

## APPENDIX 1 - CHARACTER DESCRIPTIONS

Note that we begin character numbering at 0 rather than 1, following the convention of the TNT software package.

### BASIC SHELL CHARACTERISTICS

#### 0. Shell/gladius/vestigial shell: absent (0); present (1)

This is a general character that includes any kind of molluscan shell whether it is calcified or not, internal or external, with or without siphuncle and/or chambered phragmocone. There are some living species of orders Sepioidea and Octopodoidea that lack any shell; in our dataset these are in the genera *Heteroteuthis*, *Japetella*, *Amphitretus* and *Argonauta*. *Argonauta* females secrete an external shell that functions as a brood chamber to protect eggs, but as this shell is secreted by glands of dorsal arms and is not attached to the body we do not consider it a true molluscan shell.

#### 1. Shell location in relation to the rest of the body: external (0); internal (1)

In extant cephalopods an external shell is only present in *Nautilus* (see character 0 for the exclusion of *Argonauta*).

#### 2. Shell extent along A-P axis: anterior half (0); posterior half (1); whole or most of the body length (2)

The shell of extant cuttlefish, squid, *Vampyroteuthis* and *Nautilus* usually occupies most of the mantle length, whereas in Spirulida and Octopoda the shell is located in the posterior part of the body. All Decapodiformes species in this study have a gladius which occupies whole or most of the body length except *Idiosepius*, which has a small posterior gladius (Hylleberg and Nateewathana, 1991), and *Rossia*, whose shell is anteriorly positioned (Bizikov, 2008). In fossils the gladius occupies most of the body-length where determinable, except in octopods.

#### 3. Shell extent along D-V axis: dorsal half (0); whole or most of the body height (1)

Cephalopod shells are normally positioned dorsally, but the shells of *Nautilus* and *Spirula* occupy most of the body height, as does that of the extinct *Belemnotherutis*.

#### 4. Calcium carbonate in the shell: absent (0); present (1)

This character is modified from character 3 of Young and Vecchione (1996) and character 1 of Lindgren *et al.* (2004). The gladius of extant neocoeloids is uncalcified, composed in squid of polysaccharid chitin in beta-crystalline form in association with proteins (Hunt and Nixon, 1981). Chitin (in association with calcium phosphate) seems to be also present in *Octopus* stylets (Napoleao *et al.*, 2005; Doubleday *et al.*, 2008), but reliable compositional data is not available for many other stylets within Octopoda. Original composition is often difficult to determine in fossils and data in the literature are often contradictory. For instance, Jeletzky (1966) reported that all known representatives of Loligosepiina possessed a strongly calcified gladius, while later studies (e.g. Doguzhaeva and Mutvei 2003) suggest that the gladii of this group were not biomineralised. The high frequency of secondary phosphatization also complicates the

interpretation of original mineralogy (Weaver, 2012). For these reasons we refrain from introducing more complex compositional characters, preferring to simply code the presence or absence of calcium carbonate, and follow the most recent description of the taxon concerned where there is disagreement. Nonetheless, we still code this character as unknown ('?') for many fossils where data are equivocal or not available (e.g. *Eoteuthoides caudata*, *Glyphiteuthis minor*, *Plesioeuthis subovata*, *Geopelthis simplex*).

**5. Discrete proostracum developed: no (0); yes (1)**

Character adapted from character 2 of Young and Vecchione (1996). The proostracum (or proostracum) is an anterior extension of the dorsal wall of the living chamber of the phragmocone; it is treated here (and by most authors) as homologous with a gladius. Naef (1922) and Jeletzky (1966) discussed the homologies between proostracum and fossil gladii in detail; see also Fuchs *et al.* (2009); Arkhipkin *et al.* (2012). Note that despite similarity of the term to shell-layer terms (e.g. ostracum), no shell-layer affinity is implied herein by our use of the term proostracum. All shell-bearing taxa in this study, other than *Spirula* and *Nautilus*, possess a proostracum.

**6. Proostracum U-shaped: no (0); yes (1)**

Some cirrate octopods possess a shell that is U-shaped in anterior or posterior view (with the U convex dorsally and open ventrally); in this study these are *Opisthoteuthis* and *Stauroteuthis*. Other cirrate octopods possess a saddle-shaped shell, but in our study there is only one such taxon (*Cirrothauma*), so no character has been erected for this state.

**7. Septate phragmocone: absent (0); present (1)**

A septate phragmocone is present in many fossils, in cuttlefishes (Sepiidae), Spirulidae and *Nautilus*. Note that this character is not equivalent to the presence of a phragmocone (see character 16), as the primary cone (=conus) of a gladius is the homologue of a phragmocone (see e.g. Naef, 1922), but is not normally septate. However a few living squid do possess decalcified septa in their primary cone (see character 18); these are coded as possessing a septate shell.

**8. Siphuncle linking chambers, or homologous structure: absent (0); present (1)**

Modified from character 1 of Young and Vecchione (1996). A siphuncle is plesiomorphic for coleoids, and for the living species it is clearly present in those with septate chambered shell. In *Vampyroteuthis* Young and Vecchione (1996) reported that visceropericardial coelom extends posteriorly as a slender duct to the apex of gladius, which they interpreted as a possible siphuncle homologue. Additionally, a groove on the ventral side of the cone of *Gonatus* has been interpreted as a vestigial siphuncle (Arkhipkin *et al.* 2012). Both *Vampyroteuthis* and *Gonatus* are hence coded as '1' herein. This character is undetermined for all fossil taxa in this study.

**9. Position of siphuncle within the shell: ventral (0); central (1)**

The siphuncle of living species is ventral with the exception of *Nautilus*, in which it has a central (medial) position. *Spirula* has a coiled shell but a ventral siphuncle (Clarkson, 1998).

#### **10. Proostracum: one unit (0); two units (1)**

Most cephalopods with a discrete proostracum possess a single undivided unit (e.g. a gladius), but in incirrate octopods the proostracum is divided medially, forming a pair of stylets.

#### **11. Median field (or homologous rachis): absent (0); present (1)**

In Recent teuthids the rachis extends the entire length of the gladius as a thickened axis (Donovan and Toll, 1988). In many fossil gladii (and in *Vampyroteuthis*) no thickened rachis is present, but typically a 'median field' extends along the entire length (see e.g. Fuchs and Larson, 2011b), delimited laterally by the median asymptotes (Fig. 2 of Bizikov, 1996). Most authors (see e.g. Naef 1922; Jeletzky 1966; Fuchs *et al.* 2009) have concluded that the median field and rachis are homologous structures, and we follow this assumption herein.

#### **12. Hyperbolar zones (or homologous vanes): absent (0); present (1)**

Hyperbolar zones are extensions or plates on either side of the median field, between the median and lateral asymptotes. Jeletzky (1966) analysed homologies in fossil and extant gladii and concluded that a strict differentiation between the hyperbolar (anteriorly concave) and parabolic (anteriorly convex) zones, divided by the lateral asymptotes, was imperative for correct interpretation of homology between belemnite, phragmoteuthid and teuthid proostraca. He homologised the hyperbolar zones of fossil Coleoidea with the 'vanes' of the extant gladius, which occupy the same position, and noted errors in previous work (e.g. Naef (1922, p. 120, fig. 43, 44, Roger, 1952, p. 736, fig. 85) on fossil gladii, where elements that we consider as lateral fields were designated as hyperbolar zones (Jeletzky, 1966, Fig. 4C-D). We follow Jeletzky's concept of hyperbolar zone herein, and note that it is equivalent to that of Bizikov (2004). While Bizikov has preferred the term 'lateral plates' (see also Naef, 1922), these can be homologized the hyperbolar zones of fossils and vanes of extant species respectively. Note that further terminological confusion persists (see e.g. Young *et al.* 1999, where vanes and wings are equated).

#### **13. Lateral fields (or homologous wings): absent (0); present (1)**

Lateral fields are extensions or plates located lateral to the hyperbolar zones (or vanes, see character 12). They are delimited medially by the lateral asymptote and laterally either by the edge of the proostracum, or by the marginal asymptote dividing them from the 'cone flags', where present. As for character 12, we follow the concept of Jeletzky (1966) except in the term used (Jeletzky preferred 'parabolic zones', although this is directly equivalent to lateral fields). We also follow that author in homologizing the lateral fields of fossil gladii with the wings of Recent gladii. Naef (1922) named the lateral fields 'Konusfahnen' ('conus flags'), which we consider misleading, as they are not homologous to the cone flags (or 'conus fields') of extant teuthids, which lie outside the wings.

Octopod vestigial shells have been equated with lateral fields/wings by most previous authors. Fuchs *et al.* (2008), for instance, followed Haas (2002) and Bizikov (2004) in considering a wide

gladius similar to that of *Trachyteuthis* or *Teudopsis* to be an ideal prerequisite to open and reduce the median field in a longitudinal direction to obtain the body plasticity typical of octobranchians, implying that the shell rudiments represent mainly the gladius' lateral fields (see also Fuchs *et al.*, 2009). A similar argument was presented by Donovan (1977: p. 43), who first noted that Octobranchia likely diverged from Mesozoic vampyromorphs, and that the gladius of *Palaeoctopus* could be derived from the wings or lateral fields of the loligosepiid gladius, the median field having been lost. Bizikov (2008) has presented an alternative homology model deduced from muscle-attachments, in which elements of the lateral fields (wings), hyperbolar zones (vanes) and median field (rachis) are all present in incirrate stylets. We consider, however, that the assumption that muscle attachment points indicate shell-zone homology may be flawed, as these points may have moved in concert with the reduction of portions of the shell. This model has also not been widely adopted by other workers, and hence we prefer the traditional homology model in this study, equating the octopod shell with lateral fields (wings).

#### **14. Rostrum or guard: absent (0); present (1)**

As discussed in detail by Fuchs (2012), the additional shell layers secreted from outside on the primary shell wall (conotheca) by using the epithelium of the shell sac are widely known as the 'rostrum' (Roger, 1952; Nesis, 1987; Teichert, 1988; Westheide and Rieger, 2007) or 'guard' (Donovan, 1977; Clarkson, 1998). The rostrum covers the posterior part of the belemnoid phragmocone and acts as a counterweight that brings the animal into a horizontal swimming position (Fuchs *et al.* 2007a). The term rostrum has also been used in non-belemnoid taxa, including extant forms, for any tapering posterior extension of the shell regardless of the shell-layer from which it originates. In this study, we treat all such structures as a rostrum for the purposes of coding. While we acknowledge the homology issues which this loose terminology raises, in many of the species under study here full data on exactly what type of rostrum is present is not available, and more sophisticated rostrum characters would not be simple to code. We also contend that, while the concept of a 'rostrum' is certainly a simplification, there nonetheless potential homology between the presence of all such structures, despite the use of different shell layers in different groups, as all represent the posterior extension of the shell through thickening. Despite our simplistic character model, some comments on the nature of the rostrum in taxa under study are given below.

In the studied oegopsid squids, a rostrum has been reported in *Gonatus* (Arkhipkin *et al.*, 2012), *Ommastrephes* (Bizikov, 1996, 2008; Arkhipkin *et al.*, 2012) and *Onychoteuthis* (Bizikov, 1996, 2008; Toll, 1982). No information is available as to the shell-layer associated with these structures.

In Sepiida, the protuberance at the posterior end of the cuttlebone has been variously described as a 'rostrum' or 'spine'. Fuchs (2012) preferred to avoid the term 'rostrum' in sepiids as the spine might be formed from primary shell (part of the sheath or primordial rostrum, the granulated layer that covers the dorsal shield of the cuttlebone), rather than as a tertiary formation on the outside of the primary shell (as in belemnites). However Doguzhaeva (2000) and Bizikov (2008) considered that the spine does indeed incorporate an extra layer outside the primary shell, comprising lens-like spherulites which are composed of short

acicular-prismatic crystallites Doguzhaeva (2000). We hence consider that sepiids likely *do* possess a rostrum *sensu* Fuchs (2012).

According to Fuchs (2012), the ‘rostrum-like’ structure at the posterior end of the *Vampyroteuthis gladius* might represent a rudiment of the upper (sheath) layer inherited from its ancestors. Bizikov (2004) also reported that periostracum of its shell lies dorsally and posteriorly and forms the small spine-shaped rostrum situated apically on the conus. We therefore consider the rostrum of *Vampyroteuthis* to represent a ‘sheath’ rather than a rostrum *sensu* Fuchs (2012), but code a rostrum as present in our study following our simplified character definition (see above).

**15. Rostrum length: short, up to 25% of the shell length (0); strongly developed, 25% or more of the shell length (1)**

Only two fossil belemnoids (*Hibolithes* and *Belemnotheutis*) have a strongly developed rostrum in this study; see character 14 for discussion of our definition of a rostrum.

**16. Phragmocone (or homologous primary cone): absent (0); present (1)**

The phragmocone is the core element of the cephalopod shell. Primitively it is septate (as in *Nautilus*), and in the extinct belemnoids (Fuchs *et al.* 2007a) the phragmocone-wall (conotheca) is thickened into a rostrum or guard. Most gladius-bearing extant taxa lack a septate (chambered) phragmocone, but possess instead an unchambered ‘primary cone’ or ‘conus’ (we prefer the former term), a small cup or cone-shaped structure posterior end of the gladius (Jereb and Roper 2010). The primary cone is normally considered to be a vestige (i.e. a homologue) of the phragmocone (e.g. Jeletzky, 1966; Donovan and Toll; 1988; Arkhipkin *et al.* 2012). We follow this homology model here.

In the Neocoleoidea under study here, a chambered phragmocone is present in belemnoids, *Sepia* and *Spirula*. In the living species a (reduced) primary cone is present in some squids (Oegopsida) and absent in octopuses (Octopoda). A primary cone has been described in the adult gladii of at least seven oegopsid families, notably in Onychoteuthidae, Lycoteuthidae, Gonatidae and Ommastrephidae (Donovan and Toll, 1988).

*Sepia* and close relatives possess an autapomorphic structure termed either a ‘labrum’ (Haas, 2003) or ‘inner cone’ (Bizikov, 2008), which is superficially similar to a primary cone. However as these taxa also possess a chambered phragmocone, the ‘labrum’/‘inner cone’ cannot be the homologue of the primary cone. No character for this structure is introduced in this study, as it only occurs in one taxon under study.

**17. Phragmocone coiled: no (0); yes (1)**

A coiled phragmocone is present in *Spirula* and *Nautilus*.

**18. Decalcified septa: absent (0); present (1)**

Where septa in the phragmocone are present (character 7), they are normally biomineralised. However in some living squid the siphuncle and gas-filled chambers have been lost, but non-biomineralized septa persist. According to Arkhipkin *et al.* (2012), the location, structure and

origin of these septa-like structures within the primary cone of modern squid suggest their homology with the organic components of the belemnoid and spirulid phragmocone septa.

**19. Primary cone open ventrally: absent (0); present (1)**

A ventrally open primary cone (a 'spoon-shaped conus') has been reported for several fossil taxa, but is not known from extant forms. The cone of *Rossia* is a flat thin plate with parallel lateral sides or flags (Bizikov 2008). It is unclear whether this flat shape has its origin in an opening of the primary cone or in a flattening of a closed primary cone, and we hence code the character as unknown ('?').

**20. Condition of the primary cone: cup-like cone (0); funnel-like cone (1)**

Both cup-like and funnel-like primary cones are closed at the base. Cup-like cones are hollow hemispheres, while funnel-like cones are more elongated and parallel-sided. In fossils, the former is characteristic of Loligosepiina, and the latter of Proteuthidina (Fuchs and Larson 2011b). A funnel-like cone is also present in the extant *Ommastrephes* (Bizikov, 1996 Fig. 68) and *Onychoteuthis* (Toll 1982; Toll 1988; and Bizikov 1996).

**21. Phragmocone wall (conotheca) thickened: no (0); yes (1)**

In belemnoids the conotheca (phragmocone) is thickened (see Fuchs 2007, 2012); in some belemnoids a rostrum (character 14) is also present, but all belemnoids in this study possess at least conothecal thickening, which is otherwise absent in our studied taxa.

**22. 'Cone flags': absent (0); present (1)**

'Cone flags' (= 'cone fields') are extensions of the posterolateral edge of either vanes or wings, whichever is present posterolaterally. They are not considered part of the vanes or wings, but are discrete structures, differentiated from the vanes/wings by longitudinal lines and marked changes in the orientation of the growth lines (Young *et al.*, 1999). Note that while these structures have often been described in the literature (e.g. Bizikov, 2008 for cranchiids) on which we base our coding, there appear to be no good criteria by which cone flags that occur outside vanes can be distinguished from wings.

**23. Ventral folding of posterolateral gladius margin: flat, not folded (0); folded but not fused (e.g. 'pseudocone') (1); folded and fused ventrally ('secondary cone') (2) [ordered character]**

A 'pseudocone' represents ventral flexure of the posterolateral gladius margin so that overlap but no fusion occurs (Donovan and Toll, 1988). In living species, a pseudocone is only present in six genera of Cranchidae, none of which are included in the present study. The fossil *Muensterella* however does display strong ventral folding of the posterolateral margin; while it does not form a true pseudoconus it is coded here as '1'. A 'secondary cone' is a pseudocone that has fused ventrally. The ventral line of fusion where the vanes join one another is usually apparent and helps distinguish the secondary from the primary cone. The secondary cone may be rather short or over half the gladius length (Toll, 1982).

**SHELL PROPORTIONS**

These characters relate to the shape of the gladius / proostracum, where present, and to the relative sizes and positions of the median field / rachis, hyperbolar zones / vanes, and lateral fields / wings, cones, and cone flags. For brevity the terms gladius, rachis, wings and vanes are used in character names. Where measurements occur in more than one character they are defined below.

*Rachis length*: median length of median field / rachis and phragmocone / primary cone (where present), but excluding the rostrum. See Figure A1\_1.

*Gladius length*: maximum length of gladius or proostracum and phragmocone / primary cone (where present), but excluding the rostrum. Measured parallel to the midline. For most taxa this is equivalent to rachis length, but is also determinable for taxa that lack a median field / rachis (e.g. octopods), and differs for those that have a concave anterior. See Figure A1\_1.

*Gladius width*: maximum width of the gladius. Where the proostracum is divided into stylets (i.e. in octopods), the width is taken between outer edges in life-position. See Figure A1\_1.

*Vane length*: measured from the hyperbolar zone / vane insertion on the median field / rachis to the posteriormost point of the hyperbolar zone / vane, parallel to the midline. See Figure A1\_1.

*Wing length*: measured from the lateral field / wing insertion on the hyperbolar zone / vane to the posteriormost point of the lateral field / wing, parallel to the midline. See Figure A1\_1.

*Vane width*: maximum width (measured at 90 degrees to the midline) of *one* hyperbolar zone / vane. See Figure A1\_1.

*Wing width*: maximum width (measured at 90 degrees to the midline) of *one* lateral field / wing. See Figure A1\_1.

*Total wing width*: the distance separating the most lateral parts of the wings. See Figure A1\_1.

*Rachis width at vane*: width of the median field / rachis at the point where the hyperbolar zone / vane insertion occurs. See Figure A1\_1.

*Rachis width at wing*: width of the median field / rachis at the point where the lateral field / wing insertion (onto the hyperbolar zone / vane) occurs. See Figure A1\_1.

- 24. Gladius length / gladius width: <1 (0); ≥1 (1); ≥2 (2); ≥3 (3); ≥4 (4); ≥5 (5); ≥10 (6) [ordered character]**
- 25. Vane length / rachis length: <0.3 (0); ≥0.3(1); ≥0.5 (2); ≥0.7(3); ≥0.9 (4) [ordered character]**
- 26. Wing length / rachis length: <0.3 (0); ≥0.3(1); ≥0.5 (2); ≥0.7(3); ≥0.9 (4) [ordered character]**
- 27. Phragmocone (primary cone) length / gladius length: <0.02 (0); <0.1 (1); ≥0.1 (2); ≥0.3(3); ≥0.5 (4) [ordered character]**

Phragmocone / primary cone length measured along midline. This character was coded as {0,1} for those species where a “small conus” was reported, but quantitative data were lacking.

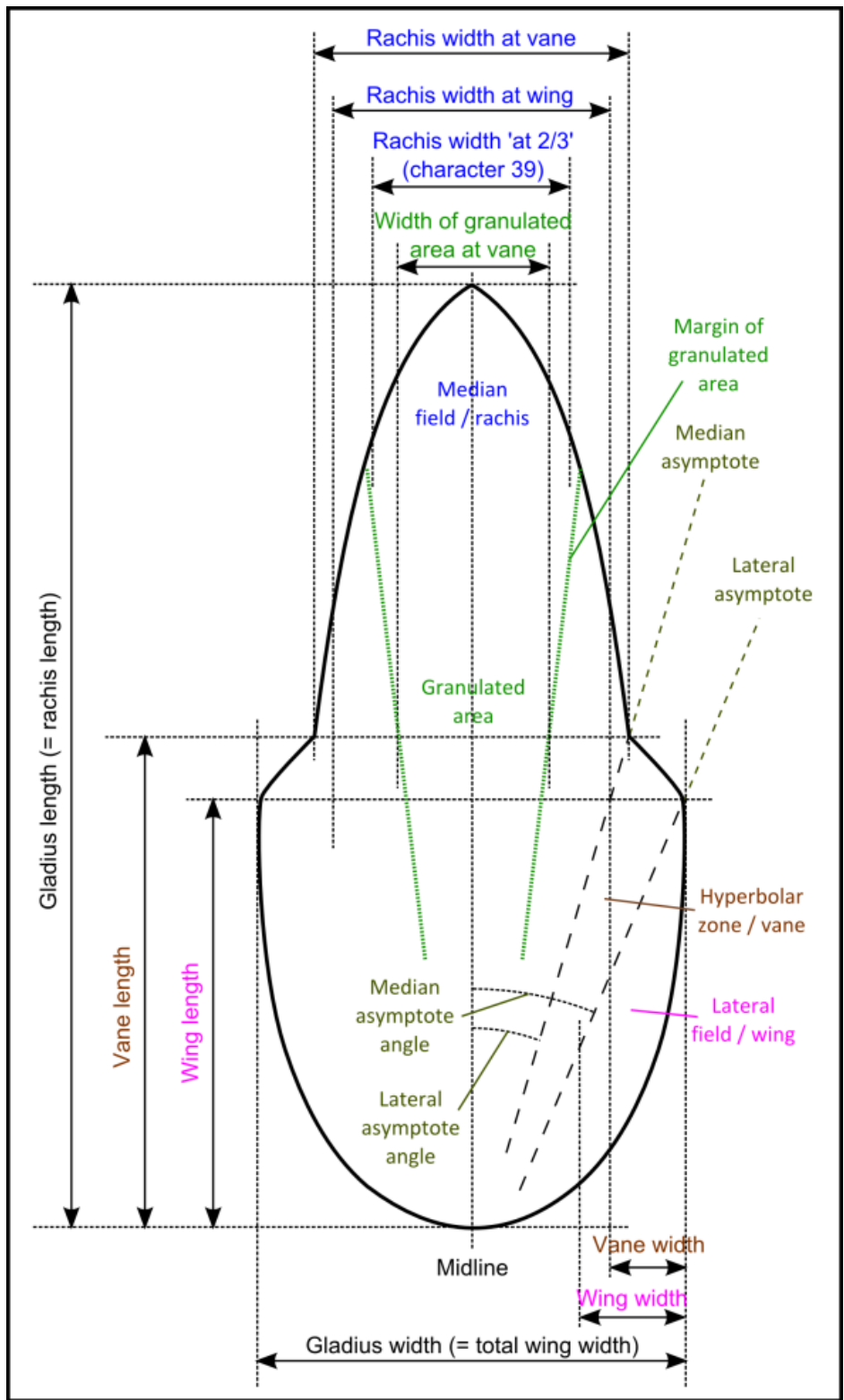


Figure A1\_1. Measurements characters related to shell dimensions and to the positions of its parts



**28. Secondary cone length / gladius length: <0.1 (0); <0.2 (1); ≥0.2(2) [ordered character]**

Secondary cone length measured along the midline. While a secondary cone was described for *Cranchia* by Toll (1982), it was not possible to measure it from Toll's figures, and hence we use a coding of unknown ('?').

**29. Cone flags length / gladius length: <0.1 (0); <0.3 (1); ≥0.3(2) [ordered character]**

Cone flags (see character 22) length measured the vane or wing insertion posteriorly to the anterior of the primary cone or secondary cone.

**30. Rachis width at vane / total wing width: <0.25 (0); <0.5 (1); <0.75 (2); ≥0.75 (3) [ordered character]**

**31. Wing length / vane length: <0.9 (0); 0.9 - 1.1 (1); >1.1 (2) [ordered character]**

**32. Vane width / wing width: <0.25 (0); <0.5 (1); <0.75 (2); <1 (3) ≥1 (4) [ordered character]**

**33. Vane width / rachis width at wing: <0.25 (0); <0.75 (1); <1.25 (2); <2.5 (3); <4 (4); ≥4 (5) [ordered character]**

**34. Vane width / rachis width at vane: <0.25 (0); <0.75 (1); <1.25 (2); <2.5 (3); <4 (4); ≥4 (5) [ordered character]**

**35. Wing width / rachis width at wing: <0.25 (0); <0.75 (1); <1.25 (2); <2.5 (3); <4 (4); ≥4 (5) [ordered character]**

#### **SHAPE CHARACTERS OF THE SHELL**

Fuchs and Weiss (2008) present detailed descriptions of growth-line characters for several fossil taxa, and note the utility of these characters in species identification. The growth lines, however, simply mirror the outline of the gladius. This must logically be true for biomineralized elements that grow by accretion and whose shape does not alter significantly through ontogeny, but is also visually obvious from figures (e.g. Fuchs and Weiss 2008, fig. 3). In specimens where outline is not determinable directly as a result of preservational problems, we concur that growth-lines provide a valuable tool by which to reconstruct it and hence to identify species. However at the level of our analysis, we do not consider that growth-line characters would add any further information beyond that already coded in our gladius-outline characters.

**36. Constriction of the lateral fields / wings: absent (0); present (1)**

A constriction of the lateral fields / wings (in dorsal view) is present in some fossil taxa (e.g. *Eoteuthoides*), but not recorded from extant squid, which normally lack wings. However octopod stylets, both fossil and Recent, often possess a constriction. As we treat these structures as homologues of lateral fields / wings (see character 13) we code these taxa here as '1'.

**37. Constriction of the lateral fields / wings: posterior (0); medial (1)**

When present, the constriction in lateral fields / wings can be medial or posterior. Within the fossils, only *Styloctopus* has the constriction in medial position. For the living species, *Octopus* and *Haliphron* have it in medial position. In all other taxa it is posterior.

- 38. Position of greatest width of median field / rachis: at hyperbolar zone / vane insertion (0); anterior to hyperbolar zone / vane insertion but not at extreme anterior (1); at extreme anterior (2) [ordered character]**

This character gives information about general shape of the median field or rachis in its anterior region. When median field / rachis width was constant for much of its length, tapering only at the tip, this character was coded as '0'.

- 39. Rachis width at vane insertion / rachis width 2/3 of the way between vane insertion and the anterior:  $\leq 1$  (0);  $\leq 1.5$  (1);  $\leq 2.5$  (2);  $>2.5$  (3) [ordered character]**

This character captures the common differentiation of median field / rachis into a wide posterior and narrow anterior region, as expressed by the ratio A / B (see Figure A1\_1). A is the median field /rachis width at hyperbolar zone / vane insertion; B is the median field / rachis width at a point 2/3 of distance from the point at which A is measured to the anterior. This character has been coded for all living squid except *Idiosepius* which has no rachis (Hylleberg and Nateewathana, 1991).

- 40. Concave inflexion or inflexions in median field / rachis: absent (0); present (1)**

Inflexions in the edge of the median field / rachis (in dorsal view) are not present in any living species, but occur in several groups of fossils.

- 41. Outline of posterior margin of lateral field / wings : convex (0); straight (1); concave (2) [ordered character]**

The posterior part of the outline of the lateral field of most fossil gladii is convex in dorsal view. In some taxa, however, it is concave (e.g. in some octopod stylets) or straight (e.g. in *Vampyrotheuthis*).

- 42. Shape of posterior end of median field / rachis: concave (0), flat (1), convex (2) [ordered character]**

- 43. Nature of convex end: rounded (0); pointed (1)**

These two characters capture the shape of the posterior end of median field (rachis). In extant species with a rachis this is always convex and pointed, except for *Sepia* in which it is rounded. Fossils show more variation.

- 44. Shape of anterior tip of gladius: concave (0), flat (1), convex (2) [ordered character]**

- 45. Nature of convex tip: rounded (0); pointed (1)**

These two characters capture the shape of the anterior tip of median field (rachis). As for the posterior tip, in extant species a convex pointed tip predominates, although *Sepia*, *Rossia*, *Haliphron* and *Vampyrotheuthis* are exceptions. Fossils show more variation.

- 46. Inflexion in gladius outline where lateral asymptote intersects margin: absent (0); weak (1); strong/sharp (2) [ordered character]**

Many fossil taxa show a deflection/inflexion of the gladius outline corresponding to the lateral asymptote (i.e. the position of the asymptote is detectable from outline alone).

**47. Tapering of the hyperbolar zone / vane both anteriorly and posteriorly (forming a spindle shape): absent (0); present (1)**

Spindle-shaped vanes, in this sense, are largely absent in fossil taxa; they are however typical of most Recent squid.

**48. Angle between inner/median asymptote and midline:  $\leq 5$  degrees (0);  $>5$  and  $\leq 10$  degrees (1);  $>10$  and  $\leq 15$  degrees (2);  $>15$  and  $\leq 20$  degrees (3)  $>20$  degrees (4) [ordered character]**

Recent species have no more than 10 degrees between median (inner) asymptote (Figure A1\_1) and the midline of the shell, with the sole exception of *Vampyroteuthis*. However fossil taxa display a wide variety of values for this angle.

**49. Angle between outer/lateral asymptote and midline:  $\leq 5$  degrees (0);  $>5$  and  $\leq 10$  degrees (1);  $>10$  and  $\leq 15$  degrees (2);  $>15$  and  $\leq 20$  degrees (3)  $>20$  degrees (4) [ordered character]**

As lateral (outer) asymptotes are located between vanes and wings (Figure A1\_1), this character is not applicable when wings are not present (i.e. in most extant Neocoleoidea, except *Vampyroteuthis*). *Rossia* was coded for this character because lateral asymptotes have been described by Bizikov (2008) outside the vanes, although we follow that author in terming the structure on the other side of the asymptote as 'cone flags' (see character 22).

**50. Median asymptotes posterior intersection: do not intersect (if extended would intersect posterior to gladius) (0); intersect at or very near to the posterior margin of the gladius (1); intersect within gladius (2) [ordered character]**

This character describes the intersection of the median asymptotes where they can be determined and are approximately linear. They may meet either within the gladius or not, or meet at its margin. All three situations are present both in fossil and living species. The gladius is defined here to include proostracum and phragmacone (but not rostrum).

## **MEDIAN FIELD / RACHIS INTERRUPTIONS**

This group of characters refer to median or sub-median interruptions (in transverse section) of the median field / rachis. Note that the rachis itself is not treated as such an interrupting structure, which has to be present within the median field / rachis. Interruptions may be present either dorsally or ventrally; these are coded separately. They may be either convex or concave. Where convex, they are classified as a 'line' (very thin and weakly convex), a 'rib' (a strongly convex U-shaped structure), or a 'keel' (strongly convex and V-shaped). These structures in some cases are split into two or three separate subparallel 'interruptions'. These are often more complicated and better documented in dorsal aspect, and hence we use two characters (57 and 58) to capture this variation dorsally, and only a single one (54) ventrally. Characters 57 and 58 also capture variation in physical location of dorsal interruptions along an anterior-posterior axis. Character 53 captures this for ventral structures. Note that in thin gladii (particularly in Recent taxa) all dorsal structures may be reflected ventrally.

Characters 53 and 56 are not treated as ordered, as it is not clear to us that a transition from 'line' to 'rib' to 'keel' represents a sequence. *Rachis length* in characters 57 and 58 is used *sensu* characters 24-35.

- 51. Ventral median field / rachis in transverse section: smooth (0); interrupted by a median or sub-median structure or structures ('interruption(s)') (1)
- 52. Form of ventral interruption(s): concave (0); line (1); rib (2); keel (3)
- 53. Anterior-posterior extent of ventral interruption(s): anterior (0); posterior (1); whole/majority length of median field (2)
- 54. Ventral interruption bipartite (at any point anterior-posterior)?: no (0); yes (1)
- 55. Dorsal median field / rachis in transverse section: smooth (0); interrupted by a median or sub-median structure or structures ('interruption(s)') (1)
- 56. Form of dorsal interruption(s): concave (0); line (1); rib (2); keel (3)
- 57. Dorsal interruption(s) at 25% of rachis length from anterior: not present (0); one structure, not split (1); split in two structures (2); split in three structures (3)
- 58. Dorsal interruption(s) at 75% length of rachis length from anterior: not present (0); one structure, not split (1); split in two structures (2); split in three structures (3)

#### **MEDIAN FIELD / RACHIS REINFORCEMENTS**

Reinforcements of the median field / rachis, normally but not exclusively at its lateral margins, occur in several groups. They were reported by Fuchs and Larson (2011a, 2011b) in several fossil taxa, and are characteristic of Plesiotheuthididae, in which reinforcements extend along the whole median field / rachis. Reinforcements also occur in some extant species, but are usually thinner and do not extend along the whole median field / rachis, except in *Gonatus* and *Rossia*. When present, they are located at the edge of median field / rachis except in *Glyphiteuthis freijii*.

- 59. Lateral reinforcements on the median field / rachis: absent (0); present (1)
- 60. Extent of lateral reinforcements: anterior (0); posterior (1); majority/whole of the median field / rachis (2)
- 61. Lateral reinforcement position: not at edge of median field (0); at edge of median field (1)
- 62. Lateral reinforcements subdivided: no (0); yes (1)

Fuchs and Larson (2011a) describe the lateral reinforcements of *Boreopeltis smithi* and *B. sagittata* as 'subdivided'.

- 63. Thin lateral plates on the dorsal median field/rachis: absent (0); present (1)

Fuchs *et al* (2007b) described thin lateral plates on the dorsal median field of *Plesiotheuthis* species. A comparable structure is present in the extant *Ommastrephes* (Toll, 1982), where the free rachis bears lateral rods or reinforcements that are attached to basal plates by narrow commissures. The three plates are connected by thin, medial fields.

#### **GRANULATION IN DORSAL SHELL**

Dorsal granules or tubercles are present on the dorsal surface of the shell in some fossils (e.g. *Actinosepia*, Trachiteuthididae) and also in extant Sepiidae. Fuchs and Larson (2011b) termed

this *Sepia*-like granulation, alluding to the close relationship previously suggested in the literature (e.g. Münster, 1837; Bizikov, 2008) between these taxa. We term the area occupied by granules the 'granulated area' (after e.g. Fuchs and Larson 2011b). This group of characters capture the variation in the arrangement, size and extent of these granules.

**64. Granules (tubercles) on the dorsal surface of the shell: absent (0); present (1)**

**65. Arrangement of granules in the anterior half: regular (0); irregular (1)**

**66. Arrangement of granules in the posterior half: regular (0); irregular (1)**

'Regular' arrangement refers to any ordered or patterned distribution of granules. *Trachiteuthis hastiformis* possesses a median 'spindle-shaped' structure in the granulated area (Fuchs *et al.* 2007a; Fuchs and Schulze, 2008); for this species we code the arrangement of granules outside the spindle.

**67. Granule size-change from posterior to anterior: decreasing (0); no change (1); increasing (2) [ordered character]**

**68. Granule size-change from midline towards lateral margin: decreasing (0); no change (1); increasing (2) [ordered character]**

**69. Row of relatively coarse granules along lateral edges of granulated area: absent (0); present (1)**

**70. Row of relatively coarse granules along median field / rachis: absent (0); present (1)**

**71. Lateral margins of the granulated area meet anteriorly at the anterior edge of the median field / rachis?: no (0); yes (1)**

**72. Lateral margins of posterior 1/3 of granulated area: straight (0); curved (1)**

**73. Width of granulated area at vane / rachis width at vane: <0.5 (0); ≥0.5 (1)**

Rachis width at vane is defined in the section describing characters 24-35 (shell proportions). Width of granulated area at vane is the width of the granulated area at the point where the hyperbolar zone / vane inserts on the median field / rachis (i.e. at the same point where rachis width at vane is measured).

#### **SOFT BODY CHARACTERS: FINS AND APPENDAGES**

Soft-part characters are mainly coded for living species, but exceptional preservation of some fossils does allow limited coding for extinct taxa. When no information was available, characters were coded as 'unknown' (?).

**74. Fins: absent (0); present (1)**

**75. Number of fin pairs: 1 pair (0); 2 pairs (1)**

These two characters are related to character number 6 of Lindgren *et al.* (2004), who coded the presence or absence of a pair of fins. Fins are absent in *Nautilus*, as well as some Neocoleoidea (incirrate octopuses). Many fossil taxa possess two pairs of fins, but all extant taxa with fins possess only one pair, except for *Vampyroteuthis*. In this taxon one pair is present at hatching, but is eventually resorbed and replaced by a more anterior pair as development proceeds (both fins are present during certain growth stages). The first pair to develop is the homologue of the fins of other cephalopods (Young and Vecchione, 1996). We thus code *Vampyroteuthis* as possessing two pairs of fins.

**76. Shape of fins: lobate (0); rhomboidal (1)**

Fins are classified, somewhat arbitrarily, by their shape as sagittate, rhomboid, circular/elliptical, lanceolate, ear-shaped, ribbed, lobate or skirt-like (Jereb and Roper, 2010); Young *et al.* (2001) reported that fin shapes are difficult to define as the shape of some fins bridge the gaps between standard shapes. In view of this, and as available data for fin shape for fossil taxa can be limited, we only code two shapes, treating lobate/rounded/circular/elliptical/ear-shaped/skirt-like or fringing fins as 'lobate', and rhomboidal or sagittate (i.e. with a concave posterolateral margin) as 'rhomboidal'. In all cases where two pairs of fins were present, they had the same shape. In fossil taxa, most fins are lobate, although *Rachiteuthis* and *Palaeololigo* have rhomboidal fins.

**77. Single fin condition: discrete (0); fringing (1)**

Fringing fins are coded as a separate character; they have a series of independent muscle bundles within each fin that resemble a series of ribs or teeth on a comb. These fins are only present in one fossil taxa (*Muensterella*) and in the extant *Ctenopteryx*. Fringing fins are treated as lobate for character 76.

**78. Posterior fin termination: subterminal (0); terminal (1)**

Subterminal fin termination, where fins terminate before (anterior to) the termination of the muscular mantle (Young *et al.* 2001), is found in many sepioids. Terminal fins terminate at about the same position as the muscular mantle or posterior to it (i.e. they meet posteriorly).

**79. Maximum length of unmodified arms compared to gladius length: shorter (0); approximately the same,  $\pm 10\%$  (1); longer (2) [ordered character]**

Detailed arm-length data is often not available for fossils, but where arms are preserved it is normally possible to determine approximate length with respect to that of the gladius (see the section describing characters 24-35, shell proportions, for our definition of gladius length). We hence avoid more complex length characters, preferring this simple and widely applicable character.

**80. Number of appendage pairs: four (0); five (1); more than five (2) [ordered character]**

The arm crown in living cephalopods has four pairs of arms (Octopodiformes), five pairs of arms (most Decapodiformes and *Vampyroteuthis*), or more than five pairs (*Nautilus*). See Figure A1\_2.

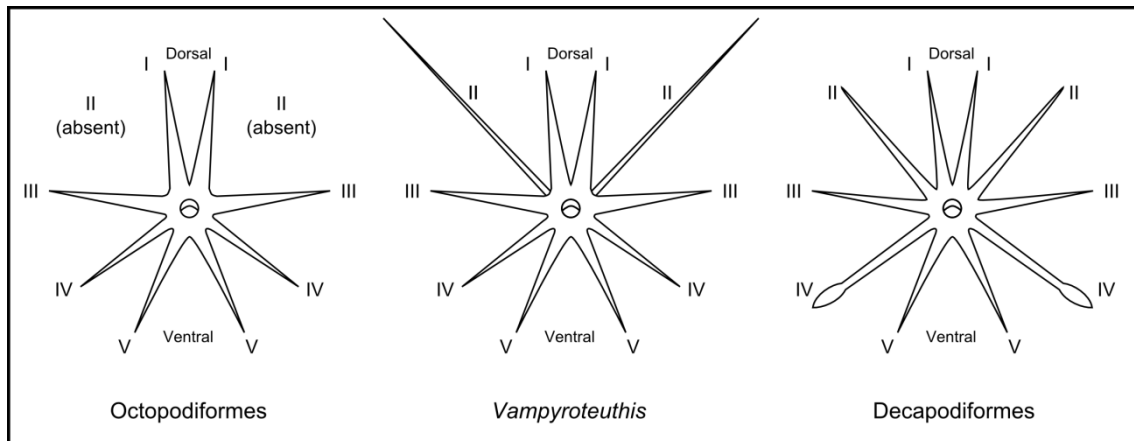


Figure A1\_2. Idealized anterior views of arm-crown of extant Octopodiformes (arm-pair II lost), *Vampyroteuthis* (arm-pair II modified into ‘filaments’) and Decapodiformes (arm-pair IV modified into ‘tentacles’). Modified from Vecchione *et al.* 1999, figure 1.

**81. Reduction of appendage II: unmodified (0), reduced to filaments (1), absent (2) [ordered character]**

Appendage II is unmodified in Decapodiformes, reduced to filaments in *Vampyroteuthis* and absent in octopods (see Figure A1\_2). In fossil taxa, a reduction of appendage II to filaments seems to be present only in *Vampyronassa*, which possesses two small ‘sensory’ appendages either side of the dorsal arms. Both Fischer and Riou (2002) and Fischer (2003) considered these to be homologues of the reduced appendage II of *Vampyroteuthis*.

**82. Modification of appendage IV into a tentacle: absent (0); present (1)**

In living species, appendage-pair IV is modified into tentacles in Decapodiformes, with the exception of *Lepidoteuthis* and *Octopoteuthis*, which lack tentacles as subadults and adults. While unambiguous homology of any tentacle-bearing appendage in a fossil with appendage IV of Decapodiformes might be problematic, tentacles are not present in any of the extinct taxa in our dataset, and hence the problem does not arise.

**83. Tentacle suckers: in up to 4 rows (0); in more than 4 rows (1)**

Suckers are muscular suction-cup on the arms and tentacles, and occasionally on the buccal supports (Young *et al.*, 1999). This character captures the number of sucker-rows in the tentacle club (the terminal, usually expanded part of the tentacle which bears suckers and/or hooks).

**84. Tentacle locking apparatus: absent (0); present on carpus only (1); present on manus and carpus (2)**

Character 30 of Lindgren *et al.* (2004). The locking apparatus on the carpal region of the club consist of several suckers with smooth rings and tubercles, corresponding to alternating rings and knobs on the opposite tentacle. This character is only applicable in extant Decapodiformes, where there is considerable variety in structure. Our codings follow Lindgren *et al.* (2004).

**85. Interbrachial web: absent (0); present (1)**

An interbrachial web is the muscular membrane that extends between the arms of many Octopodiformes, but is reduced or absent in most Decapodiformes. Some data are available for fossil taxa. This character corresponds to characters 15 and 16 of Young and Vecchione (1996) for arms I and V respectively, but we reduce it here to a single presence/absence character for simplicity and to allow the coding of poorly preserved fossils.

**86. Arm hooks: absent (0); present (1)**

This is a modification of character 27 from Lindgren *et al.* (2004). A hook is a horny structure that looks like a single claw; in hook-bearing Decapodiformes it is derived from the inner sucker ring (Young *et al.*, 1999). Hooks may be found on the arms and/or tentacular clubs of some squids and also in some fossil taxa (e.g. belemnites, *Loligosepia*). While homology between fossil and Recent hooks is not well established, a potential homology at least exists, and hence we code all such structures using this single character.

**87. Cirri or spines on arms: absent (0); present (1)**

Cirri are muscular, conical structures that arise from the sides of the arms of some octopodiforms (Young *et al.* 1999). Cirri have also been reported in fossil taxa. In the living species, the presence of cirri is typical in cirrate octopods but they are also present in *Vampyroteuthis*.

**88. Suckers on any appendage: absent (0); present (1)**

As it is usually difficult to confirm the presence of suckers in all or in specific appendages of fossil taxa, this character captures any presence of suckers in any appendage. Suckers are present in all Recent taxa under study, except *Nautilus*.

**89. Sucker symmetry: radial (0); bilateral (1)**

Character 10 of Young and Vecchione (1996, fig. 6) and Character 23 of Lindgren *et al.* (2004). Suckers are bilateral in Decapodiformes and radial in Octopodiformes. Radial sucker-symmetry has occasionally been described in fossil taxa (e.g. *Leptoteuthis*).

**90. Sucker-stalk on arms: absent (sessile, unstalked) (0); present and attached to arm muscles (1); present but not clearly attached to arm muscles (2)**

**91. Shape of stalks attached to the arm muscles: conical pillar with base and neck (0); cylinder (1)**

Both characters modified from 22 of Lindgren *et al.* (2004) and 9 of Young and Vecchione (1996). A sucker-stalk is the muscular support and connective structure between the sucker base and the arm. Stalks in Decapodiformes and Octopodiformes are flexible and attached to arm muscles, although they differ in shape (cylindrical in octopods and conical in decapods; character 91). *Vampyroteuthis*, however, has sucker-stalks with a broad base and short neck. These have a 'plug and base' attachment which does not clearly attach as a unit to the arm muscles. We follow Young and Vecchione (1996) in treating this as a separate state.



**92. Lining of arm suckers: neither horny or cuticular ring (0); horny ring (1); cuticular ring (2)**

Modified from characters 8 of Young and Vecchione (1996) and 21 of Lindgren *et al.* (2004). Suckers consist of a cup-shaped portion (the 'acetabulum') that lines the inside of the sucker ring, and a flat, distal ring (the 'infundibulum', which contacts the substrate (Young *et al.* 1999). This character refers to the infundibulum (Walla, 2007; fig. 6 of Young and Vecchione, 1996). Decapodiformes have horny rings (no chitin), Octopoda have cuticular (chitinous) rings and *Vampyroteuthis* has neither.

**93. Suckers (on arms) proximally: 0 rows (0); 1 row (1); 2 rows (2); 3 rows (3); >3 rows (4) [ordered character]**

**94. Suckers (on arms) medially: 0 row (0); 1 row (1); 2 rows (2); 3 rows (3); >3 rows (4) [ordered character]**

**95. Suckers (on arms) distally: 0 row (0); 1 row (1); 2 rows (2); 3 rows (3); >3 rows (4) [ordered character]**

These three characters code for the number of sucker rows in the unmodified arms, for the proximal, medial and distal portions respectively, capturing variation in sucker-rows along the length of the arms.

**OTHER SOFT CHARACTERS**

**96. Ink sac: absent (0); present (1)**

Character 40 of Lindgren *et al.* (2004). The ink organ is composed of a gland that secretes ink, a sac that stores ink, and a duct that connects it to the rectum. The ink sac generally appears black from the outside although it may be covered by silvery tissue in some species (Young *et al.* 1999). The presence of an ink sac has been demonstrated in several fossils, but its genuine absence is more difficult to demonstrate, as internal structures rarely fossilize. Where no ink sac is reported we thus code this character as 'unknown' (?).

Lindgren *et al.* (2004) coded an ink sac as present for *Vampyroteuthis* and *Nautilus*, but these appear to be errors. Young (2012), for instance, notes that *Vampyroteuthis* lacks an ink sac; we can find no studies reporting its presence. For *Nautilus*, Sasaki *et al.* (2010) unambiguously note that the ink gland complex (ink gland, ink sac, and ink sac duct) is absent in *Nautilus*, presumably primitively. We code the ink sac as absent for both these taxa.

**97. Nuchal cartilage: absent (0); present (1)**

Character 28 of Young and Vecchione (1996) and 8 of Lindgren *et al.* (2004). Nuchal cartilage is a cartilaginous locking structure in Decapodiformes, located mid-dorsally just posterior to the head. It is composed of the nuchal cartilage, which forms an attachment site for the collar and head retractor muscles, and cartilage on the mantle that underlies the gladius. The apparatus helps keep the head and mantle aligned dorsally during mantle contractions (Young *et al.* 1999). In fossil taxa, no information is available about this character except in *Keuppia*, which Fuchs *et al.* (2009) described as having the head fused with ventral mantle, implying the absence of nuchal cartilage. Nuchal cartilage is present in many extant taxa under consideration, but is absent in Octopoda and *Nautilus*.

**98. Chromatophores: (0) absent; (1) present.**

Character 9 of Lindgren *et al.* (2004). Chromatophores are pigment-filled, muscular sacs in the skin under individual nervous control that collectively provide the background colour, colour patterns, and colour dynamics of cephalopods (Jereb *et al.* 2014). They are common in living Neocoleoidea. Lindgren *et al.* (2004) coded this character as 'not applicable' for *Nautilus*, but this appears to be an error. *Nautilus* lacks chromatophores and other chromatic elements (Sasaki *et al.*, 2010).

**99. Buccal crown: (0) absent; (1) present**

Character 5 of Young and Vecchione (1996) and 10 of Lindgren *et al.* (2004). The buccal crown is an umbrella-like structure that surrounds the mouth and is surrounded by the brachial crown. It comprises buccal supports and the buccal membrane (Young *et al.* 1999). Buccal suckers also occur in the buccal membrane of some Decapodiformes. This character has not been determinable in any fossil under consideration, but is present in most extant Decapodiformes, and absent in extant Octopodiformes.

Young and Vecchione (1996) considered the oral arms of *Nautilus* to be homologous with the buccal crown of Decapodiformes (on the basis of a similar location and origin), but Lindgren *et al.* (2004) coded the character as 'not applicable' for *Nautilus*, as they considered this homology to be unproven. We code the character as 'unknown' (?) for this taxon.

**100. Buccal membrane connective attachment to arm-pair V: dorsal (0); ventral (1)**

Character 11 of Lindgren *et al.* (2004). Arm-pair V is the ventral unmodified arm-pair (see Fig. A1\_2). The buccal membrane is the muscular membrane that connects the buccal supports and, together with the supports, forms the buccal crown (Young *et al.* 1999; see also character 99). It may attach either dorsally or ventrally to arm-pair V.

**101. Number of buccal lappets (supports): 6 (0); 7 (1); 8 (2) [ordered character]**

Character 12 of Lindgren *et al.* (2004). Buccal lappets or supports are large muscular flaps of the buccal crown that surround the mouth and are connected by the buccal membrane; there are in all cases either 6, 7 or 8 of them. The buccal supports may be homologous with the inner ring of tentacles that surround the mouth of *Nautilus* (Young *et al.* 1999); for this reason they were treated as present in *Nautilus* by Lindgren *et al.* (2004). In view of our coding of 'unknown' (?) for the buccal crown (character 99) in this taxon, however, we also code the number of buccal lappets as unknown ('?'). Note that for this character, *Abralia* and *Onychoteuthis* were coded from the common characteristics of their families provided by Jereb and Roper (2010).

**102. Suckers on buccal membrane: absent (0); present (1)**

Character 26 of Lindgren *et al.* (2004). Small but otherwise unmodified suckers that are present on the oral surface of the buccal supports of some decapodiforms, e.g. bathyteuthid families, some loliginids and some sepiids (Young *et al.* 1999).

**103. Hydrostatic organ (swim-bladder): absent (0); present (1)**

The swim-bladder is a gas-filled structure found in the dorsal visceral mass of females of the pelagic octopod *Ocythoe* (Jereb *et al.* 2014), where it regulates buoyancy. Bizikov (2004) reported the presence of a similar hydrostatic organ in *Haliphron*.

**104. Calcareous elements in the beak: absent (0); present (1)**

The beak is one of the two chitinous jaws of cephalopods, comprising two halves bound together with powerful muscles. The dorsal beak component is referred to as the 'upper' beak and it inserts within the 'lower' (ventral) beak. The two components act in concert to cut tissue with a scissor-like action (Young *et al.*, 1999; Jereb *et al.* 2014). Calcareous elements have been reported in the beak of some fossil taxa (e.g. *Rachiteuthis*, *Dorateuthis*). Beaks are not calcified in living Neocoleoidea, but *Nautilus* beaks are strengthened by calcareous tips with denticles (Sasaki *et al.*, 2010).

**105. Radula: absent (0); present (1)**

Character 14 of Lindgren *et al.* (2004). The radula of cephalopods is a toothed ribbon that lies in the buccal mass and that aids in movement of food into the oesophagus. The radula of neocoleoid cephalopods consists of a maximum of nine elements (Young *et al.* 1999). It is absent only in some cirroctopods (e.g. *Opistoteuthis* and *Stauroteuthis*). Fossil cephalopod radulae are not known.

**106. Horizontal arm septa inserted in the arm muscles: absent (0); present (1)**

Character 18 of Lindgren *et al.* (2004). Septa, extending the length of the arm (i.e., parallel to the arm axis), that roughly divide the arm into oral and aboral regions. Such septae are characteristic of cirrate octopuses and the incirrate octopuses of the family Bolitaenidae. Their function is unknown (Young *et al.* 1999).

**107. Luminous autogenic organs: absent (0); present (1)**

Character 32 of Lindgren *et al.* (2004). Members of Histiotteuthidae possess light organs with a centrally situated luminous body, distributed over the mantle and arms (Jereb and Roper 2010).

**108. Photophores containing collagen light guides: absent (0); present (1)**

Character 33 of Lindgren *et al.* (2004). Photophores are light-producing organs. They are often complex with various color filters, reflectors, light guides, lenses and chromatophores surrounding the photogenic region. Light guides are structures in photophores that specifically direct light via internal reflection (Jereb *et al.* 2010). This kind of photophore is typical of Enoploteuthidae, Lycoteuthidae and Pyroteuthidae (Lindgren *et al.*, 2004). In this study it was coded as present only for *Abralia* and *Onychoteuthis*.

**109. Funnel: attached to ventral mantle (0); free, not attached to ventral mantle (1); fused to ventral mantle (2)**

Character 35 of Lindgren *et al.* (2004). In living taxa, the funnel is attached to ventral mantle in *Vampyroteuthis*, *Nautilus* and incirrate octopods. The funnel of *Nautilus* (also termed the

'hyponome') differs in detail from that of these other taxa, forming a seemingly tubular structure, but with unfused left and right lobes (Sasaki *et al.* 2010). As no other taxa in our dataset share this state, we code simply for attachment (i.e. all these taxa are coded as '0'). The funnel is free in all other living taxa under study, except for *Amphitretus* (Young *et al.*, 2013) and *Cranchia*, in which it is fused to ventral mantle.

**110. Funnel locking apparatus: absent (0); present (1)**

Character 36 of Lindgren *et al.* (2004). A funnel locking apparatus is the (generally cartilaginous) funnel-component of a locking mechanism between the funnel and the mantle. This character is applicable only when funnel is free (character 109). The extinct *Pohlsepia* lacks a funnel locking apparatus (Klussendorf and Doyle 2000), but no other information is available about fossil taxa. *Cranchia* was coded as lacking a funnel locking apparatus by Lindgren *et al.* (2004), but in error, as the funnel is fused to mantle; we code 'not applicable' (-) for this taxon.

**111. Funnel locking apparatus morphology: simple, straight (0); triangular, round (1); inverted T or -| shaped (2); oval with projecting knobs (3)**

Character 37 of Lindgren *et al.* (2004). When present, funnel locking apparatus may exhibit different morphologies, which are variable particularly among Decapodiformes.

**112. Funnel valve: absent (0); present (1)**

Character 27 of Young and Vecchione (1996) and 38 of Lindgren *et al.* (2004). The funnel valve is a one-way muscular flap, located in the inner dorsal wall of the funnel. The funnel valve acts as a one-way valve to prevent inspiration of water through the funnel when mantle expansion draws in water to pass over the gills for respiration (Young *et al.* 1999). In living Neocoleoidea it is absent in octopods but present in *Vampyroteuthis* and all Decapodiformes considered.

**113. Eye shape: hemispherical (0); other shapes (1)**

Neocoleoidea have mostly hemispherical eyes, but other shapes are occasionally present, e.g. tubular (*Amphitretus*), semi-tubular anteriorly directed (*Bathyteuthis*), or laterally compressed (*Japetella*). Eyes are occasionally preserved in fossils and, where determinable (two species of *Glyphiteuthis*), their shape is hemispherical.

**114. Cornea: absent (0); one-part cornea present (1); two-part cornea present (2) [ordered character]**

Character 29 of Young and Vecchione (1996) and 42 of Lindgren *et al.* (2004). The cornea in cephalopods is a smooth, thin, turgid, transparent skin without muscles that covers the eyes to protect the eye lenses of incirrate octopods and some decapodiforms (Young *et al.* 1999). *Nautilus* was coded as possessing a one-part cornea by Lindgren *et al.* (2004), but lacks either cornea or lens (Sasaki *et al.* 2010), and we code it here as absent (0).

**115. Statocyst outer capsule: absent (0); present (1)**

Character 18 of Young and Vecchione (1996) and 45 of Lindgren *et al.* (2004). A statocyst is a sense-organ, present in all cephalopods including *Nautilus* (see e.g. Neumeister and Budelmann 1997). It detects gravity, acceleration, and low-frequency sound. Statocysts occur embedded within the cephalic cartilage, and contains the statoliths (Young *et al.* 1999). In extant Octopodiformes an outer capsule is present surrounding the statocysts - this is absent in Decapodiformes and in *Nautilus*.

**116. Photosensitive vesicles: within cephalic cartilage (0); above funnel (1); on stellate ganglia (2)**

Character 33 of Young and Vecchione (1996) and 47 of Lindgren *et al.* (2004). Photosensitive vesicles are non image-forming light-receptive organs located inside the cephalic cartilage in squid and on the stellate ganglion in octopods. They perform a variety of functions (Young *et al.* 1999). They are present within the cephalic cartilage decapodiforms, present above the funnel in *Vampyroteuthis*, and present on stellate ganglia in Octopoda. They are lacking in *Nautilus*, for which we hence code 'inapplicable' (-).

**117. Inferior frontal lobe system of the brain: absent (0); partially present (1); present (2) [ordered character]**

Character 34 of Young and Vecchione (1996) and 48 of Lindgren *et al.* (2004). Octopod brains possess a system of frontal lobes, comprising the paired posterior buccal, lateral inferior frontal and subfrontal lobes, together with the single median inferior frontal lobe. These form a functional unit concerned with the chemotactile information from the arms (Young *et al.* 1999). In living Neocoleioidea it is absent in Decapodiformes, partially present in *Vampyroteuthis* and present in Octopoda. The construction of the brain of *Nautilus* is very different from Neocoleioidea (Young and Vecchione, 1996) and we hence code the character as 'inapplicable' (-).

**118. Superior buccal lobe: widely separated from brain (0); adjacent to brain (1); fused to brain (2) [ordered character]**

Character 40 of Young and Vecchione (1996) and 49 of Lindgren *et al.* (2004). Superior buccal lobes are lobes of the central nervous system that sit atop the oesophagus where the latter enters the buccal mass in Decapodiformes, but are the anterior-most lobes of the supraesophageal mass of the brain of Octopodiformes (Young *et al.* 1999). Following those authors Decapodiformes and *Nautilus* were coded as '0', *Vampyroteuthis* were coded as '1' and octopods were coded as '2'. Note that Lindgren *et al.* (2004) incorrectly coded all octopods as 'lobe adjacent to brain'. We treat this character as ordered, recognizing a logical sequence from separation through adjacency to fusion.

**119. Relative position of digestive gland duct appendages (DGDA) and the nephridial coelom: lies in nephridial coelom (0); not in nephridial coelom (1)**

Character 43 of Young and Vecchione (1996) and 51 of Lindgren *et al.* (2004). The digestive gland is the primary organ in cephalopods that secretes digestive enzyme, and also functions in absorption and excretion. Digestive gland duct appendages (DGDA) are outpocketings of the ducts leading from the digestive gland that are covered with glandular epithelium (Young *et al.*

1999). In living Decapodiformes but not Octopodiformes, the DGDA lies in nephridial coelom. *Nautilus* lacks DGDA, and the character is not applicable.

**120. Posterior salivary gland: absent (0); present (1)**

**121. Posterior salivary gland position: posterior to brain (0); proximal to buccal mass (1)**

Character 49 of Young and Vecchione (1996) and 52 of Lindgren *et al.* (2004). When present, posterior salivary glands are generally located just posterior to the head, but in some cirrate octopods they lie within the buccal mass (*Stauroteuthis*, *Cirrothrauma*). Note that both Young and Vecchione (1996) and Lindgren *et al.* (2004) coded this as a single tri-state character. To ensure that the homology of the gland is recognized, whatever its position, we prefer to split the character into a presence/absence and a position character.

**122. Branchial canal: absent (0); present; (1)**

Character 24 of Young and Vecchione (1996), and modified from character 50 of Lindgren *et al.* (2004). The branchial canal is a large opening at the base of each gill lamella, between the primary afferent and efferent blood vessels of the gill. It is absent in *Nautilus*, sepioids, spirulids and cirrate octopods.

**123. Gill-lamellae attachment: free (0); sessile (1)**

Character 55 of Lindgren *et al.* (2004). Gill-lamellae are complex gill leaflets that extend perpendicular to the axis of the gill and contain the respiratory epithelium. Lamellae are free in *Vampyroteuthis* and Decapodiformes, but sessile in octopods, where the number of lamellae is a taxonomic character (Young *et al.* 1999). Lindgren *et al.* (2004) coded the gills of *Nautilus* as sessile in error; these lie free in the mantle cavity, being attached only at their origin (Young and Vecchione, 2006).

**124. Nidamental glands: (0) absent; (1) present**

Character 57 of Lindgren *et al.* (2004). Nidamental glands are large glandular structures that lie in and open directly into the mantle cavity. The glands are composed of numerous lamellae, and are involved in secretion of egg cases or the jelly of egg masses (Young *et al.* 1999). They are present in Decapodiformes but absent in Octopodiformes. For *Nautilus* this character was erroneously coded by Lindgren *et al.* (2004) as '2', although that state was not defined in their character description. Nidamental glands are present in *Nautilus* (Sasaki *et al.*, 2010).

**125. Right oviduct: absent (0); present (1)**

Character 30 of Young and Vecchione (1996) and 58 of Lindgren *et al.* (2004). The oviducts conduct eggs from the visceropericardial coelom, that holds the ovary, to the exterior; they are often used to store eggs. All cephalopods possess a left oviduct, but the right oviduct is absent in cirrate octopods (Voight 1997), sepioids and spirulids. It is present, though not functional, in *Idiosepius* (Hylleberg and Nateewathana 1991). We follow Lindgren *et al.* (2004) in coding 'present' for this taxon.

**126. Oviducal gland symmetry: radial (0); bilateral (1); asymmetrical (2)**

Character 31 of Young and Vecchione (1996) and 59 of Lindgren *et al.* (2004). The oviducal gland surrounds the end of the primary oviduct, and is responsible for secreting some of the external coatings over spawned eggs or, in incirrates, the cement at the base of the chorion stalk. In octopods it also acts as a spermatheca (Young *et al.* 1999). Its symmetry is radial in Octopodiformes, bilateral in Decapodiformes, and asymmetrical in *Nautilus*.

**127. Oviducal gland position: gland terminal (located at end of oviduct) (0); gland subterminal (1)**

Character 32 of Young and Vecchione (1996) and 60 of Lindgren *et al.* (2004). The oviducal gland is terminally positioned in Decapodiformes, *Vampyroteuthis* and *Nautilus*, but subterminally positioned in Octopoda.

**128. Arm-pair I hectocotylyzation or other sexual modifications: absent (0); present (1)**

Character 61 of Lindgren *et al.* (2004). Arm-pair I is the most dorsal arm-pair in all taxa (figure X). The cephalopod hectocotylus is the modified arm in males used for transferring spermatophores to the female; many species of Neocoleidea lack a hectocotylus. Hectocotylyzation of arm-pair I is only present in Histioteuthidae and Sepiolidae. No true hectocotylyzation occurs in *Histioteuthis*, but both species under study have secondary sexual modifications of suckers in arm-pair I, which we treat as potentially homologous, and code as 'present' (1). *Sepia* was wrongly coded as 'present' by Lindgren *et al.* (2004), although they reported the state as 'absent' for this taxon in their text.

**129. Arm-pair IV hectocotylyzation or other sexual modifications: absent (0); present (1)**

Character 36 of Young and Vecchione (1996) and 62 of Lindgren *et al.* (2004). See figure X for the location of arm-pair IV in different taxa. Hectocotylyzation of arm-pair IV is present only in Octopods (in their third arm-pair, as they lack arm-pair II); it differs in detail from the hectocotylyzation of Decapodiformes. *Japetella* lacks true hectocotylyzation, but displays sexual dimorphism in arm IV of males, which have sucker enlargement (Young, 2013). As for character 128 we treat this as potentially homologous, and code 'present' for this taxon, following Young and Vecchione (1996), but *contra* Voight (1997) and Lindgren *et al.* (2004).

**130. Arm-pair V hectocotylyzation or other sexual modifications: absent (0); present (1)**

Character 37 of Young and Vecchione (1996) and 63 of Lindgren *et al.* (2004). Arm-pair V is the most ventral arm-pair in all studied taxa. Many species of Decapodiformes display hectocotylyzation of arm-pair V, but it is absent in Octopodiformes.

**131. Spermatophore type: with ejaculatory mechanism (0); sperm-packets as in cirrate octopods (1); with encapsulated coil (2)**

Character 39 of Young and Vecchione (1996) and 65 of Lindgren *et al.* (2004). A spermatophore is a packet of sperm passed from male to female during mating. In most neocoleoids the spermatophore is complex and includes an ejaculatory apparatus (Young *et al.* 1999), but *Nautilus* and cirrate octopods differ, the latter having a distinctive style of sperm-packet (see e.g. Young and Vecchione, 1996), and the former possessing an encapsulated coil. We follow

Young and Vecchione (1996) in coding these as three unordered states. This character was coded following Young and Vecchione (1996) where possible. Where Lindgren *et al.* (2004) was followed, we interpreted contradictions between text and coding in the matrix as an erroneous transposition of codes 0 and 1 (hence where they coded 0 we code 1, and vice versa).

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