Electronic Supplementary Material

SI Text

Geological Setting

In the Zagora area (central Anti-Atlas) (electronic supplementary material, figure S1*a*), the Lower Ordovician series consists of a ~860 m thick, monotonous succession of mudstones and siltstones lying unconformably over the middle Cambrian sandstones of the Tabanite Group (Destombes 1962, 1971; Destombes et al. 1985; Lefebvre et al. 2016; Martin et al. 2016). In the eastern part of the Anti-Atlas the Lower Ordovician series is traditionally subdivided into three successive stratigraphic units: the Lower Fezouata Shale Formation, the Upper Fezouata Shale Formation, and the Zini Sandstone Formation (Destombes 1962, 1971; Destombes et al. 1985; Vidal 1998; Van Roy et al. 2010). The boundary between the two sections is marked by an iron-rich, glauconitic marker bed, interpreted as a major flooding surface (Destombes 1962, 1971; Destombes et al. 1985). In the Zagora area, it is not possible to identify the limit between the Lower and Upper Fezouata formations, and consequently, they form together a single lithological unit: the Fezouata Shale Formation (see Martin et al. 2016; Vaucher et al. 2017; Lefebvre et al. 2018).

The lower, transgressive part of the Fezouata Shale consists of blue, green and beige argillites and fine siltstones, whereas its upper, regressive part is dominated by beige siltstones containing abundant floated micas, with more and more frequently intercalated sandstone beds towards the top (Lefebvre et al. 2016). Storm-related sedimentary structures (e.g., ripple marks, hummocky cross stratifications) occur throughout the whole Fezouata Shale and suggest the persistence of relatively stable and shallow (at or above storm wave base) environmental conditions (Martin et al. 2015, 2016; Vaucher et al. 2016, 2017).

In the revised biostratigraphic framework (see Lefebvre et al. 2016, 2018), the Tremadocian-Floian boundary occurs at ~450 m above the base of the section and more or less coincides with the maximum flooding interval. Moreover, the boundary between the two late Tremadocian *A. murrayi* and *H. copiosus* graptolite zones (Tr3) was identified at about 330 m above the base of the section (Martin et al. 2016; Gutiérrez-Marco and Martin 2016; Lefebvre et al. 2018) (electronic supplementary material, figure S1*b*).

Cantabrigiaster fezouataensis is one of three species of somasteroids found within the Zagora area (Lefebvre et al. 2016). *Cantabrigiaster* was previously reported as somasteroid sp. 1. (see Van Roy et al. 2010, supplementary figure 5.2G; Lefebvre et al. 2016, figure 2f); somasteroid sp. 2, and sp. 3 await further work. *Cantabrigiaster* is part of an extensive invertebrate fauna that has been collected in the last 15 years from various sites originally discovered by Ben Moula in the Zagora area. The somasteroid material belongs to the palaeontological collections of the Natural History Museum of London, UK (Hunter coll.), Lyon 1 University, France (Lefebvre, Reboul, Van Roy, and Vizcaïno coll.), the Natural History Museum of Nantes (Catto coll.) and Yale Peabody Museum (Hotchkiss coll.). Somasteroids are a significant albeit minor component of the fauna. The abundant echinoderm material collected in the Fezouata Shale of the Agdz-Zagora area does not display a homogeneous distribution along the stratigraphic column (Lefebvre et al. 2016). This is possibly due to a sampling bias towards the 70 m-thick stratigraphic interval of the *A. murrayi* Zone, which yielded most of the soft-bodied organisms of the Fezouata Biota (Van Roy et al. 2010; Martin et al. 2016).

Cantabrigiaster is found within the stylophoran-dominated beds in the upper part of the *A. murrayi* Zone (Lefebvre 2007; Martin et al. 2015) (Localities Z-F2, Z-F4, Z-F5, Z-F9). Occurrence is restricted to a relatively narrow stratigraphic interval, from about 260 to 330 m above the base of the Ordovician (Lefebvre et al. 2016) which corresponds approximately to the levels yielding exceptionally preserved organisms typical of the Fezouata Biota (Van Roy et al. 2010). They are also found in the particularly diverse Oued Beni Zoli (Z-F5) echinoderm assemblage *A. murrayi* Zone (about 275 m above the base of the Ordovician) and represents the oldest occurrences of somasteroids in the Fezouata Shale

Character coding for phylogenetic analysis (see electronic supplementary material, table S2, EAT character assignment).

Justification for taxon sampling

Our character coding has been designed to sample genera of all four groups of Palaeozoic asterozoans (somasteroids, stenuroids, ophiuroids and asteroids). In order to polarise our asterozoan phylogeny and in particular their relationship to the Crinoidea it was necessary to include a range of taxa from crown group Crinoidea and a sample of Cambrian stem-group representatives to take into account biases in preservation and allow greater phylogenetic coverage. We have not included the Echinozoans (echinoids and holothurians), as embryological studies and recent molecular phylogenies indicate that echinozoans are the most derived members of the echinoderm crown group and establish echinozoan/asterozoan monophyly (Telford 2014). In addition, the patchy fossil record and poor preservation of Early Palaeozoic Echinozoan taxa, which did not evolve until the (late) Middle Ordovician, makes it unfeasible to include them in the analysis.

Ambulacral floor plates

1. Perradial suture shape

(0) straight
(1) zigzag
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: See char. 40 in Shackleton (2005). This character is scored as uncertain in those taxa in which the preservation does not allow reliable interpretation of the morphology of the perradial suture (e.g. *Thoralaster*, see Shackleton 2005).

2. Calcified ambulacral floor plates

(0) absent
(1) present

Remarks: See char. 56 in Guensburg (2012). Ambulacral ossicles are an archetypical feature of echinoderms, with the notable exception of most crinoids, in which these features are secondarily lost (electronic supplementary material, figure S7); however, the ossified ambulacrals persist in some Early Ordovician representatives, such as protocrinoids, *Apetkocrinus* and *Eknomocrinus* (Guensburg and Sprinkle 2001, 2003; Guensburg and Sprinkle 2009; Guensburg 2012).

3. Ambulacral ossicle morphology in transverse section

(0) flattened plate without central axial perforations (floor plates)
(1) substantially thickened plate with rounded aboral outline and central axial perforation (brachioles)
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: Flattened ambulacrals are observed in edrioasteroids (e.g. Smith 1985; Smith and Jell 1990; Sumrall and Deline 2009; Zhao et al. 2010; Krammer et al. 2013), crinoids with calcified ossicles (e.g. Blake and Guensburg 1993, 2015; Guensburg and Sprinkle 2001, 2003, 2009; Guensburg 2012) and asterozoans (Shackleton 2005; Blake 2013). By contrast, the ambulacrals of blastozoans (i.e. brachioles) are comparatively much thicker, rounded at the aboral edge, and occasionally bear a central perforation (e.g. Parsley and Zhao 2006; Zamora et al. 2009; Clausen et al. 2010; Guensburg et al. 2010, 2015;) (electronic supplementary material, figure S7).

4. Podial basins

(0) absent
(1) present
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: See char. 57 in Guensburg (2012), and char. 12 in Smith and Zamora (2013). Podial basins, which would accommodate the soft tube feet associated with the water vascular system, are perforations expressed on the ambulacrals of edrioasteroids (e.g. Smith 1985; Smith and Jell 1990; Sumrall and Deline 2009; Zhao et al. 2010), *Apektocrinus* (Guensburg and Sprinkle 2009), and all asterozoans (e.g. Mooi et al. 2005; Shackleton 2005; Blake 2013; Jell 2014; Blake and Guensburg 2015; Guensburg et al. 2015). By contrast, podial basins are absent in *Helicosystis* (Smith and Zamora 2013) and the brachioles of blastozoans (e.g. Parsley and Zhao 2006; Zamora et al. 2009; Clausen et al. 2010; Guensburg et al. 2010, 2015; Nardin et al. 2017; Nohejlová and Fatka 2016).

5. Ambulacral ossicle arrangement

(0) ambulacral edges stepped (out of phase)
(1) ambulacral edges aligned (in phase)
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: See char. 1 in Shackleton (2005). Ambulacral ossicles are out of phase relative to each other in *Helicocystis* (Smith and Zamora 2013), edrioasteroids (e.g. Smith 1985; Sumrall and Deline 2009; Zhao et al. 2010), blastozoans (e.g. Parsley and Zhao 2006; Zamora et al. 2009; Nohejlová and Fatka 2016) and several Palaeozoic asterozoans (e.g. Shackleton 2005; Blake and Guensburg 2015). By contrast, the ambulacrals are in phase relative to each other in asteroids (e.g. Shackleton 2005; Blake 2013; Blake and Guensburg 2015).

6. Degree of ambulacral ossicle offset

(0) out of phase by half an ossicle
(1) out of phase by less than half an ossicle
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent; ambulacrals ossicles arrangement (Char. 5) in phase

Remarks: In most taxa in which the ambulacrals are offset relative to each other, the degree of offset is usually close to half an ossicle. However, offset less than half an ossicle is observed in somasteroids (e.g. *Ophioxenikos*), stenuroids (e.g. *Phragmactis*, *Rhopalocoma*), Palaeozoic ophiuroids (e.g. *Encrinaster*, *Palaeura*) and some problematic forms (e.g. *Maydenia*, *Stenaster*) (Dean 1999; Blake and Guensburg 1993, 2015; Blake 2013; Jell 2014).

7. Transverse bar on ambulacral ossicles facing abaxially

(0) absent
(1) present
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: The transverse bar is defined as an abaxial extension from the elevated perradial ridge of the ambulacral ossicle (Char. 11); as indicated by its name, this bar occupies a transverse (perpendicular) orientation relative to the perradial axis, and thus confers a distinctive T-shape to the ambulacral (when positioned centrally, see Char. 8). This feature is exclusive of asterozoans (Blake 2013; Blake and Guensburg 2015; Blake et al. 2015), and absent in edrioasteroids, blastozoans and crinoids. With the exception of *Platanaster*, details of the transverse bar are obscured in the asteroids and thus this character is scored as uncertain.

8. Position of transverse bar with respect to elevated perradial ridge

(0) central, T-shaped
(1) proximal of central, boot-shaped
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent; transverse bar (Char. 6) absent; perradial ridge (Char. 11) absent

Remarks: See char. 7 in Shackleton (2005).

9. Size of transverse bar

(0) small and thin
(1) large and thick
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent; transverse bar (Char. 7) absent

Remarks: A thin transverse bar is observed in *Cantabrigiaster* (figure 1*c*,*d*; electronic supplementary material, figure S2*a*,*g*) and many somasteroids (e.g. *Villebrunaster*, *Chinianaster*, *Thoralaster*) and stenuroids (e.g. *Rhopalocoma*, *Maydenia*, *Phragmactis*, *Pradesura*). In contrast, a thick transverse bar is present in *Archegonaster*, *Ophioxenikos*, *Stenaster*, and ophiuroids (electronic supplementary material, figure S5*e*) (e.g. Dean 1999; Blake and Guensburg 1993, 2015; Blake 2013; Jell 2014).

10. Transverse bar ends with well-developed socket

(0) absent
(1) present
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent; transverse bar (Char.7) absent

Remarks: See char. 9 in Shackleton (2005).

11. Elevated perradial ridge in ambulacrals

(0) absent
(1) present
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: The perradial ridge consists of an elevated wall expressed in the ambulacral ossicles of asterozoans (e.g. Shackleton 2005; Blake 2013; Blake and Guensburg 2015).

12. Thickness of perradial ridge

(0) less than a quarter of the ambulacral transverse width
(1) more than a quarter of the ambulacral transverse width
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent; elevated perradial ridge in ambulacrals (Char. 11) absent

Remarks: The ambulacral ossicles of *Cantabrigiaster* possess a thin perradial ridge (figure 1*c*,*d*; electronic supplementary material, figure S2*a*,*b*,*g*), as also observed in other somasteroids (e.g. *Chinianaster*, *Thoralaster*) and stenuroids (e.g. *Eriniceaster*, *Eophiuria*, *Pradesura*, *Rhopalocoma*) (electronic supplementary material, figure S5*f*; see also Blake 2013).

13. Adaxial separation between left and right perradial ridges along length of arm

(0) perradial ridges greatly separated along length of arm, forming wide perradial oral groove
(1) perradial ridges close to each other, forming narrow perradial oral groove
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent; elevated perradial ridge in ambulacrals (Char. 11) absent

Remarks: The elevated perradial ridges are widely spaced between the left and right ambulacral ossicles in the arms of *Cantabrigiaster* (figure 1*c*,*d*; electronic supplementary material, figure S2*a*–*c*,*g*) and *Chinianaster* (electronic supplementary material, figure S5*b*), forming a prominent wide perradial groove. By contrast, the perradial ridges are closely spaced adaxially in all other asterozoans (e.g. Shackleton 2005; Blake 2013; Blake and Guensburg 2015).

14. Podial basin position

(0) shared equally by adjacent ambulacrals
(1) shared with distal flange larger than proximal
(2) entirely within one ambulacral
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent; podial basins (Char. 4) absent

Remarks: See char. 3 in Shackleton (2005).

15. Shape of ambulacral ossicles spool-like from visceral view

(0) absent
(1) present
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: See char. 13 in Blake and Guensburg (2015).

16. Longitudinal ambulacral-ambulacral contact from aboral view

(0) overlapping
(1) abutting
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: See char. 26 in Shackleton (2005), char. 11 in Blake and Guensburg (2015).

17. Longitudinal ambulacral-ambulacral ridge from visceral view

(0) absent
(1) present
(-) inapplicable: calcified ambulacral floor plates (Char. 2) absent

Remarks: See char. 27 in Shackleton (2005).

Ambulacral perpendicular elements

18. Perpendicular (cover plates, virgals or podial) ossicle series articulated to ambulacrals

(0) absent
(1) present

Remarks: The perpendicular region represents the first set of ossicles adjacent to the abaxial side of the ambulacral series (electronic supplementary material, figure S7). Unlike other ossicle series that occupy a more abaxial position (i.e. adambulacral, inferomarginal, superomarginal), however, the perpendicular region is orientated perpendicularly (abaxially) relative to the perradial axis (figure 1; electronic supplementary material, figure S3). Whereas adambulacrals, inferomarginals and supramarginals grow and articulate to each other following the direction of the perradial body axis, the ossicles that constitute the perpendicular series grow and articulate following a transverse orientation relative to the perradial axis. Consequently, any given perpendiculars that correspond to adjacent ambulacral ossicles occupy a parallel position relative to the other perpendiculars, which is best observed in the multiarticulated and elongate perpendicular series (virgals) of somasteroids such as *Cantabrigiaster* (figure 1*a–d*).

Ancestrally, the perpendicular series is expressed as the moveable cover plates in *Helicocystis* (Smith and Zamora 2013), edrioasteroids (e.g. Smith 1985; Sumrall and Deline 2009; Zhao et al. 2010; Sprinkle and Sumrall 2015), blastozoans (e.g. Parsley and Zhao 2006; Zamora et al. 2009; Nardin et al. 2017) and crinoids (e.g. Ubaghs 1969; Guensburg and Sprinkle 2001, 2003, 2009; Guensburg 2012). In somasteroids (including *Cantabrigiaster*) and some stenuroids (e.g. *Rhopalocoma*), the perpendicular series is expressed as the articulating 'virgal series' that extends abaxially from each of the ambulacral ossicles, and the 'podial plate' of other stenuroids, such as *Eophiura* (e.g. Paul and Smith 1984; Smith and Jell 1990; Blake and Guensburg 1993, 2015; Shackleton 2005; Blake 2013; Jell 2014). The perpendicular series is secondarily lost in Palaeozoic ophiuroids and asteroids (electronic supplementary material, figure S7). Perpendiculars represent the most abaxial ossicle series expressed in the free appendages of blastozoans, crinoids and *Cantabrigiaster* (uniquely within Asterozoa; see also Char. 24) (electronic supplementary material, figure S7).

19. Composition of perpendicular series

(0) perpendicular series consists of multiple interconnected ossicles articulated abaxially to its corresponding ambulacral, and which taper in size towards the distal end of the series
(1) perpendicular series consists of single polygonal ossicle articulated abaxially to its corresponding ambulacral
(-) inapplicable: perpendicular series (Char. 18) absent

Remarks: The fundamental organization of the perpendiculars can be subcategorized based on the number of ossicles that constitute the series. The perpendiculars may consist of multiple articulated ossicles that become smaller abaxially (i.e. towards distal end of ossicle series), as in the multi-tiered cover plates of *Helicocystis* (Smith and Zamora 2013), *Kailidiscus* (Zhao et al. 2010), *Pseudedriophus* (Sprinkle and Sumrall 2015), *Sinoeocrinus* (Parsley and Zhao 2006) and somasteroids (electronic supplementary material, figure S7) (Shackleton 2005; Blake 2013; Blake and Guensburg 2015), or a single polygonal ossicle, as in the cover plates of *Edrioaster* (Sumrall and Deline 2009), some blastozoans (e.g. Paul and Smith 1984; Zamora et al. 2009) and crinoids (e.g. Ubaghs 1969; Guensburg and Sprinkle 2001, 2003, 2009; Guensburg 2012). In stenuroids, the perpendiculars series is also represented by a single ossicle – the podial plate – that is associated with a single ambulacral (e.g. Shackleton 2005; Blake 2013; Jell 2014; Blake and Guensburg 2015).

20. Organization of perpendicular series composed of multiple ossicles

(0) proximal perpendicular ossicle polygonal and enlarged, with intercalating smaller secondary polygonal plates (edrioasteroid)
(1) proximal perpendicular ossicle enlarged, with serially connected rectangular plates, i.e. virgal series (Cantabrigiaster)
(-) inapplicable: perpendicular series (Char. 18) absent; perpendicular series consist of single ossicle (Char. 19)

Remarks: The multi-tiered perpendicular series can be further subcategorized based on the organization of the abaxial ossicles. The perpendiculars in *Helicocystis* (Smith and Zamora 2013), *Kailidiscus* (Zhao et al. 2010), *Pseudedriophus* (Sprinkle and Sumrall 2015) and *Sinoeocrinus* (Parsley and Zhao 2006) are intercalated by secondary, smaller, polygonal ossicles. By contrast, the perpendiculars in somasteroids, including *Cantabrigiaster* (figure 1*c,d*; electronic supplementary material, figure S3), consist of a single series of articulating ossicles that extend abaxially (e.g. 'virgal series' in *Chinianaster*, *Villebrunaster*, *Thoralaster*, *Ophioxenikos*, *Archegonaster*; Smith and Jell 1990; Blake and Guensburg 1993, 2015; Shackleton 2005; Blake 2013).

21. Spines on virgal ossicles

(0) absent
(1) present
(-) inapplicable: perpendicular series (Char. 18) absent; perpendicular series consist of single ossicle (Char. 19); perpendicular ossicle enlarged with intercalary smaller secondary plates (Char. 20)

Remarks: Spines are present on the virgal ossicles of *Thoralaster* and *Chinianaster* exclusively (*contra* Shackleton 2005).

22. Proximal spacing of perpendicular series

(0) adjacent perpendicular series in direct contact with each other proximally, gaps only present distally
(1) empty gaps between adjacent perpendicular series along entire proximodistal axis
(-) inapplicable: perpendicular series (Char. 18) absent

Remarks: Within adjacent ambulacrals, the corresponding perpendicular series are organized in parallel relative to each other. Given this position, the proximal portion of the perpendiculars are in direct contact with each other in the cover plates of *Helicocystis* (Smith and Zamora 2013), edrioasteroids (e.g. Sumrall and Deline 2009, Zhao et al. 2010, Sprinkle and Sumrall 2015), blastozoans (e.g. Parsley and Zhao 2006; Zamora et al. 2009), most crinoids (e.g. Ubaghs 1969; Guensburg and Sprinkle 2001, 2003, 2009). In *Cantabrigiaster*, the perpendiculars are in direct contact proximally, but diverge distally (figure 1*c,d*; electronic supplementary material, figure S2*a–c*). The perpendiculars evince prominent gaps relative to each other – and thus not in contact – in other somasteroids and also in stenuroids (e.g. Blake and Guensburg 1993, 2015; Shackleton 2005; Blake 2013; Jell 2014) (electronic supplementary material, figure S5*f*).

23. Width of perpendicular series

(0) perpendicular series width subequal relative to corresponding ambulacral ossicle
(1) perpendicular series width much smaller than that of corresponding ambulacral ossicle
(-) inapplicable: perpendicular series (Char. 18) absent

Remarks: See char. 65 in Guensburg (2012). Ancestrally, the width of the perpendiculars is equal or subequal relative to their corresponding ambulacral ossicle, as observed in the cover plates of *Helicocystis* (Smith and Zamora 2013), edrioasteroids (e.g. Sumrall and Deline 2009, Zhao et al. 2010, Sprinkle and Sumrall 2015), blastozoans (e.g. Paul and Smith 1984; Parsley and Zhao 2006; Zamora et al. 2009), some crinoids (e.g. *Apektocrinus*, *Titanocrinus*, *Glenocrinus*; Guensburg and Sprinkle 2001, 2003, 2009), and some somasteroids (e.g. *Cantabrigiaster*, *Villebrunaster*, *Archegonaster;* see Blake 2013; Blake and Guensburg 2015). Alternatively, the cover plates may be smaller than their corresponding ambulacral, as observed in some crinoids (e.g. *Aethocrinus*, *Eknomocrinus*, *Iocrinus*; see Ubaghs 1969, Guensburg 2012), some somasteroids (e.g. *Chinianaster*, *Thoralaster*, *Ophioxenikos*) and stenuroids (e.g. *Rhopalocoma*, *Maydenia*) (see Blake and Guensburg 1993, 2015; Shackleton 2005; Blake 2013; Jell 2014).

24. Contact between perpendicular and adambulacral ossicle series

(0) one perpendicular ossicle in contact with one adambulacral ossicle
(1) one perpendicular ossicle in contact with two adambulacral ossicles (e.g. Eophiura)
(-) inapplicable: perpendicular series (Char. 18) absent; adambulacral series (Char. 25) absent

Remarks: Among asterozoans that possess a perpendicular series, the latter is invariably in contact with the ossicles that form the adambulacral series (electronic supplementary material, figures S3*e*,*f* and S7). The abaxial-most ossicle in the perpendicular series may be in direct contact with only a single adambulacral (e.g. most somasteroids) or with two (e.g. *Eophiuria*, *Phragmactis*) (see Blake and Guensburg 1993, 2015; Shackleton 2005; Blake 2013; Jell 2014). *Cantabrigiaster* as it is the only asterozoan that does not possess an adambulacral ossicle series (figure 1*c*,*d*; electronic supplementary material, figure S2), and thus this character is scored as inapplicable.

Adambulacral region

25. Adambulacral series

(0) absent
(1) present

Remarks: Adambulacral ossicles are a defining feature of Asterozoa, and are present in all members of this group with the notable exception of *Cantabrigiaster* (figure 1*c*,*d*; electronic supplementary material, figure S2) (Shackleton 2005; Blake 2013; Blake and Guensburg 2015). After the ambulacrals, the adambulacrals constitute the second ossicle series that strictly follows the perradial body axis, based on the location of the perradial suture (Char. 1) as a reference point. Adambulacral ossicles are readily distinguished from those in the adjacent perpendicular series (when present, see Char. 18) based on their pattern of growth and articulation; adambulacrals grow and articulate following the perradial axis (similarly to ambulacrals), whereas perpendicular ossicles instead follow a perpendicular orientation relative to the perradial axis. Perpendiculars are further distinguished in that they are not in direct contact abaxially (distally within perpendicular ossicle series), whereas adambulacrals are always in direct contact with each other following a perradial orientation (electronic supplementary material, figure S3*e*,*f*). Adambulacrals represent the most abaxial ossicle series expressed on the appendages of somasteroids (with the exception of *Cantabrigiaster*), stenuroids and ophiuroids (electronic supplementary material, figure S5).

26. Morphology of adambulacral ossicles

(0) small bead-like ossicles (e.g. Chinianaster)
(1) rectangular/elongate ossicles (e.g. Ophixenikos)
(2) boot-shaped ossicles (e.g. *Palaeozoic ophiuroids*)
(3) subquadrate block-like ossicles (e.g. *Palaeozoic asteroids*)
(-) inapplicable: adambulacral series (Char. 25) absent

Remarks: The ossicles of the adambulacral series can express diverse morphologies. In *Chinianaster* and *Villebrunaster* (electronic supplementary material, figure S5*a*,*d*), they consist of a string of minute bead-like ossicles that that define the margins of the arms, and extend between the abaxial tips of the perpendicular ossicles (virgal series in Shackleton 2005; Blake 2013; Blake and Guensburg 2015). In other taxa, the adambulacrals may have a rectangular (e.g. *Eriniceaster*, *Ophioxenikos*, *Stenaster*) or boot-like appearance (e.g. *Phragmactis*, *Encrinaster*, *Protaster*), or consist of robust subquadrate ossicles (e.g. *Archegonaster*, *Hudsonaster*, *Ophiocantabria*, *Petraster*, *Maydenia*) (see Blake and Guensburg 1993, 2015; Dean 1999; Shackleton 2005; Blake 2013; Jell 2014; Blake et al. 2015).

27. Spines (or articulating spine sockets) on adambulacral ossicles

(0) absent
(1) present
(-) inapplicable: adambulacral series (Char. 25) absent

Remarks: Spines, or at least articulating spine sockets, are present in the adambulacrals of several asterozoans, as strikingly preserved in *Eriniceaster* (e.g. Blake 2013), *Platanaster* (e.g. Dean 1999), *Eophiura* (Shackleton 2005) and *Maydenia* (Jell 2014), for example.

28. Adambulacral ossicles with pronounced abaxial spike

(0) absent
(1) present
(-) inapplicable: adambulacral series (Char. 25) absent

Remarks: The adambulacral series of some somasteroids (e.g. *Chinianaster*, *Villebrunaster*, *Thoralaster*) bear a spike (without an articulating socket) that faces abaxially (see also Shackleton 2005; Blake and Guensburg 2015).

Inferomarginal region

29. Inferomarginal series

(0) absent
(1) present

Remarks: Inferomarginals occur exclusively in Asteroidea. After ambulacrals and adambulacrals, inferomarginals constitute the third ossicle series that strictly follows the perradial body axis, based on the location of the perradial suture (Char. 1) as a reference point (electronic supplementary material, figure S7). There are no known representatives which the inferomarginals represent the abaxial-most ossicle series.

30. Inferomarginal ossicle morphology

(0) subquadrate block-like ossicles
(1) elongate ossicles
(-) inapplicable: inferomarginal series (Char. 29) absent

31. Inferomarginal ossicle surface paxillate

(0) absent
(1) present
(-) inapplicable: inferomarginal series (Char. 29) absent

Superomarginal region

32. Superomarginal series

(0) absent
(1) present

Remarks: Superomarginals occur exclusively in Asteroidea. After ambulacrals, adambulacrals and inferomarginals, superomarginals constitute the fourth ossicle series that strictly follows the perradial body axis, based on the location of the perradial suture (Char. 1) as a reference point. Superomarginals represent the most abaxial ossicles series expressed on the appendages of asteroids (electronic supplementary material, figure S7).

33. Superomarginal ossicle morphology

(0) subquadrate block-like ossicles
(1) elongate ossicles
(-) inapplicable: superomarginal series (Char. 32) absent

34. Superomarginal ossicle surface paxillate

(0) absent
(1) present
(-) inapplicable: superomarginal series (Char. 32) absent

Oral/circumoral region

35. Mouth/peristome symmetry

(0) symmetrical, ambulacrals arranged in 2-1-2 pattern
(1) radially symmetrical, ambulacrals reduced

Remarks: See char. 3 in Nardin et al. (2017). There is pentarradial organization in the mouth/peristome area (e.g. Zamora et al. 2012; Smith and Zamora 2013). This organization – commonly termed 2-1-2 symmetry – is expressed in the oral surface of *Helicocystis*, edrioasteroids and blastozoans (e.g. Parsley and Zhao 2006; Sumrall and Deline 2009; Zamora et al. 2009; Zhao et al. 2010; Sumrall and Waters 2012; Kammer et al. 2013; Smith and Zamora 2013; Guensburg et al. 2015; Sprinkle and Sumrall 2015; Nardin et al. 2017; Sumrall 2017). A reduced 2-1-2 pattern forming a radially symmetrical mouth/peristome is archetypical of asterozoans (e.g. Shackleton 2005; Blake 2013; Blake and Guensburg 2015). In the initial analyses (figure 2; electronic supplementary material, figure S6), the mouth symmetry was conservatively scored as uncertain in the Early Ordovician crinoids included in this study because the oral surface is generally obscured, or when ossified oral plates are present (see Char. 36), the preservation does not allow to resolve their organization in sufficient detail (e.g. Ubaghs 1969; Guensburg and Sprinkle 2001, 2003, 2009; Guensburg 2012; Guensburg et al. 2015).

36. Ossified mouth/peristome ossicles

(0) absent
(1) present

Remarks: See char. 68 in Guensburg (2012). This character is scored as uncertain in *Apektocrinus* as it is not possible to verify the morphology of the putative large oral plates reported by Guensburg and Sprinkle (2009).

37. Morphology of circumoral ossicles (jaw ambulacrals)

(0) circumoral ossicles indistinguishable from the remaining ambulacrals (of approximately same size)
(1) circumoral ossicles enlarged (virtually twice the size of the adjacent arm ambulacral)

Remarks: modified from char. 122 in Shackleton (2005).

38. Organization of first podial basin pore relative to circumoral ossicle

(0) first podial basin pore shared between mouth angle plate and circumoral ossicle
(1) first podial basin pore entirely within circumoral ossicle

Remarks: See char. 126 in Shackleton (2005).

39. Additional ossicle in jaw causing oral mouth angle plate to be L-shaped

(0) absent
(1) present

Remarks: See char. 129 in Shackleton (2005).

40. Buccal slits (defined if third recognizable jaw ambulacrals do not meet distally)

(0) absent
(1) present

Remarks: See char. 130 in Shackleton (2005).

41. Unpaired interradial plate (axillary)

(0) absent
(1) present

Remarks: See char. 133 in Shackleton (2005).

Aboral region

42. Feeding appendages that are attached to (or extensions of) the ambulacra (brachioles and arms)

(0) absent
(1) present

Remarks: Feeding appendages that are attached to (or extensions of) the ambulacra consist of two types of structures that are widely thought to be independently derived structures called brachioles and arms (e.g., Guensburg et al. 2010). Brachioles (formed only of axial elements) are expressed in blastozoans (e.g. Paul and Smith 1984; Parsley and Zhao 2006; Zamora et al. 2009; Clausen et al. 2010; Guensburg et al. 2010; Nardin et al. 2017). Arms occur in crinoids (composed axial and imperforate extraxial elements) (e.g. Ubaghs 1969; Guensburg and Sprinkle 2001, 2003, 2009; Guensburg 2012) and all asterozoans (e.g. Smith and Jell 1990; Blake and Guensburg 1993, 2015; Dean 1999; Shackleton 2005; Blake 2013; Jell 2014).

43. Body wall tissue (imperforate extraxial elements) extends distally from oral disc region, covering aboral side of ambulacral ossicle series in feeding appendages

(0) absent – aboral side of ambulacral ossicles in feeding appendages not covered by additional ossicle series (imperforate extraxial elements) only formed only of axial elements

(1) present – aboral side of ambulacral ossicles in free appendages covered by additional ossicle series (imperforate extraxial elements)
(-) inapplicable: feeding appendages (Char. 42) absent

Remarks: Among those groups that possess feeding appendages, it is possible to make a distinction between the fundamental construction of their appendages based on the presence of coelomic cavities that extend from the main body (Mooi et al. 2005). Crinoid arms are characterized by being composed of imperforate extraxial and axial elements the presence of coelomic cavities, which can be recognized by the space contained between the ambulacrals and the aboral brachial ossicle series (see Char. 50); this organization is best exemplified in Early Ordovician forms with calcified ambulacrals in addition to brachial and interbrachial ossicles extending from the body wall onto the arms (e.g. Guensburg and Sprinkle 2001, 2003, 2009; Guensburg 2012; Guensburg et al. 2015). By contrast, the feeding appendages of blastozoans are only formed of axial elements consisting of a series of interconnected ambulacrals (brachioles) that do not possess internal coelomic cavities, with the exception of a small internal channel for the water vascular system, and are devoid of aboral brachial ossicles (extraxial elements) (e.g. Parsley and Zhao 2006; Guensburg and Sprinkle 2009; Zamora et al. 2009; Clausen et al. 2010; Guensburg et al. 2010, 2015) (see Char. 3).

Asterozoan arms also express coelomic cavities extending into their free appendages, as defined by the presence of a carinal region that overlies the aboral side of the ambulacrals (see Char. 53), and which is further reinforced by the subsequent inclusion of additional ossicle series that follow a perradial orientation in the different groups (see Chars. 25, 29, 32) (electronic supplementary material, figure S7).

44. Oral disc and visceral mass enclosed by imperforate extraxial lateral walls (part of imperforate extraxial lateral wall body wall capsule) (see electronic supplementary material, table S2)

(0) absent
(1) present

45. **Imperforate extraxial lateral walls decalcified (loss of plating)** (see electronic supplementary material, table S2)

(0) absent
(1) present

46. Organization of the imperforate extraxial lateral walls (part of imperforate extraxial lateral wall body wall capsule)

(0) imperforate extraxial lateral wall body wall capsule composed of multiple plates of irregular size and shape

(1) imperforate extraxial lateral wall body wall capsule composed of multiple plates organized as circlets based with a similar size and shape
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; lateral walls are an extension of the tegmen (perforate extraxial and axial components)

Remarks: The imperforate extraxial lateral walls are part of the imperforate extraxial lateral wall body wall capsule of *Helicocystis* (Smith and Zamora 2013), edrioasteroids (e.g. Smith 1985; Sumrall and Deline 2009; Zhao et al. 2010; Sprinkle and Sumrall 2015), imbricate blastozoans (e.g. Parsley and Zhao 2006; Zamora et al. 2009; Nohejlová and Fatka 2016; Nardin et al. 2017) and protocrinoids (e.g. *Titanocrinus*, *Glenocrinus*; see Guensburg and Sprinkle 2001, 2003) are composed of several plates of irregular size and shape, in contrast with the highly ordered imperforate extraxial lateral wall body wall capsule expressed in camerates and other more derived crinoids (e.g. *Apektocrinus*, *Aethocrinus*, *Iocrinus*) (e.g. Ubaghs 1969; Guensburg and Sprinkle 2009; Guensburg 2012; Zamora et al. 2015).

47. Ambulacral flooring plates form an integral part of the body wall

(0) absent
(1) present

Remarks: See char. 5 in Zamora and Smith (2012), and char. 6 in Smith and Zamora (2013). Ambulacral flooring plates forming an integral part of the theca: The presence of ambulacra forming an integral part of the thecal plating is true for all ambulacral-bearing members included here, except *Gogia*. In *Gogia* the brachioles arise directly from perioral plates and there is no ambulacral section extending over the theca.

48. Extension of the tessellate perforate region

(0) restricted to a plateau-like oral surface, above the body capsule edge
(1) extended over the body capsule edge and forming part of the lateral vertical body capsule
(2) forming the entire body capsule enclosing viscera
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent

Remarks: See char. 5 in Nardin et al. (2017).

49. Shape of ambulacral perradial region embedded on imperforate extraxial lateral wall (part of body wall capsule)

(0) straight
(1) curved
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; ambulacral ossicles do not form integral part of imperforate extraxial lateral wall body wall capsule (Char. 47)

Remarks: See char. 9 in Smith and Zamora (2013). Ambulacra on the theca are strongly curved in *Helicoplacus*, *Helicocystis*, and *Camptostroma* and straight or only weakly curved towards the ends in *Lepidocystis* and *Stromatocystites*. In *Gogia*, although some have spiral brachioles, none have ambulacra forming an integral part of the theca and so are scored as inapplicable.

50. Imperforate extraxial lateral wall has ambulacra branching to give rise to small lateral branches to left and right

(0) absent
(1) present, numerous isotomous branches arising along its length
(2) present, one pair of isotomous branches arising from a single basal plate
(-) inapplicable: feeding appendages (Char.42) absent; imperforate extraxial lateral wall body wall capsule (Char. 44) absent

Remarks: See char. 3 in Zamora and Smith (2012) and char. 4 in Nardin et al. (2017).

51. Brachial ossicle series covering aboral /visceral side of ambulacral region

(0) absent
(1) present
(-) inapplicable: free appendages (Char. 42) absent; body wall tissue extending distally into appendages from oral disk (Char. 43) absent

Remarks: Although the body wall extends into the free appendages in both crinoids and asterozoans, the former group differs in that the aboral surface of the arms bears a discrete brachial ossicle series that is a continuation of the tessellate plates on the imperforate extraxial lateral wall body wall capsule (e.g. Guensburg and Sprinkle 2001, 2003, 2009; Guensburg 2012; Guensburg et al. 2015).

52. Interbrachial ossicles series (extended from part of imperforate extraxial lateral wall body wall capsule) separate brachial from ambulacral ossicles in proximal part of free appendage

(0) absent
(1) present
(-) inapplicable: body wall tissue extending distally into appendages from oral disk (Char. 43) absent; imperforate extraxial lateral wall body wall capsule (Char. 44) absent; brachial ossicles (Char. 51) absent

Remarks: See char. 58 in Guensburg (2012).

53. Feeding appendage attachment to imperforate extraxial lateral body wall

(0) appendages gradually emerging from part of imperforate extraxial lateral wall body wall capsule along more than two brachial ossicles
(1) appendages abruptly emerging at part of imperforate extraxial lateral wall body wall capsule along one or two brachial ossicles
(-) inapplicable: body wall tissue extending distally into appendages from oral disk (Char. 43) absent; imperforate extraxial lateral wall body wall capsule (Char. 44) absent; brachial ossicles (Char. 51) absent

Remarks: See char. 54 in Guensburg (2012).

54. Extent of coverage of carinal region

(0) carinal region extends to tips of arms
(1) carinal region extend to median part of arms
(2) carinal region restricted to oral disk
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; brachial series (Char. 51) absent

55. Peripheral shape of carinal region

(0) carinal region with pentagonal outline
(1) carinal region stellate, with regression of the carinal margin between the arms
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; brachial series (Char. 51) absent

56. Marginalia on carinal region

(0) absent
(1) present
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; brachial series (Char. 51) absent

Remarks: The marginalia consist of accessory ossicles located around the oral disk, and which occupy a perpendicular (or close to perpendicular) orientation relative to the perradial axis, but which are not connected directly with the perpendicular series (Char. 18). Marginalia are observed in *Encrinaster* and *Ophiocantabria* (e.g. Shackleton 2005; Blake et al. 2015). Although the somasteroid *Archegonaster* has well-developed block-like ossicles on the margins of the carinal region that superficially resemble marginalia, these are reliably identified as adambulacrals based on their direct connection with the perpendicular series (Char. 24).

57. Ossicle organization in carinal region

(0) ossicles randomly scattered
(1) ossicles tessellated
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent

58. Ossicle morphology in carinal region

(0) fine grain-like ossicles
(1) coarse grain like ossicles
(2) spicule-like ossicles forming a network
(3) subquadrate block-like ossicles
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent

59. Ossicle variability in carinal region

(0) homogeneous
(1) heterogeneous
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent

60. Position of madreporite/hydropore

(0) on oral surface
(1) on aboral surface

Remarks: See char. 6 in Blake and Guensburg (2015).

61. Madreporite/hydropore morphology

(0) large, many crenulations on external surface
(1) smaller, with single channel
(2) slit-like

Remarks: See char. 78 in Shackelton (2005).

62. Elevated anal cone

(0) absent
(1) present
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent

Remarks: See char. 69 in Guensburg (2012).

63. Plating at imperforate extraxial lateral wall body wall capsule juncture

(0) polymeric (stem consists of several agglutinated ossicles)

(1) holomeric (stem consist of single ossicle series – columnars)
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; differentiated stem (Char. 66) absent

Remarks: See char. 1 in Guensburg (2012)

64. Epispires on body wall

(0) absent
(1) present
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent

Remarks: See char. 14 in Zamora and Smith (2012)

65. Epispire-bearing region extended aborally

(0) absent
(1) present
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; epispires (Char. 64) absent

66. Aboral region (stalks/steles/stems)

(0) absent
(1) present
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent

67. Aboral region (stalks/steles/stems) length

(0) stem is equal or longer than imperforate extraxial lateral wall body wall capsule region and flexible
(1) stem is shorter than imperforate extraxial lateral wall body wall capsule region and with limited mobility
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; differentiated stem (Char. 66) absent

68. Basal ossicle circlet (part of imperforate extraxial lateral wall body wall capsule)

(0) absent
(1) basal ossicles differentiated, with similar size and shape around stem junction

(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; differentiated stem (Char. 66) absent

69. Differentiated infrabasal ossicle circlet (part of imperforate extraxial lateral wall body wall capsule)

(0) absent
(1) infrabasal ossicles differentiated, with similar size and shape around stem junction
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; differentiated stem (Char. 66) absent

Remarks: See char. 18 in Guensburg (2012). The ossicles that form the base of *Helicocystis* (Smith and Zamora 2013), edrioasteroids (e.g. Sumrall and Deline 2009; Zhao et al. 2010; Sprinkle and Sumrall 2015) and blastozoans are generally irregular in shape and size (e.g. Parsley and Zhao 2006; Zamora et al. 2009; Nohejlová and Fatka 2016; Nardin et al. 2017). Derived taxa such as Rhopalocystis have fixed and reduced number of (basal) thecal plates. In contrast, the ordered plates of crinoids allow to score the presence of infrabasal ossicles (e.g. Guensburg and Sprinkle 2001, 2003, 2009; Guensburg 2012).

70. Infrabasals aligned with radials

(0) inconsistent orientation relative to radials
(1) ordered relative to radials
(-) inapplicable: infrabasal ossicle circlet (Char. 69) absent

Remarks: See char. 19 in Guensburg (2012).

71. Stem width aboral region (stalks/steles/stems)

(0) broad stem
(1) narrow stem
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; differentiated stem (Char. 66) absent

72. Pentameric proximal stem

(0) absent
(1) present
(2) bowl-shaped
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; differentiated stem (Char. 66) absent

Remarks: See char. 2 in Guensburg (2012). The proximal stem of Early Ordovician crinoids included in the analysis is typified by the presence of pentameres (see Guensburg and Sprinkle 2003, 2009; Guensburg 2012; Guensburg et al. 2010; 2015), whereas this organization is not observed in Cambrian stemmed forms.

73. Nodals

(0) absent
(1) present
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; differentiated stem (Char. 66) absent

Remarks: See char. 12 in Guensburg (2012).

74. Aboral cup shape (imperforate extraxial lateral wall body wall capsule)

(0) globose
(1) conical
(2) bowl-shaped
(-) inapplicable: imperforate extraxial lateral wall body wall capsule (Char. 44) absent; differentiated aboral region (stalks/steles/stems) (Char. 66) absent

Remarks: See char. 12 in Guensburg (2012).

References

Blake DB. 2013 Early asterozoan (Echinodermata) diversification: a paleontologic quandary. *J. Paleontol.* **87**, 353–372.

Blake DB, Guensburg TE. 1993 New Lower and Middle Ordovician stelleroids (Echinodermata) and their bearing on the origins and early history of the stelleroid echinoderms. *J. Paleontol.* **67**, 103–113.

Blake DB, Guensburg TE. 2015 The class Somasteroidea (Echinodermata, Asterozoa): morphology and occurrence. *J. Paleontol.* **89**, 465–486.

Blake DB, Zamora S, García-Alcalde JL. 2015 A new Devonian asteroid-like ophiuroid from Spain. *Geol. Acta* **13**, 335–343.

Botting JP. 2004 Ordovician sponges, echinoderms and oddities of Morocco. *PalAss. Newsl.* 56, 98–101.

Clausen S, Jell PA, Legrain X, Smith AB. 2009 Pelmatozoan arms from the Middle Cambrian of Australia: bridging the gap between brachioles and brachials? *Lethaia* **42**, 283–296.

Dean J. 1999 What makes an ophiuroid? A morphological study of the problematic Ordovician stelleroid *Stenaster* and the palaeobiology of the earliest asteroids and ophiuroids. *Zoolog. J. Linn. Soc.* **126**, 225–250.

Destombes J. 1962 Stratigraphie et paléogéographie de l'Ordovicien de l'Anti-Atlas (Maroc): un essai de synthèse. Résumé. *Bull. Soc. Géolog. Fran.* **S7–IV**, 453–460.

Destombes J. 1971 L'Ordovicien au Maroc. Essai de synthèse stratigraphique. *Mémoir. Bur. Rech. Géolog. Min.* **73**, 237–263.

Destombes J, Hollard H, Willefert S. 1985 Lower Palaeozoic rocks of Morocco. In *Lower Palaeozoic Rocks of the World* (ed. CH Holland), pp. 91–336. New York: Wiley.

David B, Lefebvre B, Mooi R, Parsley R. 2000 Are homalozoans echinoderms? An answer from the extraxial-axial theory. *Paleobiology* 26, 529–555.

Guensburg TE. 2012 Phylogenetic implications of the oldest crinoids. *J. Paleontol.* **86**, 455–461.

Guensburg TE, Sprinkle J. 2001 Earliest crinoids: new evidence for the origin of the dominant Paleozoic echinoderms. *Geology* **29**, 131–134.

Guensburg TE, Sprinkle J. 2003 The oldest known crinoids (Early Ordovician, Utah) and a new crinoid plate homology system. *Bull. Amer. Paleontol.* **364**, 1–43.

Guensburg TE, Sprinkle J. 2009 Solving the mystery of crinoid ancestry: new fossil evidence of arm origin and development. *J. Paleontol.* **83**, 350–364.

Guensburg TE, Blake DB, Sprinkle J, Mooi R. 2015 Crinoid ancestry without blastozoans. *Ac. Palaeontol. Pol.* **61**, 253–266.

Guensburg TE, Mooi R, Sprinkle J, David B, Lefebvre B. 2010 Pelmatozoan arms from the mid-Cambrian of Australia: bridging the gap between brachioles and brachials? Comment: there is no bridge. *Lethaia* **43**, 432–440.

Gutiérrez-Marco JC, Martin ELO. 2016 Biostratigraphy and palaeoecology of Lower Ordovician graptolites from the Fezouata Shale (Moroccan Anti-Atlas). *Palaeogeograph. Palaeoclimatol. Palaeoecol.* **460**, 35–49.

Jell PA. 2014 A Tremadocian asterozoan from Tasmania and a late Llandovery edrioasteroid from Victoria. *Alcheringa* **38**, 528–540.

Kammer TW, Sumrall CD, Zamora S, Ausich WI, Deline B. 2013 Oral region homologies in Paleozoic crinoids and other plesiomorphic pentaradial echinoderms. *PLoS ONE* **8**, e77989.

Lefebvre B. 2007 Early Palaeozoic palaeobiogeography and palaeoecology of stylophoran echinoderms. *Palaeogeograph. Palaeoclimatol. Palaeoecol.* **245**, 156–199.

Lefebvre B, Sumrall CD, Shroat-Lewis RA, Reich M, Webster GD, Hunter AW, Nardin E, Rozhnov SV, Guensburg TE, Touzeau A. 2013 Chapter 14: Palaeobiogeography of Ordovician echinoderms. In *Early Palaeozoic Biogeography and Palaeogeography*, *Geological Society Memoir No 38* (eds DAT Harper, T Servais), pp. 173–198. London: Geological Society of London.

Lefebvre B, Allaire N, Guensburg TE, Hunter AW, Kouraïss K, Martin ELO, Nardin E, Noailles F, Pittet B, Sumrall CD, et al. 2016 Palaeoecological aspects of the diversification of echinoderms in the Lower Ordovician of central Anti-Atlas, Morocco. *Palaeogeograph. Palaeoclimatol. Palaeoecol.* **460**, 97–121.

Lefebvre B, Gutiérrez‐Marco JC, Lehnert O, Martin EL, Nowak H, Akodad M, El Hariri K, Servais T. 2018 Age calibration of the Lower Ordovician Fezouata Lagerstätte, Morocco. *Lethaia* 51, 296‐311.

Martin ELO, Lefebvre B, Vaucher R. 2015 Taphonomy of a stylophoran-dominated assemblage in the Lower Ordovician of Zagora area (central Anti-Atlas, Morocco). In *Progress in Echinoderm Palaeobiology: Cuadernos del Museo Geominero 19* (eds S Zamora, I Rabano), pp. 95–100. Madrid: Instituto Geológico y Minero de España.

Martin ELO, Pittet B, Gutiérrez-Marco J-C, Vannier J, El Hariri K, Lerosey-Aubril R, Masrour M, Nowak H, Servais T, Vandenbroucke TRA. 2016 The Lower Ordovician Fezouata Konservat-Lagerstätte from Morocco: age, environment and evolutionary perspectives. *Gondwana Res.* **34**, 274–283.

Mooi R, David B, Wray GA. 2005 Arrays in rays: terminal addition in echinoderms and its correlation with gene expression. *Evol. Dev.* **7**, 542–555.

Mooi R, David B. 1997 Skeletal homologies of echinoderms. *Paleontological Society Papers* 3, 305–335.

Mooi R, David B. 2008 Radial symmetry, the anterior/posterior axis, and echinoderm Hox genes. *Annu. Rev. Ecol. Evol. Syst.* 39, 43–62.

Nardin E, Lefebvre B, Fatka O, Nohejlová M, Kašička L, Šinágl M, Szabad M. 2017 Evolutionary implications of a new transitional blastozoan echinoderm from the middle Cambrian of the Czech Republic. *J. Paleontol.* **91**, 672–684.

Nohejlová M, Fatka O. 2016 Ontogeny and morphology of Cambrian eocrinoid *Akadocrinus* (Barrandian area, Czech Republic). *Bull. Geosci.* **91**, 141–153.

Parsley RL, Zhao Y. 2006 Long stalked eocrinoids in the basal Middle Cambrian Kaili Biota, Taijiang County, Guizhou Province, China. *J. Paleontol.* **80**, 1058–1071.

Paul CRC, Smith AB. 1984 The early radiation and phylogeny of echinoderms. *Biol. Rev.* **59**, 443–481.

Shackleton JD. 2005 Skeletal homologies, phylogeny and classification of the earliest asterozoan echinoderms. *J. Syst. Palaeontol.* **3**, 29–114.

Smith AB. 1985 Cambrian eleutherozoan echinoderms and the early diversification of edrioasteroids. *Palaeontology* **28**, 715–756.

Smith AB, Jell PA. 1990 Cambrian edrioasteroids from Australia and the origin of starfishes. *Memoirs of the Queensland Museum* **28**, 715–778.

Smith AB, Zamora S. 2013 Cambrian spiral-plated echinoderms from Gondwana reveal the earliest pentaradial body plan. *Proc. R. Soc. Lond. B: Biol. Sci.* **280**, 20131197.

Sprinkle J, Sumrall CD. 2015 New edrioasterine and astrocystitid (Echinodermata: Edrioasteroidea) from the Ninemile Shale (Lower Ordovician), central Nevada. *J. Paleontol.* **89**, 346–352.

Sumrall CD. 2017 New insights concerning homology of the oral region and ambulacral system plating of pentaradial echinoderms. *J. Paleontol.* **91**, 604–617.

Sumrall CD, Deline B. 2009 A new species of the dual-mouthed paracrinoid *Bistomiacystis* and a redescription of the Edrioasteroid *Edrioaster priscus* from the upper Ordovician Curdsville member of the Lexington limestone. *J. Paleontol.* **83**, 135–139.

Sumrall CD, Waters JA. 2012 Universal elemental homology in glyptocystitoids, hemicosmitoids, coronoids and blastoids: steps toward echinoderm phylogenetic reconstruction in derived blastozoa. *J. Paleontol.* **86**, 956–972.

Telford MJ, Lowe CJ, Cameron CB, Ortega-Martinez O, Aronowicz J, Oliveri P, Copley RR. 2014 Phylogenomic analysis of echinoderm class relationships supports Asterozoa. *Proc. R. Soc. B*. **281**, 20140479.

Ubaghs G. 1969 *Aethocrinus moorei* Ubaghs, n. gen., n. sp., le plus ancien crinoide dicyclique connu. *University of Kansas Palaeontological Contributions* **38**, 1–25.

Van Roy P, Orr PJ, Botting JP, Muir LA, Vinther J, Lefebvre B, El Hariri K, Briggs DEG. 2010 Ordovician faunas of Burgess Shale type. *Nature* **465**, 215–218.

Vaucher R, Martin ELO, Hormière H, Pittet B. 2016 A genetic link between Konzentrat-and Konservat-Lagerstätten in the Fezouata Shale (lower Ordovician, Morocco). *Palaeogeograph. Palaeoclimatol. Palaeoecol.* **460**, 24–34.

Vaucher R, Pittet B, Hormière H, Martin ELO, Lefebvre B. 2017 A wave‐dominated, tide‐modulated model for the Lower Ordovician of the Anti‐Atlas, Morocco. *Sedimentology* 64, 777‐807.

Vidal M. 1998 Le modèle des biofaciès à trilobites: un test dans l'Ordovicien inférieur de l'Anti-Atlas, Maroc. *Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science* **327**, 327–333.

Zamora S, Gozalo R, Linñán E. 2009 Middle Cambrian gogiid echinoderms from Northeast Spain: Taxonomy, palaeoecology, and palaeogeographic implications. *Ac. Palaeontol. Pol.* **54**, 253–265.

Zamora S, Rahman IA, Smith AB. 2012 Plated Cambrian bilaterians reveal the earliest stages of echinoderm evolution. *PLoS ONE* **7**, e38296.

Zhao Y, Sumrall CD, Parsley RL, Peng J. 2010 Kailidiscus, a new plesiomorphic edrioasteroid from the basal middle Cambrian Kaili Biota of Guizhou Province, China. *J. Paleontol*. **84**, 668–680.

Supplementary (S1–S7)

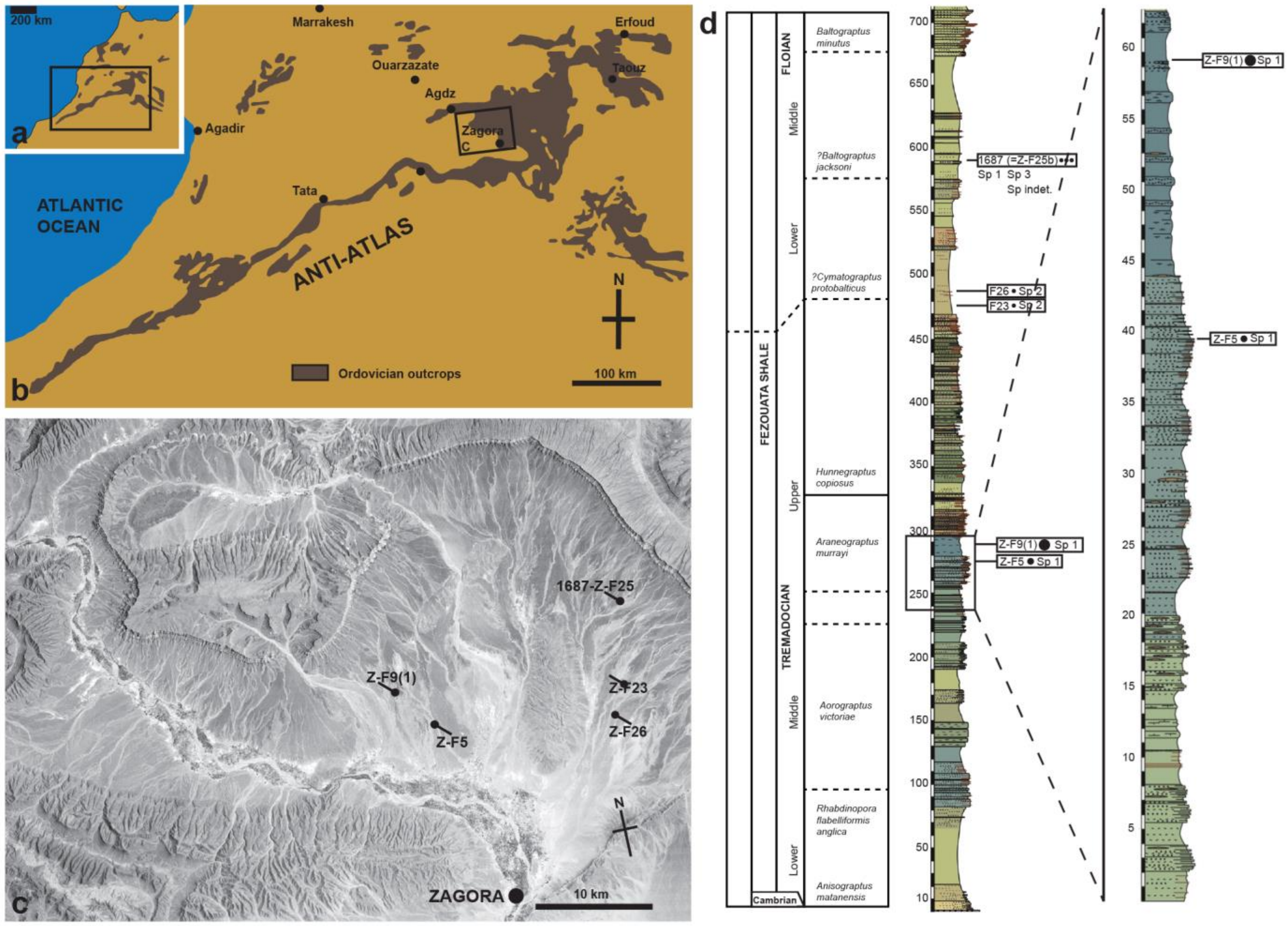

Figure S1. Locality and stratigraphic occurrence of *Cantabrigiaster* at Lower Ordovician echinoderm sites from the Anti-Atlas, Morocco. (*a*) Location of the Anti-Atlas range in northwestern Africa. (*b*) Map of the Anti-Atlas showing the distribution of Ordovician outcrops and the location of the Zagora area. (*c*) Landsat view of the Zagora area showing the location of all main Early Ordovician echinoderm localities that contain somasteroids photograph courtesy of the U.S. Geological Survey. (*d*) Synthetic, composite stratigraphic column showing the Lower Ordovician succession in the Zagora area, central Anti-Atlas, Morocco. With detailed, stratigraphic columns showing the late Tremadocian interval (*A. murrayi* Zone and part of the *H. copiosus* Zone) showing the position of the main somasteroid fossils (Redrawn from Lefebvre et al. (2016)).

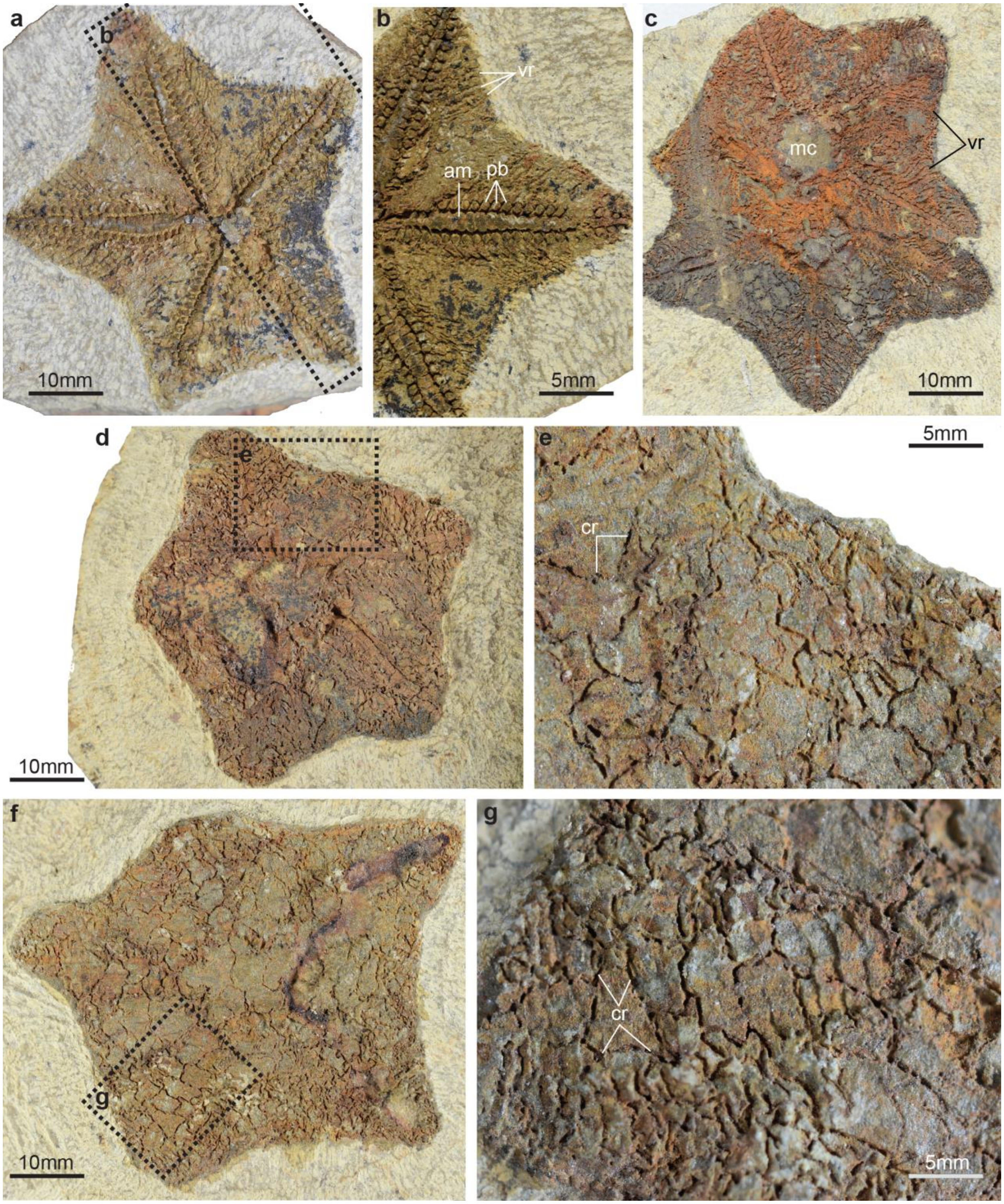

Figure S2. ***Cantabrigiaster fezouataensis*** **from the Lower Ordovician (?late Tremadocian) of Morocco.** All body fossils. (*a*) YPM 535547, oral view. (*b*) Detail of dashed area in a. (*c*) YPM IP 535557-535558, oral and aboral view. (*d*) YPM IP 535559, aboral view. (*e*) Detail of dashed area in d. (*f*) YPM 535552, aboral view. (*g*) Detail of dashed area in (*f*). Abbreviations: am, ambulacral ossicles; cr, carinal region ossicles (preserved on the aboral surface); mc, mouth cavity; pb, podial basins; vr, virgal ossicles.

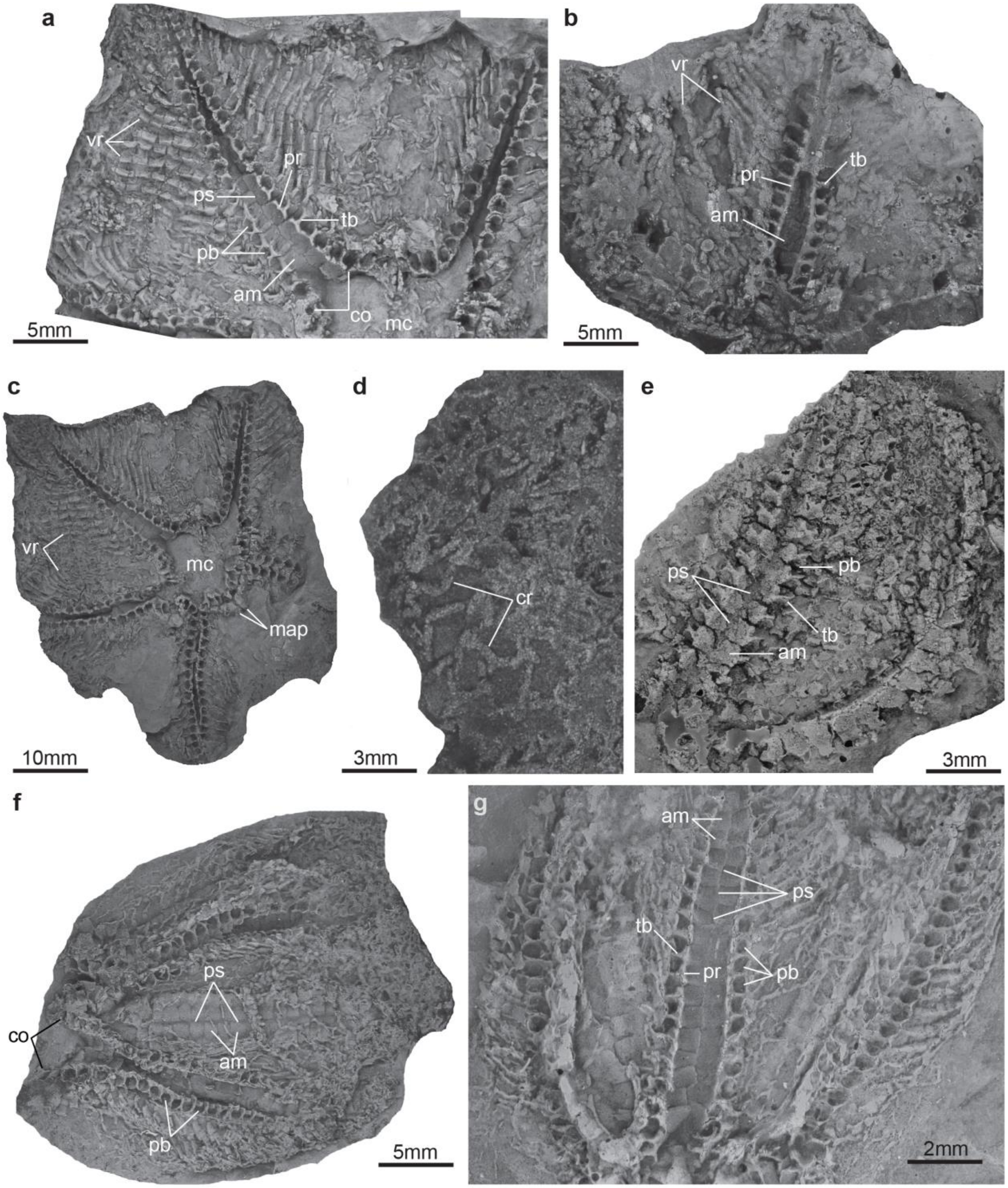

Figure S3. Cantabrigiaster fezouataensis from the Lower Ordovician (Tremadocian) of Morocco. All latex molds. (*a*) Holotype UCBL-FSL 424961 (Van Roy coll.), oral view. (*b*) UCBL-FSL 711938 (Lefebvre coll.), oral view. (*c*) UCBL-FSL 424961 (Van Roy coll.), oral view. (*d*) UCBL-FSL 711939 (Lefebvre coll.), aboral view. (*e*) MHNN.P.045596 (Catto coll.), oral view. (*f*) UCBL-FSL 424962a (Vizcaïno coll.), aboral view. (*g*) UCBL-FSL 424962b (Vizcaïno coll.). Abbreviations: am, ambulacral ossicles; co, circumoral ossicles; cr, carinal region ossicles (preserved on the aboral surface); map, mouth angle plates; mc, mouth cavity; tb, transverse bar; pb, podial basins; pr, perradial ridge; ps, perradial suture; vr, virgal ossicles.

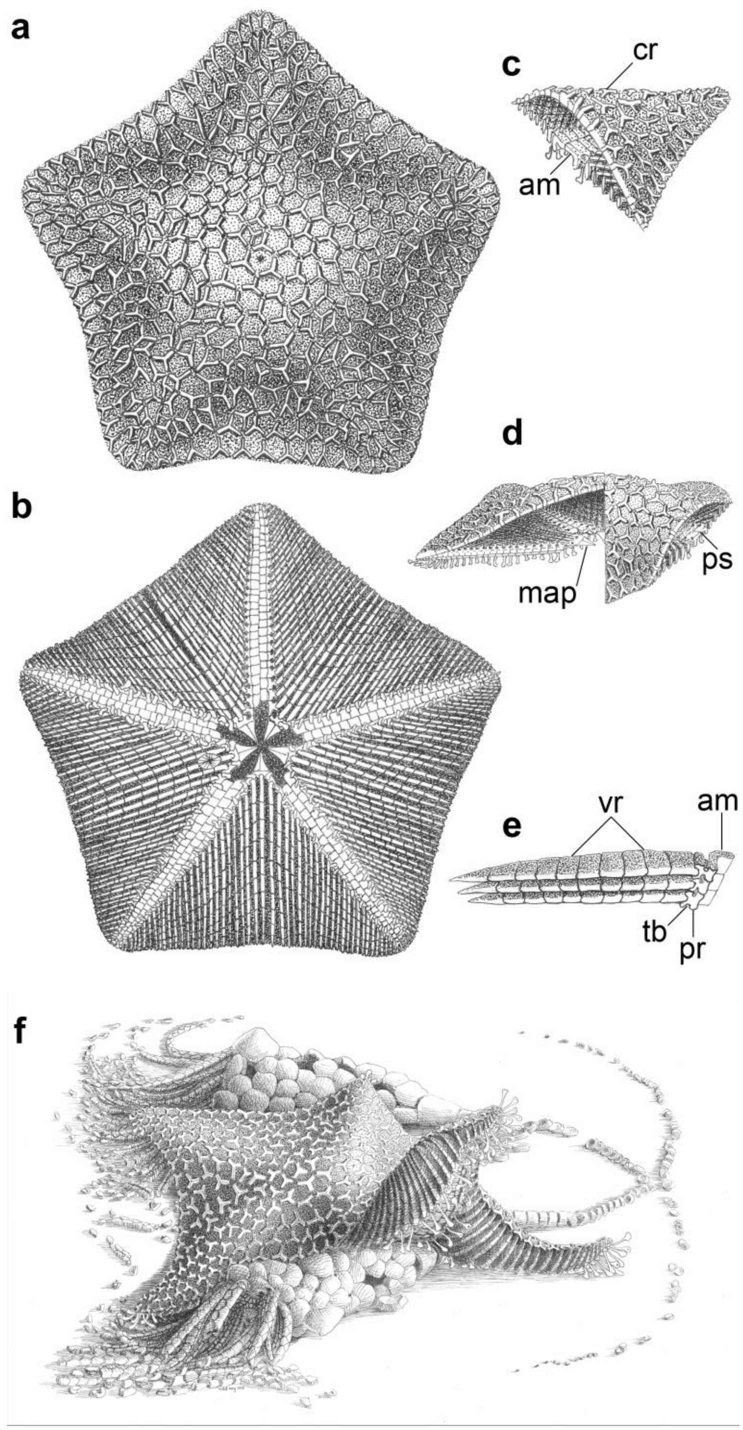

Figure S4. Morphological reconstruction of Cantabrigiaster fezouataensis. (*a*) Aboral view. (*b*) Oral view. (*c*) Cross section of isolated arm in oblique view. (*d*) Cross section of main body cavity lateral view. (*e*) Isolated virgal ossicle series and ambulacrals in oral view. (*f*) Life reconstruction of Cantabrigiaster fezouataensis. Artwork by Marguerite Lardanchet. Abbreviations: am, ambulacral ossicles; cr, carinal region ossicles (preserved on the aboral surface); map, mouth angle plates; pr, perradial ridge; ps, podial suture; tb, transverse bar; vr, virgal ossicles.

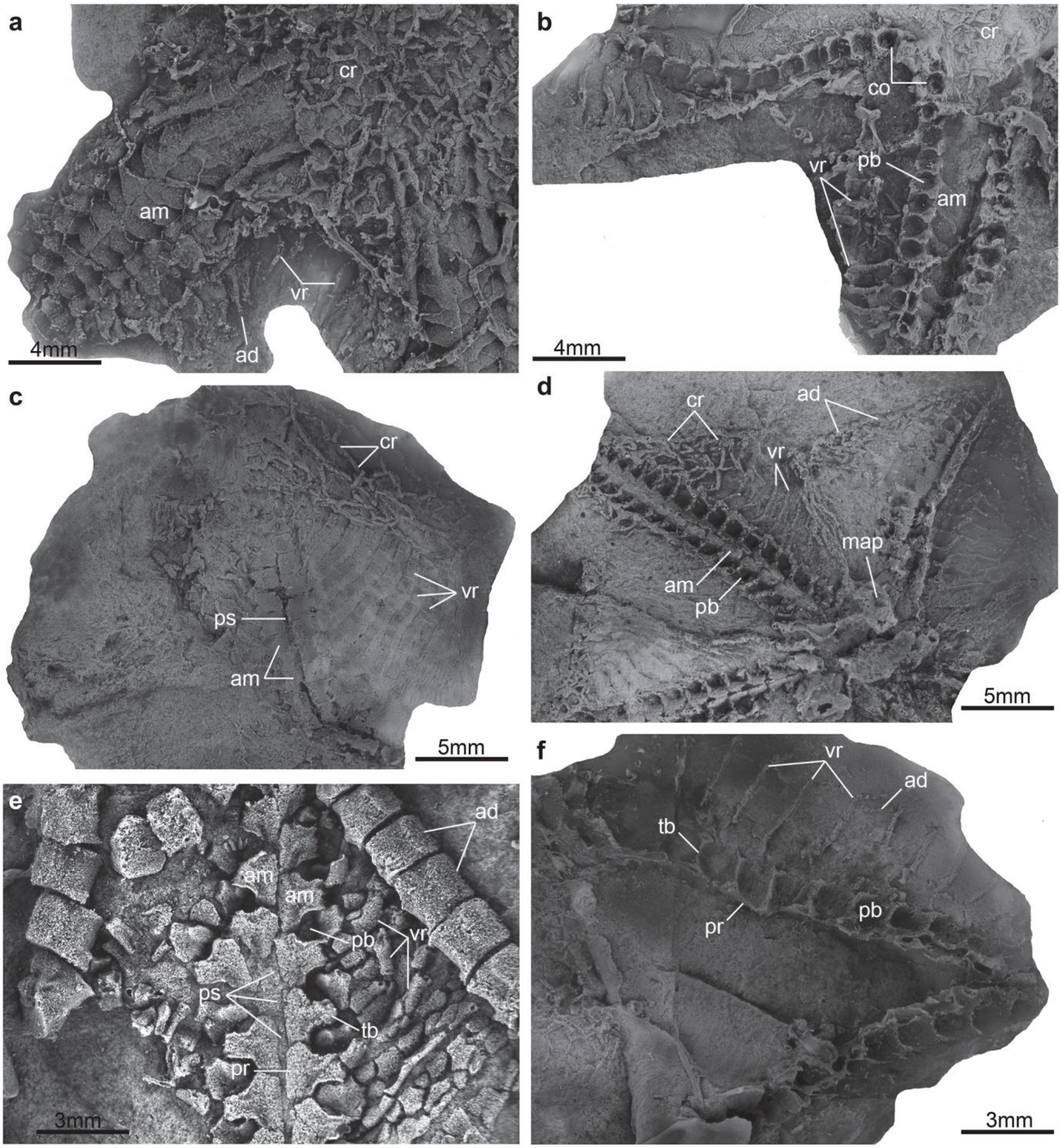

Figure S5. Somasteroid asterozoan diversity. All latex molds. (*a*) *Chinianaster levyi*, UCBL-FSL 168 691, aboral view. (*b*) *Chinianaster levyi*, UCBLFSL 168 691, lectotype oral and aboral view. Lower Ordovician of Montagne Noire (*c*) *Villebrunaster thorali*, UCBL-FSL 168 693, aboral view. Lower Ordovician of Montagne Noire (*d*) *Villebrunaster thorali*, UCBL-FSL 168 673, holotype oral view. Lower Ordovician of Montagne Noire (*e*) *Archegonaster pentagonus*, NM-P L38715, oral view. Middle Ordovician of Bohemia (*f*) *Thoralaster spiculiformis*, UCBL-FSL 168 697, oral view Lower Ordovician of Montagne Noire. Abbreviations: am, ambulacral ossicles; ad, adambulacral ossicles; co, circumoral ossicles; cr, carinal region ossicles; map, mouth angle plates; tb, transverse bar; pb, podial basins; pr, perradial ridge; ps, perradial suture; vr, virgal ossicles.

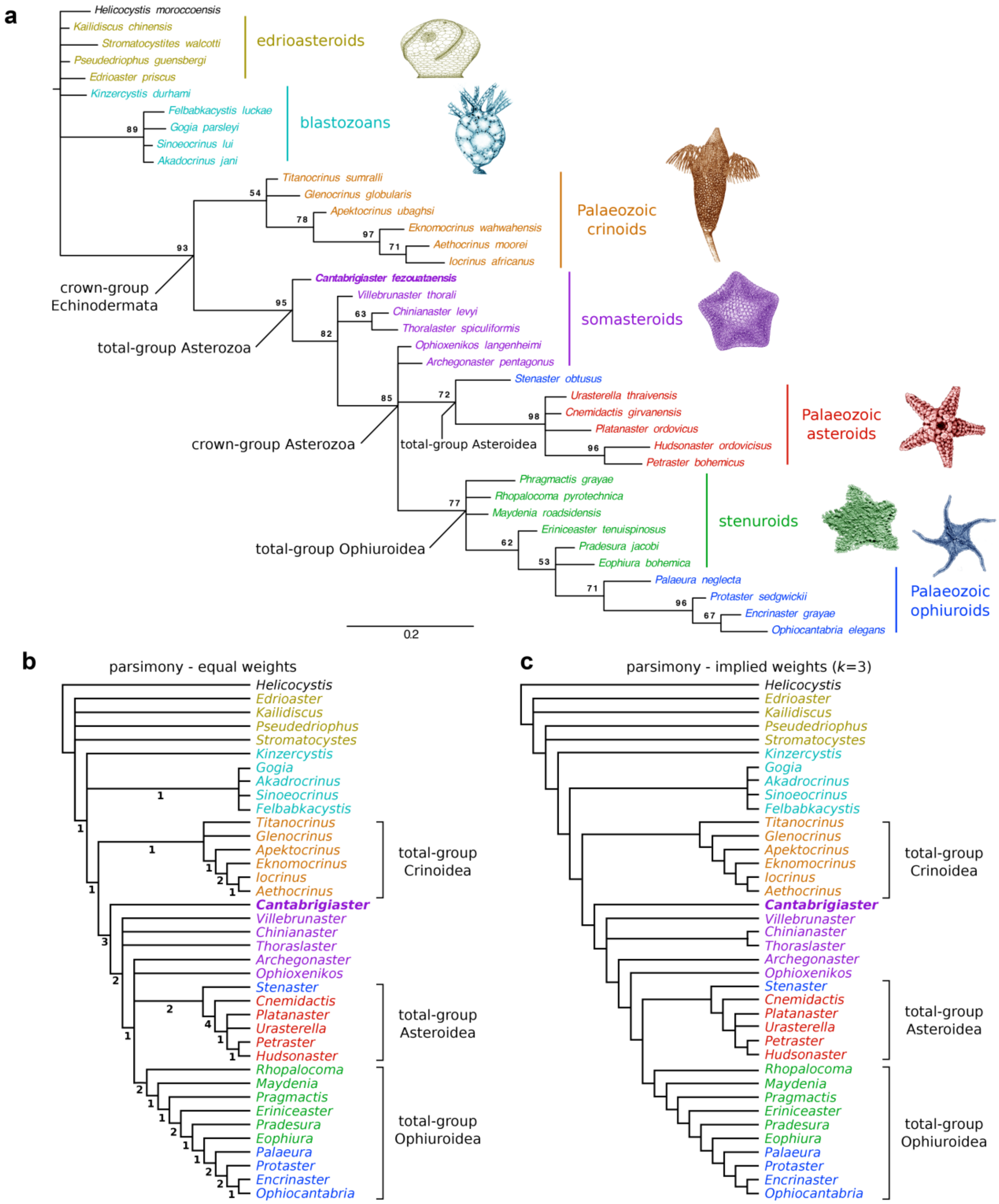

Figure S6. Comparison between results of Bayesian and parsimony-based phylogenetic analyses. (*a*) Consensus tree resulting from Bayesian analysis; numbers above nodes denote posterior probability. (*b*) Strict consensus of four most parsimonious trees (145 steps, CI=0.566, RI=0.819) recovered using parsimony under equal weights; numbers below nodes denote Bremer support values. (*c*) Single most parsimonious tree (CI=0.558, RI=0.813) recovered using parsimony under implied weights (*k*=3)

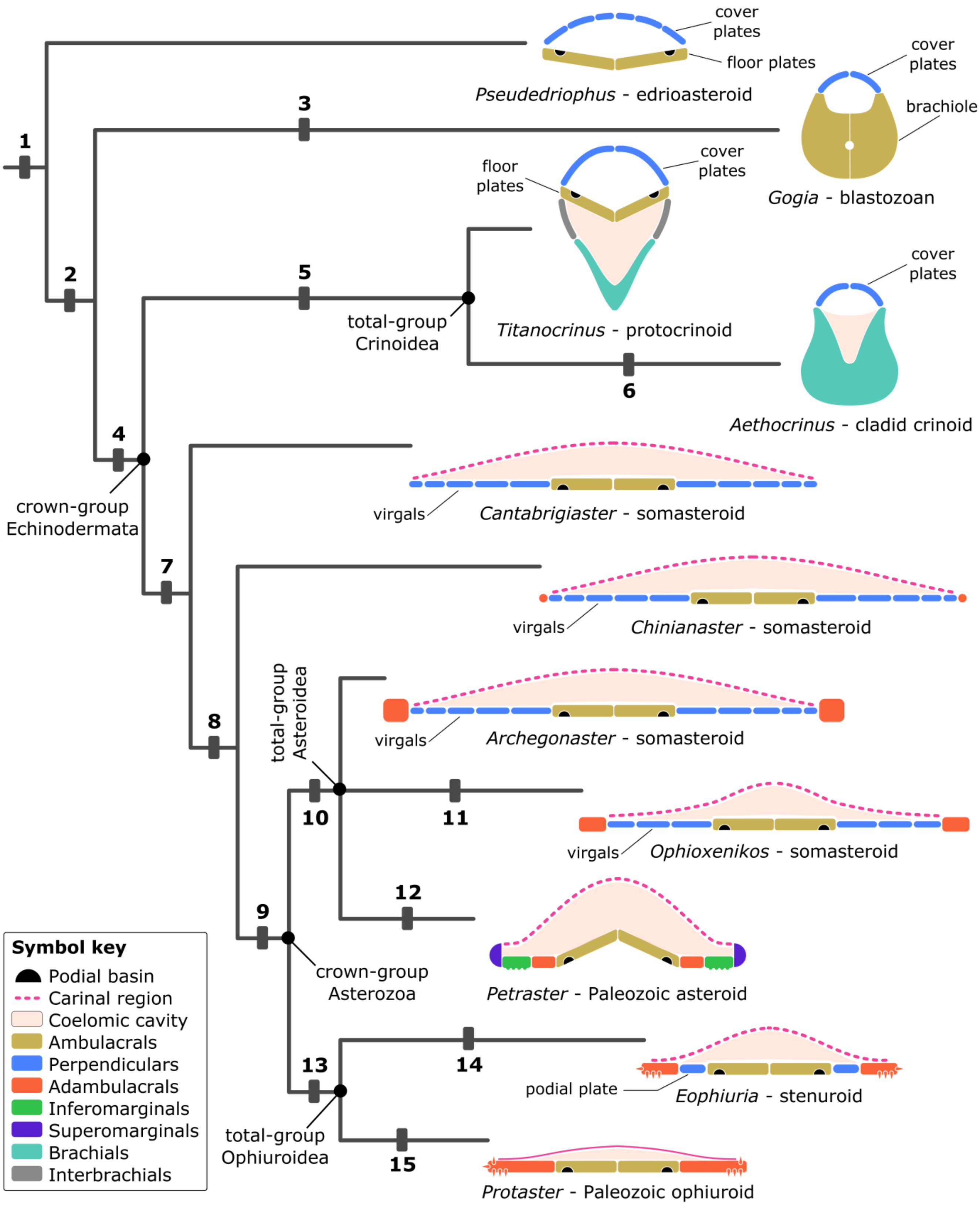

Figure S7. Homology of ossicle series and major character transformations during the early evolutionary history of crown group Echinodermata. Simplified tree topology based on the results of the phylogenetic analyses (electronic supplementary material, figure S5). Diagrams illustrate a transverse section of the ambulacral region. Major evolutionary innovations: *1*, zigzag-shaped perradial suture, calcified and flattened biserial ambulacrals with podial basins, ambulacral ossicles out of phase, perpendicular ossicles expressed as cover plates, oral region facing upwards, 2-1-2 oral symmetry, ossified circumoral ossicles, stalked habitus, body encased in the imperforate extraxial lateral wall body wall capsule composed of irregular plates; *2,* feeding appendages feeding appendages; *3*, ambulacrals modified into brachioles, loss of podial basins; *4*, straight perradial suture, body wall tissue and coelomic cavity extend distally into appendages; *5*, origin of arm brachials, interbrachials separate ambulacrals from brachials, appendages emerge gradually from the imperforate extraxial lateral wall body wall capsule; *6*, loss of calcified ambulacral floor plates, loss of ossified circumoral ossicles, imperforate extraxial lateral wall body wall capsule composed of plates with regular size and shape; *7*, wide perradial groove, perpendicular series expressed as multiple virgal ossicles, centrally positioned transverse bar on ambulacrals, oral-region facing towards substrate, pentarradial oral symmetry, enlarged circumoral ossicles, loss of the imperforate extraxial lateral wall body wall capsule, origin of aboral carinal region; *8*, origin of adambulacral series on abaxial body margins, adambulacrals expressed as small bead-like ossicles; *9*, well-developed adambulacral ossicles, narrow perradial groove; *10*, adambulacrals block-like or rectangular; *11,* perpendicular series consist of reduced number of virgal ossicles (convergent with 13); *12,* ambulacral ossicles opposite to each other, origin of inferomarginals and superomarginals, complete loss of perpendicular series ossicles (convergent with 15); *13*, perpendicular series consist of reduced number of virgal ossicles (convergent with 11); *14*, perpendiculars series expressed as single podial plate; *15*, proximally positioned transverse bar, complete loss of perpendicular series ossicles (convergent with 12).

Supplementary Tables (S1 and S2)

Table S1. Examined Specimens

Table S2. EAT Homologies**.** Source of Data: Mooi & David 2008

Supplementary Datasets (S1 and S2)

Dataset S1. Character matrix for phylogenetic analysis .xls format.

Dataset S2. Character matrix for phylogenetic analysis in nexus format.