance of a middle Cambrian (Series 3) *in situ* occurrence of the pedunculate rhynchonelliform brachiopod *Nisusia sulcata*. *Lethaia*, doi:10.1111/let.12254.
- Holmer, L. E., Skovsted, C. B., Brock, G. A., Valentine, J. L., and Paterson, J. R. (2008). The Early Cambrian tommotiid *Micrina*, a sessile bivalved stem group brachiopod. *Biology Letters*, 4:724–728, doi:10.1098/rsbl.2008.0277.
- Holmer, L. E., Skovsted, C. B., Larsson, C. M., Brock, G. A., and Zhang, Z.-F. (2011). First record of a bivalved larval shell in Early Cambrian tommotiids and its phylogenetic significance. *Palaeontology*, 54(2):235–239, doi:10.1111/j.1475-4983.2010.01030.x.
- Holmer, L. E., Zhang, Z.-F., Topper, T. P., Popov, L. E., and Claybourn, T. M. (2018b). The attachment strategies of Cambrian kutorginate brachiopods: the curious case of two pedicle openings and their phylogenetic significance. *Journal of Paleontology*, 92(1):33–39, doi:10.1017/jpa.2017.76.
- Hou, X.-G., Siveter, D. J., Siveter, D. J., Aldridge, R. J., Cong, P.-Y., Gabbott, S. E., and Purnell, M. A. (2017). Brachiopoda. In *The Cambrian Fossils of Chengjiang, China: The Flowering of Early Animal Life*. Blackwell.
- Hu, S.-X., Zhang, Z.-F., Holmer, L. E., and Skovsted, C. B. (2010). Soft-part preservation in a linguliform brachiopod from the lower Cambrian Wulongqing Formation (Guanshan Fauna) of Yunnan, South China. *Acta Palaeontologica Polonica*, 55(3):495–505, doi:10.4202/app.2009.1106.
- Jacquet, S. M., Brock, G. A., and Paterson, J. R. (2014). New data on *Oikozetetes* (Mollusca, Halkieriidae) from the lower Cambrian of South Australia. *Journal of Paleontology*, 88(5):1072–1084, doi:10.1666/13-137.
- Jamieson, B. G. M. (1991). *Fish Evolution and Systematics: Evidence from Spermatozoa: With a Survey of Lophophorate, Echinoderm and Protochordate Sperm and an Account of Gamete Cryopreservation*. Cambridge University Press.
- Jeuniaux, C. (1971). Chitinous structures. *Comprehensive biochemistry*, 26(C):595–632.
- Jin, Y.-G. and Wang, H.-Y. (1992). Revision of the Lower Cambrian brachiopod *Heliomedusa* Sun & Hou, 1987. *Lethaia*, 24:35–49, doi:10.1111/j.1502-3931.1992.tb01790.x.
- Kouchinsky, A. V. (2000). Skeletal microstructures of hyoliths from the Early Cambrian of Siberia. *Alcheringa: An Australasian Journal of Palaeontology*, 24(2):65–81, doi:10.1080/03115510008619525.
- Larsson, C. M., Skovsted, C. B., Brock, G. A., Balthasar, U., Topper, T. P., and Holmer, L. E. (2014). *Parerimitra pyramidalis* from South Australia: scleritome, shell structure and evolution of a lower Cambrian stem group brachiopod. *Palaeontology*, 57(2):417–446, doi:10.1111/pala.12072.
- Laurie, J. (1987). The musculature and vascular systems of two species of Cambrian Paterinide (Brachiopoda). *Bureau of Mineral Resources Journal of Australian Geology and Geophysics*, 10:261–265.
- Leise, E. M. (1988). Sensory organs in the hairy girdles of some mopaliid chitons. *American Malacological Bulletin*, 6(1):141–151.
- Leise, E. M. and Cloney, R. (1982). Chiton integument: ultrastructure of the sensory hairs of *Mopalia muscosa* (Mollusca: Polyplacophora). *Cell and Tissue Research*, 223(1):43–59, doi:10.1007/BF00221498.

- Lewis, P. O. (2001). A likelihood approach to estimating phylogeny from discrete morphological character data. *Systematic Biology*, 50(6):913–925, doi:10.1080/106351501753462876.
- Lundin, K., Schander, C., and Todt, C. (2009). Ultrastructure of epidermal cilia and ciliary rootlets in Scaphopoda. *Journal of Molluscan Studies*, 75(1):69–73, doi:10.1093/mollus/eyn042.
- MacKay, S. and Hewitt, R. A. (1978). Ultrastructural studies on the brachiopod pedicle. *Lethaia*, 11(4):331–339, doi:10.1111/j.1502-3931.1978.tb01891.x.
- Maddison, W. P. (1993). Missing data versus missing characters in phylogenetic analysis. *Systematic Biology*, 42(4):576–581, doi:10.1093/sysbio/42.4.576.
- Miles, C. M., Hadfield, M. G., and Wayne, M. L. (2007). Heritability for egg size in the serpulid polychaete *Hydroides elegans*. *Marine Ecology Progress Series*, 340(May 2014):155–162, doi:10.3354/meps340155.
- Moore, J. L. and Porter, S. M. (2018). Plywood-like shell microstructures in hyoliths from the middle Cambrian (Drumian) Gowers Formation, Georgina Basin, Australia. *Palaeontology*, 61, doi:10.1111/pala.12352.
- Morton, J. E. (1959). The habits and feeding organs of *Dentalium entalis*. *Journal of the Marine Biological Association of the United Kingdom*, 38(2):225–238, doi:10.1017/S0025315400006032.
- Moysiuk, J., Smith, M. R., and Caron, J.-B. (2017). Hyoliths are Palaeozoic lophophorates. *Nature*, 541(7637):394–397, doi:10.1038/nature20804.
- Nielsen, C. (1966). On the life-cycle of some Loxosomatidae (Entoprocta). *Ophelia*, 3(1):221–247, doi:10.1080/00785326.1966.10409644.
- Nielsen, C. (1971). Entoproct life-cycles and the entoproct/ectoproct relationship. *Ophelia*, 9(2):209–341.
- Nielsen, C. (1987). Structure and function of metazoan ciliary bands and their phylogenetic significance. *Acta Zoologica*, 68(4):205–262.
- Nielsen, C. (1991). The development of the brachiopod *Crania (Neocrania) anomala* (O. F. Müller) and its phylogenetic significance. *Acta Zoologica*, 72(1):7–28, doi:10.1111/j.1463-6395.1991.tb00312.x.
- Nielsen, C. and Rostgaard, J. (1976). Structure and function of an entoproct tentacle with a discussion of ciliary feeding types. *Ophelia*, 15(2):115–140, doi:10.1080/00785326.1976.10425453.
- Nixon, K. C. (1999). The Parsimony Ratchet, a new method for rapid parsimony analysis. *Cladistics*, 15(4):407–414, doi:10.1111/j.1096-0031.1999.tb00277.x.
- Orrhage, L. and Müller, M. C. M. (2005). Morphology of the nervous system of Polychaeta (Annelida). *Hydrobiologia*, 535–536(1):79–111, doi:10.1007/s10750-004-4375-4.
- Owen, G. and Williams, A. (1969). The caecum of articulate Brachiopoda. *Proceedings of the Royal Society B: Biological Sciences*, 172:187–201, doi:10.1098/rspb.1969.0019.
- Paterson, J. R., Brock, G. A., and Skovsted, C. B. (2009). *Oikozetetes* from the early Cambrian of South Australia: implications for halkieriid affinities and functional morphology. *Lethaia*, 42(2):199–203.
- Ponder, W. F. and Lindberg, D. R. (1997). Towards a phylogeny of gastropod molluscs: an analysis using morphological characters. *Zoological Journal of the Linnean Society*, 119(2):83–265, doi:10.1111/j.1096-3642.1997.tb00137.x.
- Popov, L. E. (1992). The Cambrian radiation of brachiopods. In Lipps, J. H. and Signor, P. W., editors, *Origin and Early Evolution of Metazoa*, pages 399–423. Pergamon.
- Popov, L. E., Bassett, M. G., Holmer, L. E., and Ghobadi Pour, G. M. (2009). Early ontogeny and soft tissue preservation in siphonotretide brachiopods: new data from the Cambrian-Ordovician of Iran. *Gondwana Research*, 16(1):151–161, doi:10.1016/j.gr.2009.01.009.

- Popov, L. E., Bassett, M. G., Holmer, L. E., Skovsted, C. B., and Zuykov, M. A. (2010). Earliest ontogeny of Early Palaeozoic Craniiformea: Implications for brachiopod phylogeny. *Lethaia*, 43(3):323–333, doi:10.1111/j.1502-3931.2009.00197.x.
- Porter, S. M. (2008). Skeletal microstructure indicates cancelloriids and halkieriids are closely related. *Palaeontology*, 51(4):865–879, doi:10.1111/j.1475-4983.2008.00792.x.
- Rannala, B., Zhu, T.-Q., and Yang, Z.-H. (2012). Tail paradox, partial identifiability, and influential priors in Bayesian branch length inference. *Molecular Biology and Evolution*, 29(1):325–335, doi:10.1093/molbev/msr210.
- Reger, J. F. (1967). A fine structure study on the organization and innervation of pharyngeal glands and associated ciliated epithelium in the annelid *Enchytraeus albidus*. *Journal of Ultrastructure Research*, 20:451–461, doi:10.1016/S0022-5320(67)80112-6.
- Reunov, A. A. and Klepal, W. (2004). Ultrastructural study of spermatogenesis in *Phoronopsis harmeri* (Lophophorata, Phoronida). *Helgoland Marine Research*, 58(1):1–10, doi:10.1007/s10152-003-0153-3.
- Rice, M. E. (1988). Observations on development and metamorphosis of *Siphonosoma cumanense* with comparative remarks on *Sipunculus nudus* (Sipuncula, Sipunculidae). *Bulletin of Marine Science*, 42(1):1–15.
- Rice, M. E. (1993). Sipuncula. In Harrison, F. W. and Rice, M. E., editors, *Microscopic anatomy of invertebrates, volume 12: Onychophora, Chilopoda, and Lesser Protostomata*, volume 12, pages 237–326. Wiley-Liss, New York.
- Richter, S., Loesel, R., Purschke, G., Schmidt-Rhaesa, A., Scholtz, G., Stach, T., Vogt, L., Wanninger, A., Brenneis, G., Döring, C., Faller, S., Fritsch, M., Grobe, P., Heuer, C. M., Kaul, S., Möller, O. S., Müller, C. H., Rieger, V., Rothe, B. H., Stegner, M. E., and Harzsch, S. (2010). Invertebrate neurophylogeny: suggested terms and definitions for a neuroanatomical glossary. *Frontiers in Zoology*, 7:29.
- Robinson, J. (2014). The muscles, body wall and valve-opening mechanism of extant craniid (inarticulated) brachiopods. *Journal of Natural History*, 48:1231–1252, doi:10.1080/00222933.2013.840941.
- Ronquist, F., Teslenko, M., van der Mark, P., Ayres, D. L., Darling, A., Höhna, S., Larget, B., Liu, L., Suchard, M. A., and Huelsenbeck, J. P. (2012). MrBayes 3.2: efficient Bayesian phylogenetic inference and model choice across a large model space. *Systematic Biology*, 61(3):539–42, doi:10.1093/sysbio/sys029.
- Rouse, G. W. (1999). Trochophore concepts: ciliary bands and the evolution of larvae in spiralian Metazoa. *Biological Journal of the Linnean Society*, 66(4):411–464, doi:10.1111/j.1095-8312.1999.tb01920.x.
- Rouse, G. W. (2000). Bias? What bias? The evolution of downstream larval-feeding in animals. *Zoologica Scripta*, 29(3):213–236, doi:10.1046/j.1463-6409.2000.00040.x.
- Rowell, A. J. and Caruso, N. E. (1985). The evolutionary significance of *Nisusia sulcata*, an early articulate brachiopod. *Journal of Paleontology*, 59(5):1227–1242.
- Ruppert, E. E. and Carle, K. J. (1983). Morphology of metazoan circulatory systems. *Zoomorphology*, 103(3):193–208, doi:10.1007/BF00310477.
- Ruppert, E. E., Fox, R. S., and Barnes, R. D. (2004). *Invertebrate zoology: a functional evolutionary approach*, volume 53. Thompson Learning.
- Ruppert, E. E. and Rice, M. E. (1995). Functional organization of dermal coelomic canals in *Sipunculus nudus* (Sipuncula) with a discussion of respiratory designs in sipunculans. *Invertebrate Biology*, 114(1):51–63.
- Santagata, S. (2004). Larval development of *Phoronis pallida* (Phoronida): implications for morphological convergence and divergence among larval body plans. *Journal of Morphology*, 259(3):347–358, doi:10.1002/jmor.10205.

- Scheltema, A. H. (1993). Aplacophora as progenetic aculiferans and the coelomate origin of mollusks as the sister taxon of Sipuncula. *Biological Bulletin (Woods Hole)*, 184(1):57–78.
- Schopf, T. J. M. and Manheim, F. T. (1967). Chemical composition of Ectoprocta (Bryozoa). *Journal of Paleontology*, 41(5):1197–1225, doi:10.2307/1302092.
- Schwabe, E. (2010). Illustrated summary of chiton terminology. *Spixiana*, 3(2):171–194.
- Schwaha, T. F. and Wanninger, A. (2015). The serotonin-like nervous system of the Bryozoa (Lophotrochozoa): A general pattern in the Gymnolaemata and implications for lophophore evolution of the phylum Evolutionary developmental biology and morphology. *BMC Evolutionary Biology*, 15(1):1–11, doi:10.1186/s12862-015-0508-9.
- Sereno, P. C. (2007). Logical basis for morphological characters in phylogenetics. *Cladistics*, 23(6):565–587, doi:10.1111/j.1096-0031.2007.00161.x.
- Shunkina, K. V., Zaytseva, O. V., Starunov, V. V., and Ostrovsky, A. N. (2015). Comparative morphology of the nervous system in three phylactolaemate bryozoans. *Frontiers in Zoology*, 12(1):1–27, doi:10.1186/s12983-015-0112-2.
- Skovsted, C. B., Betts, M. J., Topper, T. P., and Brock, G. A. (2015). The early Cambrian tommotiid genus *Dailyatia* from South Australia. *Memoirs of the Association of Australasian Palaeontologists*, 48(1):1–117.
- Skovsted, C. B., Brock, G. A., Paterson, J. R., Holmer, L. E., and Budd, G. E. (2008). The scleritome of *Eccentrotheca* from the Lower Cambrian of South Australia: Lophophore affinities and implications for tommotiid phylogeny. *Geology*, 36:171–174, doi:10.1130/g24385a.1.
- Skovsted, C. B., Brock, G. A., Topper, T. P., Paterson, J. R., and Holmer, L. E. (2011). Scleritome construction, biofacies, biostratigraphy and systematics of the tommotiid *Eccentrotheca helenia* sp. nov. from the early Cambrian of South Australia. *Palaeontology*, 54:253–286, doi:10.1111/j.1475-4983.2010.01031.x.
- Skovsted, C. B. and Holmer, L. E. (2003). Early Cambrian (Botomian) stem group brachiopod *Mickwitzia* from Northeast Greenland. *Acta Palaeontologica Polonica*, 48(1):1–20.
- Skovsted, C. B. and Holmer, L. E. (2005). Early Cambrian brachiopods from north-east Greenland. *Palaeontology*, 48(2):325–345, doi:10.1111/j.1475-4983.2005.00450.x.
- Skovsted, C. B., Holmer, L. E., Larsson, C. M., Höglström, A. E. S., Brock, G. A., Topper, T. P., Balthasar, U., Stolk, S. P., and Paterson, J. R. (2009). The scleritome of *Paterimitra*: an Early Cambrian stem group brachiopod from South Australia. *Proceedings of the Royal Society B: Biological Sciences*, 276:1651–1656, doi:10.1098/rspb.2008.1655.
- Skovsted, C. B., Knight, I., Balthasar, U., and Boyce, W. D. (2017). Depth related brachiopod faunas from the lower Cambrian Forteau Formation of southern Labrador and western Newfoundland, Canada. *Palaeontologia Electronica*, 20.3.54A:1–52, doi:10.26879/775.
- Skovsted, C. B. and Peel, J. S. (2010). Early Cambrian brachiopods and other shelly fossils from the basal Kinzers Formation of Pennsylvania. *Journal of Paleontology*, 84(4):754–762, doi:10.1666/09-123.1.
- Smith, M. R. (2012a). *Morphology, ecology, and affinity of soft-bodied ‘molluscs’ from Cambrian Burgess Shale-type deposits*. PhD thesis, University of Toronto, Toronto, Ontario.
- Smith, M. R. (2012b). Mouthparts of the Burgess Shale fossils *Odontogriffus* and *Wiwaxia*: implications for the ancestral molluscan radula. *Proceedings of the Royal Society B: Biological Sciences*, 279(1745):4287–4295, doi:10.1098/rspb.2012.1577.
- Smith, M. R. (2014). Ontogeny, morphology and taxonomy of the soft-bodied Cambrian ‘mollusc’ *Wiwaxia*. *Palaeontology*, 57(1):215–229, doi:10.1111/pala.12063.

- Smith, M. R. (2017). Quantifying and visualising divergence between pairs of phylogenetic trees: implications for phylogenetic reconstruction. *bioRxiv*, doi:10.1101/227942.
- Smith, M. R. (2018). TreeSearch: phylogenetic tree search using custom optimality criteria.
- Steiner, G. (1992). Phylogeny and classification of Scaphopoda. *Journal of Molluscan Studies*, 58(4):385–400, doi:10.1093/mollus/58.4.385.
- Streng, M., Butler, A. D., Peel, J. S., Garwood, R. J., and Caron, J.-B. (2016). A new family of Cambrian rhynchonelliformean brachiopods (Order Naukatida) with an aberrant coral-like morphology. *Palaeontology*, 59(2):269–293, doi:10.1111/pala.12226.
- Sumner-Rooney, L. H., Schrödl, M., Lodde-Bensch, E., Lindberg, D. R., Heß, M., Brennan, G. P., and Sigwart, J. D. (2015). A neurophylogenetic approach provides new insight to the evolution of Scaphopoda. *Evolution and Development*, 17(6):337–346, doi:10.1111/ede.12164.
- Sun, H.-J., Smith, M. R., Zeng, H., Zhao, F.-C., Li, G.-X., and Zhu, M.-Y. (2018). Hyoliths with pedicles constrain the origin of the brachiopod body plan. page submitted.
- Sutton, M. D., Briggs, D. E. G., Siveter, D. J., and Siveter, D. J. (2005). Silurian brachiopods with soft-tissue preservation. *Nature*, 436(7053):1013–1015, doi:10.1038/nature03846.
- Sutton, M. D. and Sigwart, J. D. (2012). A chiton without a foot. *Palaeontology*, 55(2):401–411, doi:10.1111/j.1475-4983.2011.01126.x.
- Temereva, E. N. (2017). Innervation of the lophophore suggests that the phoronid *Phoronis ovalis* is a link between phoronids and bryozoans. *Scientific Reports*, 7(1):1–12, doi:10.1038/s41598-017-14590-8.
- Temereva, E. N. and Kuzmina, T. V. (2017). The first data on the innervation of the lophophore in the rhynchonelliform brachiopod *Hemithiris psittacea*: what is the ground pattern of the lophophore in lophophorates? *BMC Evolutionary Biology*, 17(1):1–12, doi:10.1186/s12862-017-1029-5.
- Topper, T. P., Harper, D. A. T., and Ahlberg, P. (2013a). Reappraisal of the brachiopod *Acrotreta socialis* von Seebach, 1865: clarifying 150 years of confusion. *GFF*, 135(2):191–203, doi:10.1080/11035897.2013.811440.
- Topper, T. P., Holmer, L. E., Skovsted, C. B., Brock, G. A., Balthasar, U., Larsson, C. M., Petterson Stolk, P. S., and Harper, D. A. T. (2013b). The oldest brachiopods from the lower Cambrian of South Australia. *Acta Palaeontologica Polonica*, 58(1):93–109, doi:10.4202/app.2011.0146.
- Torrey, H. B. (1901). On *Phoronis pacifica* sp. nov. *Biological Bulletin*, 2(6):282–288, doi:10.2307/1535705.
- Ushatinskaya, G. T. (2016). Prolegulum and brephic shell of the earliest organophosphatic brachiopods. *Paleontological Journal*, 50(2):141–152, doi:10.1134/s0031030116020088.
- Ushatinskaya, G. T. and Korovnikov, I. V. (2016). Revision of the superfamily Acrotheloidea (Brachiopoda, class Linguliformea, order Lingulida) from the Lower and Middle Cambrian of the Siberian Platform. *Paleontological Journal*, 50(5):450–462, doi:10.1134/s0031030116050130.
- Vinther, J., Van Roy, P., and Briggs, D. E. G. (2008). Machaeridians are Palaeozoic armoured annelids. *Nature*, 451(7175):185–188, doi:10.1038/nature06474.
- Vogt, L. (2017). The logical basis for coding ontologically dependent characters. *Cladistics*, doi:10.1111/cla.12209.
- von Salvini-Plawen, L. and Steiner, G. (1996). Synapomorphies and plesiomorphies in higher classification of Mollusca. In Taylor, J. D., editor, *Origin and Evolutionary Radiation of the Mollusca*, pages 29–51. The Malacological Society of London, London.
- Wanninger, A. (2009). Shaping the things to come: ontogeny of lophotrochozoan neuromuscular systems and the tetra-neuralia concept. *Biological Bulletin*, 216(3):293–306.

- Wanninger, A., Fuchs, J., and Haszprunar, G. (2007). Anatomy of the serotonergic nervous system of an entoproct creeping-type larva and its phylogenetic implications. *Invertebrate Biology*, 126(3):268–278, doi:10.1111/j.1744-7410.2007.00097.x.
- Wanninger, A. and Haszprunar, G. (2001). The expression of an engrailed protein during embryonic shell formation of the tusk-shell, *Antalis entalis* (Mollusca, Scaphopoda). *Evolution & Development*, 3(5):312, doi:10.1046/j.1525-142X.2001.01034.x.
- Wanninger, A. and Haszprunar, G. (2002a). Chiton myogenesis: perspectives for the development and evolution of larval and adult muscle systems in molluscs. *Journal of Morphology*, 251(2):103–113, doi:10.1002/jmor.1077.
- Wanninger, A. and Haszprunar, G. (2002b). Muscle development in *Antalis entalis* (Mollusca, Scaphopoda) and its significance for scaphopod relationships. *Journal of Morphology*, 254(1):53–64, doi:10.1002/jmor.10004.
- Wanninger, A., Koop, D., Bromham, L., Noonan, E., and Degnan, B. M. (2005). Nervous and muscle system development in *Phascolion strombus* (Sipuncula). *Development Genes and Evolution*, 215(10):509–518, doi:10.1007/s00427-005-0012-0.
- Watkins, R. (2002). New record of the trimerellid brachiopod *Gasconsia*, a rare Silurian Lazarus taxon. *Journal of Paleontology*, 76(1):185–186, doi:10.1666/0022-3360(2002)076<0185:nrotdb>2.0.co;2.
- Wiens, J. J. (1998). Does adding characters with missing data increase or decrease phylogenetic accuracy? *Systematic Biology*, 47(4):625–640, doi:10.1080/106351598260635.
- Wiens, J. J. (2003). Missing data, incomplete taxa, and phylogenetic accuracy. *Systematic Biology*, 52(4):528–538, doi:10.1080/10635150390218330.
- Williams, A. and Brunton, C. H. C. (1993). Role of shell structure in the classification of the orthotetidine brachiopods. *Palaeontology*, 36:931–966.
- Williams, A., Carlson, S. J., Brunton, C. H. C., Holmer, L. E., and Popov, L. E. (1996). A supra-ordinal classification of the Brachiopoda. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 351(1344):1171–1193, doi:10.1098/rstb.1996.0101.
- Williams, A., Carlson, S. J., Brunton, C. H. C., Holmer, L. E., Popov, L. E., Mergl, M., Laurie, J. R., Bassett, M. G., Cocks, L. R. M., Rong, J.-Y., Lazarev, S. S., Grant, R. E., Racheboeuf, P. R., Jin, Y.-G., Wardlaw, B. R., Harper, D. A. T., and Wright, A. D. (2000). Linguliformea, Craniiformea, and Rhynchonelliformea (part). In *Treatise on Invertebrate Paleontology, Part H, Brachiopoda (Revised)*, volume 2 & 3, pages 1–919. Geological Society of America & Paleontological Institute.
- Williams, A., Cusack, M., and Mackay, S. (1994). Collagenous chitino-phosphatic shell of the brachiopod *Lingula*. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 346:223–266, doi:10.1098/rstb.1994.0143.
- Williams, A., Holmer, L. E., and Cusack, M. (2004). Chemico-structure of the organophosphatic shells of siphonotretide brachiopods. *Palaeontology*, 47(5):1313–1337, doi:10.1111/j.0031-0239.2004.00404.x.
- Williams, A., James, M. A., Emig, C. C., Mackay, S., Rhodes, M. C., Cohen, B. L., Gawthrop, A. B., Peck, L. S., Curry, G. B., Ansell, A. D., Cusack, M., Walton, D., Brunton, C. H. C., Mackinnon, D. I., and Richardson, J. R. (1997). Introduction. In *Treatise on Invertebrate Paleontology, Part H, Brachiopoda (Revised)*, volume 1, pages 1–539. Geological Society of America & Paleontological Institute.
- Williams, A., Mackay, S., and Cusack, M. (1992). Structure of the organo-phosphatic shell of the brachiopod *Discina*. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 337:83–104, doi:10.1098/rstb.1992.0086.
- Williams, A., Popov, L. E., Holmer, L. E., and Cusack, M. (1998). The diversity and phylogeny of the paterinate brachiopods. *Palaeontology*, 41:221–262.

- Williams, A., Racheboeuf, P. R., Savage, N. M., Lee, D. E., Popov, L. E., Carlson, S. J., Logan, A., Luter, C., Cusack, M., Curry, G. B., Wright, A. D., Harper, D. A. T., Cohen, B. L., Cocks, L. R. M., MacKinnon, D. I., Smirnova, T. N., Baker, P. G., Carter, J. L., Gourvennec, R., Mancenido, M. O., Brunton, C. H. C., Dong-Li, D.-S., Boucot, A. J., Bassett, M. G., Alvarez, F., Holmer, L. E., Mergl, M., Emig, C. C., Rubel, M., and Jia-Yu, J.-R. (2007). Supplement. In *Treatise on Invertebrate Paleontology, Part H, Brachiopoda (Revised)*, volume 6, pages 2321–3226. Geological Society of America & Paleontological Institute.
- Williams, A., Sandy, M. R., Carlson, S. J., Lee, D. E., Johnson, J. G., Smirnova, T. N., Jin, Y.-G., Hou, H.-F., Carter, J. L., Gourvennec, R., Racheboeuf, P. R., Brunton, C. H. C., Dagys, A. S., Curry, G. B., Baker, P. G., Sun, D.-L., and MacKinnon, D. I. (2006). Rhynchonelliformea (part). In *Treatise on Invertebrate Paleontology, Part H, Brachiopoda (Revised)*, volume 5, pages 1689–2320. Geological Society of America & Paleontological Institute.
- Wingstrand, K. G. (1985). On the anatomy and relationships of Recent Monoplacophora. *Galathea Report*, 16:7–94.
- Young, C. M. (2002). *Atlas of Marine Invertebrate Larvae*. Academic Press, New York.
- Zhang, C., Rannala, B., and Yang, Z.-H. (2012). Robustness of compound Dirichlet priors for Bayesian inference of branch lengths. *Systematic Biology*, 61(5):779–84, doi:10.1093/sysbio/sys030.
- Zhang, Z.-F., Han, J., Zhang, X.-L., Liu, J.-N., Guo, J.-F., and Shu, D.-G. (2007a). Note on the gut preserved in the Lower Cambrian *Lingulellotreta* (Lingulata, Brachiopoda) from southern China. *Acta Zoologica*, 88(1):65–70, doi:10.1111/j.1463-6395.2007.00252.x.
- Zhang, Z.-F., Holmer, L. E., Ou, Q., Han, J., and Shu, D.-G. (2011a). The exceptionally preserved Early Cambrian stem rhynchonelliform brachiopod *Longtancunella* and its implications. *Lethaia*, 44(4):490–495, doi:10.1111/j.1502-3931.2011.00261.x.
- Zhang, Z.-F., Holmer, L. E., Popov, L. E., and Shu, D.-G. (2011b). An obolellate brachiopod with soft-part preservation from the Early Cambrian Chengjiang fauna of China. *Journal of Paleontology*, 85(3):460–463, doi:10.1666/10-121.1.
- Zhang, Z.-F., Holmer, L. E., Skovsted, C. B., Brock, G. A., Budd, G. E., Fu, D., Zhang, X.-L., Shu, D.-G., Han, J., Liu, J.-N., Wang, H., Butler, A., and Li, G.-X. (2013). A sclerite-bearing stem group entoproct from the early Cambrian and its implications. *Scientific Reports*, 3:1066, doi:10.1038/srep01066.
- Zhang, Z.-F., Li, G.-X., Emig, C. C., Han, J., Holmer, L. E., and Shu, D.-G. (2009). Architecture and function of the lophophore in the problematic brachiopod *Heliomedusa orientalis* (Early Cambrian, South China). *Geobios*, 42(5):649–661, doi:10.1016/j.geobios.2009.04.001.
- Zhang, Z.-F., Li, G.-X., Holmer, L. E., Brock, G. A., Balthasar, U., Skovsted, C. B., Fu, D.-J., Zhang, X.-L., Wang, H.-Z., Butler, A. D., Zhang, Z.-L., Cao, C.-Q., Han, J., Liu, J.-N., and Shu, D.-G. (2014). An early Cambrian agglutinated tubular lophophorate with brachiopod characters. *Scientific Reports*, 4:4682, doi:10.1038/srep04682.
- Zhang, Z.-F., Shu, D.-G., Emig, C. C., Zhang, X.-L., Han, J., Liu, J.-N., Li, Y., and Guo, J.-F. (2007b). Rhynchonelliformean brachiopods with soft-tissue preservation from the early Cambrian Chengjiang Lagerstätte of South China. *Palaeontology*, 50:1391–1402, doi:10.1111/j.1475-4983.2007.00725.x.
- Zhang, Z.-F., Shu, D.-G., Han, J., and Liu, J.-N. (2004). New data on the lophophore anatomy of Early Cambrian linguloids from the Chengjiang Lagerstätte, Southwest China. *Carnets de géologie (Notebooks on geology)*, 4:1–7, doi:10.4267/2042/310.
- Zhang, Z.-F., Shu, D.-G., Han, J., and Liu, J.-N. (2007c). A gregarious lingulid brachiopod *Longtancunella chengjiangensis* from the Lower Cambrian, South China. *Lethaia*, 40(1):11–18, doi:10.1111/j.1502-3931.2006.00002.x.

- Zhang, Z.-F., Smith, M. R., and Shu, D.-G. (2015). New reconstruction of the *Wiwaxia* scleritome, with data from Chengjiang juveniles. *Scientific Reports*, 5:14810, doi:10.1038/srep14810.
- Zhang, Z.-L., Skovsted, C. B., and Zhang, Z.-F. (2018). A hyolithid without helens preserving the oldest hyolith muscle scars; palaeobiology of *Paramicrocornus* from the Shujingtuo Formation (Cambrian Series 2) of South China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 489:1–14, doi:10.1016/j.palaeo.2017.07.021.
- Zhang, Z.-L., Zhang, Z.-F., and Wang, H.-Z. (2016). Epithelial cell moulds preserved in the earliest acrotretid brachiopods from the Cambrian (Series 2) of the Three Gorges area, China. *GFF*, 138(4):455–466, doi:10.1080/11035897.2016.1143528.
- Zhao, F.-C., Smith, M. R., Yin, Z.-J., Zeng, H., Li, G.-X., and Zhu, M.-Y. (2017). *Orthrozancus elongata* n. sp. and the significance of sclerite-covered taxa for early trochozoan evolution. *Scientific Reports*, 7(1):16232, doi:10.1038/s41598-017-16304-6.
- Zhuravlev, A. Y., Wood, R. A., and Penny, A. M. (2015). Ediacaran skeletal metazoan interpreted as a lophophorate. *Proceedings of the Royal Society B: Biological Sciences*, 282(1818):20151860, doi:10.1098/rspb.2015.1860.
- Zimmer, R. L. and Woollacott, R. M. (2013). Metamorphosis, ancestrulae and coloniality in Bryozoan life cycles. In Woollacott, R. M. and Zimmer, R. L., editors, *Biology of Bryozoans*, pages 91–142. Elsevier.