Supplementary Information – B10234b (A palaeontological solution to the arthropod head problem, by Graham E. Budd)

This supplementary information consists of the character analysis and data matrix used for the cladistic analysis in the paper.

The data table used in the analysis is given in table 1. Characters:

1. "Peytoia" mouth part, the circum-oral structure possessed by anomalocaridids, with potential homologies in other basal arthropods such as *Aysheaia*[2] (coded as uncertain here). 0: absent; 1: present.

2. Mouth position. 0: ventral; 1; terminal. The terminal position is primitive for all arthropods[24] and is found in tardigrades and may be inferred in onychophorans[7]. A terminal position in *Jiangfengia*[26] is rejected as being insufficiently supported.

3. Free cephalic carapace. 0: absent; 1; present. While the attachment style for the carapace is not clear in most taxa, the free carapace extends back over the anterior thoracic segments in some taxa, and this state is hypothesised as a homology.

4. Carapace bivalved. 0: not bivalved; 1: bivalved. Clear for all the taxa with a free carapace, with the exception of *Fuxianhuia* (discussed in text); see ref. 3 for further discussion.

5. Posterior spine on head shield. 0: absent; 1: present.

6. Straight hinge in head shield. 0: absent; 1; present.

7. Last segments of trunk. 0: with limbs; 1, without limbs.

8. Frontal appendage style. 0: with multiple spines, no podomeres (*Aysheaia* and *Kerygmachela*); 1: as in *Sanctacaris*; 2: few (c. 5) podomeres with spinous last

three podomeres; 3: reduced/absent; 4: with subchelate tip. The frontal appendage of *Sanctacaris* is controversial. *Sanctacaris* was originally described as having six cephalic appendages[21], five grouped anteriorly and one lying behind them. However, two alternative reconstructions have been suggested. Bousfield[26] suggested that the most anterior appendage was the antenniform one lying behind the five anterior ones, and suggested the latter were displaced from behind to form a feeding basket: he homologised the anterior appendage with the frontal appendage, and suggested a relationship with *Emeraldella*. This direct relationship seems unlikely because of the plesiomorphic characters *Sanctacaris* possesses, for example in thoracic limb shape. Dewel and Dewel[2] suggested that the five anterior appendages were out-branches from a single appendage, the frontal appendage. The latter interpretation is adopted here; but clearly *Sanctacaris* requires more investigation. Recoding *Sanctacaris* does not materially alter the conclusions herein.

9. Two pre-oral appendages developed. 0: no; 1: yes. Characteristic of the upper stem-group of euarthropods (herein) and advanced crustaceans; although the appendages are different in each case (FA and A1 and A1 and A2 respectively). The states in some of the bivalved taxa are unclear. Briggs[20] described *Canadaspis* as possessing two rather antennal-like pre-oral appendages, but it is not clear that the most anterior of these is actually an appendage. It also possesses a structure associated with the mouth, of unclear morphology, described as a mandible. It is possible that this ventral structure is in fact the FA. Further clarification could come from redescription of the bivalved form *Waptia* (pers. comm. R. Taylor). The two pre-oral antennae of *Pectocaris*[25] have not been confirmed, and only one pair may exist. For *Occacaris*, see figs 1.1, 2 of ref. 25; for *Fortiforceps*, see figs 32, 33 of ref. 19. Note that figs 32B, C and 33A provide evidence that the antenna of *Fortiforceps* is not a misidentified eye stalk. The

anterior bulge suggested to be present at the tip of the antenna of *Fortiforceps*[19] may be artifactual.

10. Distinct tergites. 0: absent; 1: present. Not found in any taxa below the *Alalcomenaeus*/*Leanchoilia* clade.

11. Well-articulated inner branch of limb. 0: absent; 1: present.

12. Multi-segmented inner branch of limb. 0: absent; 1; present. Characteristic of the clade of bivalved upper stem-group taxa with *Fortiforceps*. The state has sometimes been considered *a priori* to be primitive[3, 19], but this analysis shows it to be derived.

13. Outer and inner branches united in biramy. 0: absent; 1: present. *Kerygmachela* probably possesses two limb branches, but they are not united into a biramous limb.

14. Form of outer branch. 0: like *Fortiforceps* and *Canadaspis*, flap with composed of radiating lobes; 1: simple oval flap; 2: divided into more than one component or "segment"; 3: long and thin. Character state 0 could conceivably be more widespread in the bivalved clade; as some of the exopods of the taxa therein are poorly-known.

15. Style of outer branch fringe. 0: absent; 1: small setae; 2: lamellae or long setal-like structures[16].

16. Outer branch small, sub-triangular. 0: no; 1; yes.

17. Outer branch setae directed towards endopod. 0: no; 1: yes[6] (inapplicable with character states 0 and 1 of character 15).

18. High number of segments (>30). 0: absent; 1: present.

19. Headshield developed. 0: absent; 1: present.

20. Gnathobasic limbs. 0: absent; 1: present. The ventral feeding structures of crustacean limbs are homologised with the gnathobase of other arthropods.

21. Differentiated A1 homologue. 0: absent; 1; present. For uncertainties about *Sanctacaris*, see character 6.

22. Posterior tergites. 0: absent; 1: present.

23. Frontal appendage with long flagella. 0: no; 1; yes. Characteristic of *Alalcomenaeus* and *Leanchoilia*.

24. Small body size. 0: absent; 1: present.

25. Terminal paired furca developed: 0: no; 1: yes.

26. Furca fringed with small setae. 0: yes; 1: no.

27. Dorsal fluke-like structure developed: 0: no; 1: yes.

28. Forehead structure anterior to headshield. 0: absent; 1; present.

29. A1 homologue biramous. 0: no; 1; yes. For *Sanctacaris*, see character 6.

30. Number of post-oral cephalic appendages. The reconstruction of *Leanchoilia* with 3^{19} is not accepted here. For crown-group euarthropods, see comments in ref. 12.

31. Last few segments differentiated into “tail” with flattened lateral flaps. 0: no; 1: yes.

32. Proximal endite. 0: absent; 1: present.

33. A1 specialised as feeding/locomotion organ. 0: no; 1: yes.

Table 1. Data matrix used in the analysis.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
Trilobita	0	0	0	0	0	0	0	3	0	1	1	0	1	2	2	0	0	0	1	1	1	1	-	0	0	-	0	0	0	3	0	0	0
Fuxianhuia	0	0	1	1	0	1	1	4	1	1	1	1	1	1	1	0	-	1	1	0	1	0	0	0	0	-	1	1	0	0	0	0	0
Canadaspis	0	0	1	1	1	1	1	?	?	1	1	1	1	0	1	0	-	0	1	0	1	0	?	0	1	0	0	0	0	0	0	0	0
Parapeytoia	1	0	0	0	-	0	0	2	0	0	1	0	1	1	0	0	-	0	1	1	0	-	0	0	0	-	0	0	-	2	1	0	0
Kerygmachela	1	1	-	-	-	0	0	0	0	0	0	-	0	1	0	0	-	0	0	0	0	-	0	0	1	-	0	0	-	0	0	0	0
Aysheaia	?	1	-	-	-	0	0	0	0	0	0	-	0	-	-	0	-	0	0	0	0	-	0	0	0	-	0	0	-	0	0	0	0
Branchiocaris	0	0	1	1	1	1	0	4	1	1	1	?	?	1	1	1	-	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0
Leanchoilia	0	0	0	0	0	0	0	2	0	1	1	0	1	1	2	0	0	0	1	?	0	0	1	0	0	-	0	0	1	2	0	0	0
Odaraia	0	0	1	1	1	1	0	?	?	1	1	?	1	1	?	1	?	1	1	0	?	0	0	0	1	0	1	0	?	0	0	0	0
Cambropachycope	0	0	0	0	0	0	1	3	0	1	1	0	1	2	2	0	1	0	1	1	1	0	-	1	0	-	0	1	0	3	0	1	1
Fortiforceps	0	0	0	0	0	0	0	2	1	1	1	1	1	0	1	0	-	0	1	0	1	1	0	0	0	-	0	0	0	3	1	0	0
Sanctacaris	0	0	0	0	0	0	0	1	?	1	1	0	1	1	2	0	0	0	1	?	1	1	0	0	0	-	0	0	1	0	0	0	0
Yohoia	0	0	0	0	0	0	1	2	0	1	1	0	1	1	2	0	0	0	1	?	0	0	0	1	0	-	0	0	-	3	0	0	0
Alalcomenaeus	0	0	0	0	0	0	0	2	0	1	1	0	1	1	2	0	0	0	1	1	0	1	1	0	0	-	0	0	-	2	0	0	0
Jiangfengia	0	0	0	0	0	0	0	2	0	1	1	0	1	1	2	0	0	0	1	?	0	1	0	1	0	-	0	0	-	3	0	0	0
Emeraldella	0	0	0	0	0	0	1	3	0	1	1	0	1	2	2	0	0	0	1	1	1	0	-	0	0	-	0	0	0	5	0	0	0
Perspicaris	0	0	1	1	1	1	1	?	?	1	1	?	?	?	?	?	?	0	1	?	1	0	?	0	1	1	0	1	0	0	0	0	0
Occacaris	?	0	1	1	0	0	0	2	1	1	1	1	1	1	1	0	-	0	1	?	1	0	0	0	0	-	?	0	0	0	0	0	0
Pectocaris	?	0	?	1	0	1	?	?	?	1	1	1	1	3	?	?	?	1	1	?	1	0	?	0	?	1	?	0	0	0	0	0	0
Clypecaris	0	0	1	1	0	0	1	?	?	1	1	?	1	?	1	0	-	0	1	?	1	0	?	0	1	1	0	0	0	0	0	0	0
Rehbachiella	0	0	1	0	0	1	1	3	1	1	1	0	1	2	2	0	1	0	1	1	1	0	-	1	1	1	0	0	0	3	0	1	1