**Supplemental material**

**The earliest chimaeriform fish from the Carboniferous of Central Russia**

Oleg A. Lebedeva\*, Evgeny V. Popovb,d, Sergey V. Bagirova, Igor P. Bolshiyanovc, Rail I. Kadyrovd, Evgeny O. Statsenkod

*aA. A. Borissiak Palaeontological Institute of the Russian Academy of Sciences, 123 Profsoyuznaya St., Moscow, 117997, Russia; bDepartment of Palaeontology, Geological Faculty, Saratov State University, 83 Astrakhanskaya St., Saratov, 410012, Russia; cInstitute of Applied Mechanics of the Russian Academy of Sciences, 7 Leningradsky Ave., Moscow, 125040, Russia; dInstitute of Geology and Petroleum Technologies, Kazan Federal University, 4/5 Kremlevskaya St., Kazan, 420008, Russia*

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\*Corresponding author: Email: elops12@yandex.ru

**Dental characters for phylogenetic analysis of *Protochimaera* gen. nov.**

Morphological characters of the dentition for the fossil and recent Holocephali (*sensu* Stahl, 1999). 0–5 = character states; (?) = unknown state of the character.

17 taxa and 20 characters, including six characters modified from Lund & Grogan (1997; 2012; etc.). Some holocephalian taxa are not used due to not having enough data regarding dentition structure.

**Characters and states:**

1. Tooth families per jaws: 0= more 12; 1= about 12; 2= 8–10; 3= 4–7. Modified from Lund & Grogan, 1997 (#23: Tooth families per jaw: 0= about 12; 1= more than 12; 2= fewer than 9; 3= fewer than 4).

2. Tooth shape on jaws: 0= teeth only; 1= teeth and tooth plates; 2= plates alone. Modified from Grogan & Lund, 2008 (#40: 0= teeth absent; 1= homodont; 2= heterodont; 3= teeth and tooth plates; 4= plates alone); Grogan et al., 2012 (#51).

3. Unpaired lower symphysial tooth (tooth plate): 0= absent, N/A; 1= plate; 2= absent. Modified from Grogan et al., 2012 (#63: 0= absent, N/A; 1= tooth; 2= whorl; 3= plate; 4= absent); Lund & Grogan, 1997 (#28).

4. Descending lamina on the tooth plates: 0= absent, N/A; 1= ‘myriacanthoid type’ (marginal nipping of cartilages); 2= ‘chimaeroid type’ (solid or reduced structure over the basal surface, a rudiment of alternative tooth).

5: ‘Myriacanthid’ descending lamina (nipping of Meckelian cartilage) on mandibular (lower posterior) tooth plates: 0= absent, N/A; 1= sectorial, undeveloped; 2= moderate; 3= high; 4= high, forming a pocket.

6. Labial component (increasing of cutting possibility) on ‘myriacanthid’ descending lamina of the paired mandibular plates: 0= absent, N/A; 1= present.

7. Paired dentition, upper dental position: 0= absent, N/A; 1= 2 anterior, 1 posterior; 2= 1 anterior; 1 posterior; 3= 1 posterior. Modified from Grogan et al., 2012 (#61: 0= absent, N/A; 1= more 3 (teeth); 2= 2 anterior, 1 posterior; 3= 1 anterior; 1 posterior; 4= 1 posterior); Lund & Grogan, 1997 (#38).

8. Paired dentition, lower anterior position: 0= absent, N/A; 1= 2 anterior; 2= 1 anterior; 3= absent. Modified from Grogan et al, 2012 (#62: 0= absent, N/A; 1= more 3 (teeth); 2= 2 anterior; 3= 1 anterior; 4= absent.), Grogan & Lund, 2008 (#51); Lund & Grogan, 1997 (#39).

9. Growth orientation in the anterior upper dentition: 0= absent, N/A; 1= symphyseal-lateral, 2= parasagittal.

10. Histology, lamellar tissue in the base of tooth/tooth plate: 0= present; 1= absent (reduced).

11. Structure of the hypermineralized tissue, paired lower posterior (mandibular) plates: 0= absent, N/A; 1= continuous, coronary; 2= coronary, longitudinally or transversally irregular (including series of knobs); 3= longitudinally or transversally variously reduced; 4= segmented (mostly tritors inside the plate).

12. Relief of the coronary hypermineralized tissue on the lower posterior (mandibular) plates: 0= absent, N/A; 1= thick, prominent; 2= thin; 3= organized in ridges; 4= mostly reduced.

13. Structure of the hypermineralized tissue, paired upper posterior (palatine) plates: 0= absent, N/A; 1= continuous, coronary; 2= coronary, longitudinally or transversally irregular (including series of pleromin-knobs); 3= longitudinally or transversally variously reduced; 4= segmented (mostly tritors inside the plate).

14. Relief of the coronary hypermineralized tissue on the upper posterior (palatine) plates: 0= absent, N/A; thick, prominent; 2= thin; 3= organized in ridges; 4= mostly reduced.

15. Distribution of hypermineralized tissue over the lower posterior (mandibular) plates: 0= absent; N/A; 1= coronary only; 2= coronary and inside the plate; 3= secondarily reduced.

16. Distribution of hypermineralized tissue over the upper posterior (palatine) plates: 0= absent; N/A; 1= coronary only; 2= coronary and inside the plate; 3= inside the plate only.

17. Type of occlusion: 0= piercing; 1= piercing/grinding; 2= crushing; 3= crushing/grinding; 4= grinding; 5= shearing. Modified after Lund and Grogan, 1997 (#27).

18: Type of hypermineralized tissue on tooth plates: 0= tubate/vascular; 1= laminated (compact type 1); 2= varitubate; 3= vascular, laminated (compact type 2) and/or solid; 5= solid only.

19. Growth orientation in the lower posterior (mandibular) plates: 0= linguo-labial lyodont; 1= disto-linguo-ventral.

20. Occlusion forms labial facet wear on posterior lower (mandibular) plates: 0= absent; N/A; 1= one facet; 2= two facet.

**Taxa-characters matrix**

Holocephalian orders *sensu* Stahl (1999) are highlighted by color.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Character / taxon | Outgroup | Chondren-chelyiformes | Cochlio-dontiformes | Menaspi-diformes |  | Chimaeriformes |
| *Chodrenchelys* | *Harpagofututor* | *Cochliodus* | *Deltodus* | *Deltoptychius* | *Traquarius* | ***Protochimaera g.n.*** | *Echinochimaera* | *Agkistracanthus* | *Myriacanyhus* | *Chimaeropsis* | *Squaloraja* | *Callorhinchus* | *Ischyodus* | *Chimaera* | *Harriotta* | *Rhinochimaera* |
| **1** | 0 | 0 | 2 | 1 | 3 | 3 | 2 | 3 | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **2** | 0 | 1 | 2 | 1 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **3** | 0 | 0 | 1 | ? | ? | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| **4** | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| **5** | 0 | 2 | 2 | 1 | 1 | 2 | 2 | 3 | 1 | 4 | 4 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| **6** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **7** | 0 | 2 | 2 | 1 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **8** | 0 | 2 | 2 | 1 | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| **9** | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 2 | ? | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| **10** | 0 | ? | ? | 0 | 0 | 0 | ? | 1 | ? | 0 | 0 | 0 | ? | 1 | 1 | 1 | 1 | 1 |
| **11** | 0 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 4 |
| **12** | 0 | 0 | 1 | 1 | 1 | 3 | 1 | 2 | 3 | 2 | 3 | 2 | 0 | 4 | 4 | 4 | 4 | 4 |
| **13** | 0 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 1 | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 4 |
| **14** | 0 | 0 | 1 | 1 | 1 | 3 | 1 | 2 | 3 | 2 | 3 | 2 | 0 | 4 | 4 | 4 | 4 | 4 |
| **15** | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 |
| **16** | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 3 |
| **17** | 0 | 1 | 3 | 2 | 2 | 2 | 2 | 5 | 4 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 3 | 5 |
| **18** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | ? | 0 | 0 | 1 | 0 | 3 | 3 | 3 | 5 |
| **19** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| **20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

Matrix as Nexus format:

#NEXUS

begin data;

dimensions ntax= 18 nchar= 20;

format missing= ? symbols= "0~5";

matrix

Outgroup 00000000000000000000

*Chondrenchelys* 010120221?2020111000

*Harpagofututor* 221120221?1111113000

*Cochliodus* 11?11011101111112000

*Deltodus* 32?11032001111112000

*Deltoptychius* 31212023101313112000

*Traquarius* 212120221?1111112000

*Protochimaera* 32213123211212115212

*Echinochimaera* 32211023??3333114000

*Agkistracanthus* 32214023101212112?10

*Myriacanthus* 22114013101313112010

*Chimaeropsis* 32111023101212112010

*Squaloraja* 322110231?1010112100

*Callorhinchus* 32220023214444112010

*Ischyodus* 32220023214444223310

*Chimaera* 32220023214444224310

*Harriotta* 32220023214444223310

*Rhinochimaera* 32220023214444335511

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end;

**Supplementary material, videos**

Supplementary video 1. Histological structure of the *Protochimaera mirabilis* Lebedev & Popov gen. et sp. nov. Holotype PIN 2878/548 as exemplified by successive sectioning of the 3D model obtained from a set of CT images in three projections.

Supplementary video 2. Position of oral (marked red), aboral (marked blue) and labial (marked green) vascular systems of the *Protochimaera mirabilis* Lebedev & Popov gen. et sp. nov. Holotype PIN 2878/548 visualized by successive sectioning of the 3D model obtained by a set of CT images in three projections.