

Supplementary material

Item 1: Phylogenetic matrix

The matrix is supplied as a NEXUS (.nex) file is available online as a Supplementary Data File.

Item 2: Phylogenetic character list

Full, referenced list of morphological characters used in phylogenetic component of this study.

Head, anterior trunk, proboscis etc.

1. Cephalization:

(0) Proboscis

(1) Distinct head region clearly discriminated

New character description

Non-panarthropod ecdysozoans typically exhibit an anterior proboscis armed with scalds or other armament, innervated by a ring-shaped circumoral brain, whereas panarthropods generally possess a distinct head region with a dorsal condensed ganglionic brain (Martin and Mayer 2014; Martin-Duran *et al.* 2016). Not all lobopodians exhibit a clearly discriminated head region however, with some taxa exhibiting an anterior trunk region with no appendages that thins anteriorly such as *Microdictyon* (Liu and Dunlop 2014), *Paucipodia* (Hou *et al.* 2004), and *Diania* (see Ma *et al.* 2014). Another study (Ou and Mayer 2018) reported head appendages and a mouth opening in *Diania* on the end of the body interpreted as posterior by Ma *et al.* (2014), but we consider these structures to be equivocal.

2. Proboscis invaginable (introvert):

(0) Absent

(1) Present

(-) Inapplicable if proboscis absent (character 1).

Modified from character 1 in Harvey *et al.* (2010)

3. Degree to which the introvert can be invaginated:

(0) Partially invaginable (i.e., part of Zone I)

(1) Completely invaginable into the trunk (i.e., to the base of Zone I)

(-) Inapplicable if proboscis not invaginable (character 2)

Modified from character 2 in Harvey *et al.* (2010)

4. Introvert represents 30-50% of body length:

(0) Absent

(1) Present

(-) Inapplicable if proboscis not invaginable (character 2)

Modified from character 71 in Harvey *et al.* (2010)

5. Bulbous head:

(0) Absent

(1) Present

(-) Inapplicable if distinct head region not clearly discriminated (character 1)

New character description

This character refers to the particularly large ovoid head region of certain lobopodians, lacking a dorsal head sclerite such as *Hallucigenia fortis* (Ma *et al.* 2012; Liu and Dunlop 2014) and *Cardiodictyon* (Liu and Dunlop 2014).

6. Anterior sclerite “cap”:

(0) Absent

(1) Present

(-) Inapplicable if distinct head not clearly discriminated (character 1)

New character description

This character refers to the isolated anterior sclerite partially covering the head region of some luolishaniid lobopodians, including *Luolishania* (Ma *et al.* 2009), *Collinsium* (Yang *et al.* 2015) and *Collinsovermis* (Caron and Aria 2020).

7. Head covered by sclerites

Absent (0)

Present (1)

(-) Inapplicable if distinct head not clearly discriminated (character 1)

Modified from character 2 in Yang *et al.* (2015)

8. Head shield formed by fused cephalic segments:

(0) Absent

(1) Present

(-) Inapplicable if head not covered by sclerites (character 7)

Modified from character 3 in Yang *et al.* (2015)

9. Isolated, articulating dorsal sclerite associated with eye-stalks and innervated by the protocerebrum:

(0) Absent

(1) Present

(-) Inapplicable if distinct head region not clearly discriminated (character 1), or head shield formed by fused cephalic segments present (character 8)

Modified from character 4 in Yang *et al.* (2015)

Additional comments: Character definition revised to indicate the association of this sclerite to the protocerebrum as well as eyestalks in radiodonts and other lower stem group arthropods (Cong *et al.* 2014; Ortega-Hernández 2015). Homology with the sclerites of luolishaniids (see character 3) not assumed, as there is no evidence these sclerite “caps” articulate.

10. Shape of isolated dorsal sclerite associated with eyestalks and protocerebrum:

(0) Semi-circular/rounded

(1) Well-developed and elongate

(-) Inapplicable if dorsal sclerite associated with eye-stalks and innervated by the protocerebrum is absent (character 9).

Modified from character 5 in Yang *et al.* (2015)

11. Extent of coverage of dorsal isolated dorsal sclerite associated with eyestalks and protocerebrum on head:

- (0) Broad attachment to the cephalic region
- (1) Narrow attachment with anterior edge of cephalic region
- (-) Inapplicable if dorsal sclerite associated with eye-stalks and innervated by the protocerebrum is absent (character 9).

Modified from character 6 in Yang *et al.* (2015)

12. Isolated lateral sclerites, forming tri-partite carapace:

- (0) Absent
- (1) Present
- (-) Inapplicable if cephalic shield formed from fused segments is present (character 8), or head not covered by sclerites (character 7).

Modified from character 7 in Yang *et al.* (2015)

Sensory structures

13. Eyes:

- (0) Absent
- (1) Present

Character 29 in Yang *et al.* (2015)

14. Eye attachment

- (0) Sessile
- (1) Stalked
- (-) Inapplicable if eyes absent (character 13).

Character 30 in Yang *et al.* (2015)

15. Five stalked eyes:

(0) Absent

(1) Present

(-) Inapplicable if eye stalks absent (character 14).

New character description

Five eyestalks are present in a similar arrangement in opabiniids (Whittington 1975; Budd 1996; Budd & Daley 2012; Pates *et al.* 2021) and *Kylinxia* (Zeng *et al.* 2020).

16. Type of eyes:

(0) Single lens eye or pigment spots

(1) Multiple visual units (including compound eyes)

(-) Inapplicable if eyes absent (character 13)

Character 31 in Yang *et al.* (2015)

17. Lateral amphids:

(0) Absent

(1) Present

New character description

This character refers to the pair of bilateral cephalic sense organs possessed by many nematodes (e.g. Jones 1979; Lee 2002).

18. Trunk tumuli:

(0) Absent

(1) Present

Character 25 in Harvey *et al.* (2010)

19. Trunk tubuli:

(0) Absent

(1) Present

Character 26 in Harvey *et al.* (2010)

20. Flosculi, N-flosculi or sensory spots:

- (0) Absent
- (1) Present

Character 27 in Harvey *et al.* (2010)

Oral, circumoral and pharyngeal morphology

21. Mouth opening orientation:

- (0) Terminal
- (1) Ventral
- (2) Posterior

Modified from character 7 in Yang *et al.* (2015)

Additional comments: A number of Cambrian lobopodians are scored as having ventral mouths in Yang *et al.* (2015). In the case of *Pambdelurion*, which has a ventral mouth similar to radiodonts (Vinther *et al.* 2016) this is justified. However, we argue this is not justified in taxa with a terminal mouth, but a downward facing head and gut track such as *Collinsium*, *Hallucigenia*, *Microdictyon* and *Luolishania* (Chen *et al.* 1995; Hou and Bergström, 1995; Ma *et al.* 2009; Yang *et al.* 2015; Ortega-Hernandez *et al.* 2017). In these taxa, the position of the mouth relative to the head does not differ from other lobopodians with terminal mouths such as *Aysheaia* or *Onychodictyon*, only the orientation of the head and gut track.

22. One or more pairs of appendages located anteriorly relative to the mouth opening:

- (0) Absent
- (1) Present
- (-) Inapplicable if limbs absent (character 77)

Character 24 in Yang *et al.* (2015)

23. Mouth cone:

- (0) Absent

(1) Present

Character 42 in Harvey *et al.* (2010)

24. Mouth tube:

(0) Absent

(1) Present

New character description

This character refers to the protruding buccal tube of some loriciferans, which extends beyond the mouth cone (Neves *et al.* 2016).

25. Subdivided pharyngostome:

(0) Absent

(1) Present

New character description

This character refers to the specialised, subdivided anterior region of the pharynx in nematodes, which may bear tooth-like structures (Decraemer *et al.* 2014).

26. Metastegosomal teeth:

(0) Absent

(1) Present

(-) Inapplicable if subdivided pharyngostome is absent (character 25)

New character description

This character refers to the teeth ornamenting the metastegosomal portion of the pharyngostome of some nematodes (Decraemer *et al.* 2014).

27. Odontostyle:

(0) Absent

(1) Present

(-) Inapplicable if metastegomal teeth absent (character 26)

New character description

This character refers to the stylet structure that may replace the metastegosomal teeth in mature stages of some nematodes (Decraemer *et al.* 2014).

28. Radially symmetrical circumoral structures (i.e. Conway Morris Zone I armed):

(0) Absent

(1) Present

Character 25 in Yang *et al.* (2015)

The zonation system of Conway Morris (1977), wherein Zone I refers to the introvert scalids, Zone II the collar, and Zone III the pharyngeal tooth rings is not applicable across the diversity of Ecdysozoa without some degree of modification and reasoning. Zone II (the collar, representing a diastema in-between the mouth and pharynx, which may or may not be armed) is only consistent between priapulans and priapulan-like fossil worms (including palaeoscolecids). However, Zone I and Zone III armament essentially equate to the circumoral armature and the pharyngeal armature respectively which are widespread in ecdysozoans (see Smith and Caron, 2015). As such, circumoral and pharyngeal armament in non-priapulans will be coded as Zone I and Zone III structures accordingly, whereas Zone II characters will be coded inapplicable to taxa not exhibiting a collar.

29. General form of radial circumoral structures (i.e. Conway Morris Zone I):

(0) Scalids – hollow spines with apical pore and sensory cells surrounded by a thin layer of cuticle (scalidophorans)

(1) Hooks composed exclusively of cuticle (nematomorphs, some nematodes)

(2) Oral papillae or lamellae (some tardigrades, some lobopodians)

(3) Radial plates organised as a mouth apparatus (some lobopodians, radiodonts)

- (4) "Lips" (some nematodes, possibly *Shergoldana*)
- (5) Cephalic setae (some nematodes)
- (-) Inapplicable if radially symmetrical circumoral structures absent (character 28)

Modified from character 26 in Yang *et al.* (2015), and character 40 in Harvey *et al.* (2010)

30. Zone I armature comprises:

- (0) Fewer than 3 rings
- (1) Many rings (i.e. more than 3)
- (-) Inapplicable if radially symmetrical circumoral structures absent (character 28).

New character description

The introverts of scalidophorans usually comprise numerous transverse rings of armature in complex radially symmetrical patterns (e.g. Adrianov & Malakhov, 2001), whereas the circumoral structures of other ecdysozoans usually comprise only 1-3 transverse rings. Nematoids exhibit up to 3 rings of circumoral structures (6 + 6 + 4 pattern typical in nematodes, Decraemer *et al.* 2014; 6 + 6 + 6 in nematomorphs, Schmidt-Rhaesa 2013), and panarthropod circumoral structures comprise typically 1 ring (e.g. the radiodont oral cone/apparatus, Daley and Bergström 2012).

31. Arrangement of Zone I armature into discrete parallel longitudinal rows:

- (0) Absent
- (1) Present
- (-) Inapplicable if radially symmetrical circumoral structures absent (character 28).

Modified from character 4 in Harvey *et al.* (2010)

32. Unarmed distal introvert:

- (0) Absent
- (1) Present

(-) Inapplicable if scalids absent (character 29).

New character description

The introverts of cricocosmiids and *Maotianshania* (Huang 2005) and seemingly *Markuelia* (see reconstruction in Dong *et al.* 2010) bear a smooth region lacking spines/scalids towards the posterior of the introvert, preceding the trunk annulations.

33. Symmetry of circumoral structures:

(0) Hexaradial

(1) Pentaradial

(2) Tetraradial

(3) Triradial

(4) Octaradial

(-) Inapplicable if circumoral structures absent (character 28).

Modified from character 5 in Harvey *et al.* (2010)

34. Anterior ring of anteriorly directed jointed, broad appendages:

(0) Absent

(1) Present

(-) Inapplicable if radially symmetrical circumoral structures absent (character 28).

New character description

This character refers to the clavoscalids of loriciferans (Neves *et al.* 2016), which are observed in the Cambrian small carbonaceous fossil taxon *Eolorica* (Harvey and Butterfield 2017).

35. Sexual dimorphism of clavoscalids:

(0) Clavoscalids all the same

(1) Branched clavoscalids in males

(-) Inapplicable if clavoscalids absent (character 34).

New character description

This character refers to the sexual dimorphism of the clivoscalids in Nanaloricidae (Neves *et al.* 2016).

36. Rings of segmented, elongated spinose appendages:

(0) Absent

(1) Present

(-) Inapplicable if radially symmetrical circumoral structures absent (character 28).

New character description

This character refers to the spinoscalids of loriciferans (Neves *et al.* 2016) and kinorhynchs (Neuhaus 2013), though their homology is uncertain.

37. Double organ:

(0) Absent

(1) Present

(-) Inapplicable if spinoscalids absent (character 35).

New character description

This character refers to the fusion of anterior spinoscalids in pliciloricids, known as the double organ (Neves *et al.* 2016).

38. Trichoscalids:

(0) Absent

(1) Present

New character description

This character refers to the scalid-like structures, with a distinct base and shaft, in loriciferans (Neves *et al.* 2016) and kinorhynchs (Neuhaus 2013).

39. Number of trichoscalids on proximal part of Zone I

(0) 0

(1) 6

(2) 14

(-) Inapplicable if trichoscalids are absent (character 38).

Character 18 in Wang *et al.* (2021)

40. Number of elements comprising the first three rings and, hence, defining the number of longitudinal rows of elements in Zone I (assuming there are more than three):

(0) ≤ 20

(1) 25

(2) >25

(-) Inapplicable if circumoral structures not arranged in many rings (character 30).

Modified from character 7 in Harvey *et al.* (2010)

41. Zone II:

(0) Unarmed

(1) Armed

(-) Inapplicable if zone II absent (see discussion in character 28)

Modified from character 10 in Harvey *et al.* (2010)

42. Number of elements in the proximal circlet of Zone II:

(0) Numerous (>8)

(1) Eight

(2) <8

(-) Inapplicable if collar/zone II absent or unarmed (character 41).

Modified from character 11 in Harvey *et al.* (2010)

43. Coronal spines at boundary of Zones I and II:

- (0) Absent
- (1) Present, undifferentiated
- (2) Present, elongate spines
- (-) Inapplicable if collar absent or unarmed (character 41).

Modified from character 13 in Wills *et al.* (2012)

44. Structure of mouth apparatus:

- (0) Variable number of undifferentiated plates
- (1) Plates with differentiation of enlarged plates
- (-) Inapplicable if radial plates organised as a mouth apparatus absent (character 29).

Modified from character 27 in Yang *et al.* (2015)

45. Zone III:

- (0) Unarmed
- (1) Armed

Character 12 in Harvey *et al.* (2010)

46. Zone III comprises sclerotized pharyngeal teeth circlets:

- (0) Absent
- (1) Present
- (-) Inapplicable if Zone III unarmed (character 45).

Modified from character 13 in Smith and Caron (2015)

47. Number of circlets of Zone III armature:

- (0) 1-4
- (1) 6-8

(2) 16 or more

(-) Inapplicable if Zone III armature does not comprise circlets of teeth (character 46).

Modified from character 13 in Harvey *et al.* (2010)

48. General morphology of proximal circlets of Zone III armature (teeth):

(0) Absent

(1) Spines or papillae

(2) Multispinose

(3) Multispinose but massively reduced

(4) Hooks

(5) Conical with a fringe of spines

(6) Sclerotized trabeculae

(7) Pectinate

(8) Conical papillae terminating in a long spine (prickle)

(-) Inapplicable if Zone III armature does not comprise circlets of teeth (character 46).

Modified from character 14 in Harvey *et al.* (2010)

49. Morphology of middle circlets of Zone III armature (teeth):

(0) Absent

(1) Spines or papillae

(2) Multispinose

(3) Pectinate

(-) Inapplicable if Zone III armature does not comprise circlets of teeth (character 46).

Modified from character 15 in Harvey *et al.* (2010)

50. Morphology of distal circlets of Zone III armature:

(0) Absent

(1) Spines

(2) Multispinose

(3) Pectinate

(-) Inapplicable if Zone III armature does not comprise circlets of teeth (character 46).

Modified from character 16 in Harvey *et al.* (2010)

51. Number of elements in the first circlet of pharyngeal armature (base on Zone III):

(0) >10

(1) 10

(2) 5

(-) Inapplicable if Zone III armature does not comprise circlets of teeth (character 456).

Modified from character 17 in Harvey *et al.* (2010)

52. Pentaradial symmetry of Zone III armature:

(0) Absent

(1) Present

(-) Inapplicable if Zone III unarmed, i.e. pharyngeal armature absent (character 45).

Modified from character 18 in Harvey *et al.* (2010)

53. Number of proximal pentagonal circlets in Zone III:

(0) None

(1) Five

(2) Six

(3) Seven

(-) Inapplicable if Zone III armature does not comprise circlets of teeth (character 46).

Modified from character 18 in Harvey *et al.* (2010)

54. Teeth of second circle of the larvae with very small median denticle:

(0) Absent

(1) Present

(-) Inapplicable if Zone III armature does not comprise circlets of teeth (character 46).

Character 72 in Harvey *et al.* (2010)

55. Distal portion of Zone III expanded into a bulb:

(0) Absent

(1) Present

(-) Inapplicable if Zone III not eversible (character 56).

Modified from character 20 in Harvey *et al.* (2010)

56. Zone III eversibility:

(0) No degree of eversibility

(1) Eversible (to any degree)

Modified from character 21 in Harvey *et al.* (2010)

57. Eversibility of Zone III:

(0) Completely eversible

(1) Incompletely eversible, eversible beyond the proximal teeth

(2) Eversible only as far as the proximal teeth

(-) Inapplicable if Zone III not eversible (character 56).

Modified from character 21 in Harvey *et al.* (2010).

58. Cone-like eversible pharynx:

- (0) Absent
- (1) Present
- (-) Inapplicable if pharynx not eversible (character 56)

Character 70 in Harvey *et al.* (2010)

59. All Zone III elements:

- (0) Of approximately equal size
- (1) Decreasing regularly in size from the posterior to the anterior
- (-) Inapplicable if Zone III armature does not comprise circlets of teeth (character 46).

Modified from character 22 in Harvey *et al.* (2010)

60. Radial oral stylets in mouth cone:

- (0) Absent
- (1) Present
- (-) Inapplicable if mouth cone absent (character 23).

Character 34 in Wang *et al.* (2021)

61. Number of radial oral stylets:

- (0) 4
- (1) 6
- (2) 8
- (3) 9
- (-) Inapplicable if radial oral stylets absent (character 60).

Character 35 in Wang *et al.* (2021)

62. Placids:

(0) Absent

(1) Present

Character 43 in Wang *et al.* (2021)

63. Number of placids

(0) 8

(1) 16

(-) Inapplicable if placids absent (character 62).

Character 44 in Wang *et al.* (2021)

64. Triradial cuticular thickenings ornamenting pharynx:

(0) Absent

(1) Present

New character description

This character refers to triradial cuticular thickenings in the pharynxes of tardigrades (mucrons, Guidetti *et al.* 2012) and loriciferans (placoids, Neves *et al.* 2016).

65. Pharyngeal lumina:

(0) Round

(1) Triradiate

Character 73 in Harvey *et al.* (2010)

Trunk region

66. Locomotion by peristaltic contraction:

(0) Absent

(1) Present

Modified from character 68 in Harvey *et al.* (2010)

67. Body musculature:

- (0) Circular and longitudinal peripheral musculature
- (1) Longitudinal peripheral only
- (2) Metameric skeletal musculature

Modified from characters 112-114 in Zhang *et al.* (2016)

68. Circular musculature inside longitudinal musculature:

- (0) Circular muscles inside longitudinal
- (1) Longitudinal muscles inside circular
- (-) Inapplicable if circular peripheral musculature absent, or metameric skeletal musculature is present (character 67).

Character 115 from Zhang *et al.* (2016)

69. Dorsal integument sclerotized and connected by arthrodial membranes:

- (0) Absent
- (1) Present

Character 33 in Yang *et al.* (2015)

70. Sternites connected by arthrodial membranes:

- (0) Absent
- (1) Present
- (-) Inapplicable if dorsal sclerotized integument absent (character 69).

Character 34 in Yang *et al.* (2015)

71. Trunk integument subdivided into 11 subunits covered by dorsal and ventral plates:

(0) Absent

(1) Present

New character description

This character refers to the 11 zonites of kinorhynchs, which externally subdivide the trunk morphology of all living members of the group (see Neuhaus, 2013).

72. Neck-like constriction on lobopodous trunk:

(0) Absent

(1) Present

(-) Inapplicable if paired appendages absent (character 78), or sclerotized dorsal integument with arthrodial membranes present (character 69).

Character 35 in Yang *et al.* (2015)

73. Annulations:

(0) Absent

(1) Present

Character 26 in Daley *et al.* (2009)

74. Papillae on annulations:

(0) Absent

(1) Present

(-) Inapplicable if annulations absent (character 73).

Modified from character 41 in Ma *et al.* (2009)

75. Branching of annular rings:

(0) Unbranched

(1) Branched

(-) Inapplicable if annulations absent (character 73).

Character 51 in Zhang *et al.* (2016)

76. Serially repeated mid-gut glands:

(0) Absent

(1) Present

Character 52 in Yang *et al.* (2015)

Serially repeated trunk nodes/sclerites

77. Trunk with serially repeated paired ventral/ventrolateral structures:

(0) Absent

(1) Present

New character description

See main text.

78. Form of serially repeated paired ventral/ventrolateral trunk structures:

(0) Spines/protuberances

(1) Moveable limbs producing an overall gait – i.e. paired appendages

(-) Inapplicable if paired ventral structures are absent (character 77).

New character description

See main text.

79. Serially repeated epidermal specializations:

(0) Absent

(1) Present

Modified from character 39 in Yang *et al.* (2015).

See main text.

80. Position of serially repeated epidermal specializations:

(0) Dorsal/lateral/dorsolateral longitudinal rows

- (1) Incomplete transverse rings
- (2) Complete transverse rings
- (-) Inapplicable: serially repeated epidermal specializations absent (character 79).

New character description

See main text.

81. Nature of serially repeated epidermal dorsolateral specializations:

- (0) Epidermal depressions
- (1) Epidermal evaginations
- (-) Inapplicable: serially repeated epidermal specializations absent (character 79).

Modified from character 40 in Yang et al. (2015).

Additional comments: Only *Cricocosmia* was scored by Yang *et al.* (2015), which was coded as present for evaginations, as in lobopodians. We score *Tabelliscolex* and *Tylotites* as evaginations in addition.

82. Proportions of serially repeated epidermal trunk evaginations:

- (0) Wider than tall (e.g. nodes or plates)
- (1) Taller than wide (e.g. spines)
- (-) Inapplicable if serially repeated epidermal evaginations are absent (character 81).

Modified from character 41 in Yang et al. (2015)

Additional comments: Wider than tall (nodes, plates) coded for *Cricocosmia* and *Tabelliscolex*, taller than wide coded for *Tylotites*.

83. Serially repeated epidermal evaginations with acute distal termination:

- (0) Absent
- (1) Present
- (-) Inapplicable if serially repeated epidermal evaginations are absent (character 81).

Modified from character 42 in Yang et al. (2015)

84. Acute distal termination in serially repeated epidermal evaginations is curved:

(0) Absent

(1) Present

(-) Inapplicable if serially repeated epidermal evaginations with acute distal termination are absent (character 83).

Modified from character 43 in Yang *et al.* (2015).

Additional comments: Coded absent for *Cricocosmia* and present for *Tylotites*.

85. Sclerotization of serially repeated epidermal evaginations:

(0) Absent

(1) Present

(-) Inapplicable if serially repeated epidermal evaginations are absent (character 81).

Modified from character 44 in Yang *et al.* (2015).

Additional comments: Coded present for *Cricocosmia*, *Tabelliscolex* and *Tylotites*. Coded uncertain (?) for the hallucigeniid lobopodian *Thanohita* (Siveter *et al.* 2018), which has unique specializations that are difficult to assess in terms of composition owing to the mode of preservation (within siderite concretion, reconstructed tomographically).

86. Serially repeated sclerite ornamentation:

(0) Net-like

(1) Scaly

(-) Inapplicable if serially repeated epidermal specializations not sclerotized (character 85).

Modified from character 45 in Yang *et al.* (2015).

Additional comments: *Tabelliscolex* bears the distinct net-like ornament (see Fig. 4 in main text and Han *et al.* 2007) similar to *Cricocosmia* and various lobopodians (see Steiner *et al.* 2012). *Tylotites* sclerites have not been investigated.

87. Composition of serially repeated sclerites:

(0) Phosphatic

(1) Carbonaceous.

(-) Inapplicable if serially repeated epidermal specializations not sclerotized (character 85).

New character description

Not all sclerite-bearing taxa have been investigated in a geochemical context, but work so far shows two alternative compositions: phosphatic or carbonaceous. The lobopodians *Microdictyon*, *Onychodictyon* and *Hallucigenia hongmeia* appear to be phosphatic (Steiner et al. 2012). *H. sparsa* and *H. fortis* however exhibit carbonaceous sclerites (Caron et al. 2013; Smith and Ortega-Hernandez 2014).

88. Sclerites (including serially repeated sclerites) consist of a stack of constituent elements:

- (0) Absent
- (1) Present
- (-) Inapplicable if sclerites absent

Modified from character 46 in Yang et al. (2015)

Additional comments: In the original version of this character, the absence of appendages with terminal claws in taxa was also coded inapplicable (-). We have removed this criteria so as to be inclusive of the sclerite-bearing palaeoscolecid-like taxa, which are all coded as uncertain (?).

89. Maximum number of primary serially repeated epidermal specializations above each pair of paired ventral structures:

- (0) One
- (1) Two
- (2) Three
- (3) Four
- (4) Five
- (5) Seven
- (-) Inapplicable if serially repeated epidermal specializations are absent (character 79).

Modified from character 47 in Yang et al. (2015)

Additional comments: *Tabelliscolex* has up to three sclerites above the paired ventral projections, two lateral and one dorsal. The exact number of sclerites in the transverse rings

of *Tylotites* is not clear, and it is also unclear whether it has paired ventral projections, and so is coded uncertain (?).

90. **'Secondary' sclerotized dorsolateral spines:**

(0) Absent

(1) Present

(-) Inapplicable if epidermal evaginations absent (character 81).

Character 48 in Yang *et al.* (2015)

91. **Serially repeated sclerotized spine-like evaginations of variable length along the body:**

(0) Similar length along body

(1) Variable length along body

(-) Inapplicable if serially repeated epidermal evaginations not spinose (character 82).

Modified from character 49 in Yang *et al.* (2015)

Additional comments: The Burgess Shale Collins' Monster has now been described as *Collisovermis monstruosus* (Caron and Aria 2020) and can now be coded as present for this character.

92. **Spacing between serially repeated epidermal specializations along longitudinal body axis:**

(0) Regularly spaced

(1) Irregularly spaced

(-) Inapplicable if serially repeated epidermal specializations absent (character 79).

Modified from character 50 in Yang *et al.* (2015)

Additional comments: Coded as regularly spaced for *Cricocosmia*, *Tabelliscolex* and *Tylotites*. *Collinsovermis* and *Acinocricus* scored as regularly spaced from Caron and Aria (2020).

93. **Correspondence of serially repeated dorsolateral epidermal specializations to ventral paired structures:**

(0) 1:1 relationship

(1) 2:1 relationship

(2) 3:1 relationship

(3) 4:1 relationship

(-) Inapplicable if serially repeated epidermal specializations (character 79) or paired ventral structures absent (character 77).

New character description

See main text.

94. Variation in morphology of serially repeated epidermal specializations between groups:

(0) Absent

(1) Two alternating morphologies along length of trunk

(2) Two alternate morphologies in anterior and posterior regions of trunk

(-) Inapplicable if serially repeated epidermal specializations are absent (character 79).

New character description

This character discriminates the alternating morphologies of sclerite groups in *Luolishania* and *Collinsovermis*. In *Luolishania*, there are set alternating sets of serially repeated spinose sclerites along the length of the trunk – triplets of elongate spines (with associated trunk lobopods) and pairs short spines (see Figs. 4, 5 and 11 in Ma *et al.* 2009). In *Collinsovermis*, the first three pairs of trunk lobopods are associated with a pair of spines, whereas lobopods 4-14 are associated with a triplet (see Figs. 3 and 4 in Caron and Aria, 2020).

Anterior and head appendages

95. Differentiated anterior appendages:

(0) Absent

(1) Present

(-) Inapplicable if paired appendages absent (character 78).

New character description

Many lobopodian taxa exhibit structurally/functionally differentiated appendages in their anterior trunk/head region. This includes the antenniform head appendages of some luolishaniids (Ma *et al.* 2009; Ortega-Hernandez *et al.* 2017; Caron and Aria 2020), *Onychodictyon* (Ou *et al.* 2012) and *Antennacanthapodia* (Ou *et al.* 2011). Other examples include the raptorial head appendages of *Aysheaia* (Whittington 1978), giant lobopodians (Liu *et al.* 2006; 2007; Dzik 2011; Vannier *et al.* 2014), and gilled lobopodians (Budd and Daley 2012; Vinther *et al.* 2016; Park *et al.* 2018; Pates *et al.* 2021). Some lobopodians however exhibit no appendages on their head/anterior region. *Paucipodia* (Hou *et al.* 2004), *Microdictyon* (Liu and Dunlop 2014), *Xenusion* (Dzik and Krumbiegel 1989) and *Diania* (Ma *et al.* 2014) bear no appendages on their anteriormost trunk region, and appear to lack a distinct head. Hallucigeniids show differentiated trunk appendages, but no appendages on the head, which is distinct however (Smith and Ortega-Hernandez 2014; Smith and Caron 2015).

96. Nature of post-ocular (post-protocerebral) body appendages:

- (0) Lobopodous
- (1) Arthropodized (sclerotized, arthrodial membranes present)
- (-) Inapplicable if paired appendages absent (character 78).

Character 8 in Yang *et al.* (2015)

97. Sclerotization of pre-ocular (protocerebral) limb pair:

- (0) Not sclerotized
- (1) Sclerotized
- (-) Inapplicable if paired appendages absent (character 78).

Character 9 in Yang *et al.* (2015)

98. Pre-ocular (protocerabral) limb pair with arthrodial membranes:

- (0) Absent
- (1) Present
- (-) Inapplicable if protocerebral limbs not sclerotized (character 97).

Character 10 in Yang *et al.* (2015)

99. Nature of post-ocular lobopodous inner branch:

- (0) Cylindrical/subconical appendage
- (1) Laterally expanded swimming flap
- (-) Inapplicable if post-ocular limbs are arthropodized (character 96).

Character 11 in Yang *et al.* (2015)

100. Nature of first post-ocular (deutocerebral) appendage:

- (0) Lobopodous ambulatory limb
- (1) Lobopodous sensorial limb
- (2) Lobopodous limb with sclerotized jaw
- (3) Arthropodized antenniform with distinct podomeres
- (4) Arthropodized short great-appendage
- (5) Arthropodized undifferentiated biramous appendage
- (-) Inapplicable if paired appendages absent (character 78).

Character 12 in Yang *et al.* (2015)

101. Inner blade of deutocerebral jaw with diastema:

- (0) Absent
- (1) Present
- (-) Inapplicable if deutocerebral jaw absent (character 100).

Character 13 in Yang *et al.* (2015)

102. Deutocerebral limb pair structurally differentiated from rest of trunk appendages:

- (0) Absent
- (1) Present
- (-) Inapplicable if paired appendages absent (character 78).

Character 14 in Yang *et al.* (2015)

103. **Nature of second post-ocular (tritocerebral) appendage:**

- (0) Undifferentiated lobopodous limb
- (1) Specialized papillae
- (2) Arthropodized ambulatory limb with distinct podomeres
- (3) Arthropodized specialized post-antennal appendage
- (–) Inapplicable if paired appendages absent (character 78).

Character 15 in Yang *et al.* (2015)

104. **Position of pre-ocular (protocerebral) appendage pair:**

- (0) Lateral
- (1) Ventral
- (2) Terminal
- (–) Inapplicable if paired appendages are absent (character 78).

Character 16 in Yang *et al.* (2015)

105. **Pre-ocular (protocerebral) appendage pair fused:**

- (0) Not fused
- (1) Fused
- (–) Inapplicable if paired appendages absent (character 78).

Character 17 in Yang *et al.* (2015)

106. **Nature of pre-ocular (protocerebral) appendage fusion:**

- (0) Basal only, with separate distal elements
- (1) Fused into a labrum or equivalent structure
- (2) Reduced labrum
- (–) Inapplicable if protocerebral appendages not fused (character 105).

Character 18 in Yang *et al.* (2015)

Additional discussion: Additional state added (2) to incorporate the further reduction of the labrum in chelicerates, which has also recently been described in the megacheiran *Leancoilia* (Liu *et al.* 2020).

107. **Spines/spinules on pre-ocular (protocerebral) appendage:**

(0) Absent

(1) Present

(–) Inapplicable if paired appendages absent (character 78), or protocerebral appendages fused into a labrum (character 106).

Character 19 in Yang *et al.* (2015)

108. **Number of spine/spinule series on pre-ocular (protocerebral) frontal appendage:**

(0) One series

(1) Two series

(–) Inapplicable if protocerebral appendages fused into labrum (character 106), or spines/spinules on protocerebral appendages absent (character 107).

Character 20 in Yang *et al.* (2015)

109. **Coplanar spine/spinule series in pre-ocular (protocerebral) frontal appendages:**

(0) Absent

(1) Present

(–) Inapplicable if protocerebral appendages fused into labrum (character 106), or spines/spinules on protocerebral appendages absent (character 107).

Character 21 in Yang *et al.* (2015)

110. **Multifurcate distal termination of protocerebral appendage**

(0) Absent

(1) Present

(-) Inapplicable if protocerebral appendages fused into labrum (character 106) or spines/spinules on protocerebral appendages absent (character 107).

Character 22 in Yang *et al.* (2015)

Trunk appendages:

111. Trunk exites:

(0) Absent

(1) Present

(-) Inapplicable if paired appendages absent (character 78).

Character 20 in Van Roy *et al.* (2015)

112. Exite organisation:

(0) Lanceolate dorsal blades

(1) Simple oval paddle with marginal spines

(2) Bipartite shaft with lamellar setae

(3) Book gill/lung or equivalent

(-) Inapplicable if trunk exites absent (character 111)

Character 54 in Yang *et al.* (2015)

113. Exites/lanceolate dorsal blades associated with dorsolateral flaps:

(0) Absent

(1) Present

(-) Inapplicable if post-ocular limbs biramous (character 115).

Character 55 in Yang *et al.* (2015)

114. Exite/setal blade distribution:

(0) Confined laterally

(1) Present dorsally

(-) Inapplicable if exites absent (character 111), or if dorsal integument is sclerotized (character 69).

Character 51 in Van Roy *et al.* (2015)

115. **Dorsal flaps/exites fused with endopod into biramous appendage:**

(0) Not fused

(1) Fused

(-) Inapplicable if trunk exites absent (character 111).

Character 57 in Yang *et al.* (2015)

116. **Antero-posteriorly compressed protopodite with gnathobasic endites in post-deutocerebral appendage pair:**

(0) Absent

(1) Present

(-) Inapplicable if post-ocular limbs not arthropodized (character 96).

Character 58 in Yang *et al.* (2015)

117. **Setae on lobopodous limbs:**

(0) Absent

(1) Present

(-) Inapplicable if post-ocular limbs not lobopodous (character 96).

Modified from character 59 and 60 in Yang *et al.* (2015)

118. **Appendicules on lobopodous limbs:**

(0) Absent

(1) Present

(-) Inapplicable if limbs not lobopodous (character 96).

Modified from character 59 and 60 in Yang *et al.* (2015)

119. **Papillae on lobopodous limbs:**

(0) Absent

(1) Present

(-) Inapplicable if limbs not lobopodous (character 96).

Character 10 in Ma et al. (2014)

120. **Papillae with terminal spine:**

(0) Spine absent

(1) Spine present

(-) Inapplicable if papillae on lobopods absent (character 119).

Character 77 in Zhang et al. (2016)

121. **Finger-like elements in distal tip of limbs:**

(0) Absent

(1) Present

(-) Inapplicable if paired appendages absent (character 78).

Character 63 in Yang et al. (2015)

122. **Terminal claws on trunk limbs:**

(0) Absent

(1) Present

(-) Inapplicable if paired appendages absent (character 78).

Character 64 in Yang et al. (2015)

123. **Terminal claws with multiple branches:**

(0) Absent

(1) Present

(-) Inapplicable if terminal claws absent (character 122).

Character 65 in Yang et al. (2015)

124. **Number of claws on trunk limbs:**

- (0) One
- (1) Two
- (2) Three
- (3) Four
- (4) Seven
- (-) Inapplicable if terminal claws absent (character 122).

Character 66 in Yang *et al.* (2015)

125. **Differentiated distal foot in lobopodous trunk limbs:**

- (0) Absent
- (1) Present
- (-) Inapplicable if paired appendages absent (character 78), post-ocular appendages arthropodized (character 96), or inner branch modified as lateral flaps (character 113).

Character 67 in Yang *et al.* (2015)

126. **Hypertrophied set of anterior body flaps**

- (0) Absent
- (1) Present
- (-) Inapplicable if inner branch is not a lateral flap (characters 111-115) and dorsolateral flaps absent

Character 68 in Yang *et al.* (2015)

127. **Strengthening ray in lateral flaps:**

- (0) Absent
- (1) Present
- (-) Inapplicable if inner branch is not a lateral flap and dorsolateral flaps absent (characters 111-115).

Character 37 in Daley *et al.* (2009)

128. **Posterior tapering of lateral flaps:**

(0) Absent

(1) Present

(-) Inapplicable if inner branch is not a lateral flap and dorsolateral flaps absent (characters 111-115).

Character 40 in Daley *et al.* (2009)

129. **Anterior sets of reduced lateral flaps**

(0) Absent

(1) Present

(-) Inapplicable if inner branch is not a lateral flap and dorsolateral flaps absent (characters 111-115).

Character 71 in Yang *et al.* (2015)

130. **Lobopodous limbs differentiated into two batches of multiple anterior/long and posterior/short limbs:**

(0) Absent

(1) Present

(-) Inapplicable if post-ocular limbs not lobopodous (character 96)

Character 38 in Ma *et al.* (2014)

131. **Number of anterior morphologically differentiated elongated limbs:**

(0) Five

(1) Six

(-) Inapplicable if lobopodous morphologically distinct batches absent (character 130).

Character 73 in Yang *et al.* (2015)

132. **Appendages comprise 15 or more podomeres:**

(0) Absent

(1) Present

(-) Inapplicable if postocular limbs not arthropodized (character 96).

Character 74 in Yang *et al.* (2015)

Posterior region

133. Limbless posterior extension of the lobopodous trunk beyond the last appendage pair:

(0) Absent

(1) Present

(-) Inapplicable if trunk limbs arthropodized (character 96) or dorsal trunk covered by sclerotized plates (character 69).

Character 75 in Yang *et al.* (2015)

134. Posterior tagma composed of three paired lateral flaps:

(0) Absent

(1) Present

(-) Inapplicable if inner branch is not a lateral flap and dorsolateral flaps absent (characters 111-115).

Character 42 in Daley *et al.* (2009)

135. Posterioormost trunk appendage pair structurally differentiated:

(0) Absent

(1) Present

(-) Inapplicable if paired appendages absent (character 78)

Character 77 in Yang *et al.* (2015)

136. Nature of differentiated posterior appendages:

(0) Appendicular tail

(1) Partially fused/reduced walking legs

(-) Inapplicable if posterior appendages undifferentiated (character 135).

Character 78 in Yang *et al.* (2015)

137. **Nature of appendicular tail:**

(0) Tail rami

(1) Tail flaps

(2) Setiferous tail

(-) Inapplicable if appendicular tail absent (character 136).

Character 79 in Yang *et al.* (2015)

138. **Claws on posterior appendages directed anteriad:**

(0) Normal orientation (claws pointing posteriad)

(1) Rotated anteriad

(-) Inapplicable if appendages lack terminal claws (character 122) or appendicular tail is present (character 136).

Character 80 in Yang *et al.* (2015)

139. **Swollen hook-bearing posterior:**

(0) Absent

(1) Present

Character 184 in Howard *et al.* (2020)

140. **Posterior ring papillae:**

(0) Absent

(1) Present

Character 28 in Harvey *et al.* (2010)

141. **Eversible bursa:**

(0) Absent

(1) Present

Character 29 in Harvey *et al.* (2010)

142. **Caudal appendage(s):**

(0) Absent

(1) Present

Character 31 in Harvey *et al.* (2010)

143. **Division of caudal appendage(s):**

(0) Unpaired

(1) Paired

(-) Inapplicable if caudal appendage absent (character 142).

Modified from character 32 in Harvey *et al.* (2010)

144. **Caudal appendage vesiculate:**

(0) Absent

(1) Present

(-) Inapplicable if caudal appendage absent (character 142).

Character 33 in Harvey *et al.* (2010)

145. **Caudal appendage thin and tail-like:**

(0) Absent

(1) Present

(-) Inapplicable if caudal appendage absent (character 142).

New character description

146. **Terminally posterior spines, hooks, or cones of basal diameter >20% of trunk diameter:**

- (0) Absent
- (1) Present

Character 93 in Harvey *et al.* (2010)

147. **Number of terminally posterior spines, hooks:**

- (0) One
- (1) One pair
- (2) Three
- (3) Two pairs
- (4) Three pairs

(-) Inapplicable if terminally posterior spines, hooks, cones etc. absent (character 146).

Modified from character 94 in Harvey *et al.* (2010)

148. **Arc or ring of posterior spines or hooks:**

- (0) Absent
- (1) Present

Character 95 in Harvey *et al.* (2010)

Cuticle:

149. **Cuticle surface with ornament of tessellating polygons:**

- (0) Absent
- (1) Present

Character 91 in Harvey *et al.* (2010)

Soft tissue organisation

150. **Polythyridium:**

- (0) Absent
- (1) Present

Character 34 in Harvey *et al.* (2010)

151. **Ventral nerve cord unpaired throughout its length:**

- (0) Paired
- (1) Unpaired

Character 48 from Harvey *et al.* (2010)

152. **Ventral nerve cord with paired ganglia:**

- (0) Absent
- (1) Present

Character 81 in Yang *et al.* (2015)

153. **Brain type:**

- (0) Condensed dorsal ganglional
- (1) Circumpharyngeal

Character 57 in Harvey *et al.* (2010)

154. **Apical part of the brain composed on perikarya:**

- (0) Absent
- (1) Present

Character 58 in Harvey *et al.* (2010)

155. **Two rings of retractor muscles attached through the collar-shaped brain:**

(0) Absent

(1) Present

(-) Inapplicable if collar-shaped (circumpharyngeal) brain absent (character 153).

Modified from character 60 in Harvey *et al.* (2010)

156. **Pharyngeal nervous system comprised of numerous tooth ganglia connected by a diagonal nerve net:**

(0) Absent

(1) Present

Character 66 in Harvey *et al.* (2010)

157. **Number of neuromeres integrated into the dorsal condensed brain:**

(0) One

(1) Two

(2) Three

(-) Inapplicable if dorsal condensed brain absent (character 153).

Character 83 in Yang *et al.* (2015)

158. **Mouth innervation relative to brain neuromeres:**

(0) Protocerebral innervation

(1) Deutocerebral innervation

(2) Innervation from multiple neuromeres

(-) Inapplicable if dorsal condensed brain absent (character 153).

Character 84 in Yang *et al.* (2015)

159. **Nerve cord lateralised:**

(0) Absent

(1) Present

(-) Inapplicable if dorsal condensed brain absent (character 153).

Character 85 in Yang *et al.* (2015)

160. **Dorsal heart:**

(0) Absent

(1) Present

Character 86 from Yang *et al.* (2015)

161. **Protonephridia:**

(0) Absent

(1) Present

Character 52 in Harvey *et al.* (2010)

162. **Protonephridia flow into the gonoduct and/or are integrated into the gonad (= urogenital system):**

(0) Absent

(1) Present

(-) Inapplicable if protonephridia absent (character 161).

Modified from character 53 in Harvey *et al.* (2010)

163. **Urogenital system attached to the body wall by a ligament:**

(0) Absent

(1) Present

(-) Inapplicable if protonephridia/urogenital system absent (character 162).

Modified from character 54 in Harvey *et al.* (2010)

Development and reproduction:

164. **Developmental mode:**

- (0) Direct
- (1) Distinct larval stages

Modified from character 36 in Harvey *et al.* (2010)

165. **Loricata stage in life cycle:**

- (0) Absent
- (1) Present

Modified from character 37 in Harvey *et al.* (2010)

166. **Lorica present in larva:**

- (0) Absent
- (1) Present
- (-) Inapplicable if loricate stage absent (character 165).

New character description

167. **Lorica present in adult:**

- (0) Absent
- (1) Present
- (-) Inapplicable if loricate stage absent (character 165).

New character description

168. **Loricata macrofaunal form:**

(0) Absent

(1) Present

(-) Inapplicable if loricata stage absent (character 165).

New character description

169. **Lorica subdivided into two transverse bands of seven plates:**

(0) Absent

(1) Present

(-) Inapplicable if loricata stage absent (character 165).

New character description

170. **Lorica opens posteriorly and preceded by a vermiform trunk:**

(0) Absent

(1) Present

(-) Inapplicable if loricata stage absent (character 165).

New character description

171. **Lorica with circular cross-section:**

(0) Absent

(1) Present

(-) Inapplicable if loricata stage absent (character 165).

New character description

172. **Lorica of the larvae dorso-ventrally flattened (at least in older stages), with 6 lateral plates in-folded accordion-like:**

(0) Absent

(1) Present

(-) Inapplicable if lorica is absent (character 165).

Character 63 in Harvey *et al.* (2010)

173. **Cuticle of the lorica thickened in dorsal and ventral plates (at least) with sculpture of four to six longitudinal rows of narrow, rectangular fields:**

(0) Absent

(1) Present

(-) Inapplicable if lorica is absent (character 165).

Character 64 from Harvey *et al.* (2010)

174. **Lorica with plicae:**

(0) Absent

(1) Present

(-) Inapplicable if lorica is absent (character 165).

New character description

175. **Lorica separated from introvert by a neck:**

(0) Absent

(1) Present

(-) Inapplicable if lorica is absent (character 165).

New character description

176. **Larvae with six long pharynx retractor muscles:**

(0) Absent

(1) Present

(-) Inapplicable if direct developing (character 164).

Character 67 in Harvey *et al.* (2010)

177. **Division of the body into a distinct proboscis and abdomen in the
juvenile/larva:**

(0) Absent

(1) Present

Modified from character 44 in Harvey *et al.* (2010)

178. **Cloaca in both sexes:**

(0) Absent

(1) Present

Character 51 from Harvey *et al.* (2010)

179. **Spermatozoa without a flagellum:**

(0) Absent

(1) Present

Character 55 in Harvey *et al.* (2010)

Supplementary references

1. Adrianov, A.V. & Malakhov, V.V. 2001. Symmetry of priapulids (Priapulida). 1. Symmetry of adults. *Journal of Morphology*, **247**, 99-110.
2. Budd, G.E. 1996. The morphology of *Opabinia regalis* and the reconstruction of the arthropod stem-group. *Lethaia*, **29**, 1-14.
3. Budd, G.E. & Daley, A.C. 2012. The lobes and lobopods of *Opabinia regalis* from the middle Cambrian Burgess Shale. *Lethaia*, **45**, 83-95.
4. Caron, J-B. & Aria, C. 2020. The Collins' monster, a spinous suspension-feeding lobopodian from the Cambrian Burgess Shale of British Columbia. *Palaeontology*, **63**, 979-994.
5. Caron, J.B., Smith, M.R. & Harvey, T. H. 2013. Beyond the Burgess Shale: Cambrian microfossils track the rise and fall of hallucigeniid lobopodians. *Proceedings of the Royal Society B: Biological Sciences*, **280**, 20131613.
6. Chen, J-Y., Zhou, G-Q. & Ramsköld, L. 1995. The Cambrian lobopodian *Microdictyon sinicum*. *Collection and Research*, **5**, 1-93.
7. Cong, P-Y., Ma, X-Y., Hou, X-G., Edgecombe, G.D. & Strausfeld, N.J. 2014. Brain structure resolves the segmental affinity of anomalocaridid appendages. *Nature*, **513**, 538-542.
8. Conway Morris, S. 1977. Fossil priapulid worms. *Special Papers in Palaeontology*, **20**, 1-95.
9. Daley, A.C. & Bergström, J. 2012. The oral cone of *Anomalocaris* is not a classic "peytoia". *Naturwissenschaften*, **99**, 501-504.
10. Daley, A.C., Budd, G.E., Caron, J.B., Edgecombe, G.D. & Collins, D. 2009. The Burgess Shale anomalocaridid *Hurdia* and its significance for early euarthropod evolution. *Science*, **323**, 1597-1600.
11. Decraemer, W., Coomans, A. & Baldwin, J. 2014. Morphology of Nematoda. In Schmidt-Rhaesa, A. (ed.) *Handbook of Zoology Gastrotricha, Cycloneuralia and Ganthifera Volume 2: Nematoda*. Walter de Gruyter GmbH, Berlin/Boston, pp. 1-59.
12. Dong, X-P., Bengtson, S., Gostling, N.J., Cunningham, J.A., Harvey, T.H.P., Kouchinsky, A., Val'Kov, A.K., Repetski, J.E., Stampanoni, M., Marone, F. & Donoghue, P.C.J. 2010.

- The anatomy, taphonomy, taxonomy and systematic affinity of *Markuelia*: Early Cambrian to Early Ordovician scalidophorans. *Palaeontology*, **53**, 1291–1314.
13. Dzik, J. 2011. The xenusian-to-anomalocaridid transition within the lobopodians. *Bollettino della Società Paleontologica Italiana*, **50**, 65-74.
 14. Dzik, J., & Krumbiegel, G. 1989. The oldest 'onychophoran' *Xenusion*: a link connecting phyla? *Lethaia*, **22**, 169–182.
 15. Guidetti, R., Altiero, T., Marchioro, T., Amade, L.S., Avdonina, A.M., Bertolani, R. & Rebecchi, L. 2012. Form and function of the feeding apparatus in Eutardigrada (Tardigrada). *Zoomorphology*, **131** 127–148.
 16. Harvey, T.H.P., Dong, X-P. & Donoghue, P. C. J. 2010. Are palaeoscolecsids ancestral ecdysozoans? *Evolution & Development*, **12**, 177–200.
 17. Harvey, T.H. & Butterfield, N.J. 2017. Exceptionally preserved Cambrian loriciferans and the early animal invasion of the meiobenthos. *Nature Ecology & Evolution*, **1**, 1-5.
 18. Hou, X-G., Ma, X-Y., Zhao, J., and Bergström, J. 2004. The lobopodian *Paucipodia inermis* from the Lower Cambrian Chengjiang fauna, Yunnan, China. *Lethaia*, **37**, 235–244.
 19. Hou, X-G. & Bergström, J. 1995. Cambrian lobopodians-ancestors of extant onychophorans? *Zoological Journal of the Linnean Society*, **114**, 3-19.
 20. Howard, R.J., Edgecombe, G.D., Shi, X-M., Hou, X-G. & Ma, X-Y. 2020. Ancestral morphology of Ecdysozoa constrained by an early Cambrian stem group ecdysozoan. *BMC Evolutionary Biology*, **20**, 1-18.
 21. Huang, D-Y. 2005. *Early Cambrian Worms from SW China: Morphology, Systematics, Lifestyle and Evolutionary Significance*. Unpublished PhD thesis, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing. 245 pp.
 22. Jones, G.M. 1979. The development of amphids and amphidial glands in adult Syngamus trachea (Nematoda: Syngamidae). *Journal of Morphology*, **160**, 299-321.
 23. Lee, D.L. 2002. The biology of nematodes. CRC Press.
 24. Liu, Y., Ortega-Hernández, J., Zhai, D-Y. & Hou, X-G. 2020. A reduced labrum in a Cambrian great-appendage Euarthropod. *Current Biology*, **30**, 3057-3061.

25. Liu, J-N. & Dunlop, J.A. 2014. Cambrian lobopodians: a review of recent progress in our understanding of their morphology and evolution. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **398**, 4–15.
26. Liu, J-N., Shu, D-G., Han, J., Zhang, Z-F. & Zhang, X-L. 2006. A large xenusiid lobopod with complex appendages from the Lower Cambrian Chengjiang Lagerstätte. *Acta Palaeontologica Polonica*, **51**, 215-222.
27. Liu, J-N., Shu, D-G., Han, J., Zhang, Z-F. & Zhang, X-L.(2007. Morpho-anatomy of the lobopod *Magadictyon* cf. *haikouensis* from the Early Cambrian Chengjiang Lagerstätte, South China. *Acta Zoologica*, **88**, 279-288.
28. Ma, X-Y., Hou, X-G. & Bergström, J. 2009. Morphology of *Luolishania longicuris* (Lower Cambrian, Chengjiang Lagerstätte, SW China) and the phylogenetic relationships within lobopodians. *Arthropod Structure & Development*, **38**, 271–291.
29. Ma, X-Y., Hou, X-G., Aldridge, R.J., Siveter, D.J., Siveter, D.J., Gabbott, S.E., Purnell, M.A., Parker, A.R. & Edgecombe, G.D. 2012. Morphology of Cambrian lobopodian eyes from the Chengjiang Lagerstätte and their evolutionary significance. *Arthropod Structure & Development*, **41**, 495-504.
30. Ma, X-Y., Edgecombe, G.D., Legg, D.A. & Hou, X-G. 2014. The morphology and phylogenetic position of the Cambrian lobopodian *Diania cactiformis*. *Journal of Systematic Palaeontology*, **12**, 445-457.
31. Martín-Durán, J.M., Wolff, G.H., Strausfeld, N.J. & Hejnol, A. 2016. The larval nervous system of the penis worm *Priapulius caudatus* (Ecdysozoa). *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371**, 20150050.
32. Martin, C. & Mayer, G. 2014. Neuronal tracing of oral nerves in a velvet worm—implications for the evolution of the ecdysozoan brain. *Frontiers in Neuroanatomy*, **8**, 7.
33. Neuhaus, B. 2013. Kinorhyncha. In Schmidt-Rhaesa, A. (ed.) *Handbook of Zoology Gastrotricha, Cycloneuralia, and Ganthifera Volume 1: Nematomorpha, Priapulida, Kinorhyncha, Loricifera*. Walter de Gruyter GmbH, Berlin/Boston, pp. 181–348.
34. Neves, R.C., Reichert, H., Sørensen, M.V. & Kristensen, R.M. 2016. Systematics of phylum Loricifera: identification keys of families, genera and species. *Zoologischer Anzeiger*, **265**, 141-170.

35. Ortega-Hernández, J. (2015). Homology of head sclerites in Burgess Shale euarthropods. *Current Biology*, 25(12), 1625-1631.
36. Ortega- Hernández, J., Janssen, R. & Budd, G. 2017. Origin and Evolution of the Panarthropod Head-a Deep Time Perspective. *Integrative and Comparative Biology*, 57, 369.
37. Ou, Q. & Mayer, G. 2018. A Cambrian unarmoured lobopodian, † *Lenisambulatrix humboldti* gen. et sp. nov., compared with new material of † *Diania cactiformis*. *Scientific Reports*, 8, 1-10.
38. Ou, Q., Shu, D-G. & Mayer, G. 2012. Cambrian lobopodians and extant onychophorans provide new insights into early cephalization in Panarthropoda. *Nature communications*, 3, 1-7.
39. Ou, Q., Liu, J-N., Shu, D-G., Han, J., Zhang, Z-F., Wan, X-Q. & Lei, Q-P. 2011. A rare onychophoran-like lobopodian from the Lower Cambrian Chengjiang Lagerstätte, southwestern China, and its phylogenetic implications. *Journal of Paleontology*, 85, 587-594.
40. Park, T-Y.S., Kihm, J-H., Woo, J., Park, C., Lee, W.Y., Smith, M.P., Harper, D.A.T., Young, F., Nielsen, A.T. & Vinther, J. (2018). Brain and eyes of Kerygmachela reveal protocerebral ancestry of the panarthropod head. *Nature communications*, 9(1), 1-7.
41. Pates, S., Wolfe, J.M., Lerosey-Aubril, R., Daley, A.C., & Ortega-Hernández, J. (2021). New opabiniid diversifies the weirdest wonders of the euarthropod lower stem group. *bioRxiv*.
42. Schmidt-Rhaesa, A. 2013. Nematomorpha. In Schmidt-Rhaesa, A. (ed.) *Handbook of Zoology Gastrotricha, Cycloneuralia, and Ganthifera Volume 1: Nematomorpha, Priapulida, Kinorhyncha, Loricifera*. Walter de Gruyter GmbH, Berlin/Boston, pp. 29–145.
43. Siveter, D.J., Briggs, D.E.G., Siveter, D.J., Sutton, M.D. & Legg, D. 2018. A three-dimensionally preserved lobopodian from the Herefordshire (Silurian) Lagerstätte, UK. *Royal Society Open Science*, 5, 172101.
44. Smith, M.R. & Caron JB. 2015. *Hallucigenia*'s head and the pharyngeal armature of early ecdysozoans. *Nature*, 523, 75–78.
45. Smith, M.R. & Ortega-Hernández, J. 2014. *Hallucigenia*'s onychophoran-like claws and

- the case for Tactopoda. *Nature*, **514**, 363–366.
46. Steiner, M., Hu, S-H., Liu, J-N. & Keupp, H. 2012. A new species of *Hallucigenia* from the Cambrian Stage 4 Wulongqing Formation of Yunnan (South China) and the structure of sclerites in lobopodians. *Bulletin of Geosciences*, **87**, 107–124.
 47. Van Roy, P., Daley, A.C. & Briggs, D.E. 2015. Anomalocaridid trunk limb homology revealed by a giant filter-feeder with paired flaps. *Nature*, **522**, 77-80.
 48. Vannier, J., Liu, J-N., Lerosey-Aubril, R., Vinther, J. & Daley, A.C. 2014. Sophisticated digestive systems in early arthropods. *Nature communications*, **5**, 1-9.
 49. Vinther, J., Porras, L., Young, F.J., Budd, G.E. & Edgecombe, G.D. 2016. The mouth apparatus of the Cambrian gilled lobopodian *Pambdelurion whittingtoni*. *Palaeontology*, **59**, 841-849.
 50. Wang, D., Vannier, J., Aria, C., Sun, J. & Han, J. (2021). Tubicolous priapulid *Selkirkia* from early Cambrian, south China. Online preprint.
 51. Whittington, H.B. 1975. The enigmatic animal *Opabinia regalis*, middle Cambrian, burgess shale, British Columbia. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **271**, 1-43.
 52. Whittington, H.B. 1978. The Lobopod Animal *Aysheaia pedunculata* Walcott, Middle Cambrian, Burgess Shale, British Columbia. *Philosophical Transaction of the Royal Society London B: Biological Sciences*, **284**, 165–197.
 53. Wills, M.A., Gerber, S., Ruta, M. & Hughes, M. 2012. The disparity of priapulid, archaeopriapulid and palaeoscolecoid worms in the light of new data. *Journal of Evolutionary Biology*, **25**, 2056–2076.
 54. Yang, J., Ortega-Hernández, J., Gerber, S., Butterfield, N.J., Hou, J., Lan, T. & Zhang, X-G. 2015. A superarmored lobopodian from the Cambrian of China and early disparity in the evolution of Onychophora. *Proceedings of the National Academy of Sciences USA*, **112**, 8678–8683.
 55. Zeng, H., Zhao, F-C., Niu, K-C., Zhu, M-Y. & Huang, D-Y. 2020. An early Cambrian euarthropod with radiodont-like raptorial appendages. *Nature*, **588**, 101-105.
 56. Zhang, X-G., Smith, M.R., Yang, J., & Hou, J-B. 2016. Onychophoran-like musculature in a phosphatized Cambrian lobopodian. *Biology Letters*, **12**, 20160492.

Item 3: Four supplementary figures

Three full phylogenetic topologies not included in Figure 7 in the main text, and an additional graph showing the relationship between length-width ratio of *Tabelliscolex* sclerites from anterior to posterior.

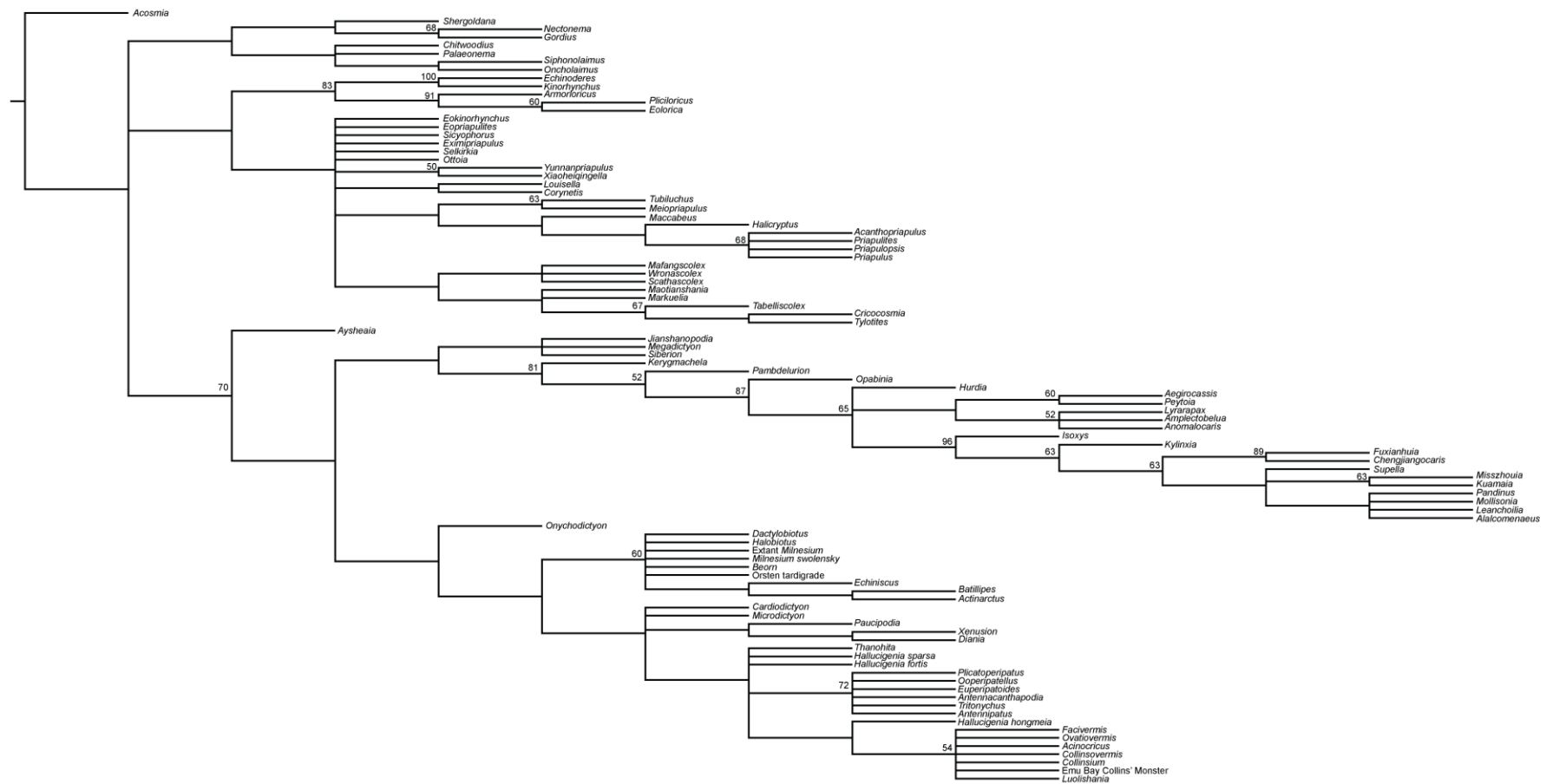


Figure S1. Full results of equal weights parsimony tree searches. New technology search under default parameters, showing a strict consensus of six most parsimonious trees, with nodal supports above 50% shown from Jack-knife resampling under default settings

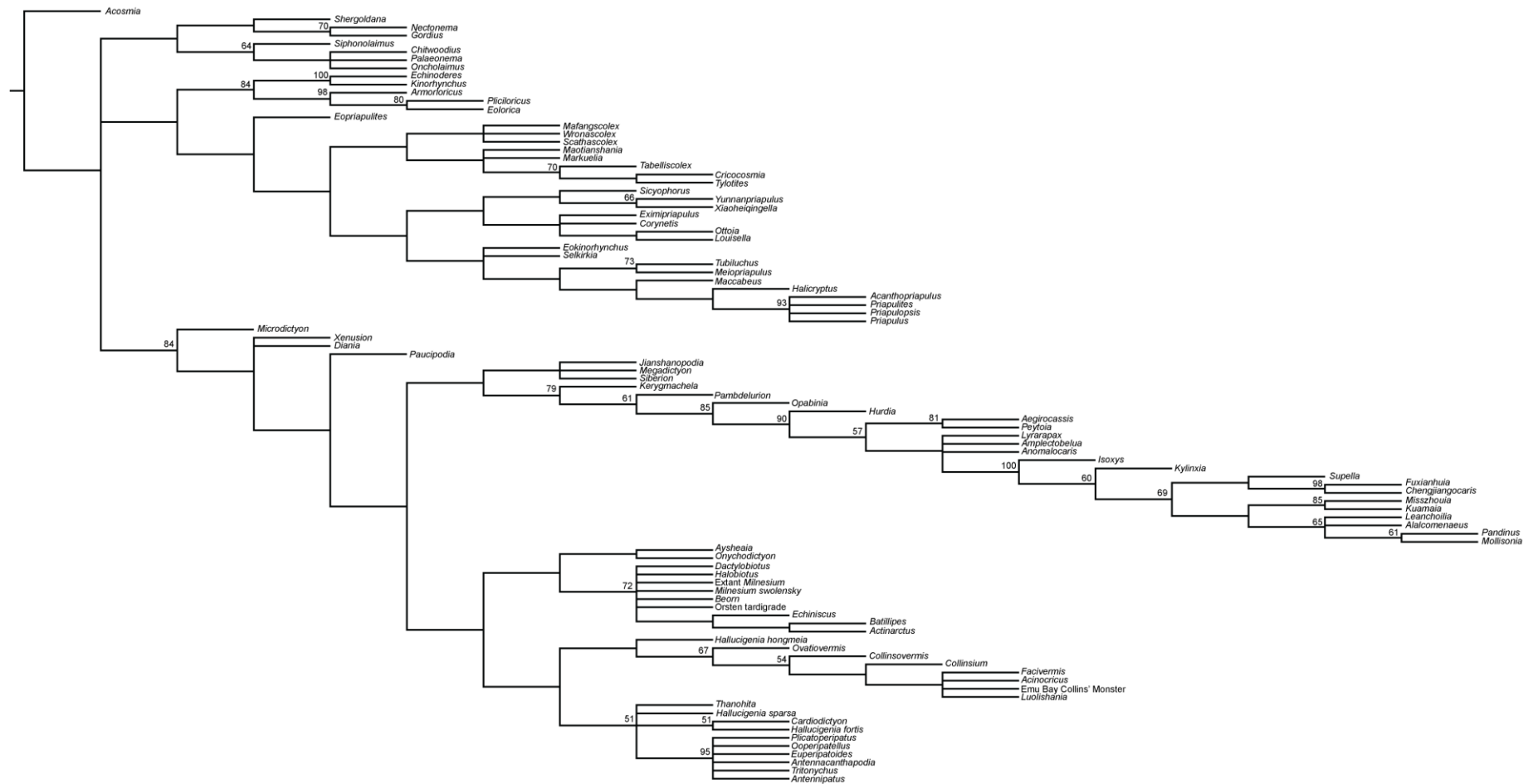


Figure S2. Full results of implied weights parsimony tree searches. New technology search under default parameters with default concavity constant ($k=3$), showing a strict consensus of four most parsimonious trees, with nodal supports above 50% shown from symmetric resampling under default settings.

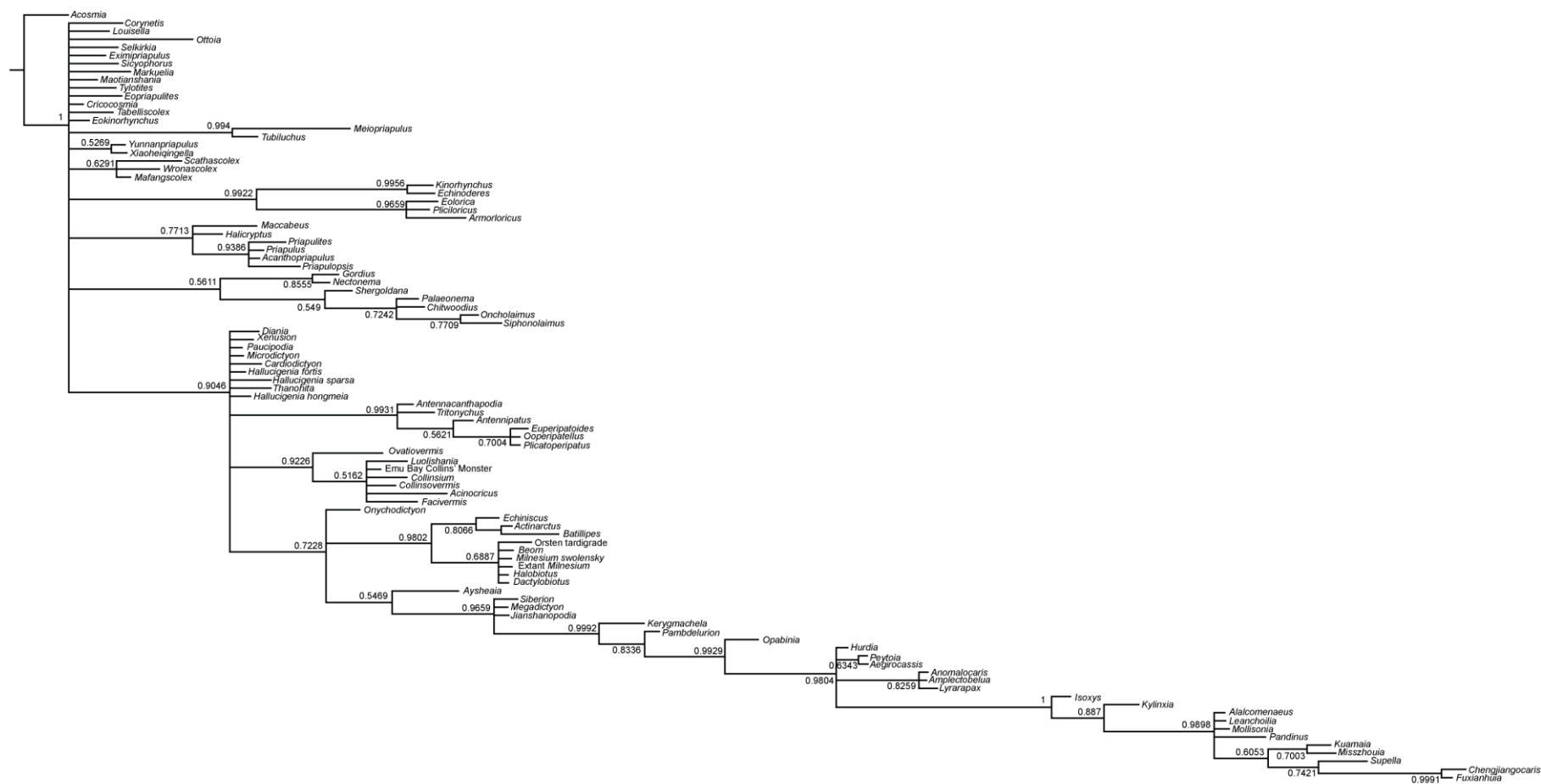


Figure S3. Full results of Bayesian inference trees search. 50% majority rule consensus after convergence of MCMC chains over 6 million generations.

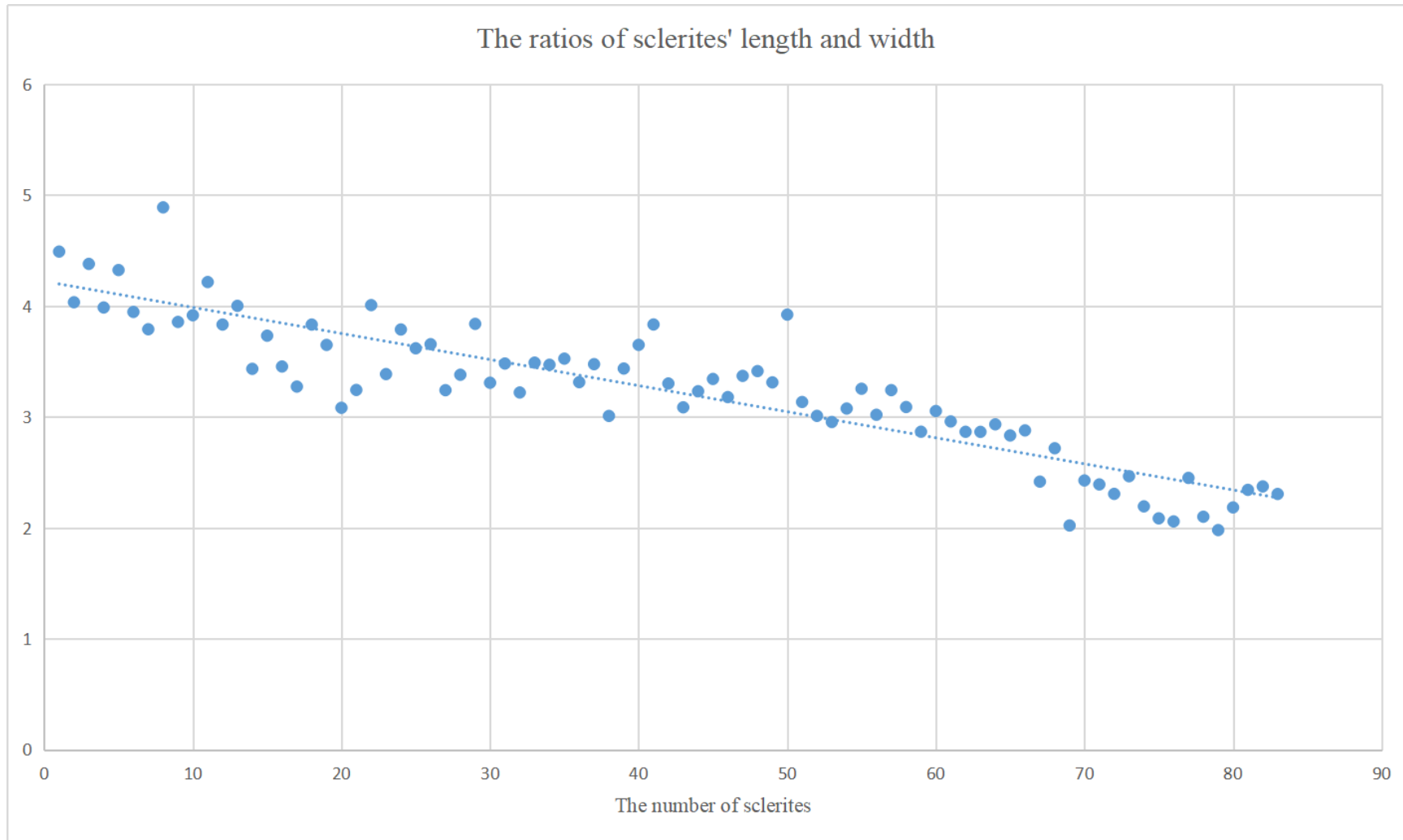


Figure S4. Ratio of sclerite length to width from anterior to posterior. Plot shows the length/width ratio of individual sclerites (Y-axis, measured in mm) from the first to the final lateral sclerite (along the X-axis) in the best preserved individual, showing the ratio decreases from anterior to posterior.