The early elasmobranch *Phoebodus*: phylogenetic relationships, ecomorphology, and a new time-scale for shark evolution

Linda Frey[1], Michael Coates[2], Michał Ginter[3], Vachik Hairapetian [4], Martin Rücklin[5], Iwan Jerjen[6] and Christian Klug[1]

ELECTRONIC SUPPLEMENTARY MATERIALS

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SUPPLEMENTARY FIGURES

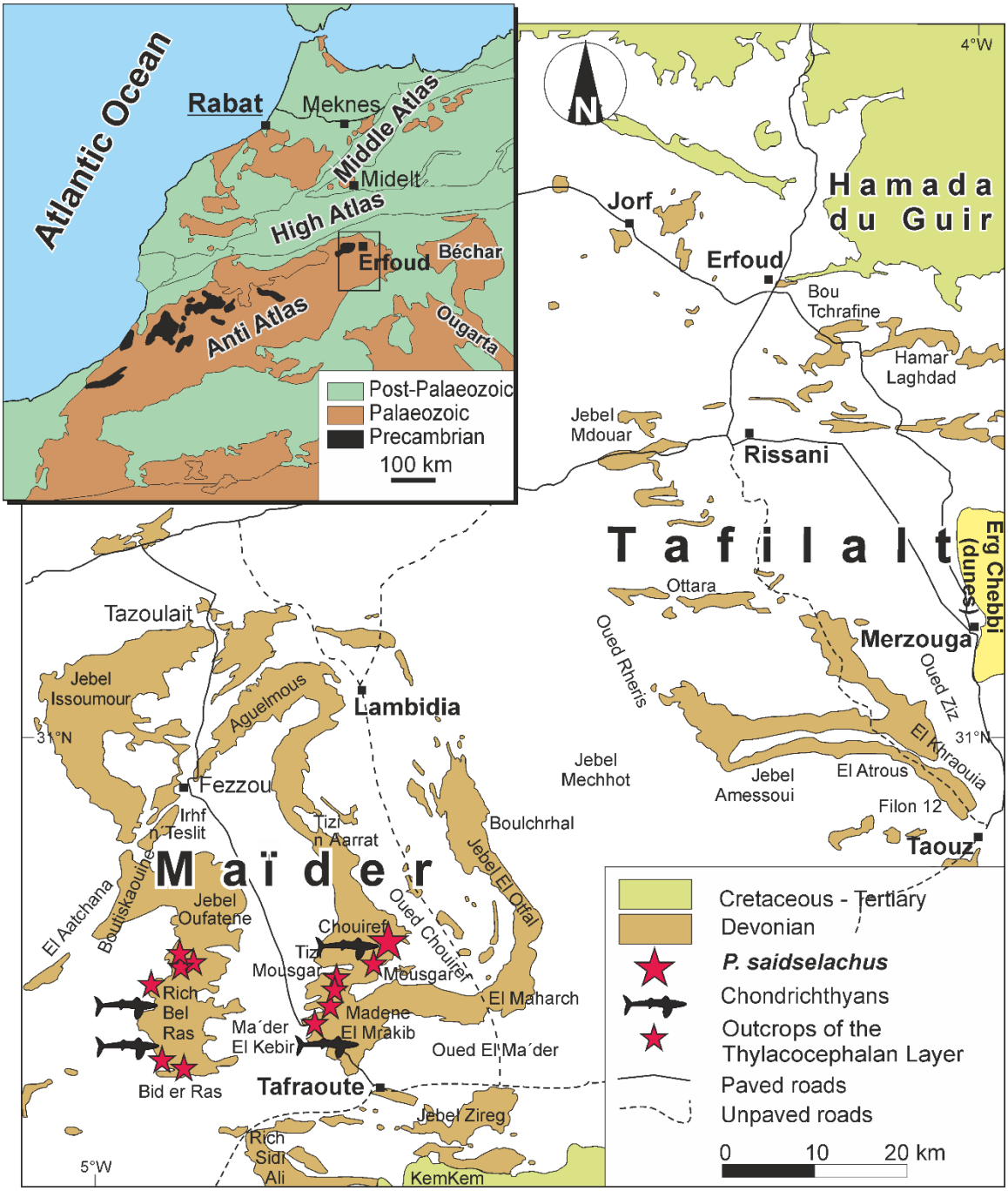

Figure S1. Geological map of the southeastern Anti-Atlas of Morocco. The Thylacocephalan Layer with gnathostomes crops out in the Maïder region. Remains of *Phoebodus* were collected from the Famennian (Late Devonian) of Madene (30°44`407`` N, 4°42`899``W; 30°47`188`` N, 004°40`965`` W).

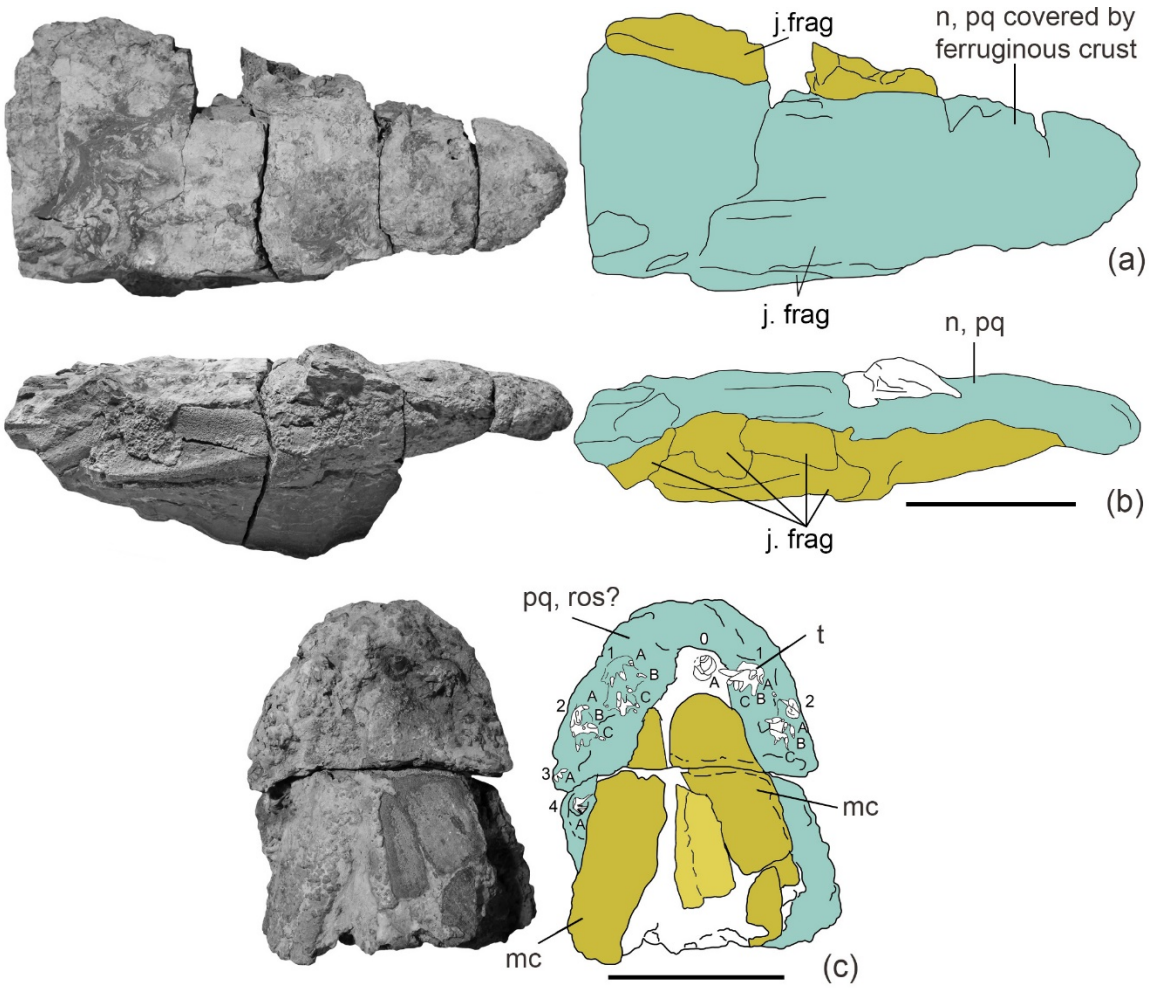

Figure S2. *Phoebodus saidselachus* sp. nov. (PIMUZ A/I 4659), neurocranium and jaw fragments with mandibular teeth. (a) dorsal and (b) lateral aspects, scale bar = 100 mm. (c) ventral aspect of the anterior part of the snout and jaws with exposed tooth families, scale bar = 50 mm. j. frag, jaw fragments -palatal ramus of palatoquadrate; mc, Meckel's cartilage; n, neurocranium; pq, palatoquadrate; ros, rostrum; t, teeth.

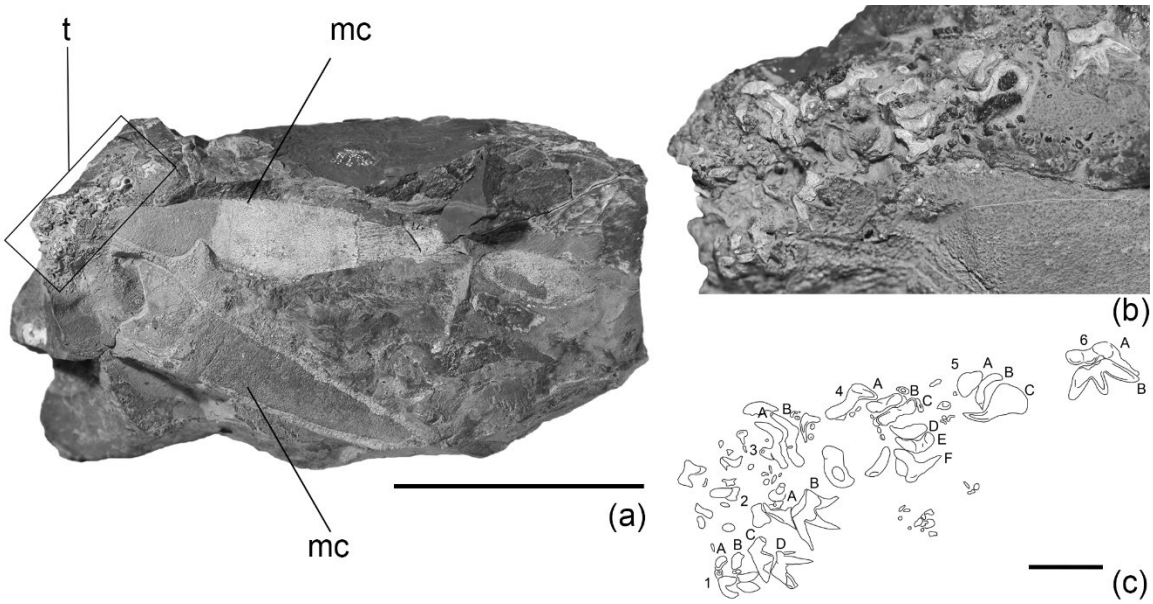

Figure S3. *Phoebodus saidselachus* sp. nov. (PIMUZ A/I 4710), Meckel`s cartilages (mc) with intact anterior tooth whorls in situ (t). (a) ventral view, scale bar =100 mm. (b) detail and (c) drawing of the at least six most anterior tooth families of the right ramus of the lower jaw, scale bar = 10 mm. mc, Meckel`s cartilage; t, teeth.

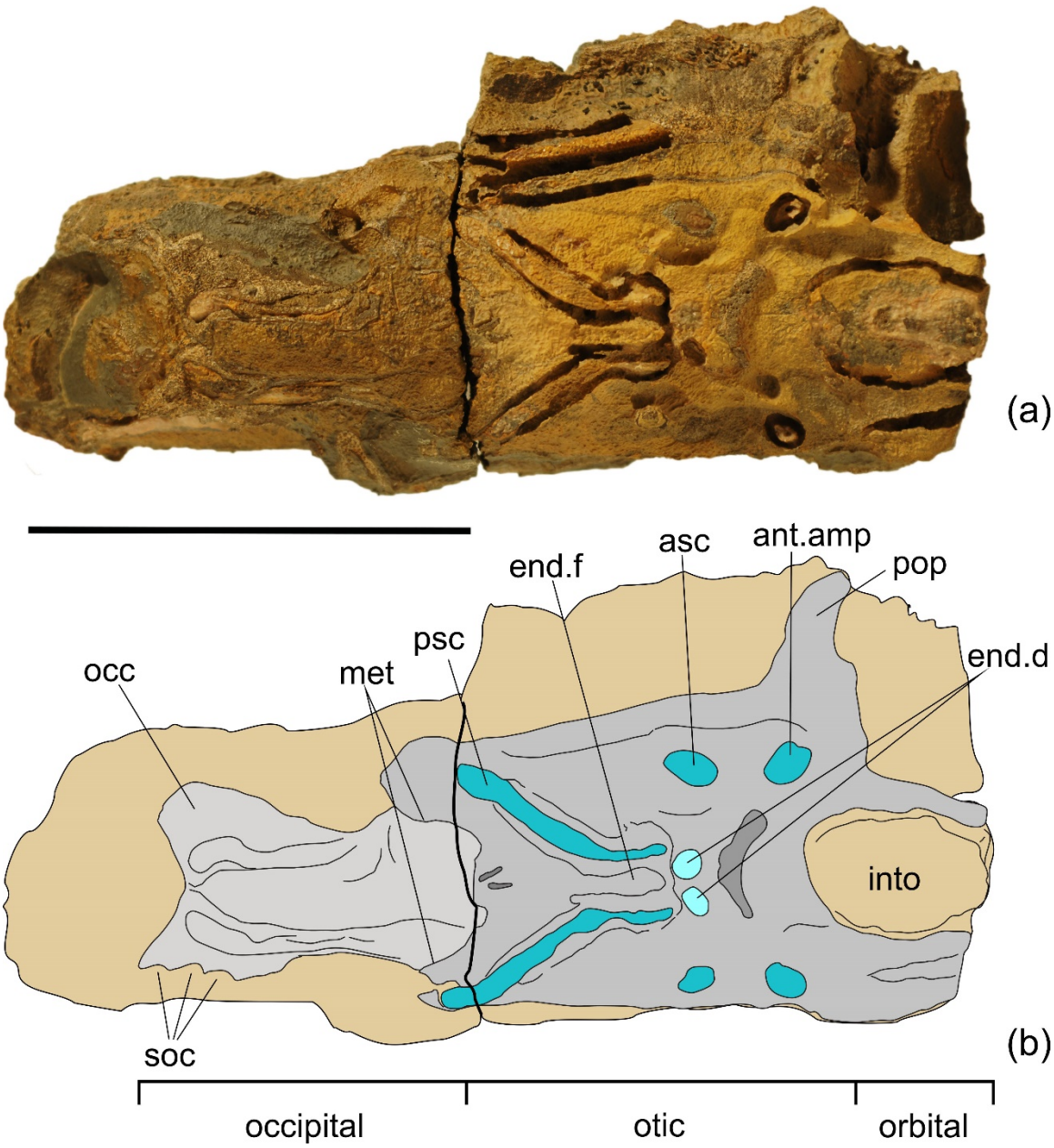

Figure S4. Braincase of *Phoebodus* sp. (PIMUZ A/I 4713): weathered specimen showing near-horizontal section through cranium below level of chondrocranial roof, and infilling of enodcranial spaces within the otico-occiput. (a) Photograph and (b) illustration (in dorsal view); scale bar = 100 mm. ant.amp, ampulla of anterior semicircular canal; asc, anterior semicircular canal; end.d, endolymphatic ducts; end.f, space directly ventral to endolymphatic fossa; into, interorbital space; met, metotic fissure; occ, occipital cotylus; psc, posterior semicircular canal; pop, postorbital process; soc, spino-occipital canal.

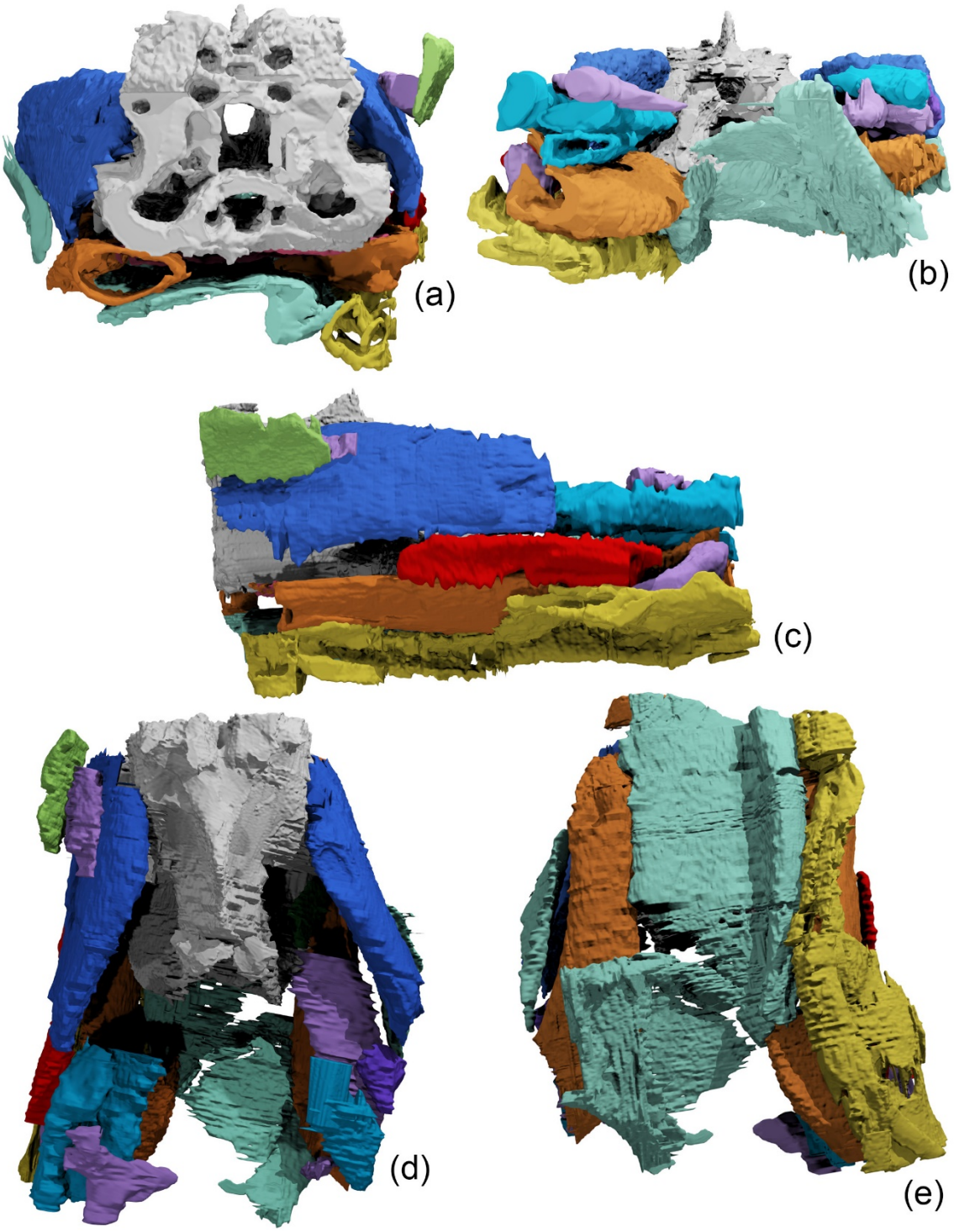

Figure S5. *Phoebodus* sp. (PIMUZ A/I 4711), rendering of braincase, mandibular, hyoid and branchial arches in (a) anterior, (b) posterior, (c) lateral, (d) dorsal and (e) ventral views. Colour coding: grey, braincase; orange, ceratohyal; blue, hyomandibula; turquoise, right palatoquadrate (otic process); yellow, Meckel`s cartilage; light blue, likely fragments of epibranchials; purple, gill arch fragments; red, ceratobranchial; green, possible fragment of left palatoquadrate.

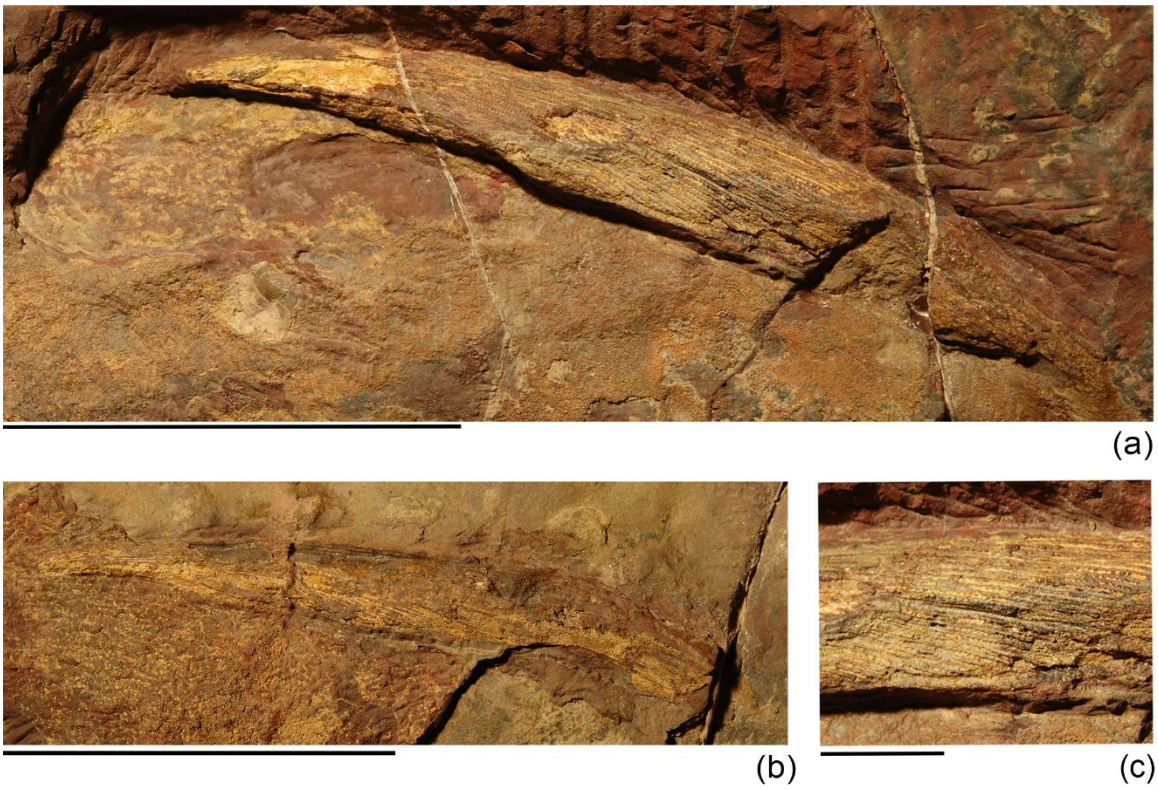

Figure S6. *Phoebodus saidselachus* sp. nov. (PIMUZ A/I 4712), dorsal fin spines. Lateral view of (a) anterior and (b) posterior dorsal fin spines, scale bar = 50 mm. (c) detail showing ctenacanthid ornamentation, scale bar = 10 mm.

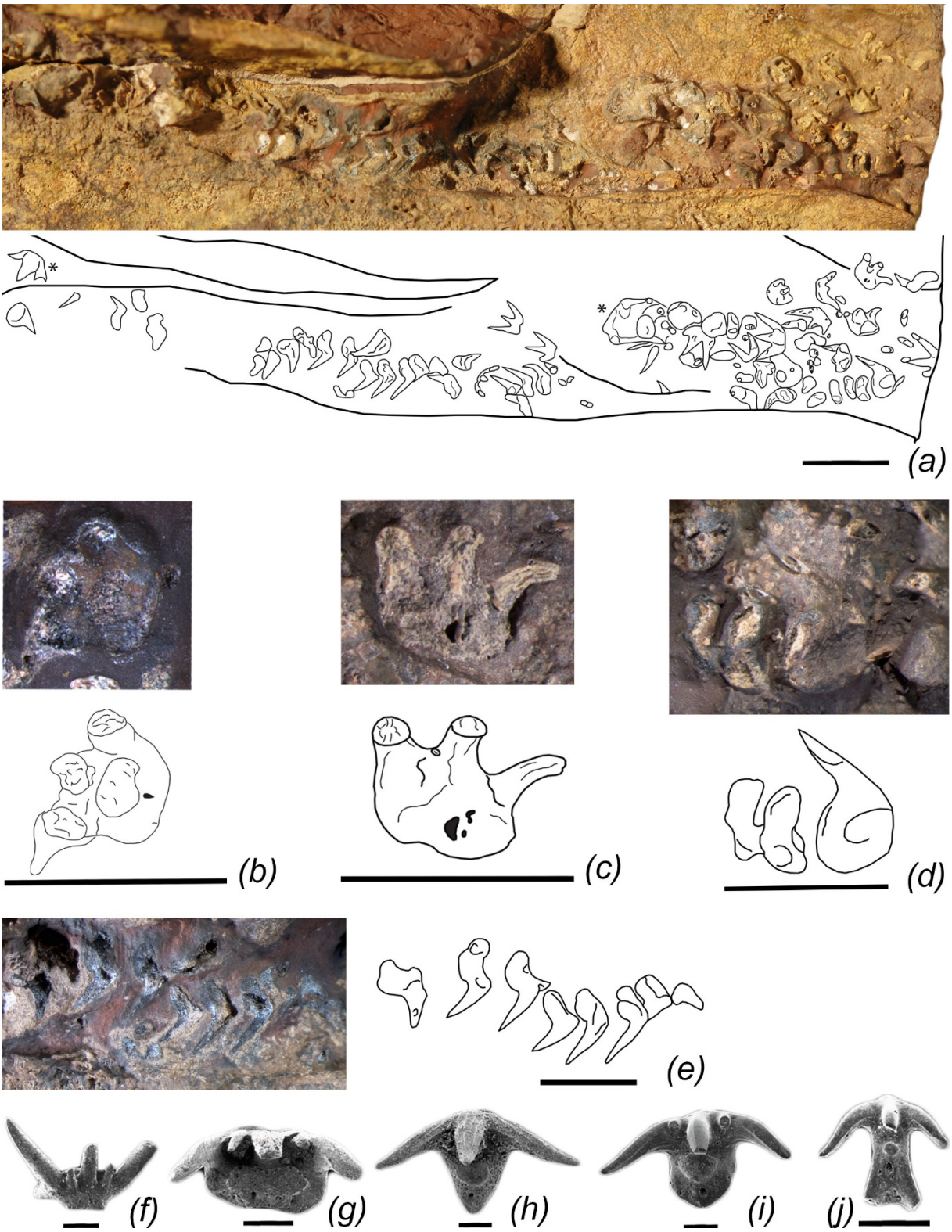

Figure S7. Mandibular teeth of *Phoebodus saidselachus* sp. nov. and other phoebodontids. Photo of the dentition with explanatory drawing (a); scale bar = 10 mm. (b - e) detail of the dentition, photo with explanatory drawing, (b, c) oral views of teeth, (d) teeth in aborolateral view, (e) lateral cross-section of teeth in a row. (f - j) teeth of related species of Phoebodus, slightly modified from Ginter *et al.* (2010). (f) *Ph. fastigatus*, (g) *Ph. sophiae,* (h) *Ph. gothicus*, (i) *Ph. gothicus transitans*, (j) *Ph. depressus*. Scale bars in (b-j) = 5 mm.

Figure S8. Scales in the cranial region of *Phoebodu*s sp. (PIMUZ A/I 4713). Scale bar = 5 mm.

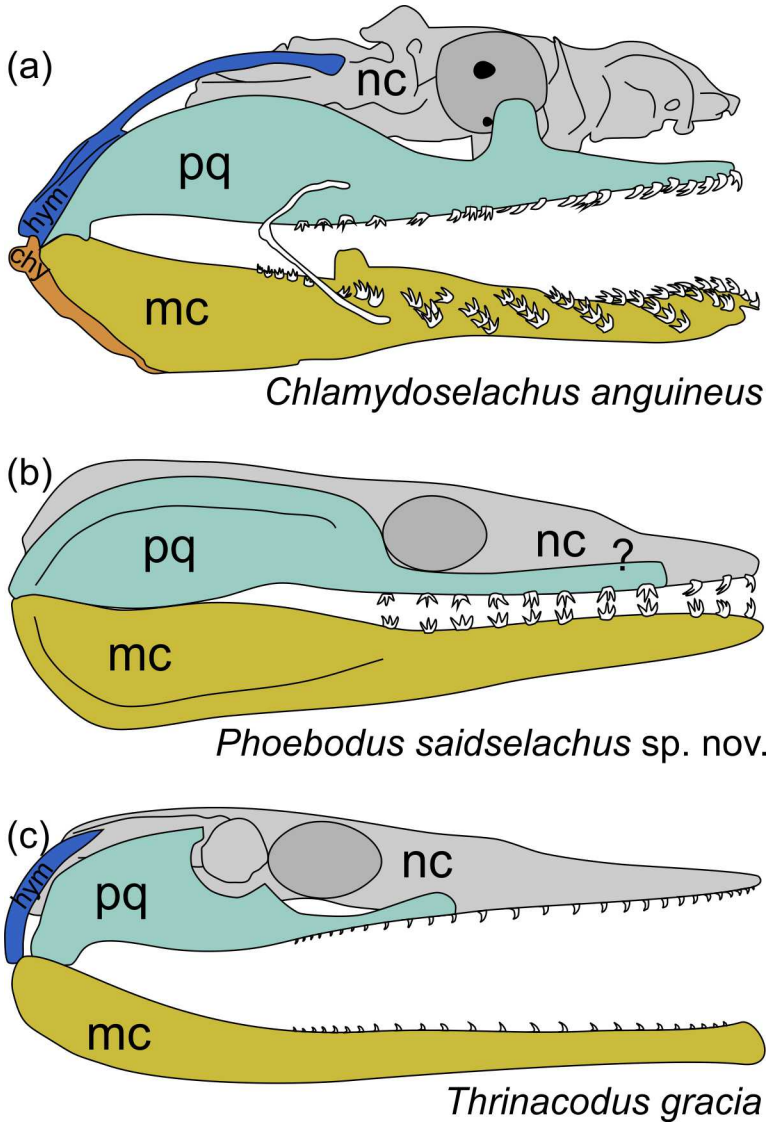

Figure S9. Chondrichthyan crania in lateral view: sketch diagrams of contrasting shapes and sizes of cranial cartilages, all in lateral view: (a) the extant frilled shark, (b, c) pheobodontids; *T. gracia* after Grogan and Lund 2008. chy (bright green), ceratohyal; hym (light grey), hyomandibula; mc (pale green), Meckel's cartilage; nc (dark grey), neurocranium; pq (yellow), palatoquadrate.

SUPPLEMENTARY NOTES

1. Devonian gnathostomes of Morocco and remarks on preservation at the Maïder locality

Morocco is famous for its often highly fossiliferous Devonian outcrops, which bear sometimes abundant invertebrates but also, somewhat rarer, inarticulated as well as articulated remains of vertebrates. Concerning vertebrates, macro- and microremains of placoderms and sarcopterygians are locally abundant in some strata and they were repeatedly reported from the Tafilalt and Maïder regions of the southeastern Anti-Atlas (Lehmann 1956, 1964, 1976, 1977, 1978; Lelièvre & Janvier 1986, 1988; Lelièvre *et al*. 1993; Rücklin 2010, 2011; Rücklin *et al*. 2015, Rücklin & Clément 2017). Many taxa of Devonian chondrichthyans (e.g. *Jalodus*, *Thrinacodus*, *Phoebodus*, *Ctenacanthus*, *Stethacanthus*, *Symmorium*, *Cobelodus*, *Denaea*, *Orodus*, *Protacrodus*, *Siamodus*, *Clarina)* are documented by abundant isolated teeth and fin spines, while cartilaginous structures such as a jaw were documented only once thus far (Lehman 1976; Derycke 1992; Hampe *et al*. 2004; Derycke *et al*. 2008; Ginter *et al*. 2002; Derycke 2017). Only recently, more or less complete skeletons and braincases of chondrichthyans were found in the southern Maïder Basin (Fig. S1). The skeletal remains are preserved in ferruginous clayey nodules of reddish color found in the early/ middle Famennian Thylacocephalan Layer in which thylacocephalans are highly abundant (Frey *et al*. 2018). *Phoebodus* is accompanied by numerous haematitic internal molds of cephalopods and phosphatised thylacocephalan as well as a few benthic invertebrates (*Buchiola*, *Guerichia*, ostracods and brachiopods). Concerning other gnathostomes, several species of well-preserved placoderms, sarcopterygians and cladodont chondrichthyans were found in and above the Thylacocephalan Layer. The palaeoenvironment at Madene el Mrakib was, during much of the Famennian stage, characterized by well-oxagenated waters in much of the water column while deeper water levels near the sea floor were oxygen-depleted, as inferred from the scarcity and low diversity of benthic invertebrates and the absence of bottom dwelling vertebrates (Frey *et al*. 2018). Taxa of invertebrates and vertebrates inhabiting higher water levels were more common and diverse, thus suggesting a better oxygenated water column.

In spite of its unique completeness, especially when compared to the previously known fossil record of *Phoebodus* consisting of countless teeth mainly, the preservation of the material described here is far from perfect. For example, the caudal fin and much of both pelvic and pectoral fins are missing. This is a widespread characteristic for the taphonomy of the gnathostomes of the Thylacocephalan Layer in the southern Maïder (Frey *et al*. in press). Usually, the fish remains are incorporated in large flat nodules rich in haematite and limonite. The head and gill regions tend to be encased in the thickest part of the nodule, while most of the postcranium lies on top of the nodule that thins out posteriorly. In rare cases, the caudal fin still rests on the nodule while in most instances, the posterior of the skeleton is eroded because it was embedded in the deeply weathered crumbling claystone. Nevertheless, the nodule shapes approximate the outline of the former carcass, thus documenting the overall body shape, fin position their rough dimensions. Based on this indirect evidence, we suggest that the caudal fin resembled that of *Thrinacodus* in lacking strongly developed dorsal and ventral lobes as in, e.g., modern elasmobranchs like *Carcharodon*. Instead, the tail probably resembled that of *Thrinacodus* (although less elongate) of *Chlamydoselachus*.

Several tooth-based species of *Phoebodus* with almost identical tooth crowns and differing by only minor aspects of the bases have been described from the Famennian. These include: *Ph. rayi* (Ginter & Ivanov 1992), *Ph. typicus* (Ginter & Ivanov 1995), *Ph. turnerae* (Ginter & Ivanov 1992), *Ph. gothicus* (Ginter 1990) (figure S7*h*) and *Ph. politus* (Newberry 1889). From this list, *Ph. rayi* and *Ph. turnerae* can easily be removed from the comparison with *Ph. saidselachus* sp. nov., because their orolingual button is not situated in the centre of the base, but at the lingual rim. The typical specimens of *Ph. gothicus* have much longer bases, lingually rounded or ending with an angle. However, *Ph. typicus* and *Ph. politus* are very similar to the teeth of *Ph. saidselachus* and, in fact, can be difficult to distinguish. Close observation shows that the tooth bases in *Ph. typicus* are more rectangular and wider than in *Ph. saidselachus*, but, on the other hand, they are more circular in *Ph. politus.* The published teeth of the latter species (Newberry 1889: pl. 27, figs 27, 28; 24: pl. 7, fig. 5; 1908, pl. 1, fig. 9) are large, relative to other *Phoebodus* tooth species, with base width about 7-8 mm, in the size range of *Ph. saidselachus*, whereas all the known teeth of *Ph. typicus* do not exceed 2 mm. In terms of tooth morphology, it

appears that *Ph. saidselachus* is situated between the stratigraphically older species (*Ph. typicus*, early-middle Famennian) and the younger one (*Ph. politus*, late Famennian).

2. Phylogenetic Analysis: Notes.

Phylogenetic data set. The taxon and character matrix (60 taxa, 221 characters) was adapted from the data set (86 taxa, 262 characters) used in Coates *et al*. (2018). The 'maxillate placoderm' *Entelognathus* was retained to serve as an outgroup. Agnathans, placoderms, and a selection of osteichthyans and acanthodians were culled from the taxon list, in light of the very large number of MPTs obtained in the original analysis and the efficacy of taxon reduction as a means of focusing on nodes of particular interest (Coates *et al*. 2018). Taxonomic additions were limited to *Phoebodus* and *Thrinacodus* (Grogan and Lund, 2008). Character exclusions were selected on the basis of preliminary analysis of the reduced taxon set, and subsequent identification of uninformative characters (variable and constant).

Phylogenetic analysis. Phylogenetic analysis was performed in PAUP* (Swofford 2003) using maximum parsimony. All characters were treated as unordered and of equal weight. The matrix is of moderate size, but the widespread occurrence of missing, uncertain, and inapplicable entries made it likely *a priori* that finding optimum trees would be difficult. Therefore, a ratchet procedure was employed to maximise chances of finding optimal islands: 50,000 random stepwise additions followed by TBR (tree bisection-reconnection) branch-swapping search, retaining one tree in memory (MAXTREES=1). Searches hit shortest trees (513 steps) 105 times. Subsequent search on all shortest trees found the same island of trees, as did a simple search using the heuristic option in PAUP*. Bootstrap values (Felsenstein 1985) were calculated in PAUP* using the stepwise addition option with 10,000 replicates, retaining all groups with frequency >50%. Bremer decay indices (Bremer 1988) for the strict consensus cladogram were calculated via the heuristic search option, saving trees of successively increased lengths up to five extra steps (MAXTREES=1,000,000).

Characters deleted from Coates *et al*. 2018 data set:

6, 19, 27, 28, 32, 34, 35, 36, 38, 42, 43, 44, 45, 49, 50, 52, 53, 54, 56, 65, 92, 93, 100, 103, 104, 116, 120, 124, 126, 129, 132, 134, 154, 156, 158, 165, 175, 176, 207, 215, 216, 218, 236, 238, 239.

Characters changed/added

5. Tubular Dentine: absent (0); present (1).

20. Cranial cap denticles, single-crowned, non-growing: absent (0); present (1).

52. Ceratohyal spatulate or bladed anteriorly: absent (0); present (1).

66. Teeth with three slim main cusps almost equal to each other, strongly recurved: absent (0); present (1).

99. Orbitonasal lamina expanded: absent (0); present (1).

100. Elongate, tooth-bearing, pre-nasal ethmo-rostral region: absent (0); present (1).

3. Included Taxa and Sources.

Acanthodes: Benznosov 2009; Brazeau & de Winter 2015; Coates 1994; Davis *et al.* 2012; Heidtke 1993, 2011a,b; Jarvik 1977, 1980; Miles 1968, 1973a, b; Nelson 1968.

Acronemus: Maisey 2011; Rieppel 1982.

Akmonistion: Coates & Sequiera 1998, 2001a, b; Coates *et al.* 1998; Coates et al. 2017.

Brachyacanthus: Denison 1979; Miles 1973a; Watson 1937.

Brochoadmones: Bernacsek & Dineley 1977; Gagnier & Wilson 1996b; Hanke & Wilson 2006.

Callorhinchus/Hydrolagus: Cole 1896; De Beer 1937; De Beer & Moy-Thomas 1935; Didier 1995; Didier *et al*. 1994, 1998, 2012; Howard *et al*. 2013; Kesteven 1937; Patterson 1965, 1992; Pradel *et al*. 2013; Stahl 1999.

Cheiracanthus: Denison 1979; Miles 1973a; Watson 1937.

Cheirolepis: Arratia & Cloutier 1996; Pearson & Westoll 1979; Giles *et al*. 2015a.

Chondrenchelys: Finarelli & Coates 2012, 2014; Lund 1982; Moythomas 1935.

Cladodoides: Gross 1937, 1938; Maisey 2005.

Cladoselache: Bendix-Almgreen 1975; Harris 1938a, b; Maisey 1989a, 2007; Schaeffer 1981; Williams 2001; Woodward & White 1938.

Climatius: Miles 1973a, b; Watson 1937.

Cobelodus: Zangerl & Case 1976; Zidek 1992.

Culmacanthus: Long 1983.

Damocles: Lund 1986.

Debeerius: Grogan & Lund 2000.

Diplacanthus: Gagnier 1996; Miles 1973a; Watson 1937.

Diplodoselache: Dick 1981.

Doliodus: Miller *et al.* 2003; Maisey *et al.* 2009, 2013, 2017; Long *et al*. 2015.

Dwykaselachus: Coates *et al.* 2017; Oelofsen 1986.

Egertonodus: Maisey 1982, 1983; Lane, 2010.

Entelognathus: Zhu *et al*. 2013.

Gladbachus: Heidtke & Krätschmer 2001; Heidtke 2009; Burrow & Turner 2013.

Guiyu: Zhu *et al*. 2009.

Gyracanthides: Miles 1973a; Warren *et al*. 2000; Turner *et al*. 2005.

Halimacanthodes: Burrow *et al*. 2012.

Hamiltonichthys: Maisey 1989b.

Helodus: Patterson 1965; Stahl 1999.

Homalacanthus: Gagnier 1996; Watson 1937.

Homalodontus: Mutter *et al*. 2007, 2008.

Iniopera: Zangerl & Case 1973; Pradel *et al*. 2009b, Pradel 2010; Pradel *et al*. 2010.

Ischnacanthus; Miles 1973a; Watson 1937.

Kawichthys: Pradel *et al*. 2011.

Kathemacanthus: Gagnier & Wilson 1996a; Hanke & Wilson 2010.

Latviacanthus: Schultze & Zidek 1982.

Lupopsyrus: Hanke & Davis 2012; Bernacsek & Dineley 1977.

Mesacanthus: Miles 1973a; Watson 1937.

Mimipiscis: Gardiner & Bartram 1977; Gardiner 1984; Choo 2011; Giles & Friedman 2014.

Moythomasia: Gardiner & Bartram 1977; Gardiner 1984; Coates et al. 2017; specimen MV P222915.

Obtusacanthus: Hanke & Wilson 2004; specimen UALVP 41488.

Onychoselache: Dick & Maisey 1980; Coates & Gess 2007.

Orthacanthus: Heidtke 1982, 1999; Hotton 1952; Schaeffer 1981; Maisey 1983; Lane & Maisey 2009.

Ozarcus and FMNH PF 13242: Maisey 2007; Pradel *et al.* 2014; Coates *et al*. 2017.

Parexus: Watson 1937; Miles 1973a.

Phoebodus: Ginter *et al*. 2002; Ginter & Ivanov, 1992, 1995; Ginter 1990; Newberry, 1889. Specimens PIMUZA/I 4656, PIMUZ A/I 4710, PIMUZ A/I 4712, PIMUZ A/I 4711, PIMUZ A/I 4713.

Psarolepis: Yu 1998; Zhu & Schultze 1997; Zhu *et al.* 1999; Qu *et al.* (2013a).

Ptomacanthus: Brazeau 2009, 2012; Denison 1979; Miles 1973a.

Pucapampella: Maisey 2001a; Maisey & Anderson 2001; Maisey & Lane 2010; Janvier & Maisey 2010.

Raynerius: Giles *et al*. 2015b.

Rhadinacanthus: Burrow *et al*. (2016).

Squalus: Schaeffer 1981; Gans & Parsons 1964; Marinelli & Strenger 1959.

Synechodus: Maisey 1985.

Tamiobatis: Schaeffer 1981.

Tetanopsyrus: Gagnier & Wilson 1995; Gagnier *et al*. 1999; Hanke *et al.* 2001.

Thrinacodus: Grogan & Lund 2008**.**

Tribodus: Maisey & de Carvalho 1997; Lane 2010; Lane & Maisey 2009, 2012.

Triodus: Solér-Gijon, R. & Hampe 1998; Hampe 2003; Heidtke *et al*. 2004.

Tristychius: Dick1978; Coates & Gess 2007; Coates & Tietjen 2018; Coates et al. 2019.

Uraniacanthus: Bernacsek & Dineley 1977; Hanke & Davis 2008; Newman *et al.* 2012; Burrow *et al*. 2016.

Youngolepis: Chang & Yu 1981; Chang 1982, 1991, 2004.

4. Character List

C numbers in square brackets refer to character number in Coates *et al*. 2018.

Skeletal tissues

1. **Tessellate calcified cartilage: absent (0); present (1**). [C1] Dean & Summers (2006); Dean *et al*. (2009); Maisey (1984, 2013); Seidel *et al*. (2016) Lund & Grogan (1997, 2004a, b); Coates & Sequeira (2001a, b); Maisey (2001); Brazeau (2009); Davis et al. (2012); Grogan *et al*. (2012); Pradel *et al.* (2014).

2. **Perichondral bone: present (0); absent (1).** [C2] Janvier (1996); Donoghue & Aldridge (2001); Brazeau (2009); Davis *et al.* (2012).

3. **Extensive endochondral ossification: absent (0); present (1).** [C3] Forey (1980); Gardiner (1984); Brazeau (2009); Davis *et al.* (2012).

4. **Extensive calcified cartilage: absent (0); present (1).** [C4] To capture all taxa in which the neurocranium, jaws, hyoid and gill arches, as well as parts of the axial and appendicular skeleton are mineralized in the absence of perichondral bone.

5. **Tubular Dentine: absent (0); present (1).** [C5 in part] Stahl (1999), see also Patterson (1965): present in chimaeroids, edestids, *Helodus*, and petalodonts, but absent in symmoriids and iniopterygians (Zangerl & Case 1973).

6. **Pore canal network: absent (0); present (1).** [C7] Lu *et al*. (2016).

7. **Acrodin tooth caps (enameloid cap restricted to crown apex): absent (0); present (1).** [C8] Friedman & Brazeau (2010); Zhu *et al.* (2013, 2009); Lu *et al*. (2016).

Squamation & related structures

8. **Trunk scales monocuspid (0); multicuspid (1).** [C9] Revised after Davis *et al.* (2012); see Burrow *et al*. (2016) and Coates *et al.* (2018).

9. **Scale growth concentric: absent (0); present (1).** [C10] Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Burrow *et al*. (2016).

10. **Peg-and-socket articulation: absent (0); present (1).** [C11] Gardiner (1984); Coates (1999); Brazeau (2009); Davis *et al.* (2012).

11. **Anterodorsal process on scale: absent (0); present (1).** [C12] Zhu *et al.* (2009, 2013); Gardiner (1984); Coates (1999); Brazeau (2009); Davis *et al.* (2012). Notably present in *Cheirolepis*, see Pearson and Westoll (1979).

12. **Body scales with bulging base: absent (0); present (1).** [C13] Brazeau (2009); Davis *et al.* (2012); Burrow *et al*. (2016).

13. **Body scales with flattened base: absent (0); present (1).** [C14] Brazeau (2009) ; Davis *et al.* (2012); Burrow *et al*. (2016). Note that both flat- and bulge-based scales occur in conjunction in *Ptomacanthus* (Brazeau 2012).

14. **Body scales with basal canal or open basal vascular cavity: absent (0); present (1).** [C15] Chondrichthyan placoid scales are distinguished, in part, by the presence of a basal canal (Reif 1978). Early chondrichthyan scales that depart from the standard placoid morphology also exhibit basal canals, e.g. *Akmonistion* (Coates & Sequeira 2001a, fig. 12E) and *Antarctilamna* (Young 1982, p.830). Basal canals are present in putative chondrichthyan scale forms such as *Elegestolepis* (Karatajūte-Talimaa 1992), *Polymerolepis* and *Seretolepis* (Hanke & Wilson 2010).

15. **Neck canal: absent (0) present (1). [C16]** Although a standard feature of placoid scales, presence of a neck canal is widespread among early vertebrates: Coates *et al.* (2018).

16. **Sensory line canal passes between or beneath scales (0); passes over scales and/or is partially enclosed or surrounded by scales (1); perforates and passes through scales (2).** [C17] Davis (2002); Friedman & Brazeau (2010); Davis *et al.* (2012); Zhu *et al*. (2013); Brazeau & Friedman (2014); Burrow *et al.* (2016).

17. **Lepidotrichia: absent (0); present (1). [C18].**

18. **Fringing fulcra: absent (0); present (1).** [C20] Zhu *et al.* (2009; 2013); Coates (1999). Scored inapplicable in taxa lacking lepidotrichia.

19. **Scute-like ridge scales (fulcra): absent (0); present (1).** [C21] Giles *et al.* (2015c).

Cranial dermal skeleton

20. **Cranial cap denticles, single-crowned, non-growing: absent (0); present (1).** A characteristic of some, but not all, symmoriids, present in *Akmonistion* and other stethacanthids, but see also genera such as *Kawichthys*.

21. **Sclerotic ring: 0 absent (0); present (1).** [C22] Giles *et al*. (2015, c.52), Qiao *et al*. (2016, c.277), Zhu *et al*. (2016, c.275); Burrow *et al.* (2016); Coates et al. (2018).

22. **Number of sclerotic plates: four or less (0); more than four (1).** [C23] Zhu *et al*. (2013, c170); Qiao *et al*. (2016, c.241); Zhu *et al*. (2016, c.239); Burrow *et al.* (2016).

23. **Dermal skull roof includes large dermal plates (0); consists of plates, tesserae or scales (1); naked or largely scale free (2).** [C25] Forey (1980); Gardiner (1984); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Brazeau & Friedman (2014).

24. **Dermal ornamentation: smooth (0); parallel, vermiform ridges (1); concentric ridges (2); tuberculate (3).** [C24] Giles *et al*. (2015c). Coded inapplicable where dermal plates absent.

25. **Cranial tessera morphology: large interlocking plates (0); microsquamose, no larger than body squamation (1).** [C26] Brazeau (2009) through to Giles *et al.* (2015c). Coded inapplicable where tesserae are absent.

26. **Anterior or mesial edge of nasal notched for anterior nostril: absent (0); present (1)**. [C29] Contra Zhu *et al.* (2013), the anterior rim of the nasal in *Cheirolepis* is notched.

27. **Supraorbital: absent (0); present (1).** [C30] Zhu *et al.* (2009, 2013).

28. **Broad supraorbital vaults: absent (0); present (1).** Dennis & Miles (1981); Giles *et al.* (2015c). [C31] As noted by Giles *et al*., this character is contingent on the presence of a dermal skull roof composed of large dermal bones.

29. **Large median bone contributes to posterior margin of skull roof: absent (0); present (1).** [C33] Zhu *et al.* (2016).

30. **Pineal opening perforates dermal skull roof: present (0); absent (1).** [C37] Davis *et al.* (2012); Giles *et al.* (2015c).

31. **Consolidated cheek plates: absent (0); present (1).** [C39] Davis (2002); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Burrow *et al.* (2016).

32. **Enlarged postorbital tessera separate from orbital series: absent (0); present (1).** [C40] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Burrow *et al.* (2016).

33. **Dermal intracranial joint: absent (0); present (1).** [C41] Zhu *et al.* (2009, 2013).

34. **Sensory line network preserved as open grooves (sulci) in dermal bones (0); sensory lines pass through canals enclosed within dermal bones (1).** [C45] (Davis 2002); Davis *et al.* (2012); Zhu *et al.* (2013).

35. **Sensory canal or pit-line associated with maxilla: absent (0); present (1).** [C46] Contra Zhu *et al.* (2013) this structure is not reported or figured in *Mimipiscis* (Gardiner 1984, Choo 2011); Friedman (2007) notes correctly that this feature is present in onychodonts, *Moythomasia* and *Cheirolepis*.

36. **Jugal portion of infraorbital canal joins supramaxillary canal: present (0); absent (1).** [C47] Brazeau (2009), but see redefinition in Davis *et al.* (2012); Zhu *et al.* (2013).

37. **Anterior pit line of skull roof: absent (0); present (1).** [C48] Giles *et al.* (2015c).

38. **Spiracular opening in dermal skull roof bounded by bones carrying otic canal: absent (0); present (1).** [C51] Giles *et al*. (2015); Lu *et al*. (2016).

39. **Dermohyal (submarginal) ossification: absent (0); present (1).** [C55] Alternative homology hypotheses discussed in Coates *et al*. (2018).

40. **Branchiostegal series: absent (0); present (1).** [C57] Davis (2002); Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Burrow et al. (2016).

41. **Opercular and subopercular bones: absent (0); present (1).** [C58] Scores for opercular bones contingent on branchiostegal series presence.

42. **Branchiostegal plate series along ventral margin of lower jaw: absent (0); present (1).** [C59] Davis (2002); Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

43. **Branchiostegal ossifications plate-like (0); narrow and ribbon-like (1); filamentous (2).** [C60] Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Lu *et al.* (2016).

44. **Branchiostegal ossifications ornamented (0); unornamented (1).** [C61] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

45. **Branchiostegals imbricated: absent (0); present (1).** [C62] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

46. **Opercular cover of branchial chamber complete or partial (0); separate gill covers and gill slits (1).** [C63] Lund & Grogan (1997); Hanke & Wilson (2004); Davis *et al.* (2012); Zhu *et al.* (2013). See alternative scores and arguments in Dearden *et al*. (2019).

47. **Gular plates: absent (0); present (1).** [C64] Gardiner (1984); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

Hyoid and gill arches

48. **Gill skeleton mostly beneath otico-occipital region (0); mostly posterior to occipital region (1).** [C66] Zangerl (1981); Lund & Grogan (1997); Stahl (1999). Both conditions (states '0' and '1') are likely present among acanthodians, but see alternative argument in Dearden *et al*. (2019).

49. **Perforate hyomandibula: absent (0); present (1).** [C67] Zhu *et al.* (2009, 2013); Lu *et al.* (2016).

50. **Interhyal: absent (0); present (1).** [C68] Davis *et al.* (2012); Zhu *et al.* (2013).

51. **Ceratohyal smooth with posterior, lateral fossa: absent (0); present (1).** [C69] Ceratohyals of extant elasmobranchs present a smooth lateral surface (elliptical in cross section). Posteriorly, the cartilage curves laterally, containing a hollow within the lateral surface: a distinct fossa. Fossil examples include *Egertonodus* (Maisey, 1983), *Orthacanthus* (Hotton, 1952; pers. obs. M.I.C.), and *Tristychius*. Hyoid arches are known in Bear Gulch

chondrichthyans such as *Debeerius* (Grogan & Lund 2000) and *Thrinacodus* (Grogan & Lund 2008) but the cartilages are flattened, presenting limited information about their 3D morphology in life.

52. **Ceratohyal spatulate or bladed anteriorly: absent (0); present (1).** [C70] Present in *Tristychius* and *Phoebodus*, and possibly more widespread among early elasmobranchs. However, certainly absent in *Orthacanthus* (Hotton 1952).

53. **Hypohyals: absent (0); present (1).** [C71] Friedman & Brazeau (2010); Pradel *et al.* (2014).

54. **Basihyal absent, hyoid arch articulates directly with basibranchial (0); basihyal present (1).** [C72] Pradel *et al.* (2014);Carr *et al.* (2009); Brazeau *et al*. (2017); Dearden *et al*. (2019).

55. **Separate supra- and infra-pharyngobranchials absent (0); present (1).** [C73] Gardiner (1984); Pradel *et al*. (2014).

56. **Pharyngobranchials directed anteriorly (0); posteriorly (1).** [C74] Pradel *et al*. (2014).

57. **Posteriormost branchial arch bears epibranchial unit: absent (0); present (1).** [C75]

58. **Epibranchials bear posterior flange: absent (0); present (1).** [C76]

59. **Hypobranchials directed anteriorly (0); hypobranchials of second and more posterior gill arches directed posteriorly (1).** [C77]

Dentition & tooth-bearing bones

60. **Oral dermal tubercles borne on jaw cartilages: absent (0); present (1).** [C78] Hanke & Wilson (2004); Brazeau (229); Davis *et al.* (2012); Zhu *et al.* (2013). This character is concerned only with position and form, and not with histological, and by inference, developmental distinctiveness (cf. Rücklin *et al.* 2012).

61. **Pharyngeal teeth or denticles: absent (0); present (1).** [C79].

62. **Tooth families/whorls/generative tooth sets: absent (0); present (1).** [C80] Davis (2002); Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

63. **Bases of tooth families/whorls: single, continuous plate (0); some or all whorls consist of separate tooth units (1).** [C81] Adjusted from Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Giles *et al*. (2015).

64. **Lingual torus: absent (0); present (1).** [C82] This platform or ledge (Ginter *et al.* 2010) is notably absent in early elasmobranchs and many of the non-toothplate dentitions of stem holocephalans.

65. **Basolabial shelf: absent (0); present (1).** [C83] (Ginter *et al.* 2010.)

66. **Teeth with three slim main cusps almost equal to each other, strongly recurved: absent (0); present (1).** Adapted from Ginter *et al*. (2010): a classic and distinctive characteristic of phoebodont teeth.

67. **Tooth families/generative sets restricted to symphysial region (0); distributed along jaw margin (1).** [C84] Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013). Revised in light of discussion by Tucker and Fraser (2013): tooth whorl restricted to symphysial region appears to be the more general condition, whereas tooth whorls distributed continuously along the gape margin likely represents a chondrichthyan synapomorphy.

68. **Number of tooth families/whorls per jaw ramus: 15 or fewer (0); 20 or more (1).** [C85]

69. **Toothplates absent (0); present (1).** [C86] Patterson (1965); Stahl (1999).

70. **Toothplates consolidated into one to three large posterior plates, and one to three smaller anterior tooth plates, occupying each quadrant of the jaw: absent (0); present (1).** [C87] Adapted from Stahl (1999), the character captures conditions in chondrenchelyids, cochliodonts, and more derived taxa.

71. **Toothplate complement restricted to two pairs in the upper jaw and a single pair in the lower jaw: absent (0); present (1).** [C88] After Patterson (1965).

72. **Mandibular teeth fused to dermal plates on biting surfaces of jaw cartilages: absent (0); present (1).** [C89] Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

73. **Dermal plates on biting surface of jaw cartilages: absent (0); present (1).** [C90] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Giles et al. (2015c).

74. **Gnathal plates mesial to and/or above (or below) jaw cartilage: absent (0); present (1).** [C91] Zhu *et al*. (2016).

75. **Maxilla and premaxilla *sensu stricto* (upper gnathal plates lateral to jaw cartilage without palatal lamina): absent (0); present (1)**. [C94] Zhu *et al*. (2016).

76. **Dentary bone encloses mandibular sensory canal: absent (0); present (1).** [C95] Gardiner (1984); see aslo Zhu *et al.* (2009, 2013).

77. **Infradentary foramen and groove, series: absent (0); present (1**). [C96] Zhu *et al*. (2010): note discussion of the lower jaw attributed, to *Meemannia*.

78. **Tooth-bearing median rostral: absent (0); present (1).** [C97] Zhu *et al.* (2009, 2013).

79. **Median dermal bone of palate (parasphenoid): absent (0); present (1).** [C98] Gardiner (1984); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

80. **Denticulated field of parasphenoid: without spiracular groove (0); with spiracular groove (1).** [C99] Friedman (2007); Zhu *et al.* (2009, 2013).

81. **Denticle field of parasphenoid with multifid anterior margin: absent (0); present (1).** [C101] Friedman (2007); Zhu *et al.* (2009, 2013); Lu *et al*. (2016).

Mandibular arch

82. **Large otic process of the palatoquadrate: absent (0); present (1).** [C102] Coates & Sequeira (2001a); Davis (2002); Brazeau (2009); Zhu *et al.* (2009, 2013).

83. **Oblique ridge or groove along medial face of palatoquadrate: absent (0); present (1).** [C105] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Lu et al. (2016).

84. **Fenestration of palatoquadrate at basipterygoid articulation: absent (0); present (1).** [C106] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Lu et al. (2016).

85. **Perforate or fenestrate anterodorsal (metapterygoid) portion of palatoquadrate: absent (0); present (1).** [C107] Davis (2002); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

86. **Articulation surface of the palatoquadrate with the postorbital process directed anteriorly (0); laterally (1); dorsally (2).** [C108]

87. **Palatoquadrate fused to the neurocranium: absent (0); present (1).** [C109]

88. **Pronounced dorsal process on Meckelian bone or cartilage: absent (0); present (1).** [C110] Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Burrow *et al*. (2016).

89. **Mandibular mesial process/ knob/ preglenoid articular process or condyle: absent (0); present (1).** [C111) Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Burrow *et al*. (2016)..

90. **Jaw articulation located on rearmost extremity of mandible: absent (0); present (1).** [C112] Davis *et al.* (2012); Zhu *et al.* (2013).

91. **Dental sulcus (trough) adjacent to oral rim on Meckel's cartilage and palatoquadrate: absent (0); present (1).** [C113]

92. **Scalloped tooth-bearing margin on Meckel's cartilage and palatoquadrate: absent (0); present (1).** [C114]

93. **Mandibular symphysis fused: absent (0); present (1).** [C115]

Neurocranium

94. **Internasal vacuities: absent (0); present (1).** [C117] Lu *et al.* (2016).

95. **Precerebral fontanelle: absent (0); present (1).** [C118] Schaeffer (1981); Lund & Grogan (1997); Coates & Sequeira (1998, 2001a, b); Maisey (2001a); Brazeau (2009); Pradel *et al*. (2011) Davis *et al.* (2012); Zhu *et al.* (2013); Brazeau & Friedman (2014).

96. **Space for forebrain and (at least) proximal portion of olfactory tracts narrow and elongate, extending between orbits: absent (0); present (1**). [C119]

97. **Rostral bar: absent (0); present (1).** [C121] Maisey (1985).

98. **Internasal groove absent (0); present (1).** [C122]

99. **Orbitonasal lamina expanded: absent (0); present (1).** [C123] Patterson (1965). The orbitonasal lamina forms the wall between olfactory capsule and the orbit. Anteroposterior expansion separates the nasal capsule from the orbit; dorsal expansion/elevation has been argued to be a contributory factor in the evolution of the chimaeroid ethmoid canal (Patterson 1965, and references therein).

100. **Elongate, tooth-bearing, pre-nasal ethmo-rostral region: absent (0); present (1).** Extended rostra are reasonably widespread in early gnathostomes and their jawless relatives, but extended rostra that include the gape almost to the anterior tip (of the rostrum) are unusual. This results in the kind of elongate jaws associated with garpike and crocodiles among living taxa; *Saurichthys* and ichthyosaurs among fossil vertebrates. In the present context, it appears to be unique to *Phoebodus* and *Thrinacoselache*.

101. **Palatobasal (or orbital) articulation posterior to the optic foramen (0); anterior to the optic foramen, grooved, and overlapped by process or flange of palatoquadrate (1); anterior to optic foramen, smooth, and overlaps or flanks articular surface on palatoquadrate (2).** [C125] Pradel *et al.* (2011); Coates *et al*. (2017); Maisey (2005).

102. **Trochlear nerve foramen anterior to optic nerve foramen: absent (0); present (1).** [C127]

103. **Supraorbital shelf broad with convex lateral margin: absent (0); present (1).** [C128] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

104. **Interorbital space broad (0); narrow (1).** [C130] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Coates et al. (2017).1

105. **Optic pedicel: absent (0); present (1).** [C131] Dupret (2014); Zhu et al. (2009, 2013); Coates et al. (2017).

106. **Ophthalmic foramen in anterodorsal extremity of orbit communicates with enclosed cranial space: absent (0); present (1).** [C133]

107. **Extended prehypophysial portion of sphenoid: absent (0); present (1).** [C135] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

108. **Canal for efferent pseudobranchial artery within basicranial cartilage: absent (0); present (1).** [C136] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

109. **Entrance of internal carotids: through separate openings flanking the hypophyseal opening or recess (0); through a common opening at the central midline of the basicranium (1).** [C136] Schaeffer (1981); Coates & Sequeira (1998); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

110. **Internal carotids: entering single or paired openings in the basicranium from a posterolateral angle (0); entering basicranial opening(s) head-on from an extreme, lateral angle (1); absent (2).** [C138]

111. **Ascending basisphenoid pillar pierced by common internal carotid: absent (0); present (1).** [C111] Miles (1973b); Brazeau (2009); Friedman & Brazeau (2010); Davis *et al.* (2012); Zhu *et al.* (2013).

112. **Spiracular groove on basicranial surface: absent (0); present (1).** [C140] Davis *et al.* (2012); Zhu *et al.* (2013).

113. **Spiracular groove on lateral or transverse wall of jugular canal: absent (0); present (1).** [C141] Davis *et al.* (2012); Zhu *et al.* (2013).

114. **Spiracular groove open (0); enclosed by spiracular bar or canal (1).** [C142] Lu *et al.* (2016); (Patterson 1982).

115. **Orbit larger than otic capsule: absent (0); present (1)**. [C143] Lund & Grogan (1997); Coates *et al*. (2017).

116. **Postorbital process and arcade: absent (0); present (1). [C144]** Pradel *et al.* (2011).

117. **Postorbital process and arcade short and deep - width not more than maximum braincase width (excluding arcade) (0); process and arcade wide - width exceeds maximum width of braincase, and anteroposteriorly narrow (1); process and arcade massive (2); arcade forms postorbital pillar (3).** [C145]

118. **Postorbital process downturned, with anhedral angle relative to basicranium: absent (0); present (1).** [C146] (Maisey 2011).

119. **Jugular canal diameter small (0); large (1); canal absent (2).** [C147] Pradel *et al.* (2011).

120. **Canal, likely for trigeminal nerve (V) mandibular ramus, passes through the postorbital process from proximal dorsal entry to distal and ventral exit: absent (0); present (1).** [C148]

121. **Postorbital process expanded anteroposteriorly: absent (0); present (1).** [C149]

122. **Postorbital process articulates with palatoquadrate: absent (0); present (1).** [C150] Schaeffer (1981); Coates & Sequeira (1998); Maisey (2001a); Pradel *et al.* (2011); Davis *et al.* (2012); Zhu *et al.* (2013).

123. **Trigemino-facial recess: absent (0); present (1).** [C151] Goodrich (1930); Gardiner (1984); Pradel (2010); Pradel *et al*. (2011); Davis *et al.* (2012).

124. **Jugular canal long, extends throughout most of otic capsule wall posterior to the postorbital process (0); short and/or groove present on exterior of otic wall (1); absent, path of jugular removed from otic wall (2**). [C152] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Giles *et al.* (2015c); Coates *et al.* (2017).

125. **C-bout notch separates postorbital process from supraotic shelf: absent (0); present (1).** [C153]

126. **Hyoid ramus of facial nerve (N. VII) exits through posterior jugular opening: absent (0); present (1).** [C155] Friedman (2007); Brazeau (2009); Friedman & Brazeau (2010); Davis *et al.* (2012); Zhu *et al.* (2013).

127. **Periotic process: absent (0); present (1).** [C157] Maisey (2007); Coates *et al*. (2017).

128. **Relative position of jugular groove and hyomandibular articulation: hyomandibula dorsal or same level (i.e. on bridge) (0); jugular vein passing dorsal or lateral to hyomandibula (1).** [C159] Brazeau & de Winter (2015).

129. **Transverse otic process: absent (0); present (1).** [C160] Lu *et al*. (2016); Giles *et al*. (2016); Giles *et al.* (2015).

130. **Craniospinal process: absent (0); present (1).** [C161] Giles *et al.* (2015); Lu *et al*. (2016).

131. **Lateral otic process: absent (0); present (1).** [C162] Schaeffer (1981); Coates & Sequeira (1998); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

132. **Hyomandibula articulates with neurocranium beneath otic shelf: absent (0); present (1).** [C163]

133. **Sub-otic occipital fossa: absent (0); present (1).** [C164]

134. **Postotic process: absent (0); present (1).** [C166] Pradel *et al.* (2011).

135. **Otic capsule extends posterolaterally relative to occipital arch: absent (0); present (1).** [C167] Maisey (1985).

136. **Otic capsules: widely separated (0); approaching dorsal midline (1).** [C168]

137. **Otic capsules project anteriorly between postorbital processes: absent (0); present (1).** [C169] (Maisey 1983).

138. **Endocranial roof anterior to otic capsules domelike, smoothly convex dorsally and anteriorly: absent (0); present (1).** [C170].

139. **Roof of skeletal cavity for cerebellum and mesencephalon significantly higher than dorsal-most level of semicircular canals: absent (0); present (1).** [C171]

140. **Roof of the endocranial space for telencephalon and olfactory tracts offset ventrally relative to level of mesencephalon: absent (0); present (1).** [C172] Coates *et al*. (2017).

141. **Labyrinth cavity separated from the main neurocranial cavity by a cartilaginous or ossified capsular wall (0); skeletal medial capsular wall absent (1).** [C173] Pradel *et al*. (2011); Davis *et al.* (2012); Zhu *et al.* (2013).

142. **Double octaval nerve foramena in chondrified mesial wall of otic capsule: absent (0); present (1).** [C174]

143. **External (horizontal) semicircular canal joins the vestibular region dorsal to posterior ampulla (0); joins level with posterior ampulla (1).** [C177] Davis *et al.* (2012); Zhu *et al.* (2013).

144. **Angle of external semicircular canal: in lateral view, straight line projected through canal intersects anterior ampulla, external ampullae, and base of foramen magnum: absent (0); present (1).** [C178] Maisey (2007).

145. **Left and right external semicircular canals approach or meet the posterodorsal midine of the hindbrain roof: absent (0); present (1).** [C179]

146. **Preampullary portion of posterior semicircular canal absent (0); present (1).** [C180]

147. **Crus commune connecting anterior and posterior semicircular canals: present (0); absent (1).** [C181]

148. **Sinus superior: absent or indistinguishable from union of anterior and posterior canals with saccular chamber (0); present, elongate and nearly vertical (1).** [C182] Davis *et al.* (2012); Zhu *et al.* (2013).

149. **Lateral cranial canal: absent (0); present (1).** [C183] Zhu *et al.* (2009, 2013); Lu *et al.* (2016). Gardiner (1984); Coates (1998).

150. **Endolymphatic ducts: posteriodorsally angled tubes (0); tubes oriented vertically through endolymphatic fossa/posterior dorsal fontanelle (1).** [C184] Schaeffer (1981); Coates & Sequeira (1998, 2001); Davis (2002); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

151. **Posterior dorsal fontanelle connected to persistent otico-occipital fissure (0); posterior tectum separates fontanelle from fissure (1).** [C185] Schaeffer (1981); Coates & Sequeira (1998); Pradel *et al.* (2011).

152. **Subcircular endolymphatic foramen: absent (0); present (1).** [C186] Pradel *et al*. (2015); Maisey & Lane (2010).

153. **External opening for endolymphatic ducts anterior to crus commune: absent (0); present (1).** [C187] Coates *et al*. (2017).

154. **Supraotic shelf broad: absent (0); present (1).** [C188]

155. **Dorsal otic ridge: absent (0); present (1).** [C189] Coates & Sequeira (1998, 2001); Maisey (2001); Davis (2002); Davis *et al.* (2012); Zhu *et al.* (2013); Brazeau & Friedman (2014). As discussed by Brazeau and Friedman, the utility of this likely chondrichthyan synapomorphy is challenged by the difficulty of coding for presence in taxa with firmly attached dermatocranial bones.

156. **Dorsal otic ridge forms a crest posteriorly: absent (0); present (1).** [C190] Coates & Sequeira (1998, 2001); Pradel *et al.* (2011).

157. **Endolymphatic fossa: absent (0); present (1).** [C191] Pradel *et al*. (2011).

158. **Endolymphatic fossa elongate (slot-shaped), dividing dorsal otic ridge along midline: absent (0); present (1).** [C192] Coates *et al.* (2017).

159. **Perilymphatic fenestra within the endolymphatic fossa: absent (0); present (1).** [C193] Pradel *et al*. (2011); Coates *et al.* (2017).

160. **Ventral cranial fissure: absent (0); present (1).** [C194] Janvier (1996); Coates & Sequeira (2001); Maisey (2001); Davis (2002); Brazeau (2009); Pradel *et al.* (2011); Davis *et al.* (2012); Zhu *et al.* (2013).

161. **Endoskeletal intracranial joint: absent (0); present (1).** [C195] Janvier (1996, and references therein); Davis *et al.* (2012); Zhu *et al.* (2013).

162. **Metotic (otic-occipital) fissure: absent (0); present (1).** [C196] Schaeffer (1981); Janvier (1996); Coates & Sequeira (1998); Maisey (2001); Davis (2002); Brazeau (2009); Pradel *et al*. (2011); Davis *et al.* (2012); Zhu *et al.* (2013).

163. **Vestibular fontanelle: absent (0); present (1).** [C197] Brazeau (2009); Friedman & Brazeau (2010). Davis *et al.* (2012); Zhu *et al.* (2013).

164. **Hypotic lamina: absent (0); present (1).** [C198] Schaeffer (1981); Maisey (1984, 2001); Brazeau (2009); Pradel *et al*. (2011, 2013); Davis *et al.* (2012); Zhu *et al.* (2013); Coates *et al*. (2017).

165. **Glossopharyngeal nerve path: directed laterally, across floor of the saccular chamber and exits via foramen in side wall of the otic capsule (0); directed posteriorly, and exits through metotic fissure or foramen in posteroventral wall of otic capsule (1); exits laterally through a canal contained ventrally (floored) by the hypotic lamina (2); exits through a foramen anterior to the posterior ampulla (3).** [C199] Coates et al. (2017), adapted from Schaeffer (1981); Coates & Sequeira (1998, 2001); Brazeau (2009): Davis *et al.* (2012); Zhu *et al.* (2013); Pradel *et al*. (2011, 2013).

166. **Glossopharyngeal and vagus nerves share common exit from neurocranium: absent (0); present (1).** [C200]

167. **Basicranial morphology: platybasic (0); tropibasic (1).** [C201] Brazeau (2009); Pradel *et al.* (2011); Davis *et al.* (2012); Zhu *et al.* (2013); Maisey (2007); Pradel *et al* (2011).

168. **Channel for dorsal aorta and/or lateral dorsal aortae passes through basicranium (0): external to basicranium (1).** [C202] Schaeffer (1981); Coates & Sequeira (1998); Brazeau (2009); Pradel *et al.* (2011); Brazeau & Friedman (2014); Coates et al. (2017).

169. **Dorsal aorta divides into lateral dorsal aortae posterior to occipital level (0); anterior to level of the occiput (1).** [C203] Pradel *et al*. (2011); Giles *et al.* (2015); Coates et al. (2017).

170. **Ventral portion of occipital arch wedged between rear of otic capsules: absent (0); present (1).** [C204] Schaeffer (1981); Coates & Sequeira (1998); Maisey (2001a); Brazeau (2009); Pradel *et al.* (2011); Davis *et al.* (2012); Coates *et al.* (2017).

171. **Dorsal portion of occipital arch wedged between otic capsules: absent (0); present (1).** [C205] Schaeffer (1981); Coates & Sequeira (1998); Maisey (2001a); Brazeau (2009); Pradel *et al.* (2011); Davis *et al.* (2012); Coates *et al.* (2017).

172. **Occipital crest anteroposteriorly elongate, and extends from the roof of the posterior tectum: absent (0); present (1).** [C206]

Axial and appendicular skeleton

173. **Calcified vertebral centra: absent (0); present (1).** [C208] Maisey (1985): biconcave calcified disc centra surrounding constricted notochord, suggested synapomorphy of crown elasmobranchs (Coates *et al.* 2017).

174. **Chordacentra: absent (0); present (1).** [C209] Stahl (1999); Coates and Sequeira (2001); Coates *et al*. (2017).

175. **Chordacentra polyspondylous and consist of narrow closely packed rings: absent (0); present (1).** [C210] Patterson (1965); Coates *et al*. (2017).

176. **Synarcual: absent (0); present (1).** [C211] Stahl (1999); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Coates *et al.* (2017).

177. **Macromeric dermal pectoral girdle (0); micromeric or lacking dermal skeleton entirely (1).** [C212] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

178. **Macromeric dermal pectoral girdle composition: ventral and dorsal components (0); ventral components only (1).** [C213] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

179. **Macromeric pectoral dermal skeleton forms complete ring around the trunk: present (0); absent (1).** [C214] Goujet & Young (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

180. **Median dorsal plate: absent (0); present (1).** [C217] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

181. **Scapular process (dorsal) of shoulder endoskeleton: absent (0); present (1).** [C219] Coates & Sequeira (2001a); Zhu & Schultze (2001); Davis (2002); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Brazeau & Friedman (2014).

182. **Ventral margin of separate scapular ossification: horizontal (0); deeply angled (1).** [C220] Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

183. **Cross sectional shape of scapular process: flattened or strongly ovate (0); subcircular (1).** [C221] Davis (2002); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Burrow *et al.* (2016).

184. **Flange on trailing edge of scapulocoracoid: absent (0); present (1).** [C222] Davis (2002); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Burrow *et al.* (2016).

185. **Scapular process with posterodorsal process. Absent (0); present (1).** [C223] Coates & Sequeira (2001a); Davis *et al.* (2012); Zhu *et al.* (2013).

186. **Mineralisation of internal surface of scapular process: mineralised all around (0); un-mineralised on internal face forming a hemicylindrical cross-section.** [C224] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Burrow *et al.* (2016).

187. **Coracoid process: absent (0); present (1).** [C225] Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

188. **Procoracoid mineralisation: absent (0); present (1).** [C226] Davis (2002); Hanke & Wilson (2004): Brazeau (2009).

189. **Fin base articulation on scapulocoracoid: stenobasal, deeper than wide (0); eurybasal, wider than deep (1).** [C227] Lu et al. (2016).

190. **Pectoral fin articulation monobasal (0); dibasal (1); three or more basals (2).** [C228]

191. **Metapterygium pectinate subtriangular plate or bar supporting numerous (six or more)**

radials along distal edge: absent (0); present (1). [C229].

192. **Metapterygial whip absent (0); present (1).** [C230] Coates *et al*. (2017).

193. **Biserial pectoral fin endoskeleton: absent (0); present (1).** [C231] Lu *et al*. (2016).

194. **Propterygium perforated: absent (0); present (1).** [C232] Rosen *et al.* (1981); Patterson (1982); Davis *et al.* (2012); Zhu *et al.* (2013).

195. **Pelvic girdle with fused puboischiadic bar: absent (0); present (1).** [C234] Maisey (1984); Coates & Sequeira (2001a); Coates *et al*. (2017).

196. **Mixipterygial/mixopterygial claspers: absent (0), present (1).** [C235] Brazeau & Friedman (2014); Coates & Sequeira (2001a,b); Compagno (1999); Liem & Summers (1999); Long *et al*. (2015); Trinajstic *et al*. (2014).

197. **Pre-pelvic clasper or tenaculum: absent (0); present (1).** [C237] Patterson (1965); Coates et al. (2017).

198. **Number of dorsal fins, if present: one (0); two (1); one, extending from pectoral to anal fin level (2).** [C240] Coates & Sequeira (2001a); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

199. **Brush complex of bilaterally distributed calcified tubes flanking or embedded in calcified cartilage core: absent (0); present (1).** [C241]

200. **Posterior or pelvic-level dorsal fin with calcified base plate: absent (0); present (1).** [C242] Coates & Sequeira (2001a, b).

201. **Posterior dorsal fin with delta-shaped cartilage: absent (0); present (1).** [C243] Coates & Sequeira (2001a, b).

202. **Posterior or pelvic-level dorsal fin shape, base approximately as broad as tall and not broader than other median fins (0); base much longer than fin height, substantially longer than other median fins (1).** [C244] Brazeau & deWinter (2015); Lu *et al*. (2017).

203. **Anal fin: absent (0); present (1).** [C245] Coates & Sequeira (2001); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

204. **Anal fin base narrow, posteriormost proximal segments radials broad: absent (0); present (1).** [C246]

205. Caudal radials restricted to axial lobe (0); extend beyond level of body wall and deep into hypochordal lobe (1). [C247] Davis *et al.* (2012); Zhu *et al.* (2013).

206. Caudal neural and/or supraneural spines or radials short (0); long, expanded, and supporting high aspect-ratio (lunate) tail with notochord extending to posterodorsal extremity (1); notochord terminates pre-caudal extremity, neural and heamal radial lengths near symmetrical and support epichordal and hypochordal lobes respectively (2). [C248]

Spines: fins, cranial and elsewhere

207. Dorsal fin spine or spines: absent (0); present (1). [C249] Zhu *et al*. (2001); Zhu & Yu (2002); Friedman (2007); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013); Lu *et al*. (2016).

208. Dorsal fin spine at anterior (pectoral level) location only: absent (0); present (1). [C250]

209. Dorsal fin spine cross section: horseshoe shaped (0); flat sided with rectangular profile (1); subcircular (2). [C251] Hampe (2002); Brazeau & de Winter (2015).

210. Anterior dorsal fin spine leading edge concave in lateral view: absent (0); present (1). [C252]

211. Anal fin spine: absent (0); present (1). [C253] Maisey (1986); Davis (2002); Brazeau (2009).

212. Pectoral fin spines: absent (0); present (1). [C254] Davis (2002); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

213. Pectoral fin spine with denticles along posterior surface: absent (0); present (1). [C255] Burrow *et al*. (2016).

214. Prepectoral fin spines: absent (0); present (1). [C256] Davis (2002); Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013). Present in *Doliodus* (Maisey *et a*l. 2017).

215. Admedian pectoral spines absent (0); present (1). [C257] Burrow *et al*. (2016); see also description of *Doliodus* pectoral girdle (Maisey *et al*. 2017).

216. Median fin spine insertion: shallow, not greatly deeper than dermal bones/ scales (0); deep (1). [C258] Davis (2002); Hanke & Wilson (2004); Brazeau (2009). Davis *et al.* (2012); Zhu *et al.* (2013).

217. Intermediate (pre-pelvic) fin spines: absent (0); present (1). [C259] Davis (2002); Hanke & Wilson (2004); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

218. Fin spines with ridges: absent (0); present (1). [C260] Davis (2002); Brazeau (2009); Davis *et al.* (2012); Zhu *et al.* (2013).

219. Fin spines with nodes: absent (0); present (1). [C261] Davis (2002); Hanke & Wilson (2004); Brazeau (2009). Davis *et al.* (2012); Zhu *et al.* (2013).

220. Fin spines (dorsal) with rows of large denticles: absent (0); on posterior surface (1); on lateral surface (2). [C262] Maisey (1989b); Davis *et al.* (2012); Zhu *et al.* (2013); Brazeau & Friedman (2014).

221. Cephalic spines: absent (0); present (1). [C263] Maisey (1989); Coates *et al.* (2017).

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