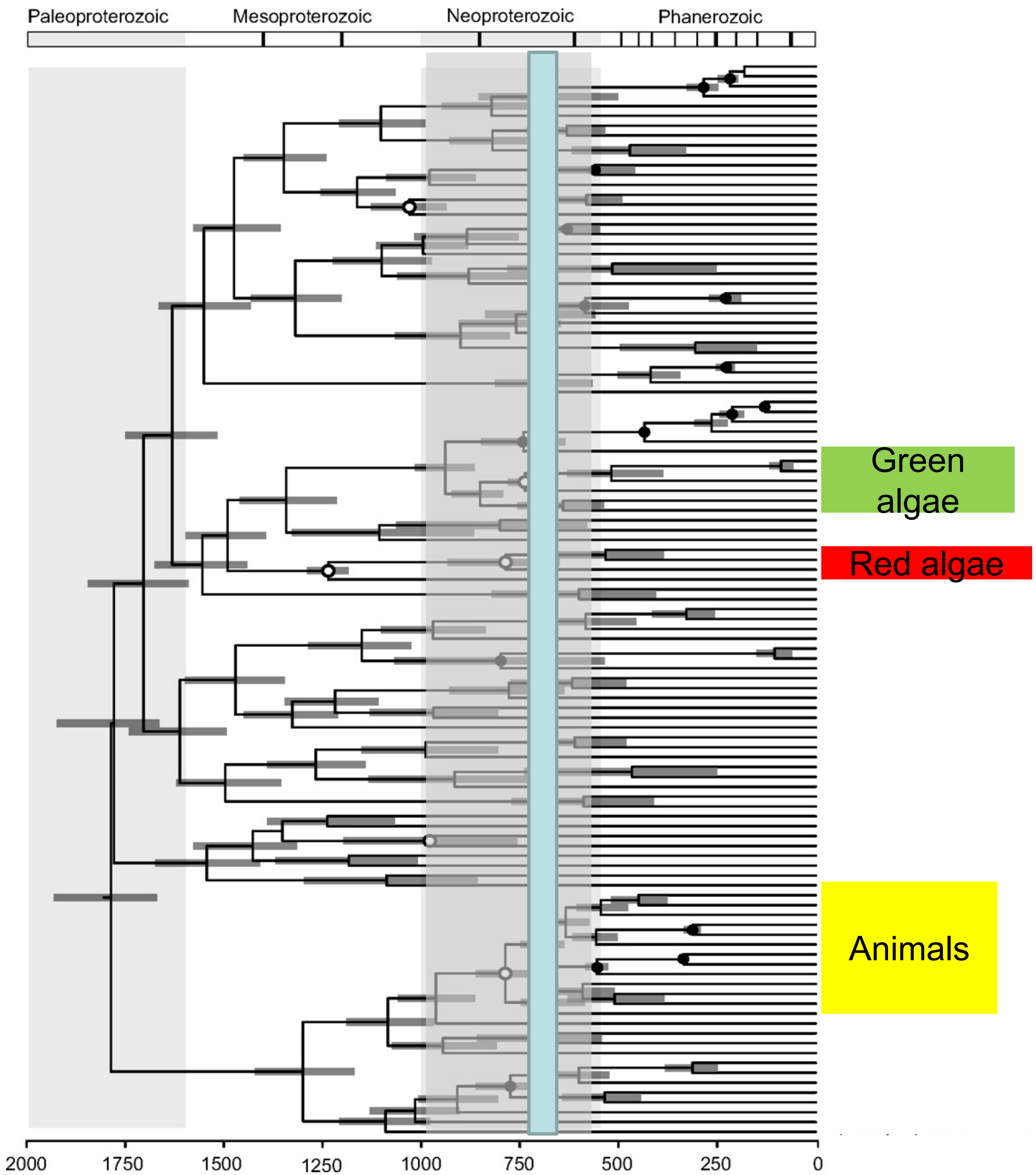
THE RISE OF ANIMALS

Concepts: molecular clock, timing of the rise of animals, fossil evidence for early animals, Ediacaran fauna, trace fossils, body plans, Cambrian radiation

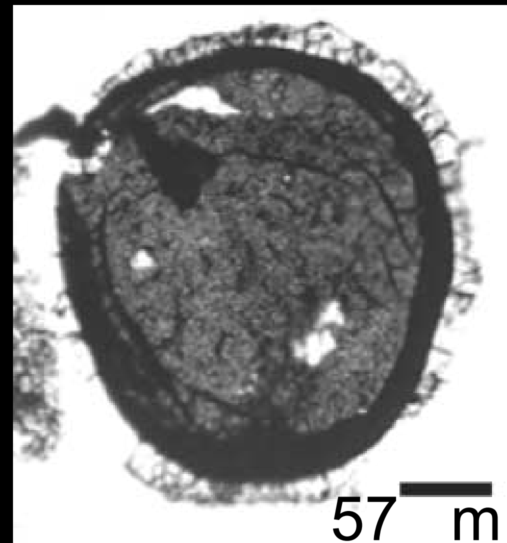
Reading: Prothero 206-221, Marshall review, Narbonne 2005 Annu. Rev.

EVOLUTION OF MODERN EUKARYOTES

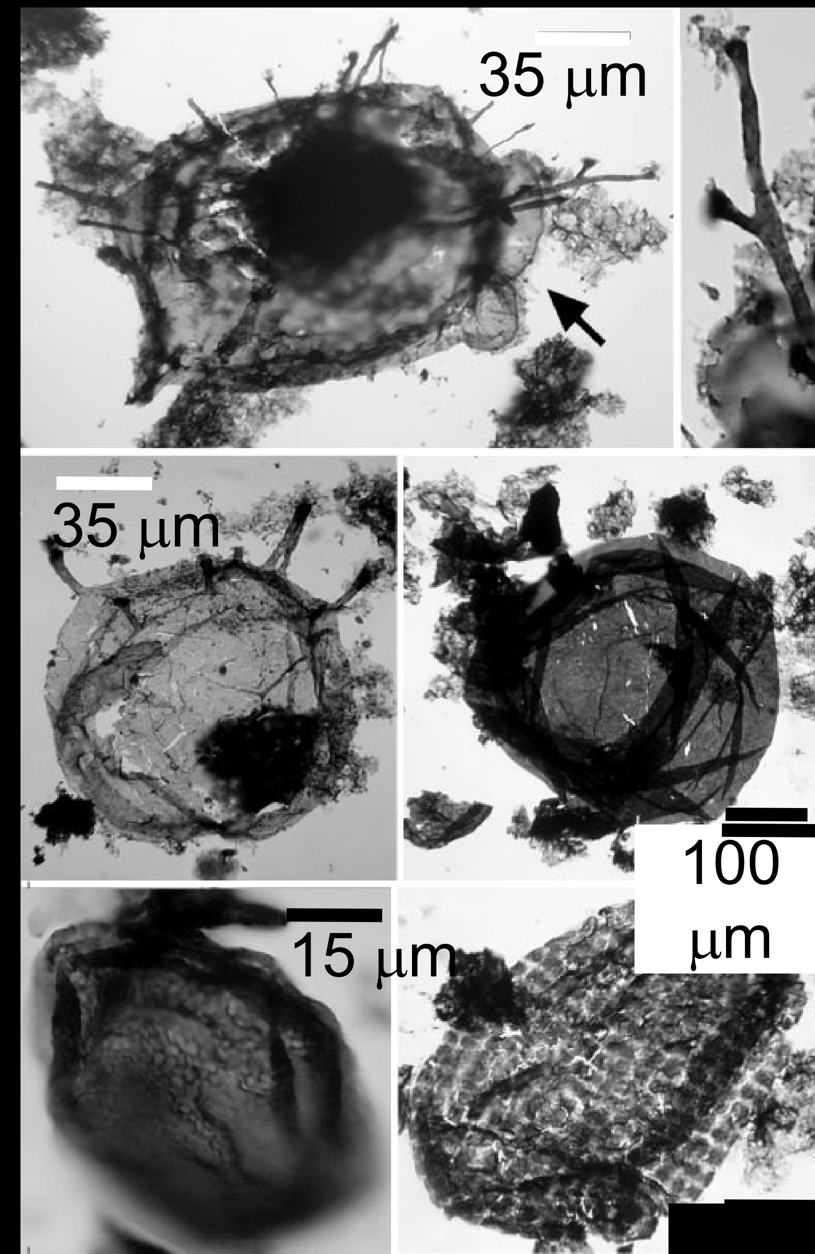


Source: Parfrey, L.W. et al. "Estimating the Timing of Early Eukaryotic Diversification with Multigene Molecular Clocks." *Proceedings of the National Academy of Sciences* 108, no. 33 (2011): 13624-9.

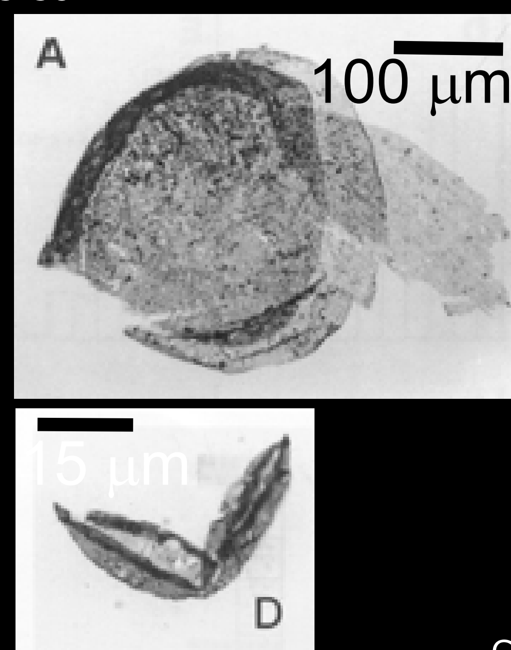
EUKARYOTIC FOSSIL RECORD BEFORE ~ 1.2 BILLION YEARS AGO



Knoll et al. 2006



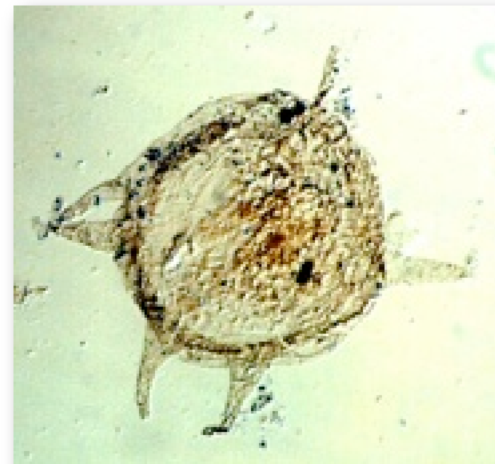
Javaux et al. 2001

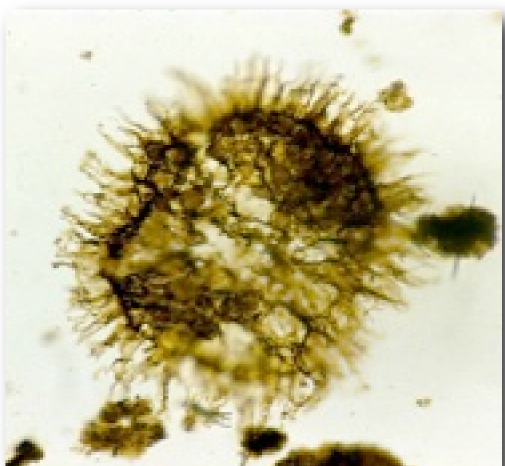


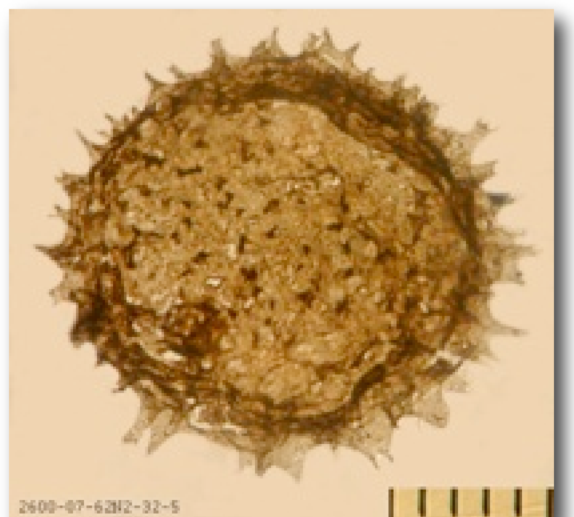
Butterfield and Chandler, 1992

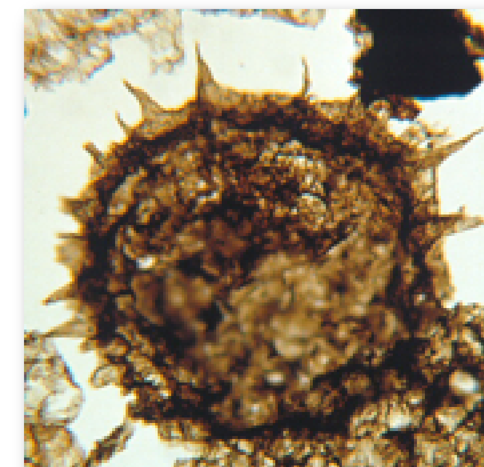
ACRITARCH *ákritos* Greek for *confused*

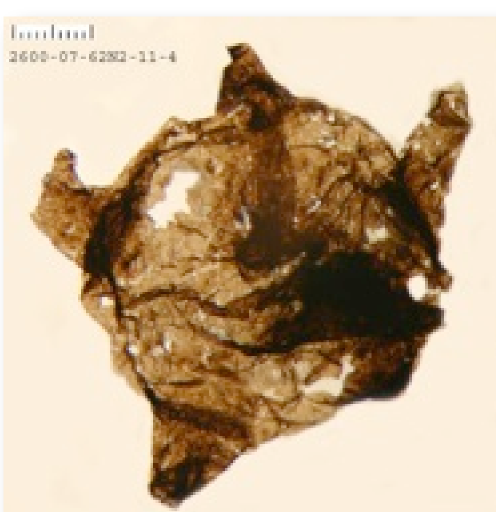
Most diverse and abundant record of eukaryotes in Ediacaran

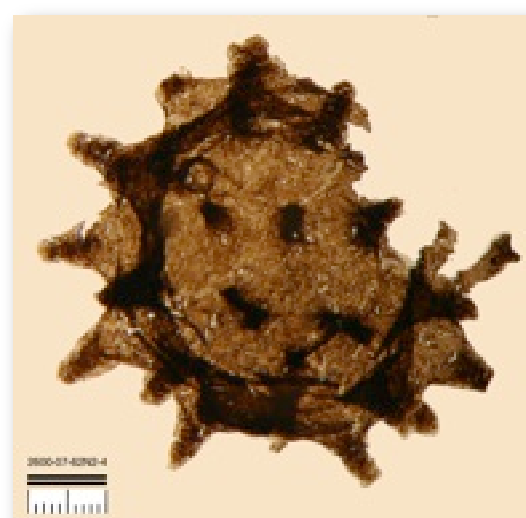




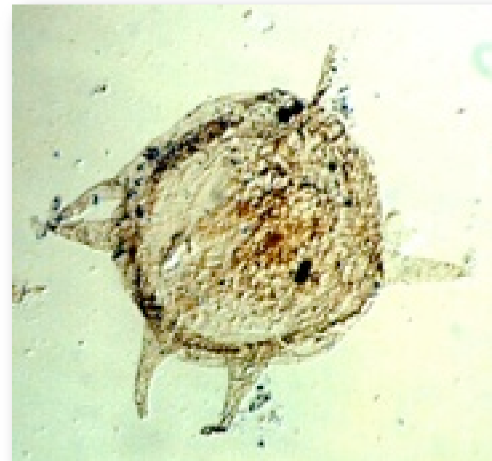


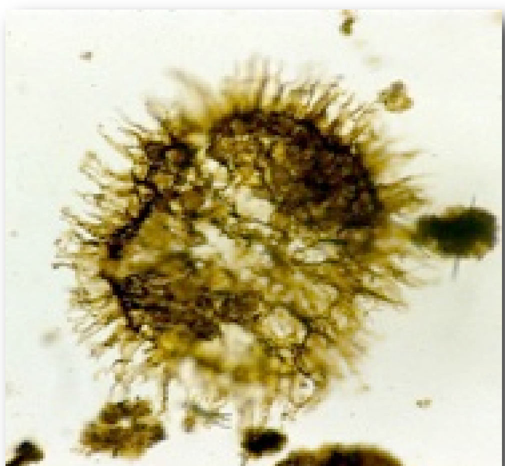


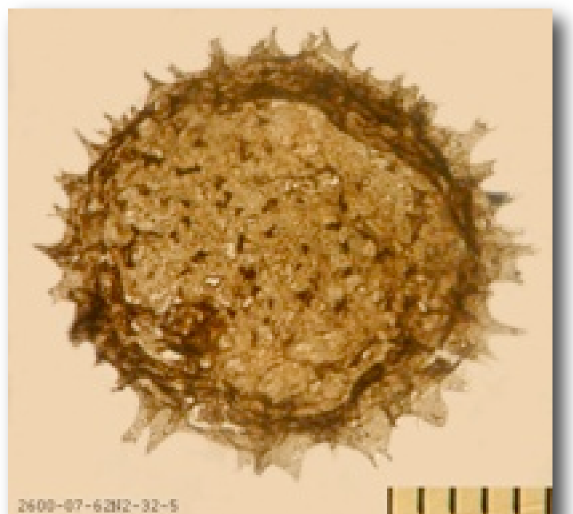


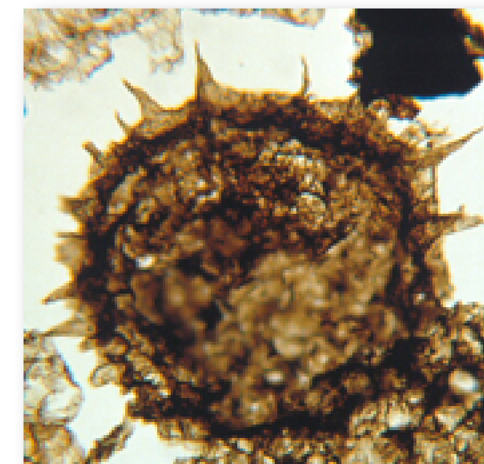


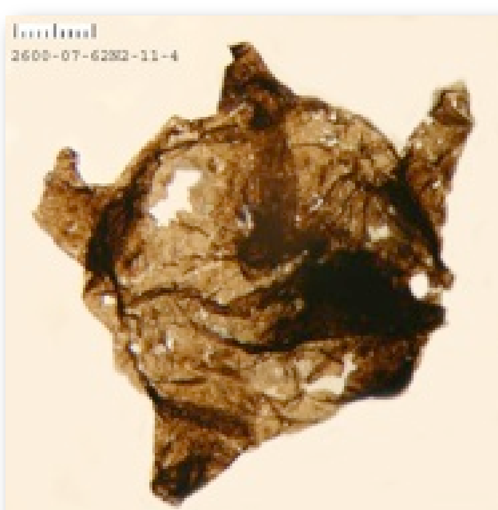
So what ARE these things?

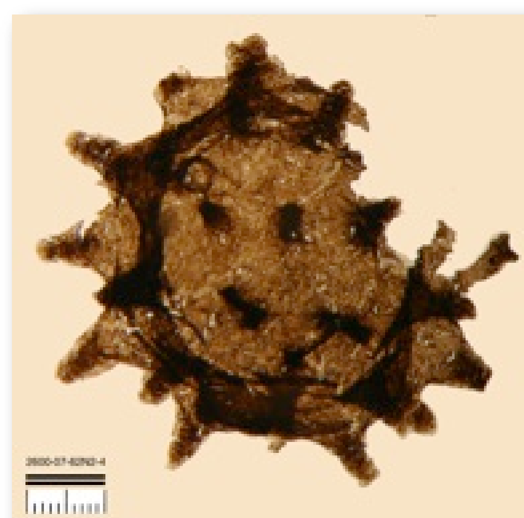




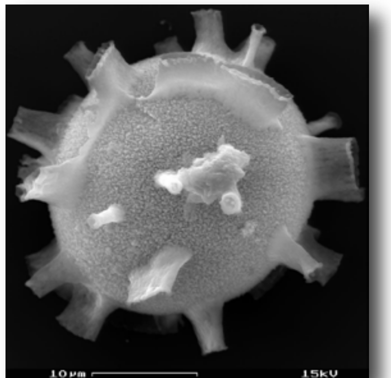


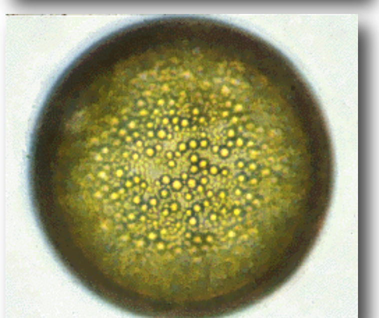


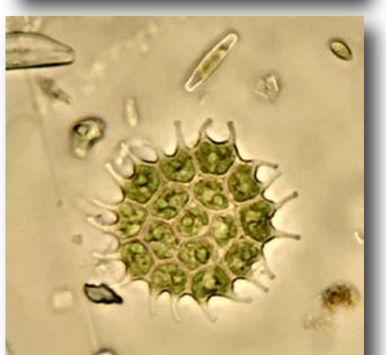


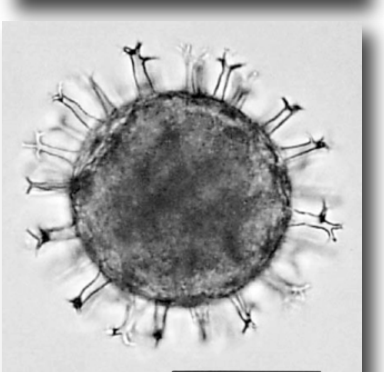


Modern groups that create structures that could potentially fossilize



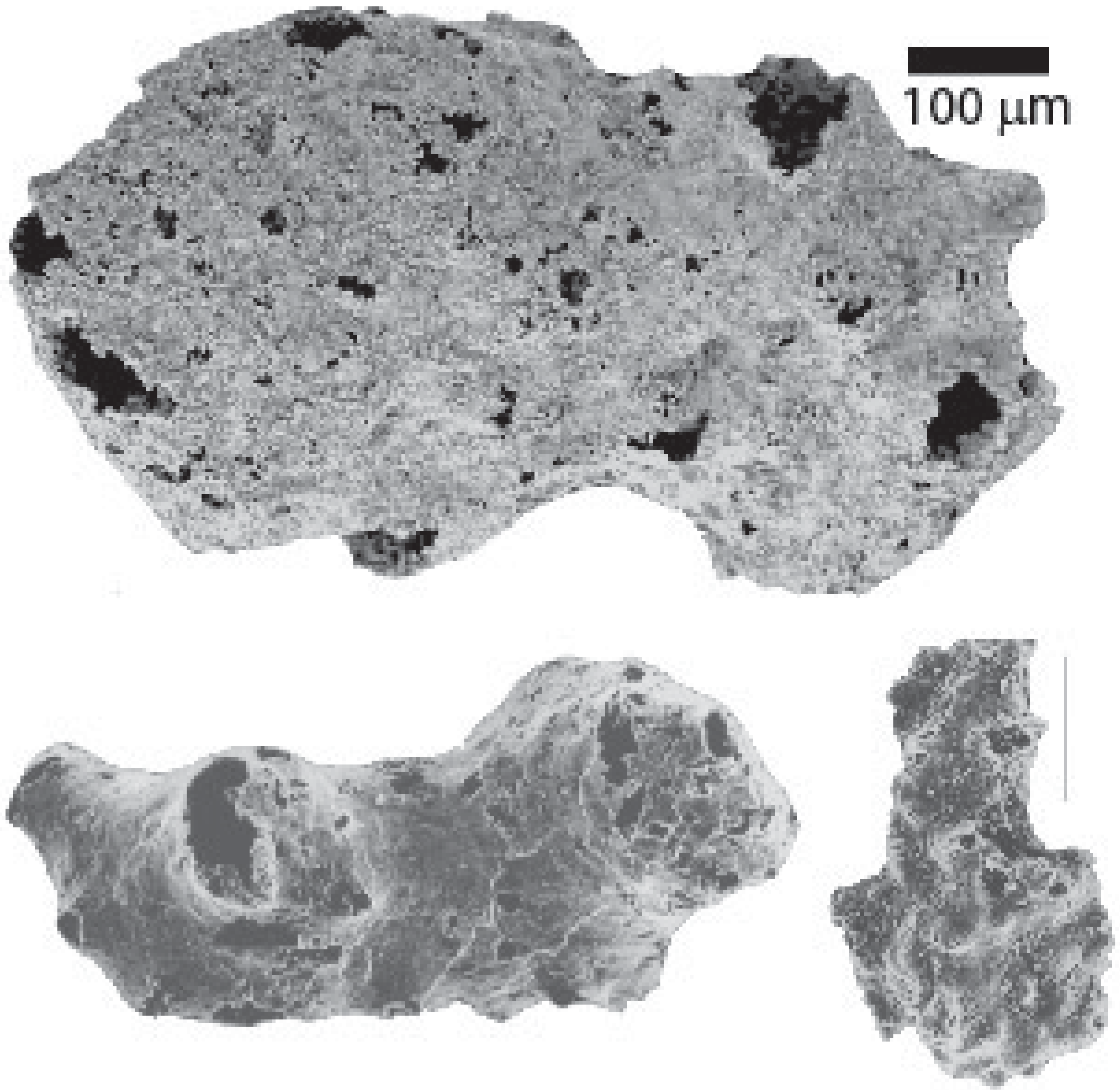




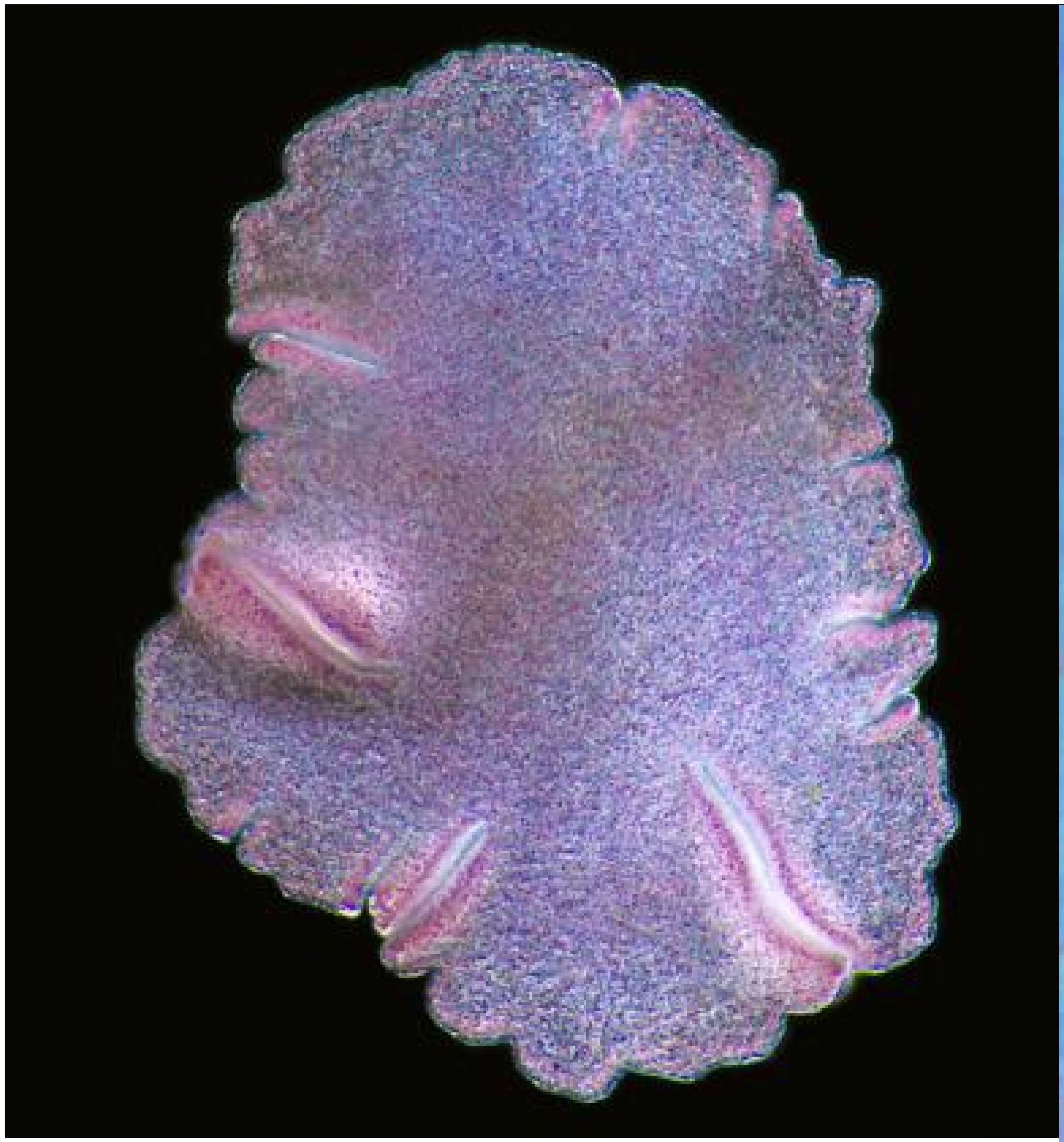


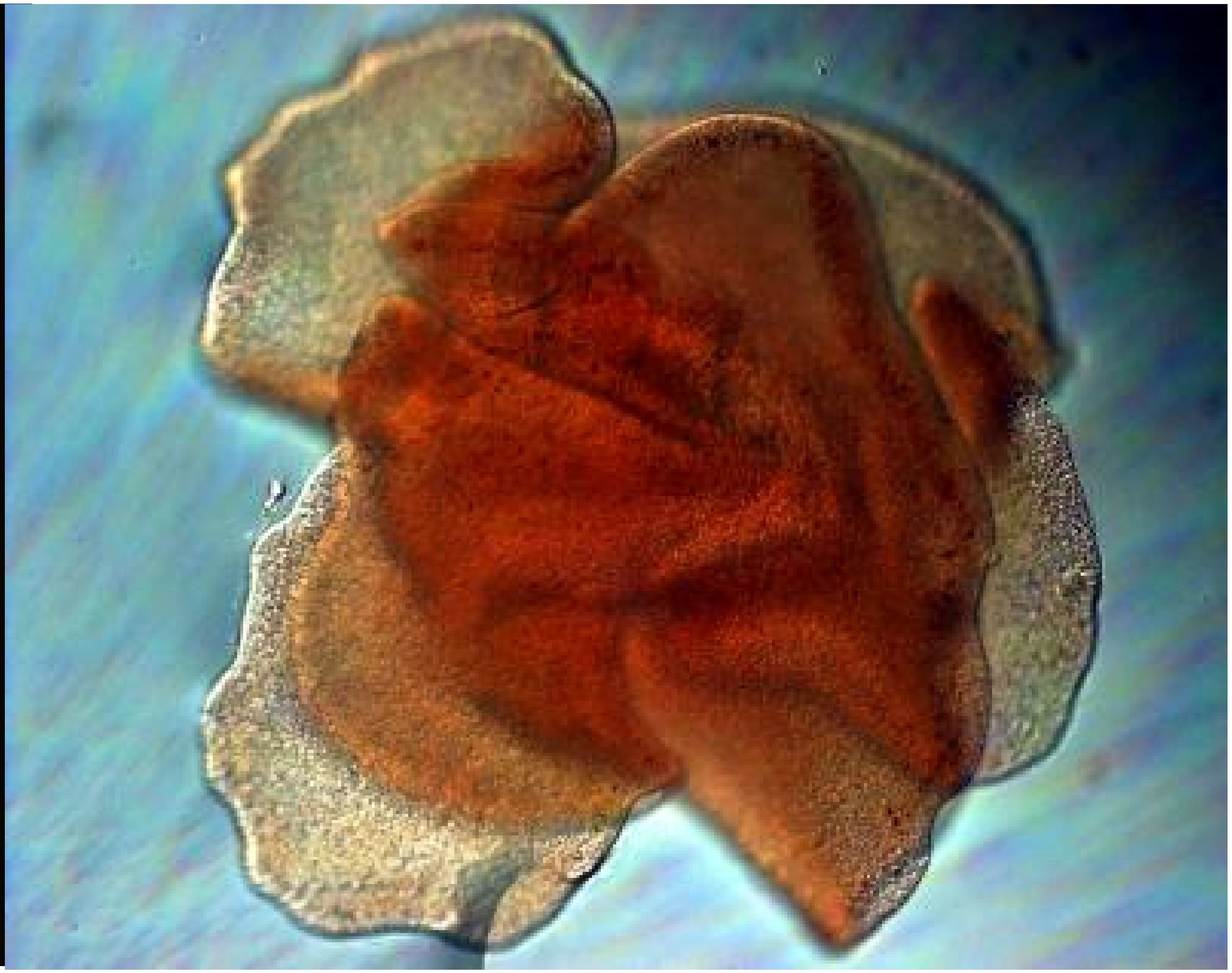
- Dinoflagellate cysts
- Prasinophyte green algae reproductive structures called phycomata
- Green algal resting cysts
- Animal (metazoan) diapause / resting eggs

FOSSILS FROM 760-635 Ma NAMIBIAN CARBONATES



Source: Prave, A. R., et al. "The First Animals: Ca. 760-million-year-old Sponge-like Fossils from Namibia." *S Afr J Sci* 108, no. 1/2 (2012).

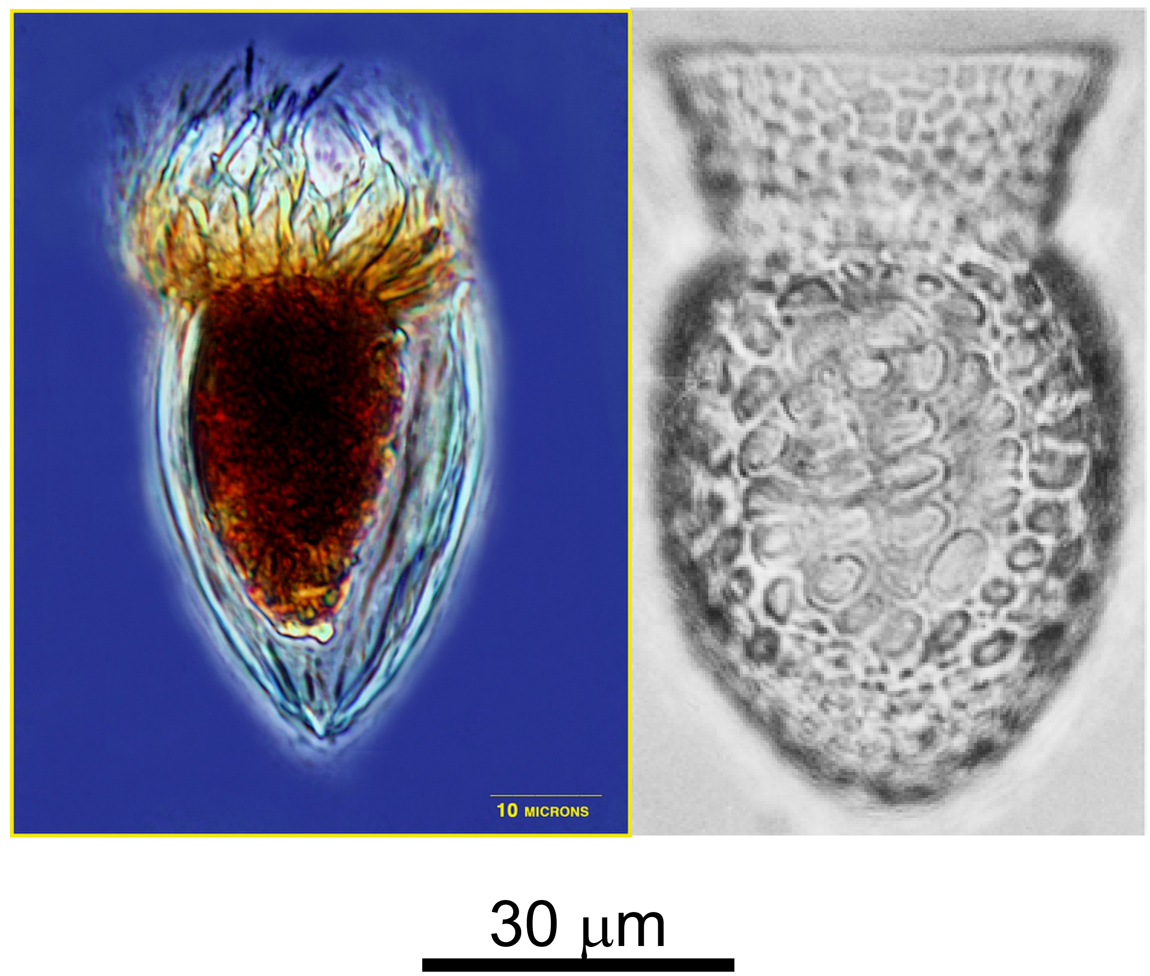




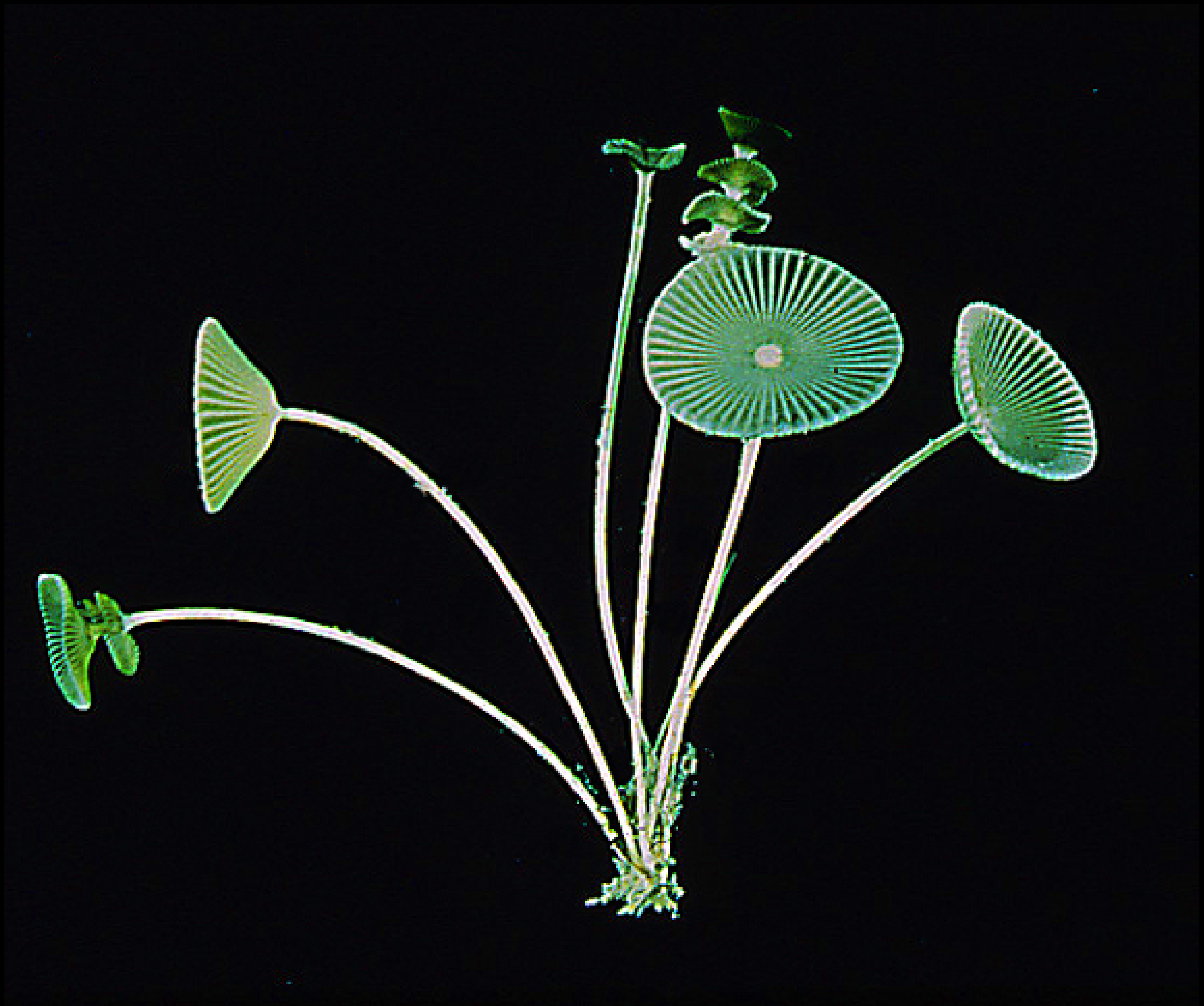
http://diertjevandedag.classy.be/eenvoudige%20dieren/plakdiertjes.htm

Courtesy of Stephen Friedt. Used with permission.

http://en.wikipedia.org/wiki/Hydra_%28genus%29



Source: Bosak, T., et al. "Putative Cryogenian ciliates from Mongolia." *Geology* 39, no. 12 (2011): 1123-26.



www.coexploration.org/bbsr/coral/assets/images/acetabularia.jpg

Courtesy of Absolutecaliber on wikipedia. Photograph in the public domain.

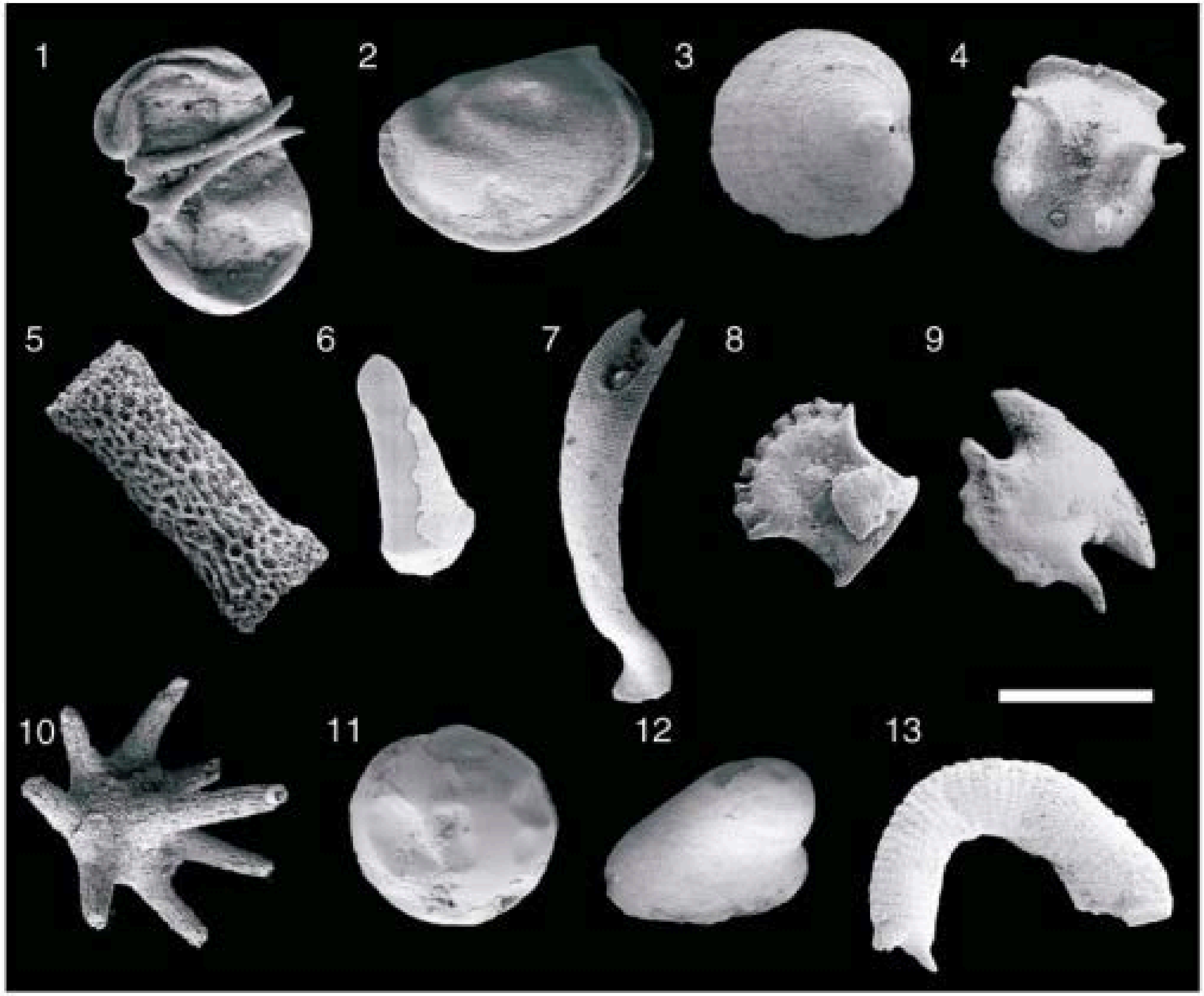
Courtesy of Naples Sea Shell Company. Used with permission.

http://www.leeds.ac.uk/ruskinrocks/Geology%20pictures%20and%20files/Tabulate%20coral.jpg

Courtesy of Florent Charpin. Used with permission.

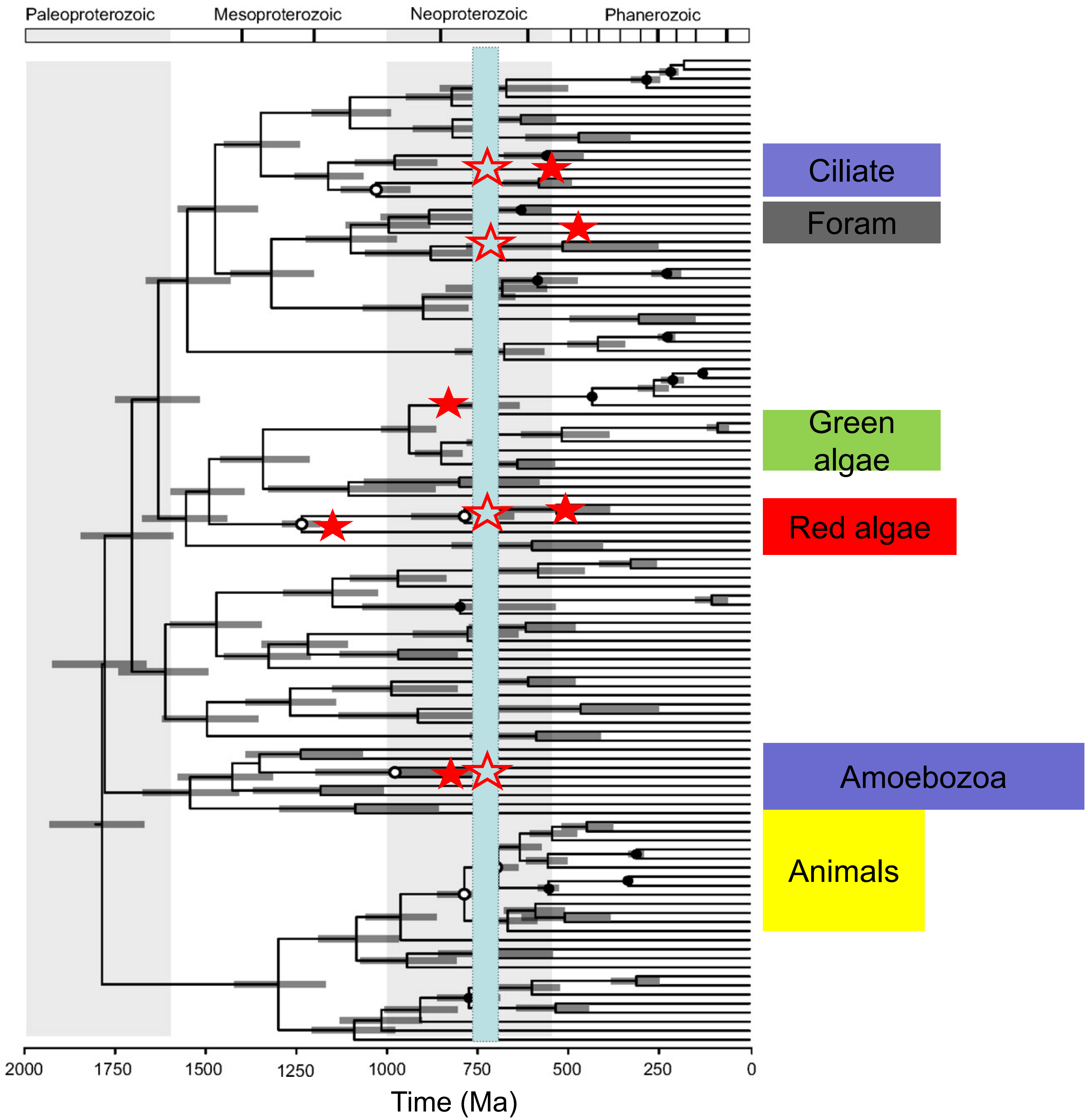
http://reefguide.org/carib/pixhtml/crustosecorallinealgae1.html

Courtesy of Phoebe Cohen. Used with permission.

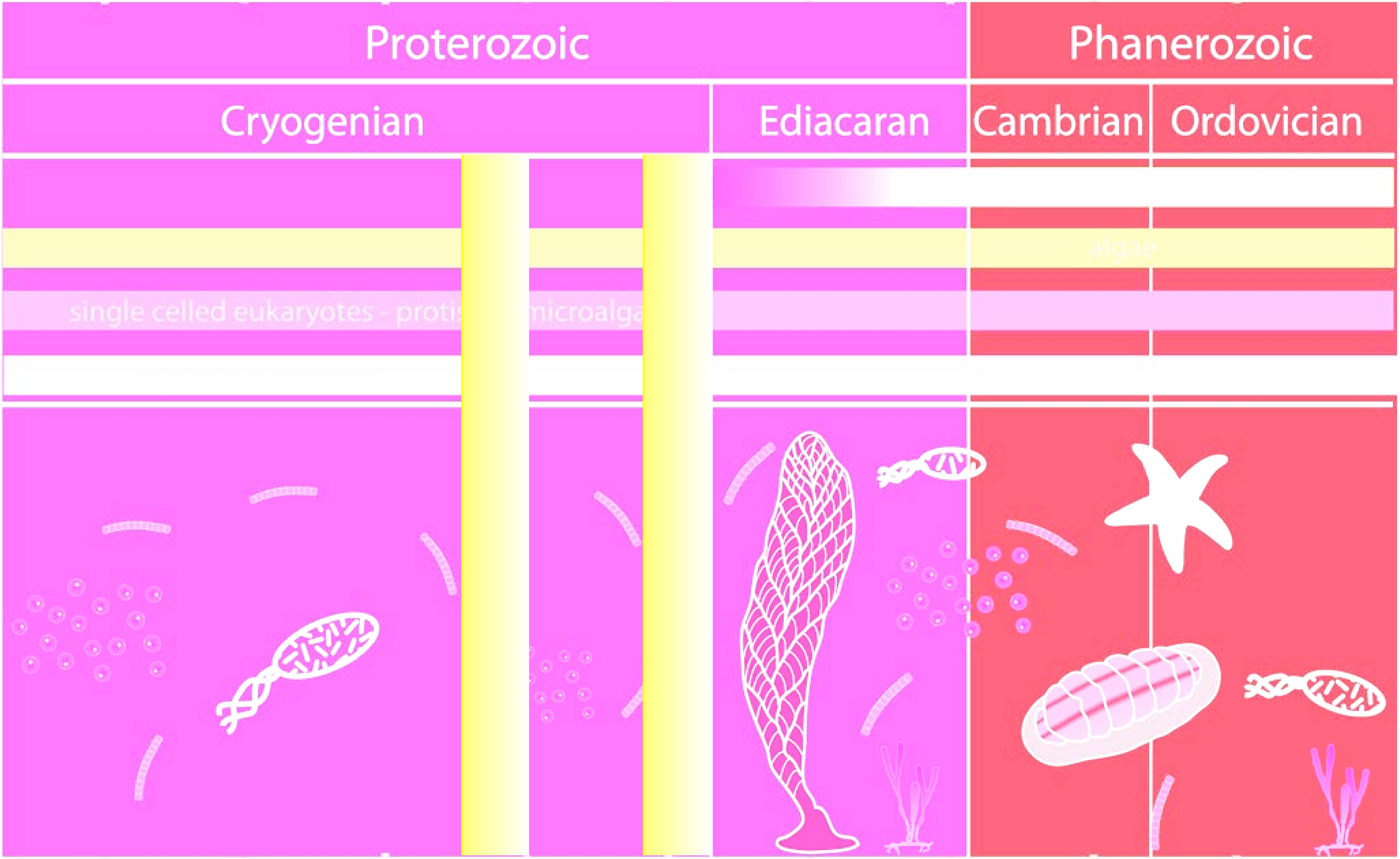


(Porter 2011)

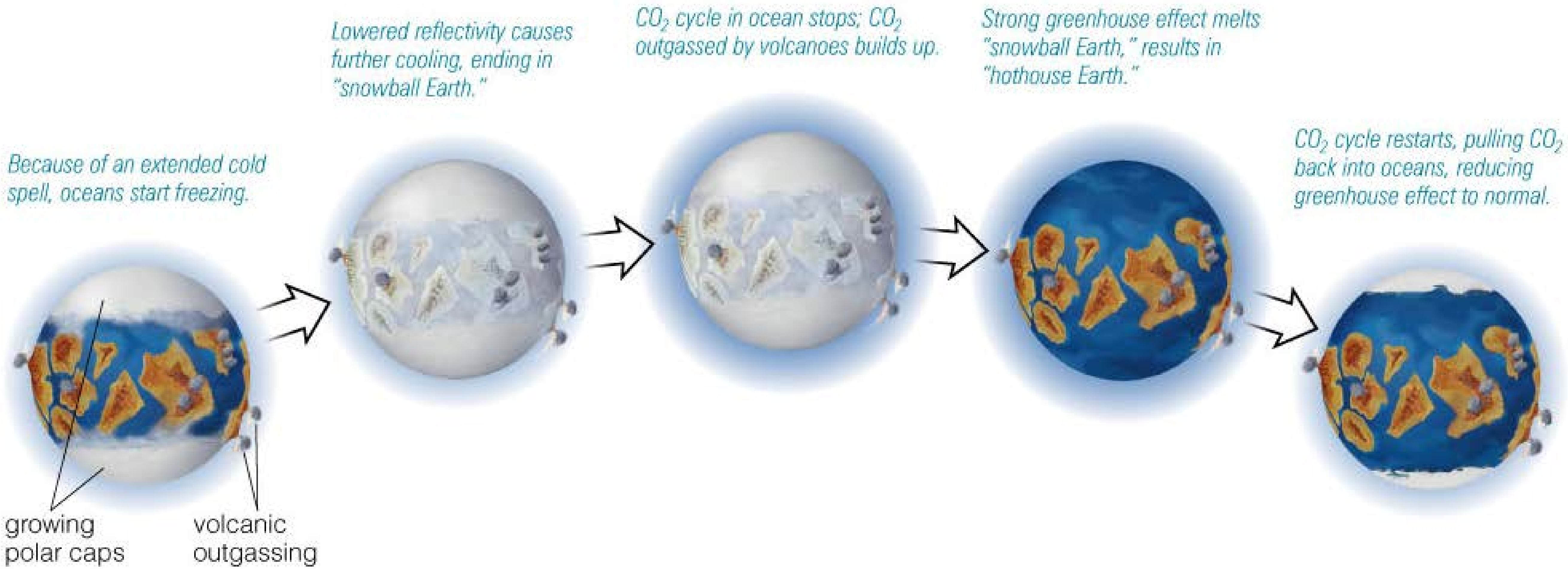
Source: Porter, Susannah M. "Halkieriids in Middle Cambrian Phosphatic Limestones from Australia." *Journal of Paleontology* 78, no. 3 (2004).



Source: Parfrey, L.W. et al. "Estimating the Timing of Early Eukaryotic Diversification with Multigene Molecular Clocks." *Proceedings of the National Academy of Sciences* 108, no. 33 (2011): 13624-9.


Proterozoic
Phanerozoic
Cryogenian
Ediacaran
Cambrian
Ordovician
algae
single celled eukaryotes - protis
microalga

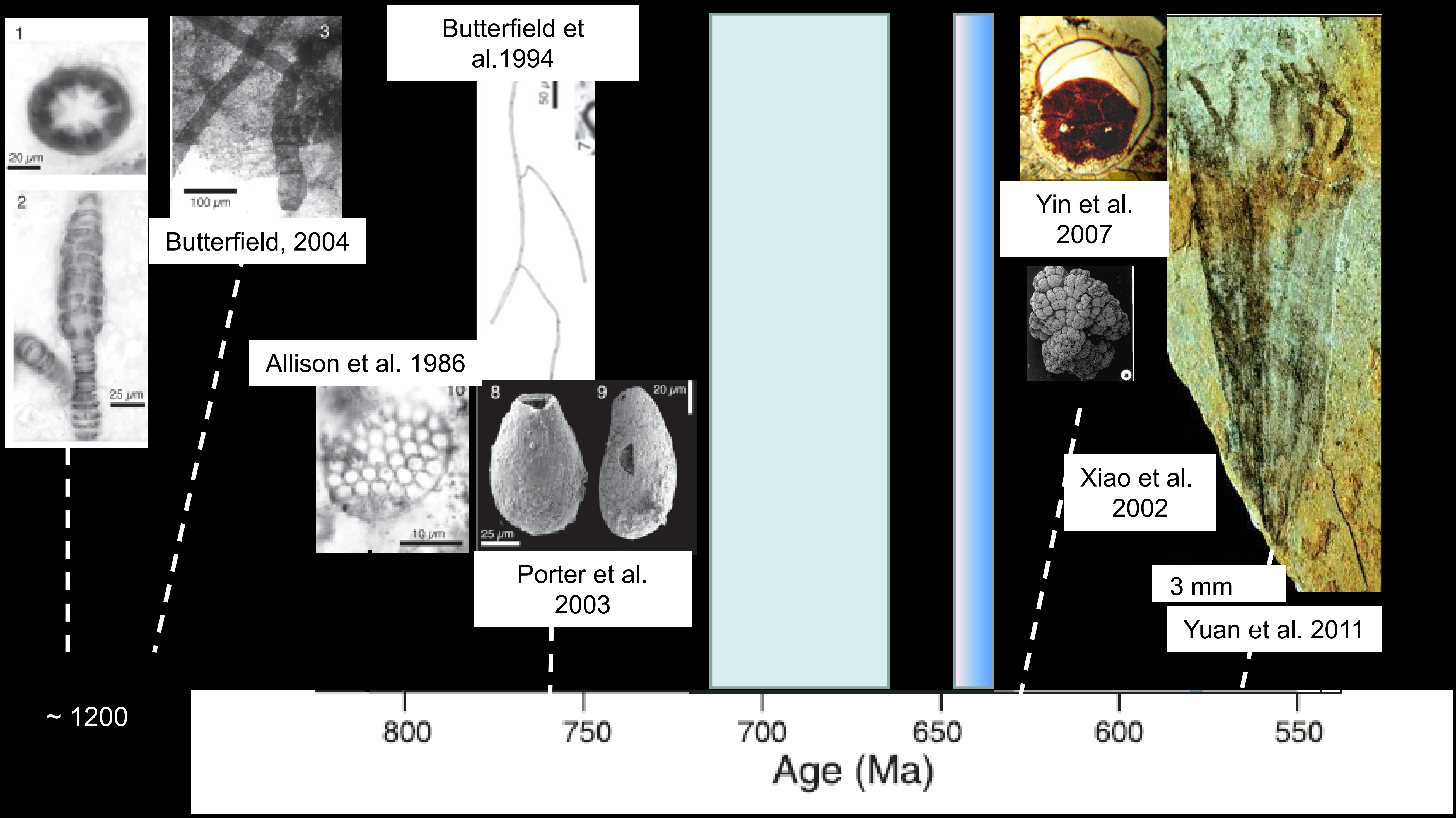
“Snowball Earth”



Q: what is our first ‘non-molecular fossil’ evidence of animals?

A: it’s complicated...

MORPHOLOGICALLY MODERN EUKARYOTES



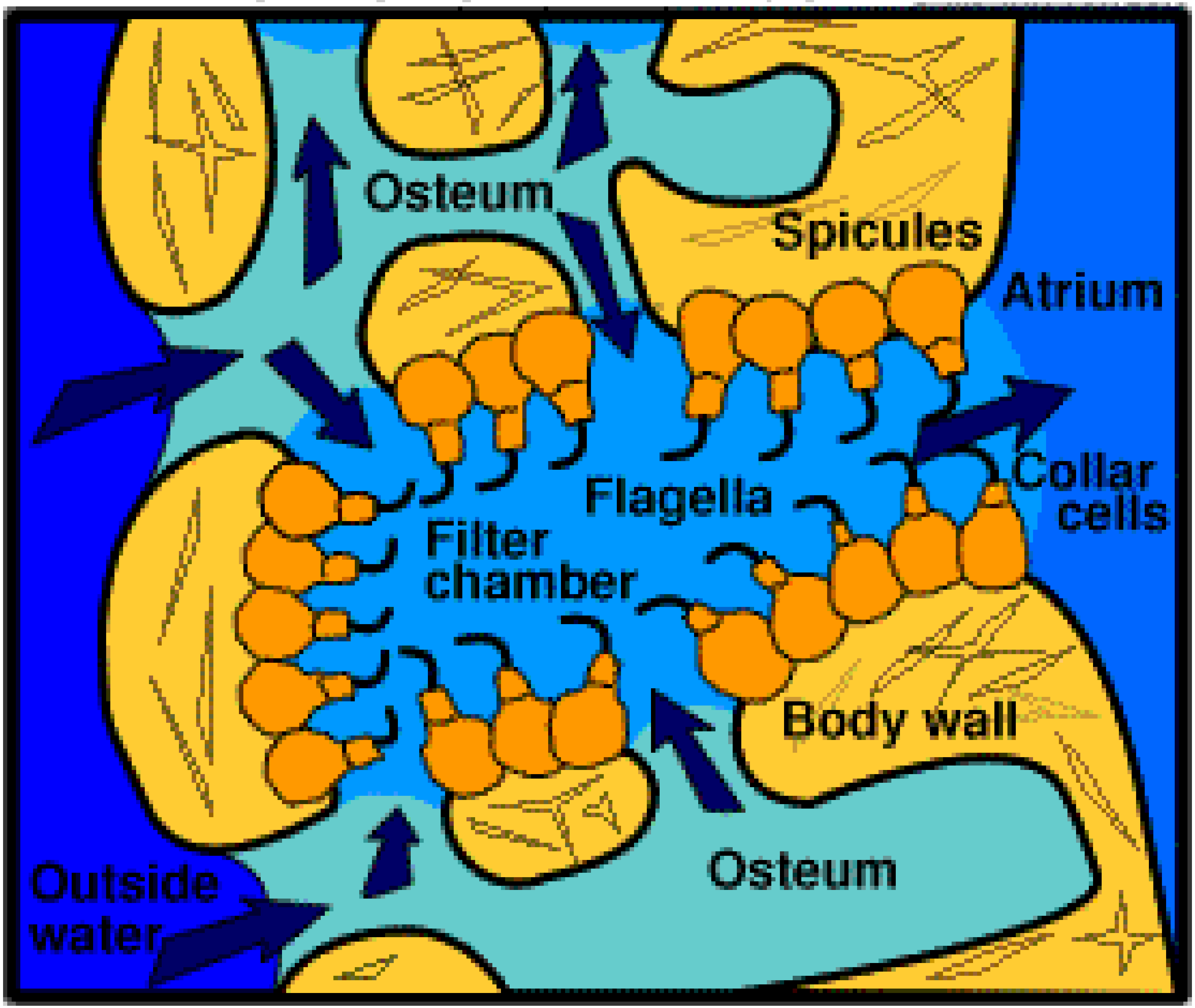
Complex Multicellularity

- Requires cell-cell communication
- Adhesion
- Soma and germ cells
- Differentiation

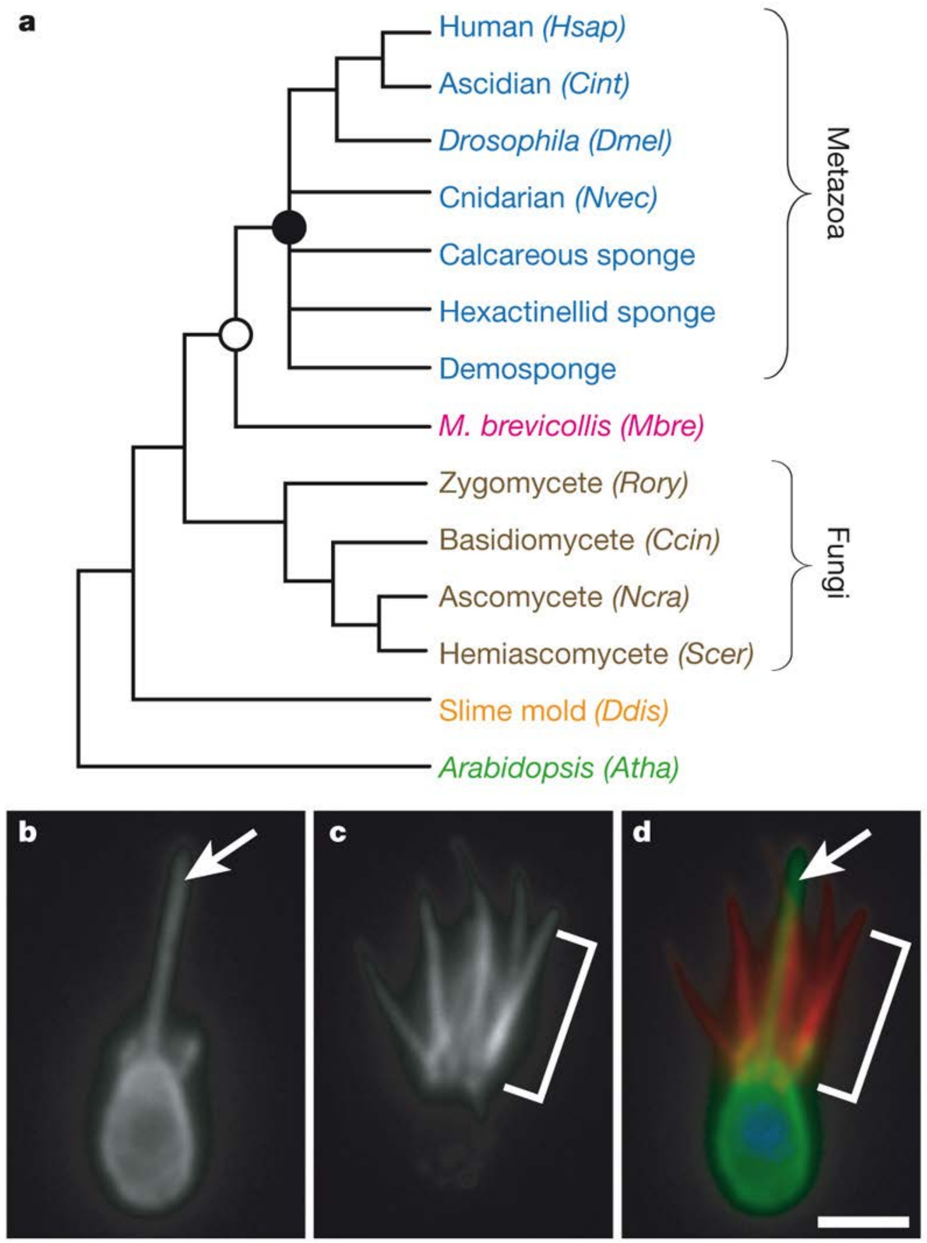
Why do it?

- Access resources better
- Predation / consumption
- Protection from predation

How a Sponge gets it's oxygen and food



Who did it first?



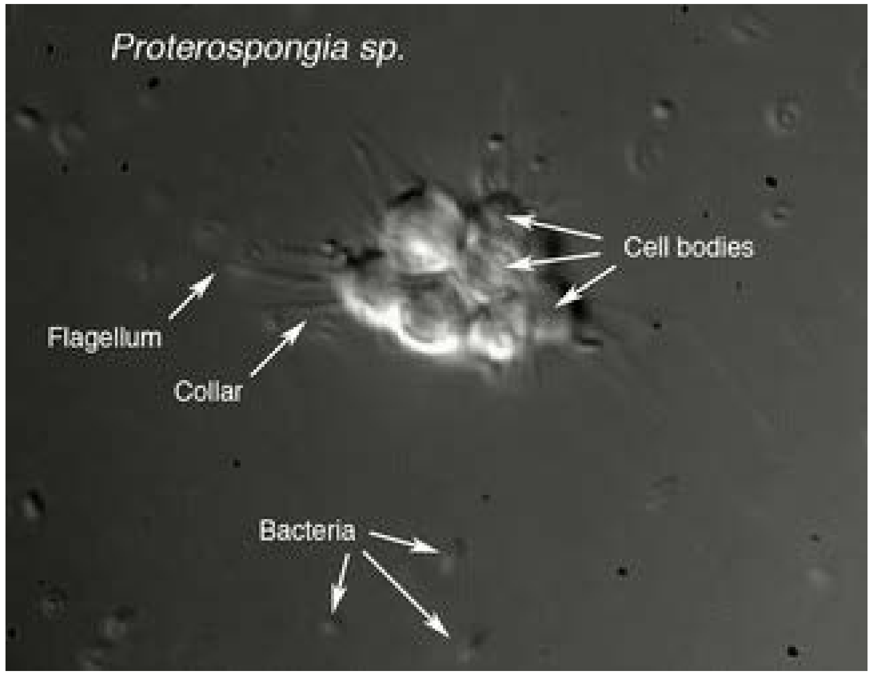
 Source: King, N. M., et al. "The Genome of the Choanoflagellate Monosiga Brevicollis and the Origin of Metazoans." *Nature* 451, no. 7180 (2008): 783-8.

From the following article:

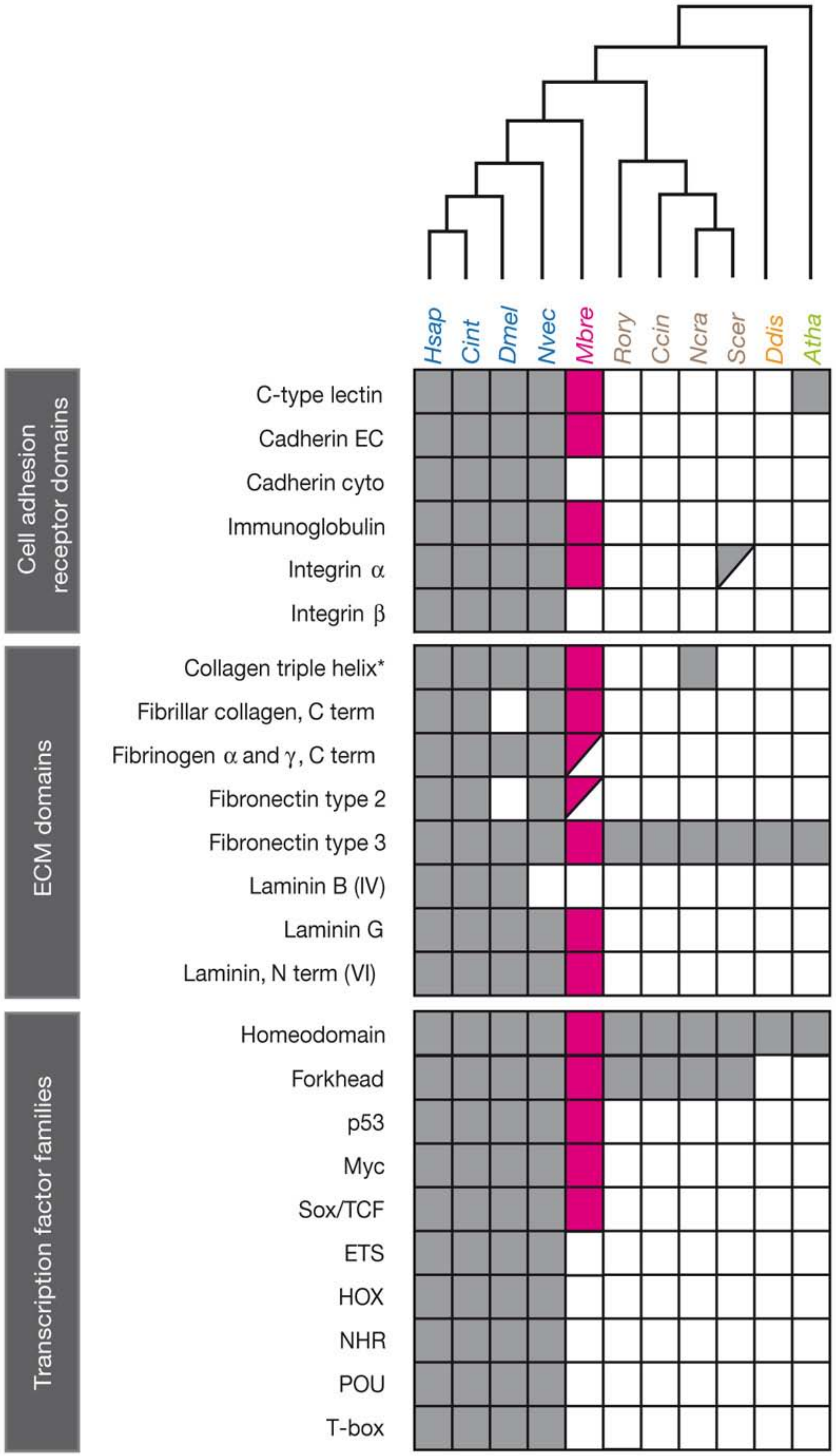
The genome of the choanoflagellate *Monosiga brevicollis* and the origin of metazoans

Nicole King, M. Jody Westbrook, Susan L. Young, Alan Kuo, Monika Abedin, Jarrod Chapman, Stephen Fairclough, Uffe Hellsten, Yoh Isogai, Ivica Letunic, Michael Marr, David Pincus, Nicholas Putnam, Antonis Rokas, Kevin J. Wright, Richard Zuzow, William Dirks, Matthew Good, David Goodstein, Derek Lemons, Wanqing Li, Jessica B. Lyons, Andrea Morris, Scott Nichols, Daniel J. Richter, Asaf Salamov, JGI Sequencing, Peer Bork, Wendell A. Lim, Gerard Manning, W. Todd Miller, William McGinnis, Harris Shapiro, Robert Tjian, Igor V. Grigoriev & Daniel Rokhsar

Nature **451**, 783-788(14 February 2008)
doi:10.1038/nature06617

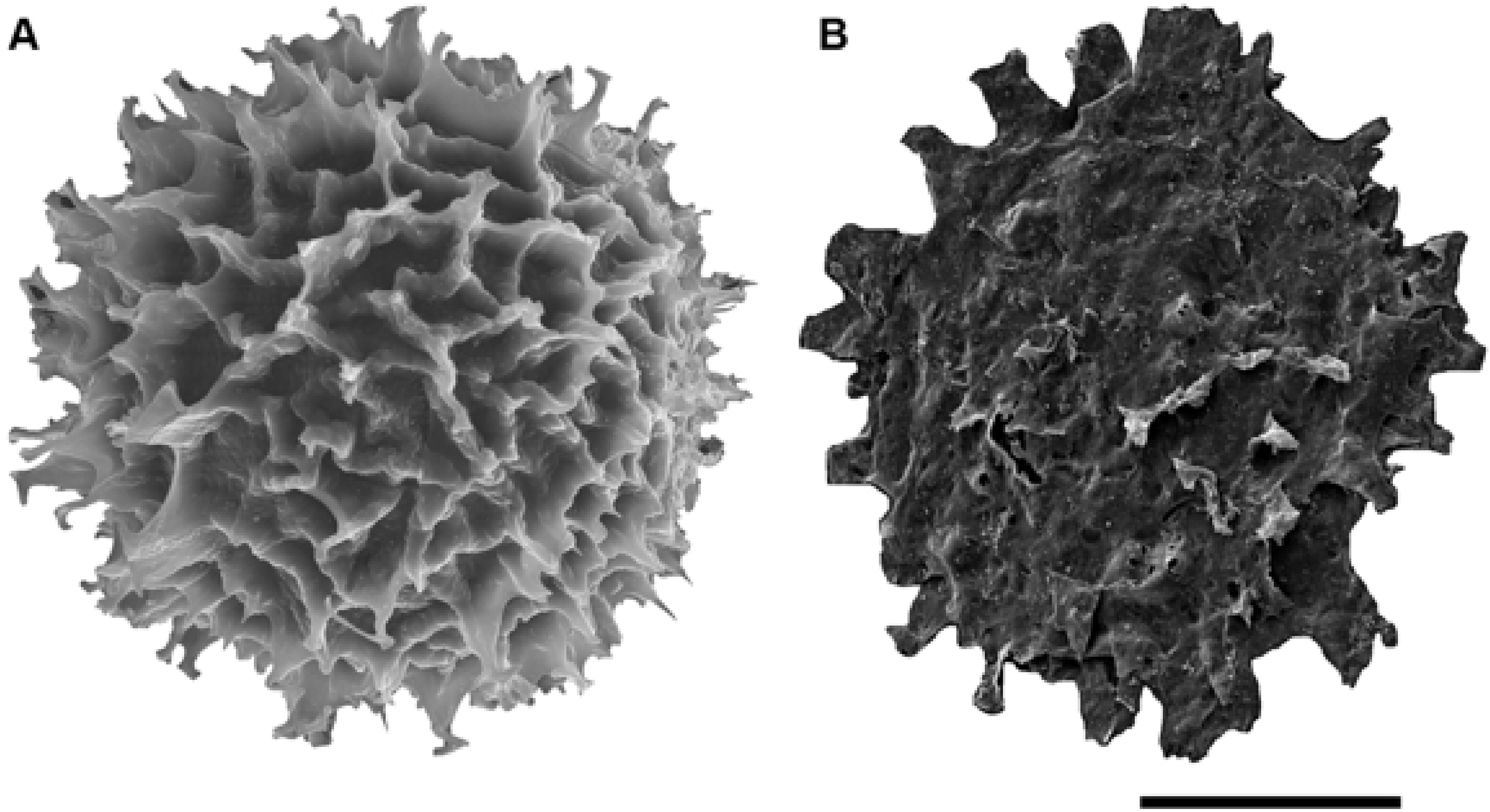


http://kinglab.berkeley.edu



 Source: King, N. M., et al. "The Genome of the Choanoflagellate Monosiga Brevicollis and the Origin of Metazoans." *Nature* 451, no. 7180 (2008): 783-8.

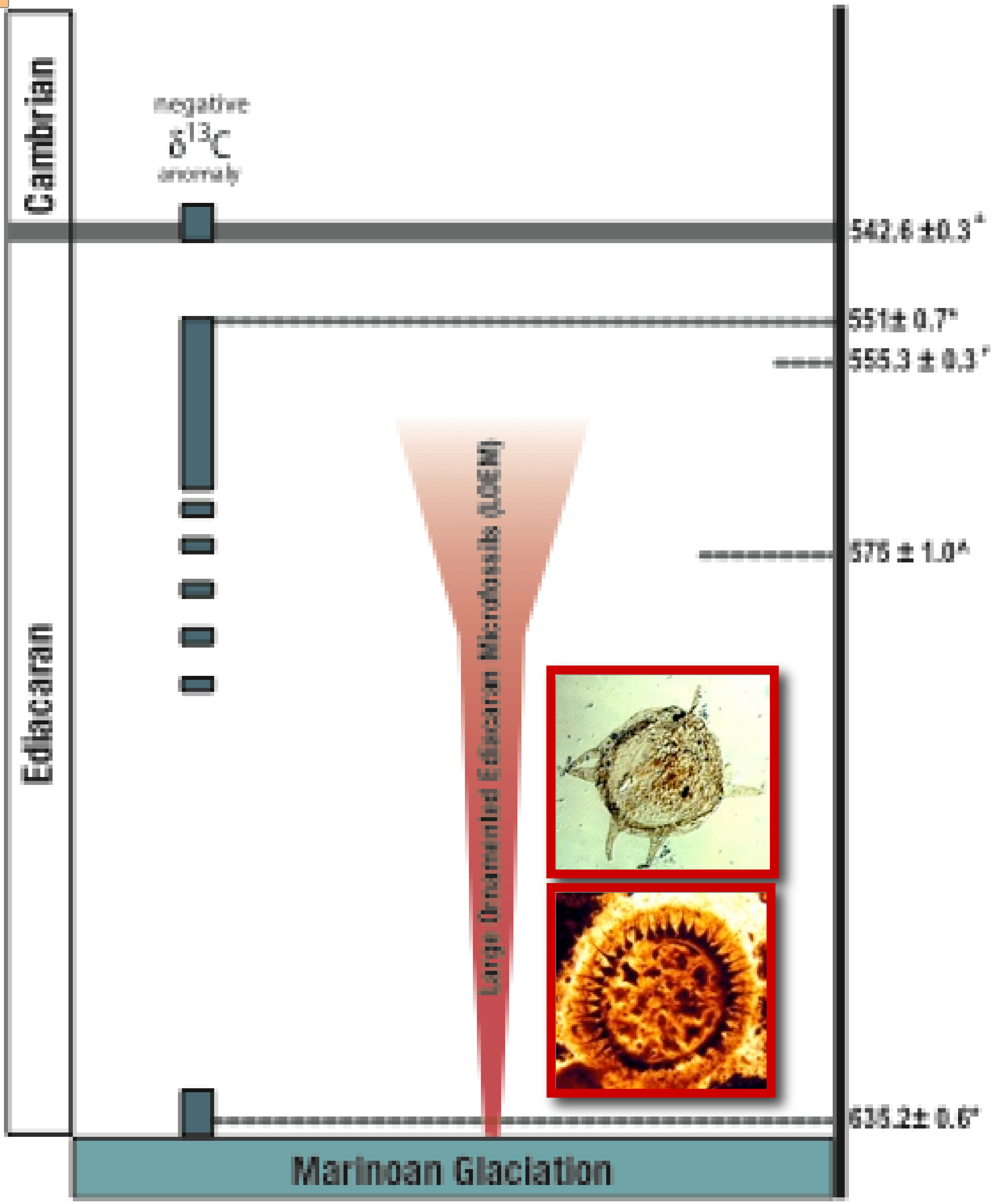
Modern ~ 580 Million years old



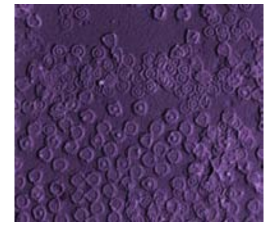
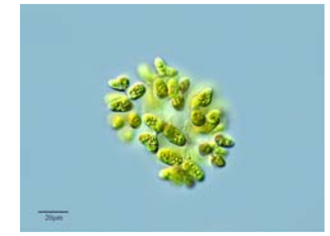
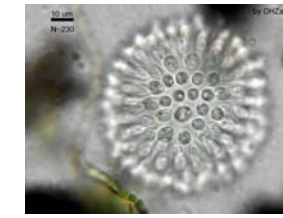
Scale bar: 200μm Scale bar: 100μm

Cohen et al. 2009

Radiation of large spiny organic walled microfossils in the Ediacaran

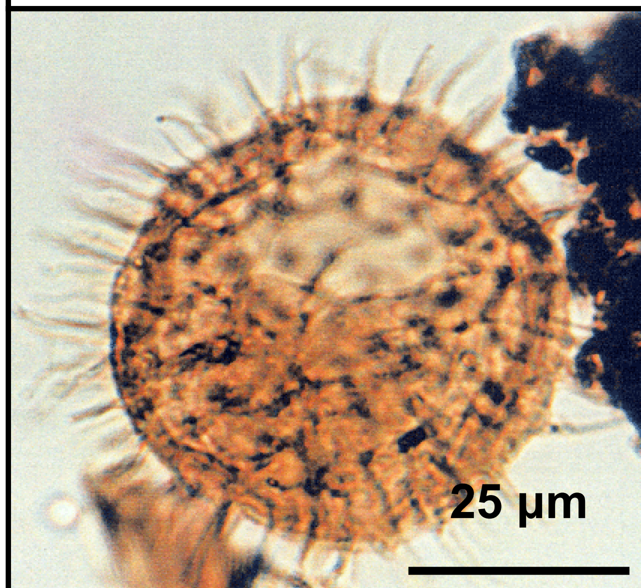
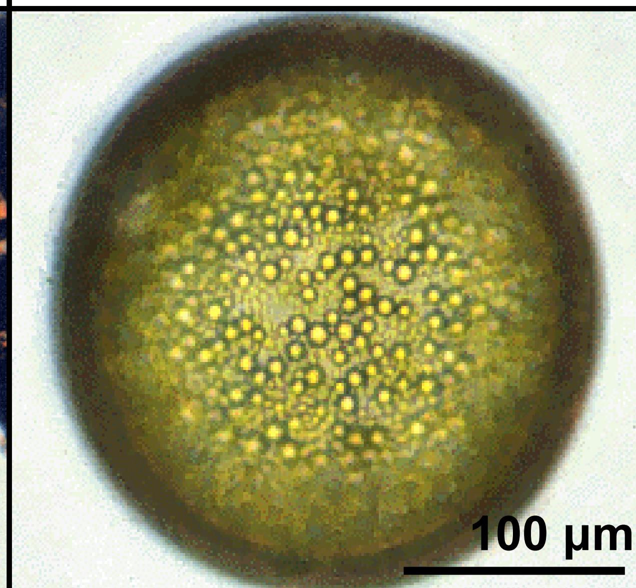
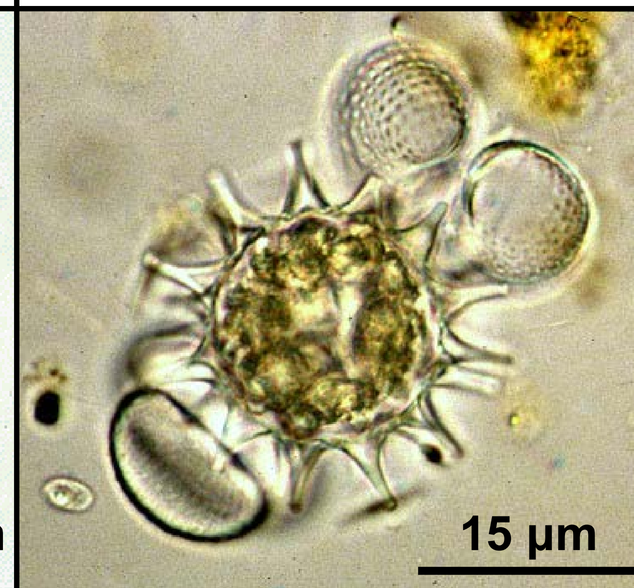
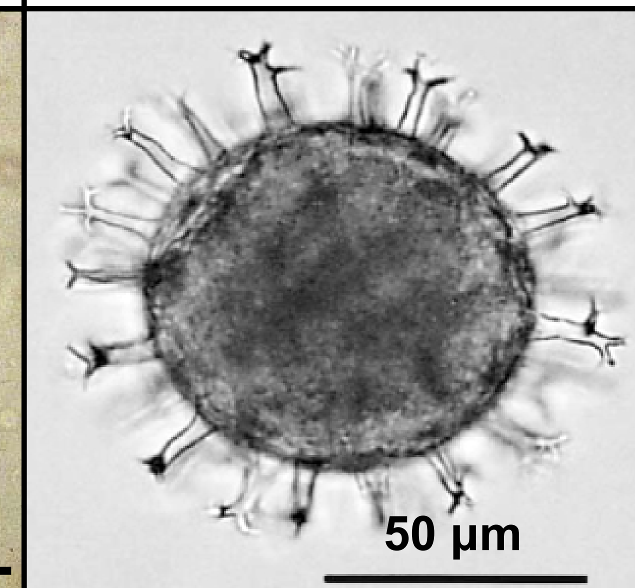


Cohen et al. 2009

	dinoflagellates	prasinophytes	other greens	metazoans
size				
external morphology				
ultrastructure				
internal contents				

Modern Candidate Groups: Examples of Morphology

dinoflagellates (plankton)	prasinophyte green algae	resting stages of other greens	animal egg casings
			
Dinocyst, photo: MIRACLE	*Halosphaera dubii* R. Kodner	*Cosmarium zygospore*, Image: Peter Coesel	Copepod *Acartia steuri*, Onoue et al 2004

Ultrastructure: Fossil vs Animal Resting Stage

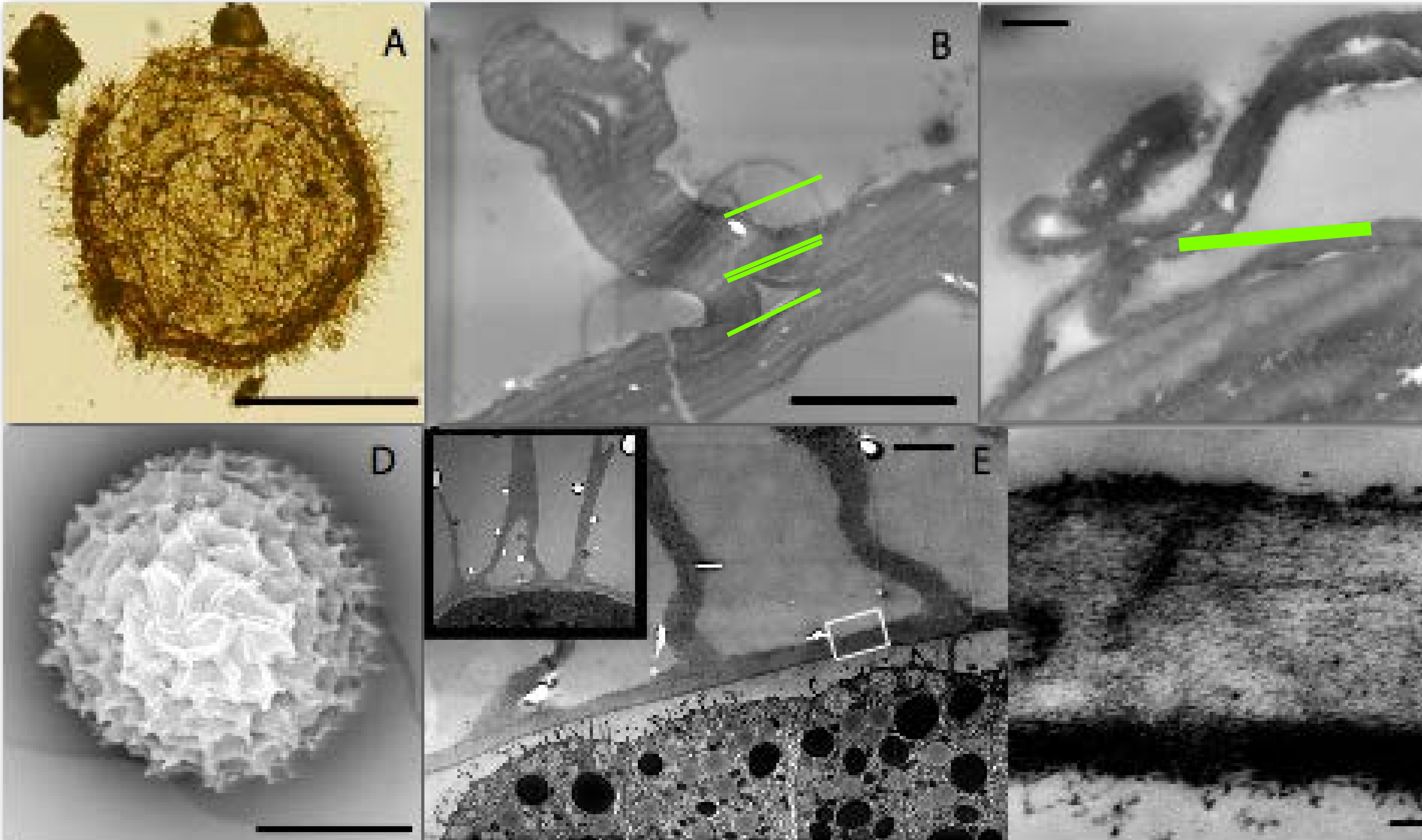
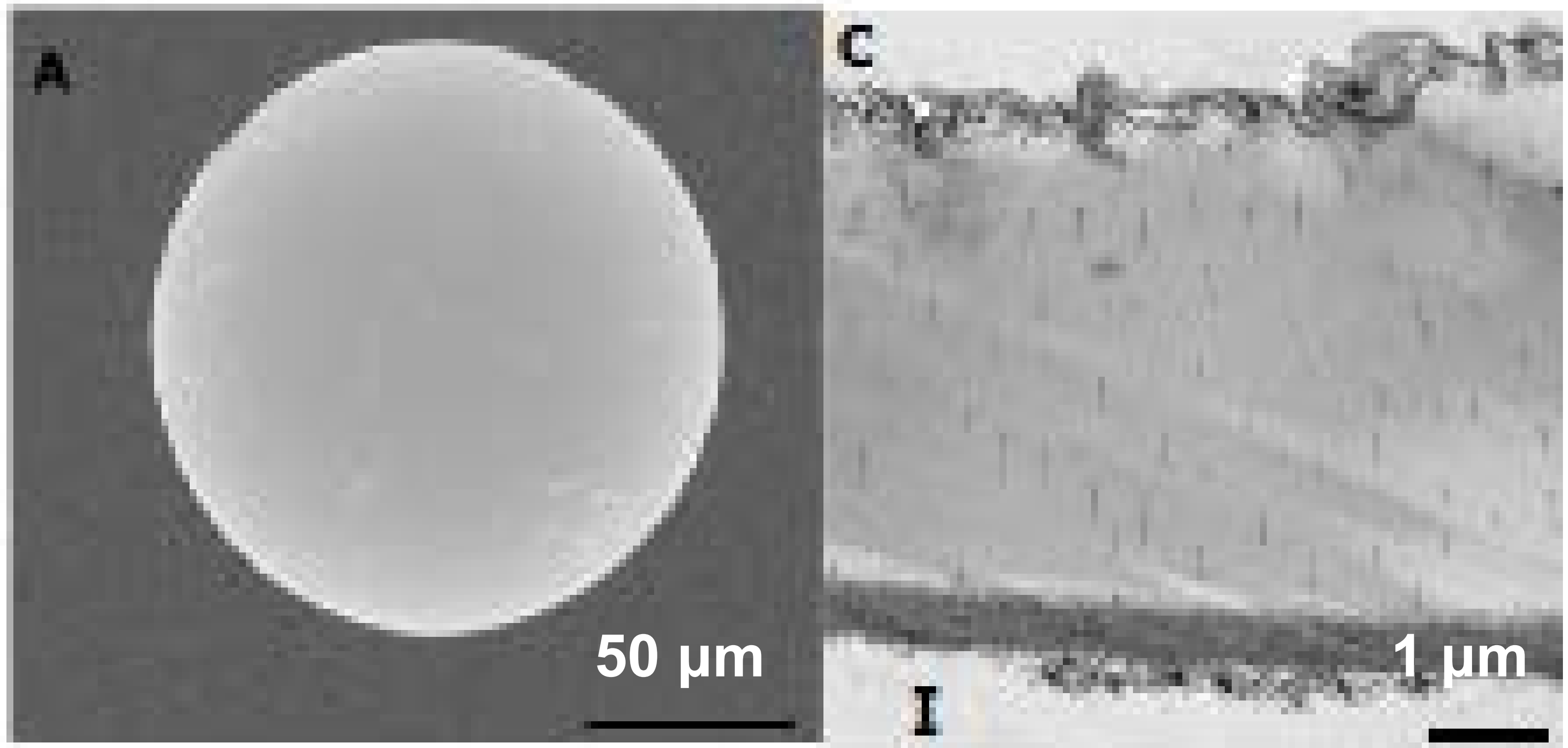


Fig. 5. Comparison of a LOEM fossil and a modern crustacean analog. (*A–C*), *Gyalosphaeridium* sp. (*A*) Light micrograph. (*B* and *C*) TEM. (*D–F*) *Branchinella longirostris.* (*D*) SEM. (*E*) TEM. (*Inset*) Hollow process. (*F*) TEM of outer wall. (Scale bars: *A* and *D*, 100 μm; *B* and *C*, 500 nm; *E*, 4 μm; *F*, 200 nm.)

Cohen et al. 2009

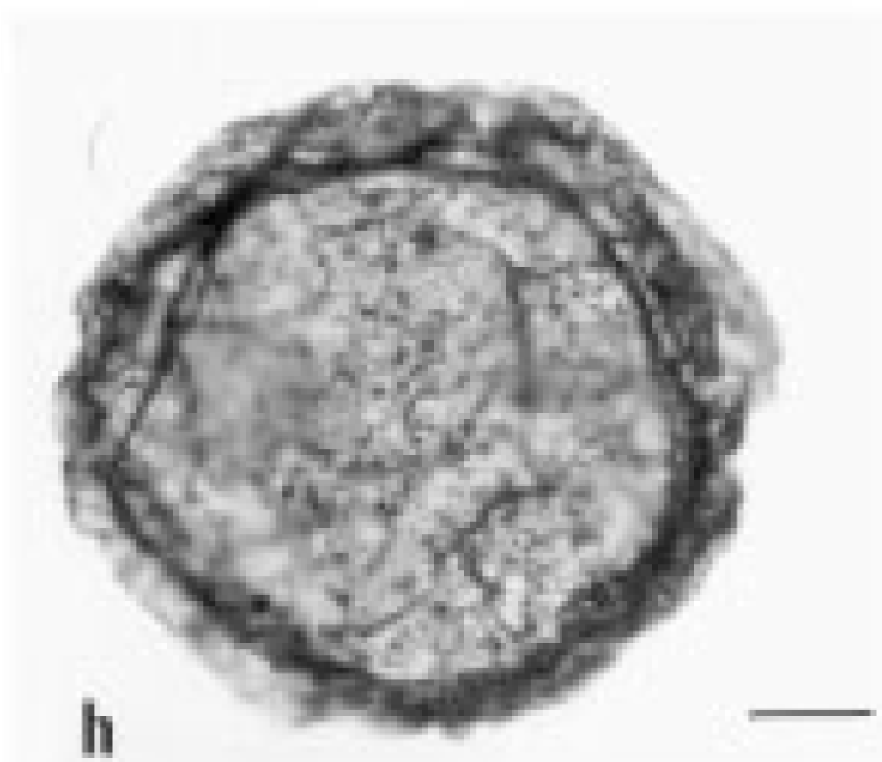
Prasinophytes in the Ediacaran fossil record

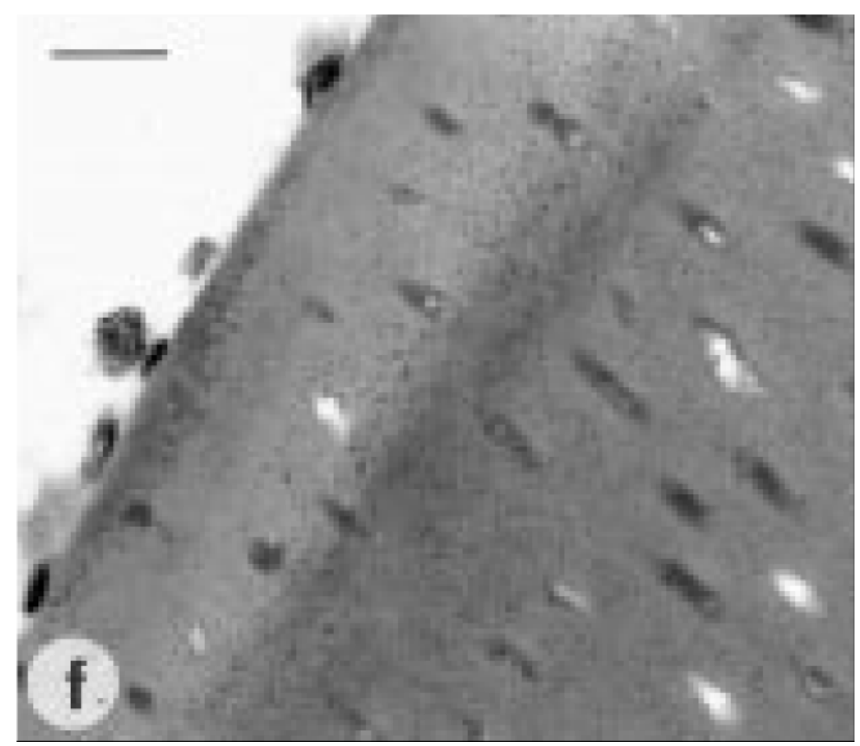
Modern



Halosphaera sp. phycoma B: TEM of phycoma

Ediacaran Fossil



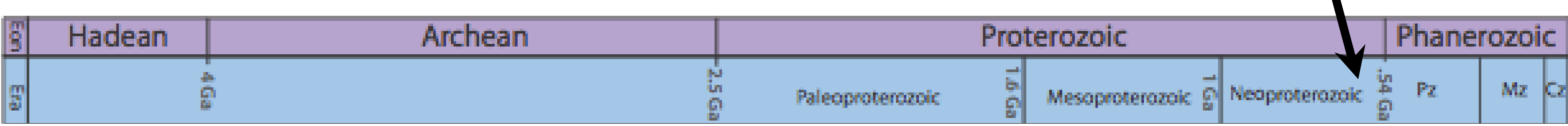


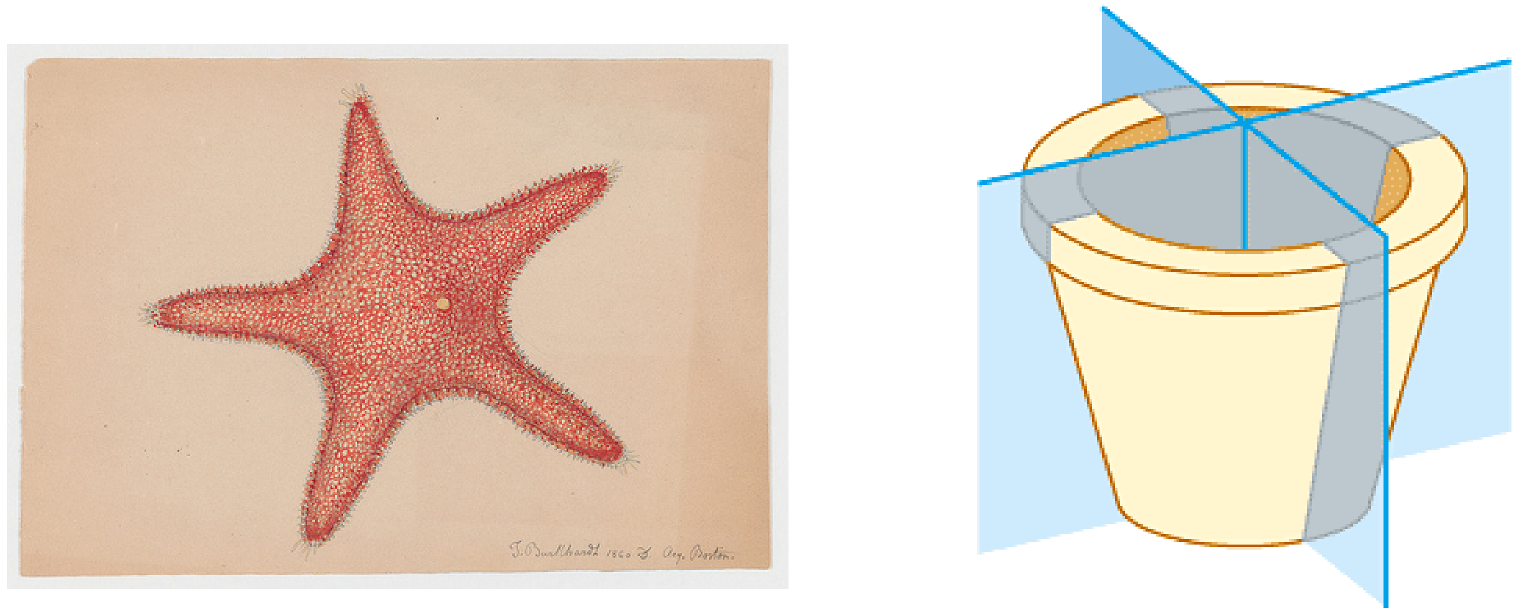
Tasmanites sp., Aurori et al 2000

More early fossil evidence of animals - Doushantuo Fm phosphatized embryos

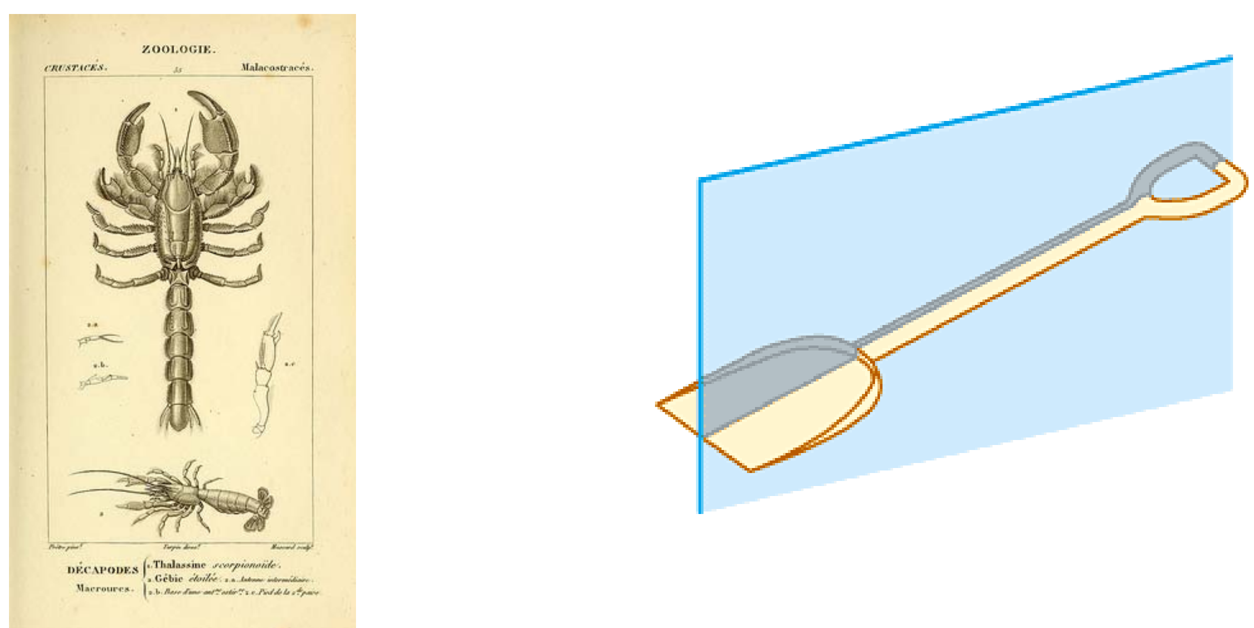
Xiao et al Nature

Yin et al Nature





(a) Radial symmetry



(b) Bilateral symmetry

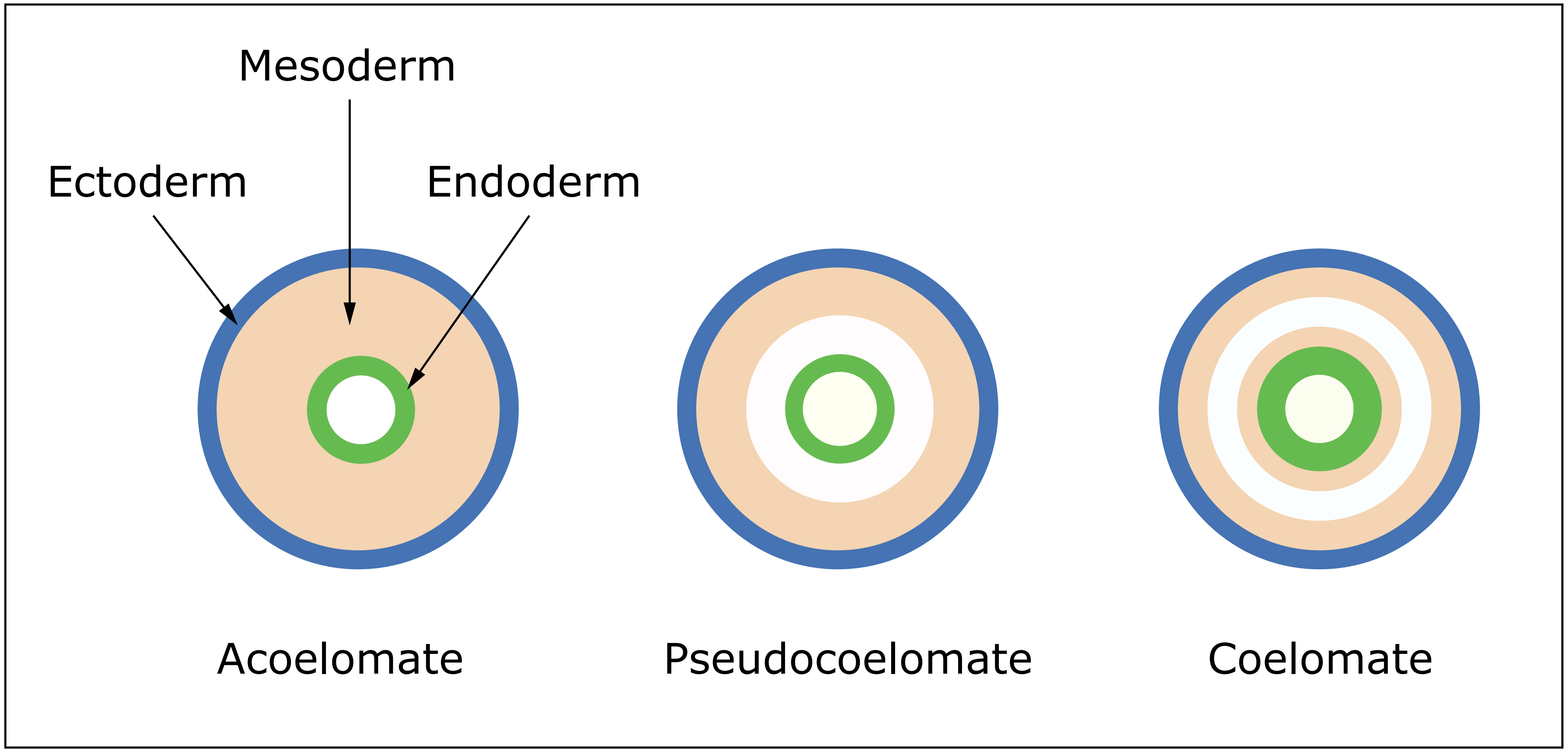
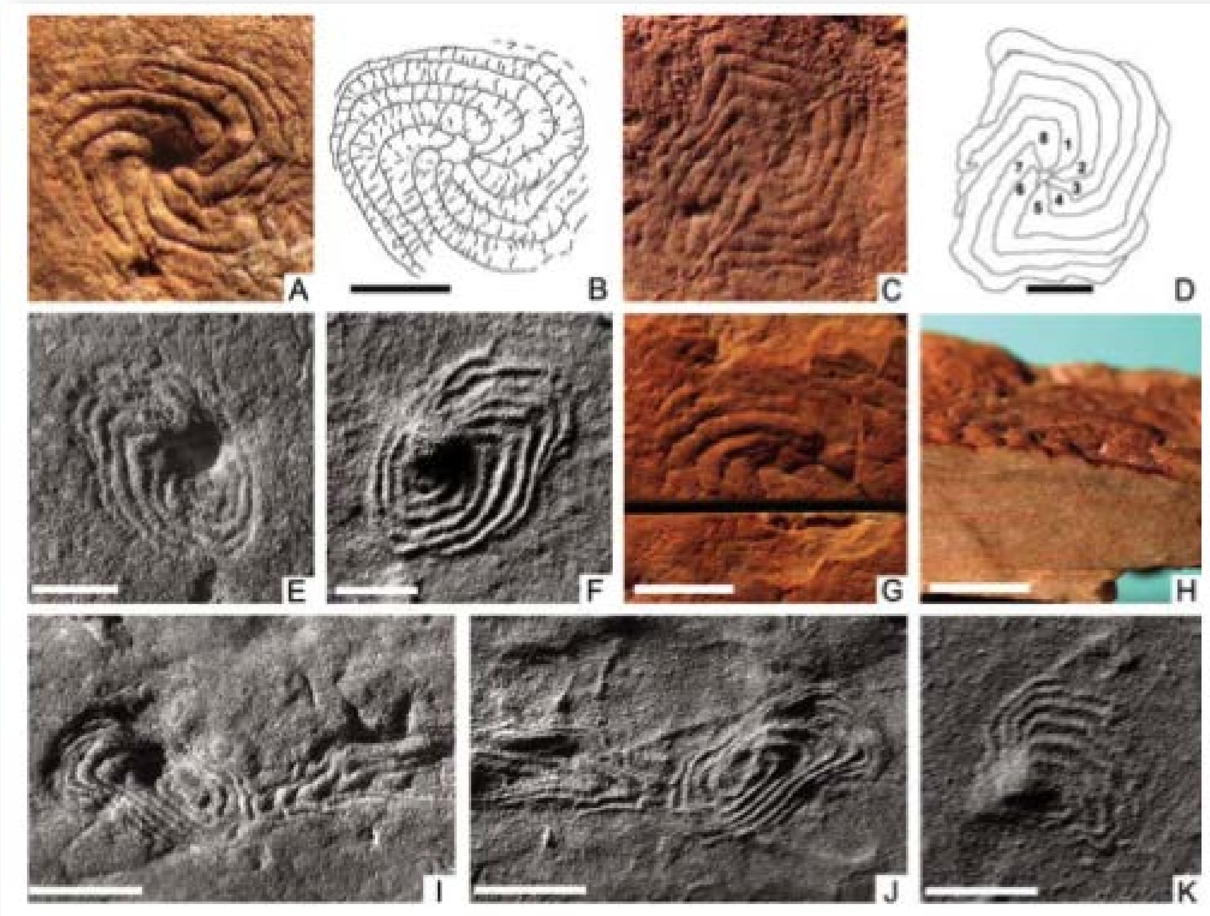


Image by MIT OpenCourseWare.

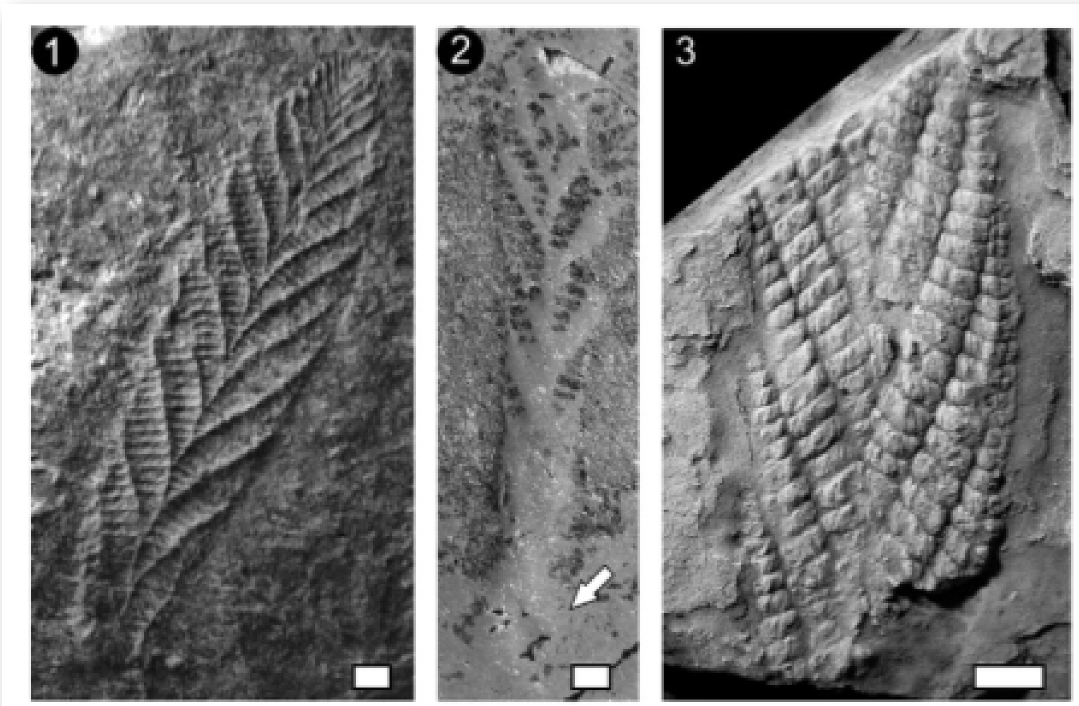
Courtesy of Phoebe Cohen. Used with permission.

Enigmatic Ediacaran Fauna

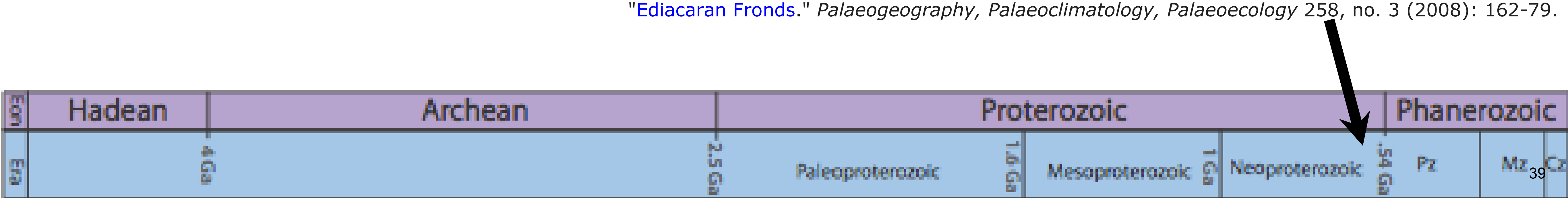


Zhu et al 2008

Globally distributed from ca 570 Ma - Cambrian boundary



Charnia, Laflamme & Narbonne 2008



Courtesy of Phoebe Cohen. Used with permission.

Courtesy of Phoebe Cohen. Used with permission.

Courtesy of Phoebe Cohen. Used with permission.

Synchronous Aggregate Growth in an Abundant New Ediacaran Tubular Organism

Mary L. Droser[1]* and James G. Gehling[2]

"First Sex" Found in Australian Fossils?

Brian Handwerk
for National Geographic News
April 1, 2008

Courtesy of Phoebe Cohen on flickr.

The clusters of similarly sized individuals of Funisia are strongly suggestive of "spats," huge numbers of offspring an organism gives birth to at once. Besides producing spats, the individual tubular organisms reproduced by budding, and grew by adding bits to their tips.

Courtesy of Phoebe Cohen. Used with permission.

Courtesy of Phoebe Cohen. Used with permission.

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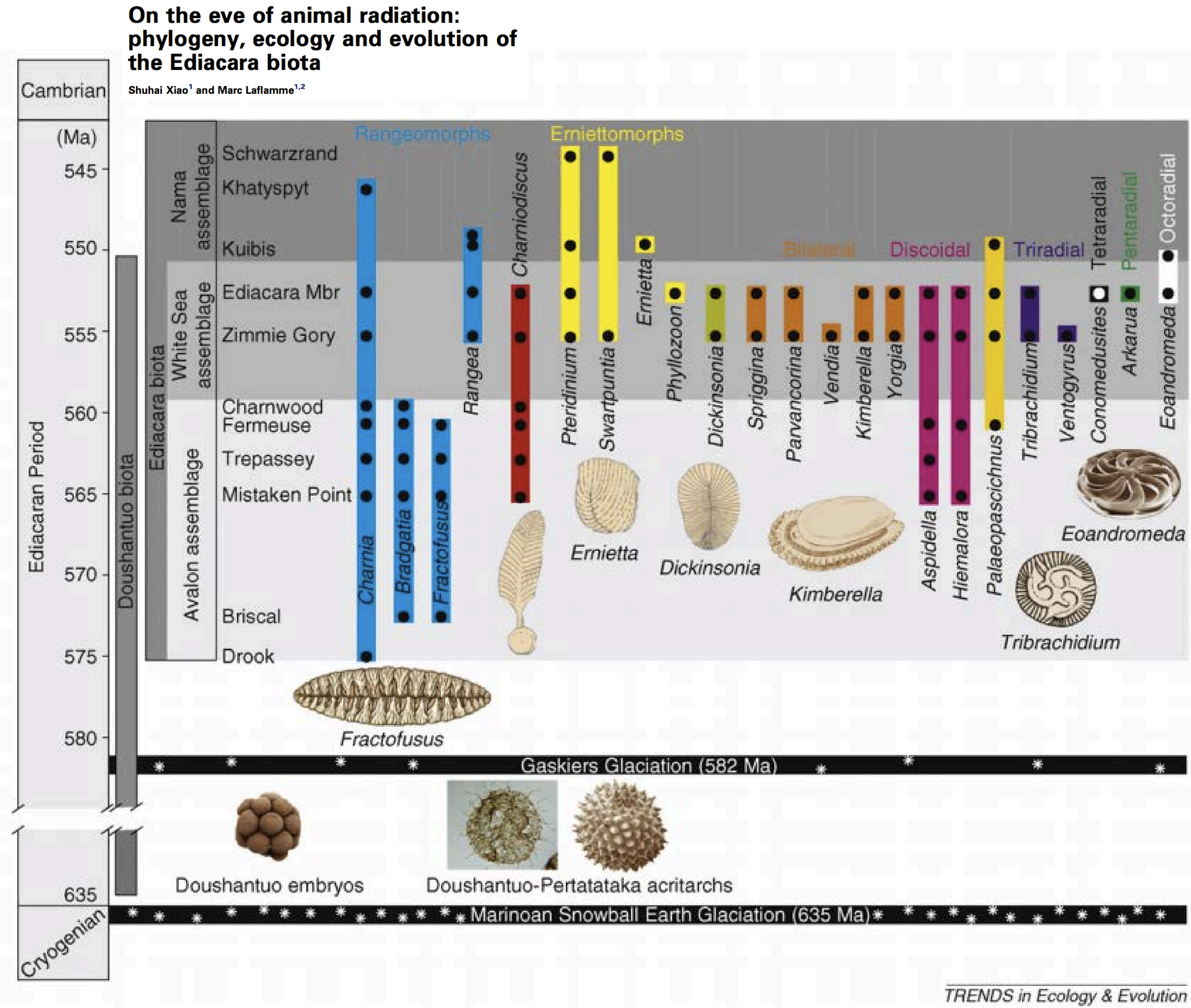
http://vft.asu.edu/VFTNilpenaH5/panos/np1h5main/np1h5main.html


On the eve of animal radiation: phylogeny, ecology and evolution of the Ediacara biota
Shuhai Xiao[1] and Marc Laflamme[1,2]
Cambrian
(Ma)
545
550
555
560
565
570
575
580
635
Ediacaran Period
Cryogenian
Doushantuo biota
Ediacara biota
Nama assemblage
White Sea assemblage
Avalon assemblage
Schwarzrand
Khatyspyt
Kuibis
Ediacara Mbr
Zimmie Gory
Charnwood
Fermeuse
Trepassey
Mistaken Point
Briscal
Drook
Rangeomorphs
Erniettomorphs
Bilateral
Discoidal
Triradial
Tetraradial
Pentaradial
Octoradial
Charnia
Bradgatia
Fractofusus
Rangea
Charniodiscus
Pteridinium
Swartpuntia
Ernietta
Phyllozoon
Dickinsonia
Spriggina
Parvancorina
Vendia
Kimberella
Yorgia
Aspidella
Hiemalora
Palaeopascichnus
Tribrachidium
Ventogyrus
Conomedusites
Arkarua
Eoandromeda
Ernietta
Dickinsonia
Kimberella
Eoandromeda
Tribrachidium
Fractofusus
Gaskiers Glaciation (582 Ma)
Doushantuo embryos
Doushantuo-Pertatataka acritarchs
Marinoan Snowball Earth Glaciation (635 Ma)
TRENDS in Ecology & Evolution

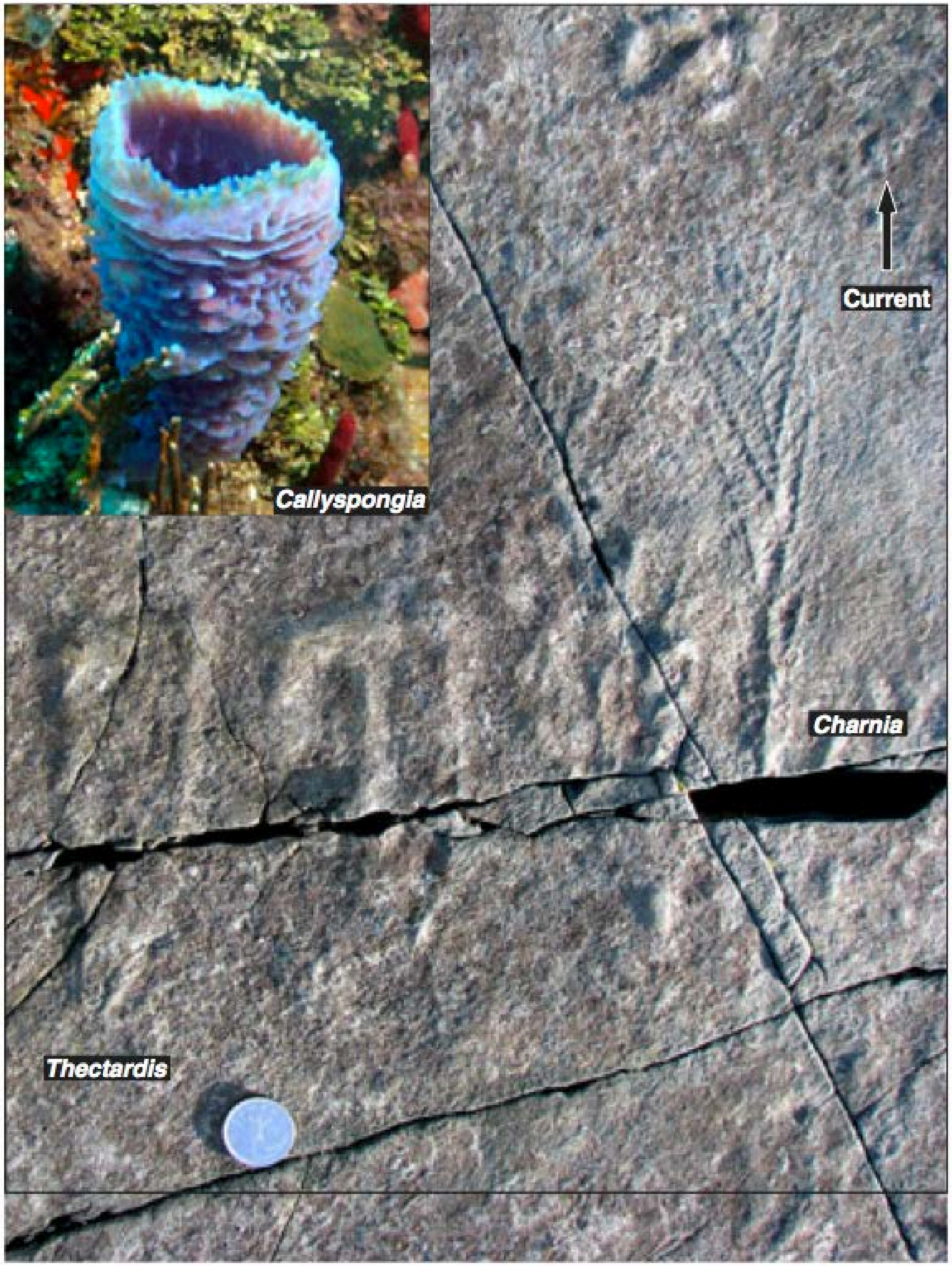
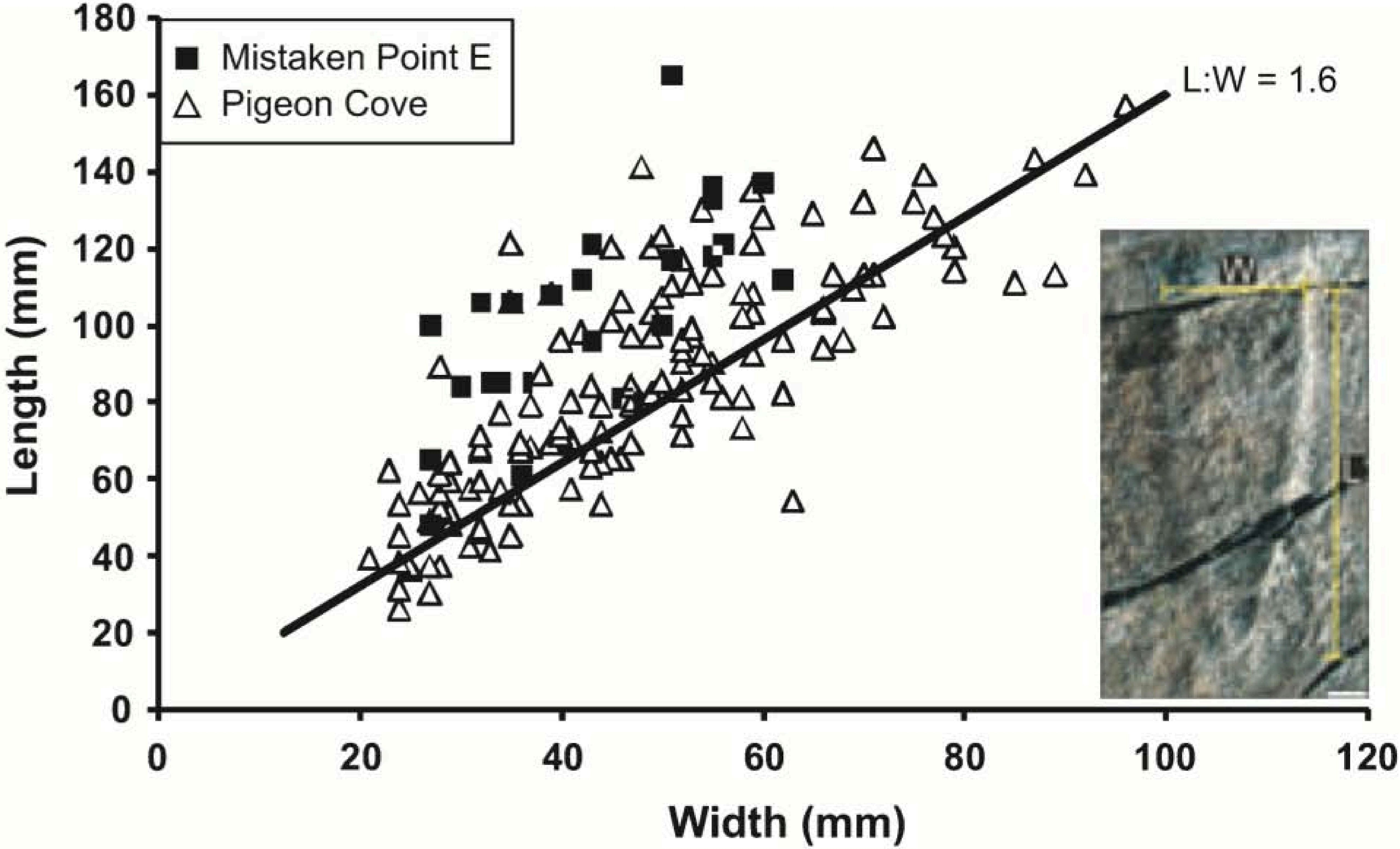


Fig. 1 The Ediacaran fossil *Thectardis avalonensis* from the mid-Ediacaran (<580 Ma) of the Avalon Peninsula, Newfoundland, Canada. Diameter of Canadian quarter = 23.81 mm. *Thectardis* fossils are consistently oriented parallel to fronds, such as the *Charnia antecedens* holotype, indicating that they were originally erect and felled by currents. From the upper Drook Fm. at Pigeon Cove, Newfoundland. (Inset) Modern vase sponges show a form similar to the reconstruction of *Thectardis* by Clapham *et al.* (2004) and demonstrate that the fossil is consistent with the hydrodynamics of the sponge body plan. Image kindly provided by Robert Aston.

Rangeomorphs, *Thectardis* (Porifera?) and dissolved organic carbon in the Ediacaran oceans

E. A. SPERLING,[1,2] K. J. PETERSON[3] AND M. LAFLAMME[1]



For a perfectly coni- cal sponge, the length (height) should be □1.6 times the width (diameter of oscula) in order to maintain an oscular area greater than the area of the com- bined incurrent pores.

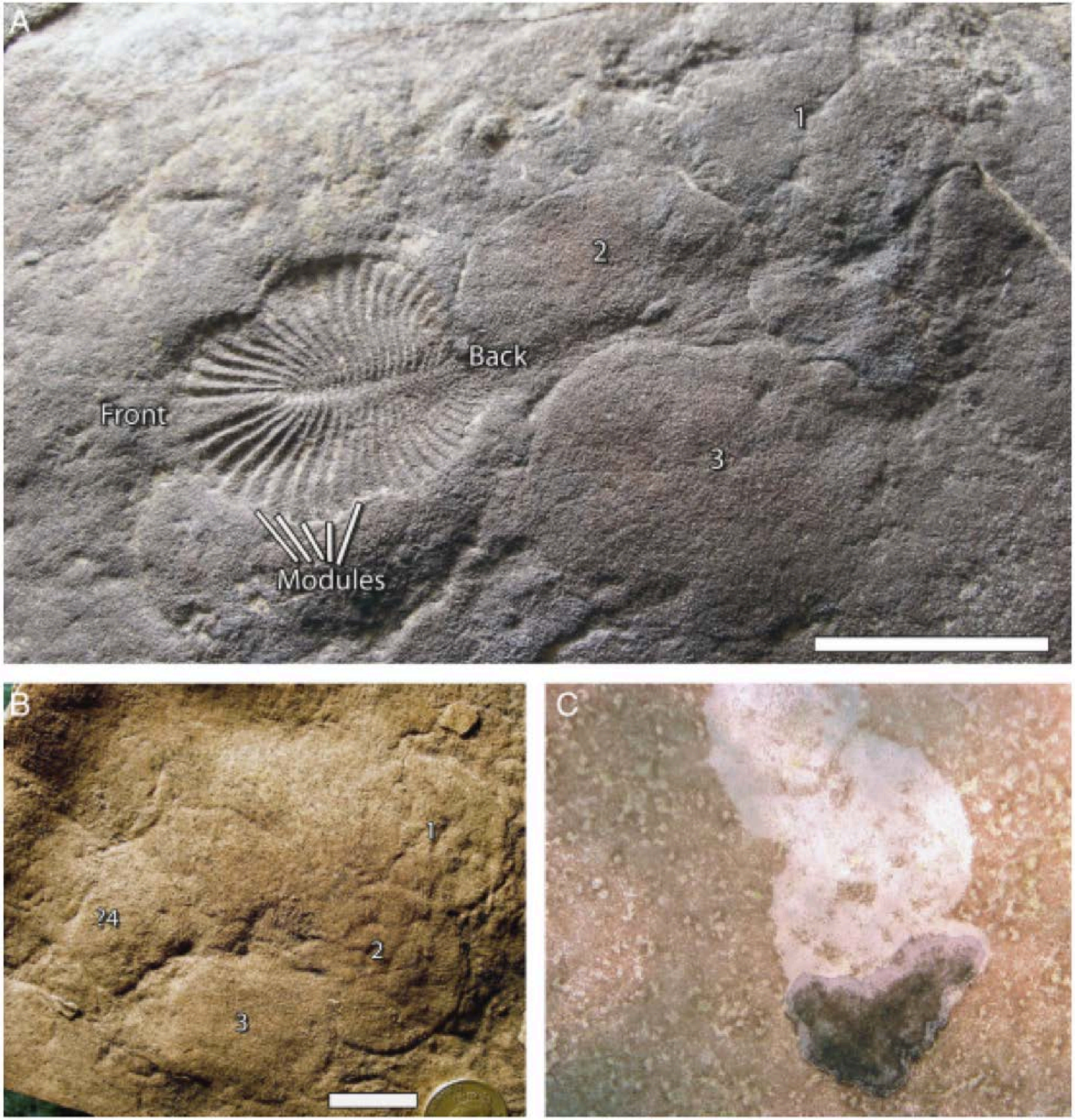
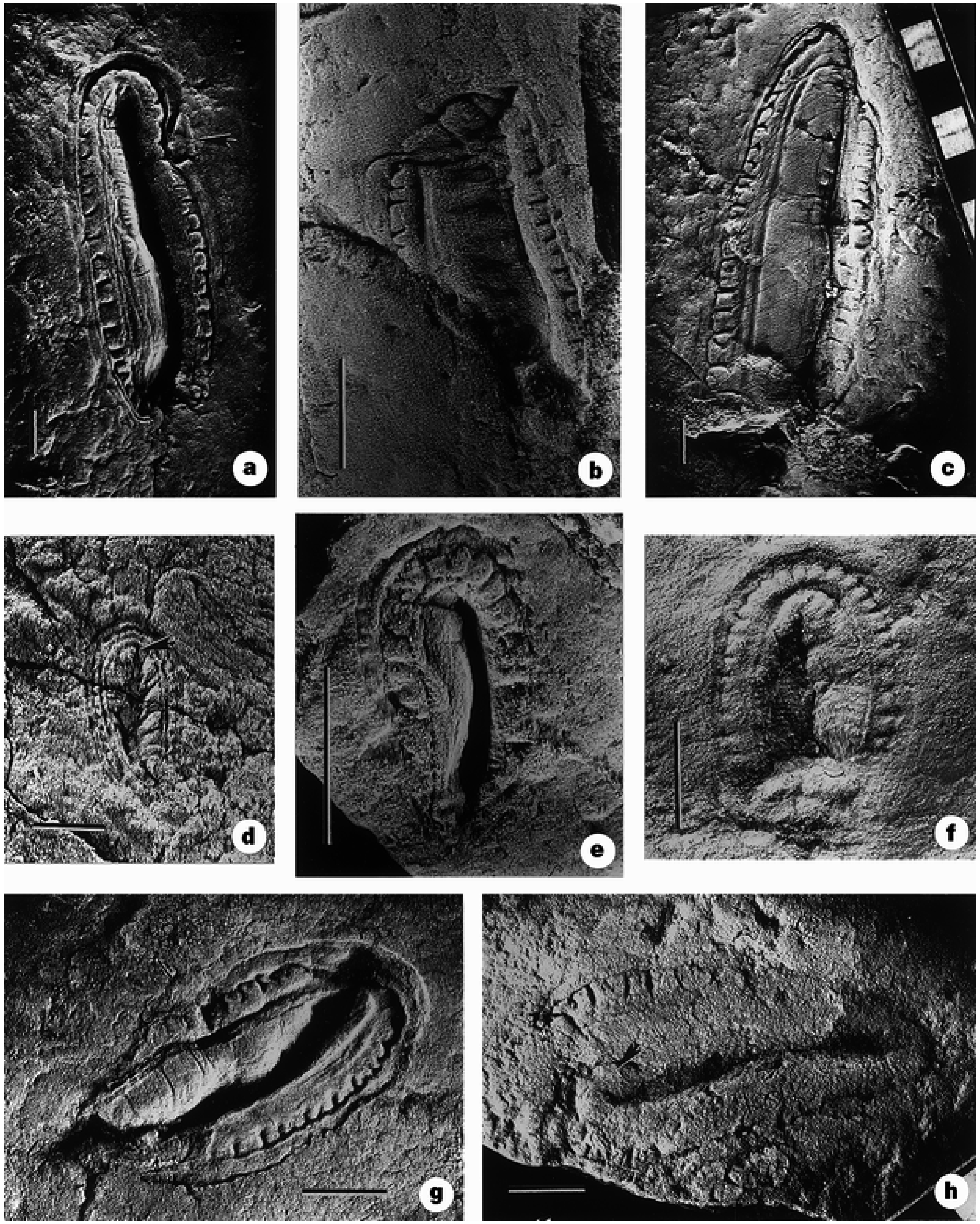


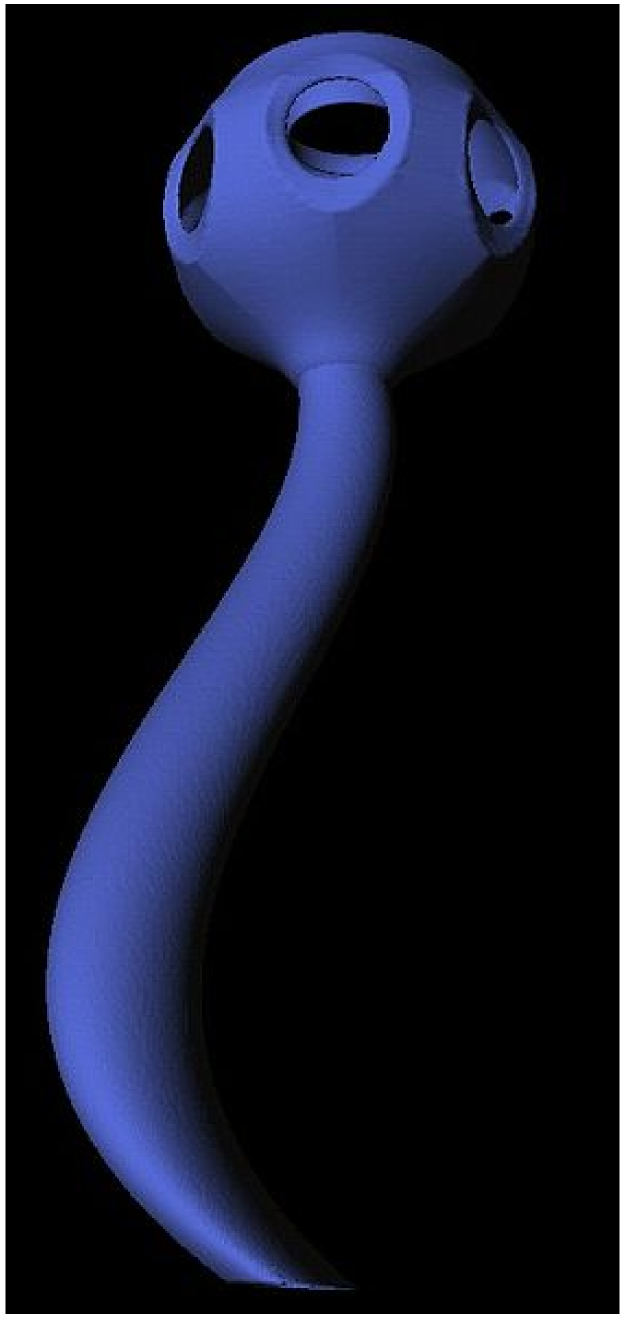
Fig. 1. Body fossils of *Dickinsonia* and feeding traces. (A) Body fossil of *Dickinsonia costata* associated with a series of feeding traces (previously figured by Gehling et al. 2005; South Australia Museum specimen 40845a). Numbers delineate the order of their formation in relation to the body fossil at the end of the series of traces (trace #3 made last). Note the distinct difference in relief between the trace fossils and the body fossil and the overlapping nature between the traces. Terminology used in the article is indicated on the body fossil. Scale bar is 2 cm. (B) Circular series of traces preserving indications of modules and distinct overlap between the traces (previously figured by Gehling et al. 2005; SAM 40844). Along with previously figured specimens (Ivantsov and Malakhovskaya 2002; Gehling et al. 2005; Fedonkin and Vickers-Rich 2007) showing circular movements this demonstrates that the tracks are not current-driven features. Scale bar is 2 cm. (C) *Trichoplax adhaerens* (Placozoa) feeding trace on algal surface in Petri-dish culture. Animal is approximately 2 mm in length.



 Source: Fedonkin, M.A., and B. M. Waggoner. "The Late Precambrian Fossil Kimberella is a Mollusc-like Bilaterian Organism." *Nature* 388, no. 6645 (1997): 868-71.

Modern Kimberella analog – chiton, a mollusk

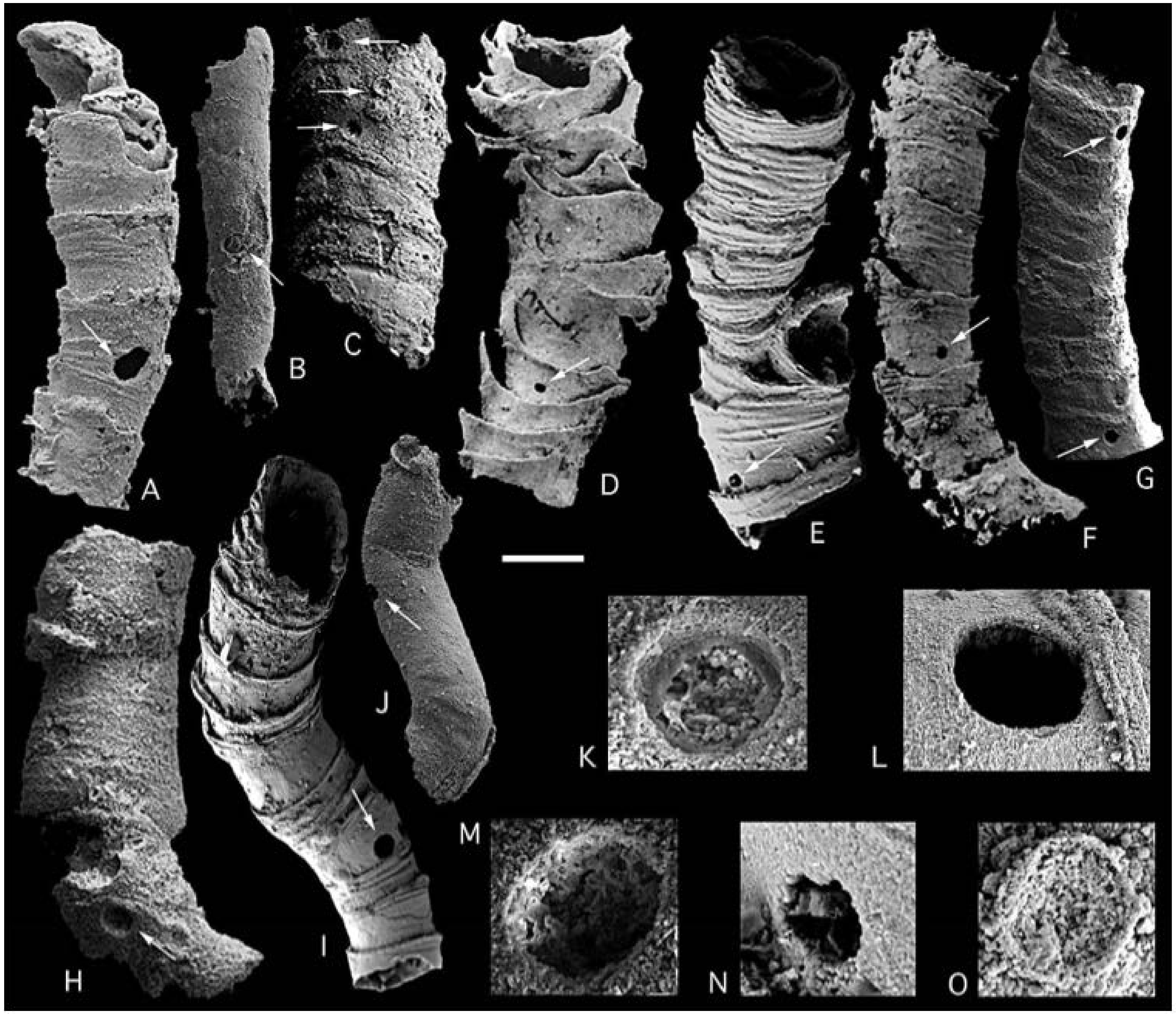
Namacalathus – early calcified animal, sponge-like



Courtesy of Cetomedes on wikipedia. Used with permission.

Courtesy of Chris Rowan. Used with permission.

Cloudina – early calcified animal, cnidarian-like



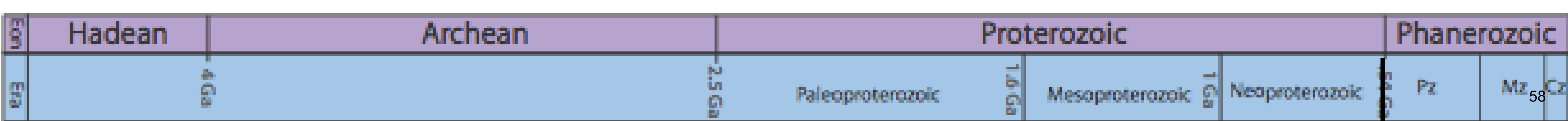
Hua et al 2003

FIGURE 3—*Cloudina* shells with borings from the Gaojiashan Member, Dengying Formation; scanning electron photomicrographs. Arrows point to individual boreholes. A–J are consecutively ELI 20000201–20000210. Scale bar: A, G = 200 μm; B = 300 μm; C, E, H = 150 μm; D, J = 250 μm; F = 350 μm; K, N, O = 20 μm; L = 50 μm; M = 35 μm. K and O are close-ups of C; L is close-up of I; M is close-up of H; N is close-up of E.

What actually defines the Cambrian Boundary?

- Trace fossils – tracks / trails of the first bilaterian (front-back) animals - *Trichophycus pedum*
- Type section at Fortune Head, Newfoundland

Courtesy of Geological Society of America. Used with permission. Source: Vannier, J., et al. "Priapulid Worms: Pioneer Horizontal Burrowers at the Precambrian-Cambrian Boundary." *Geology* 38, no. 8 (2010): 711-4.



early cambrian faunas

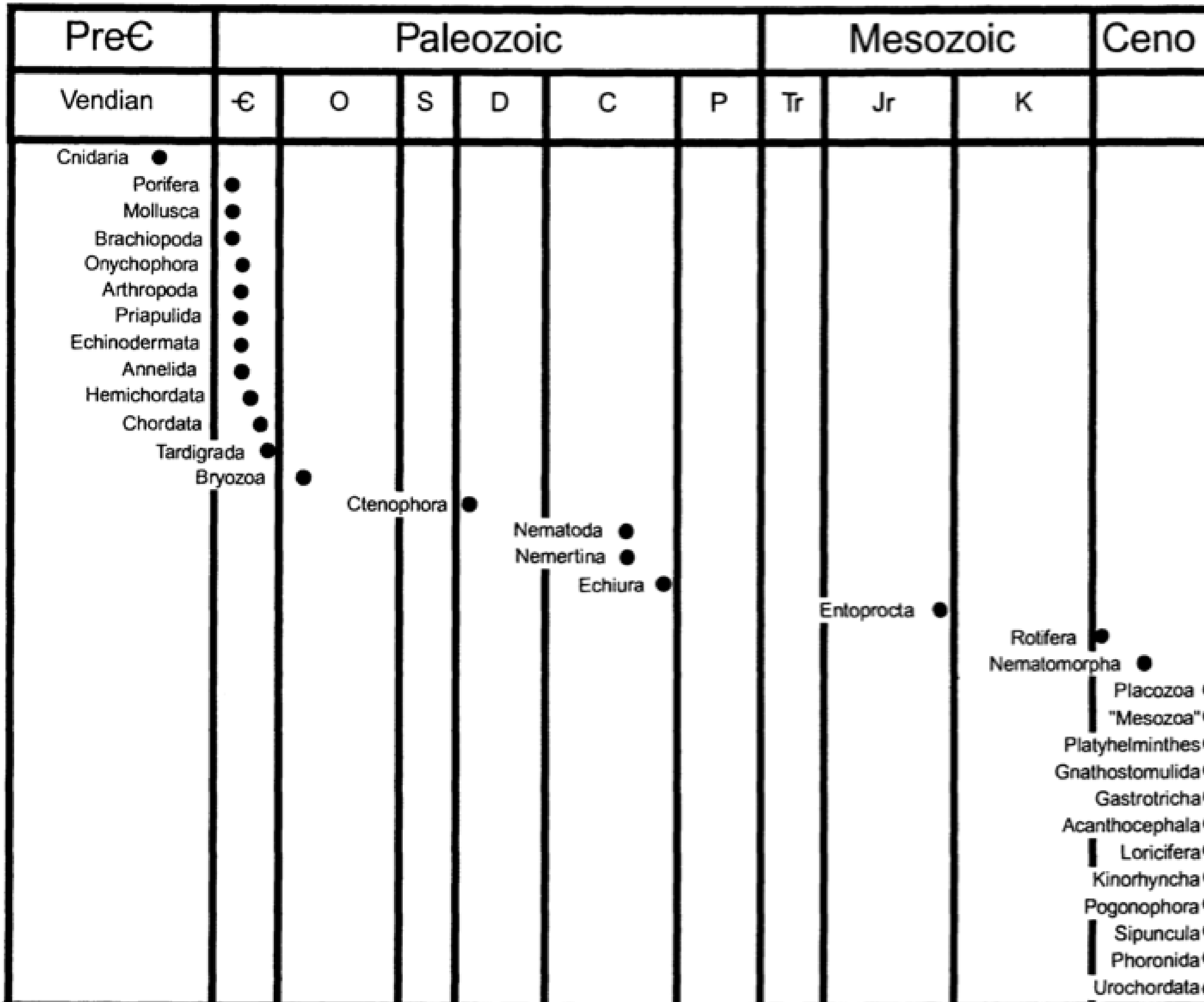
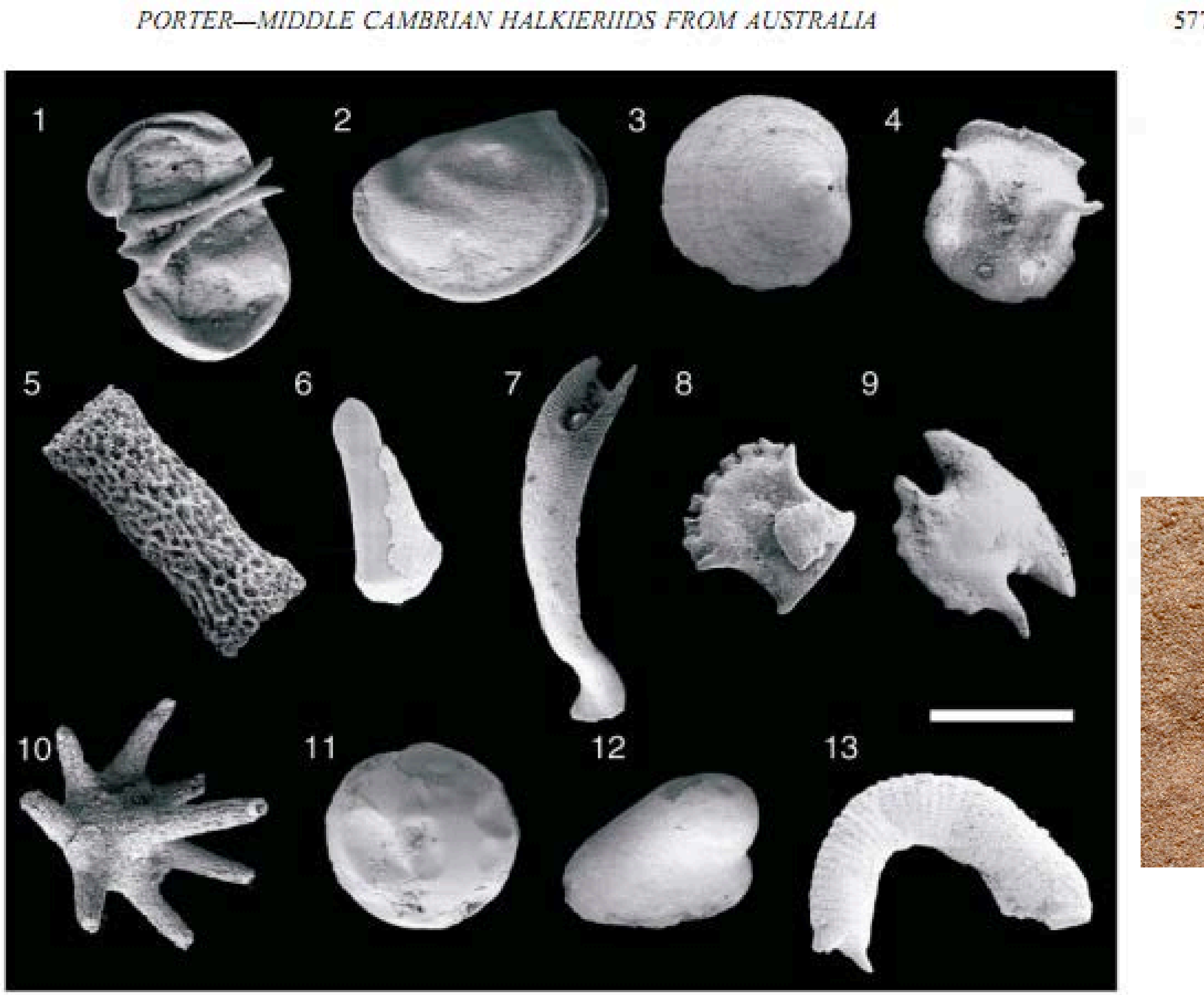
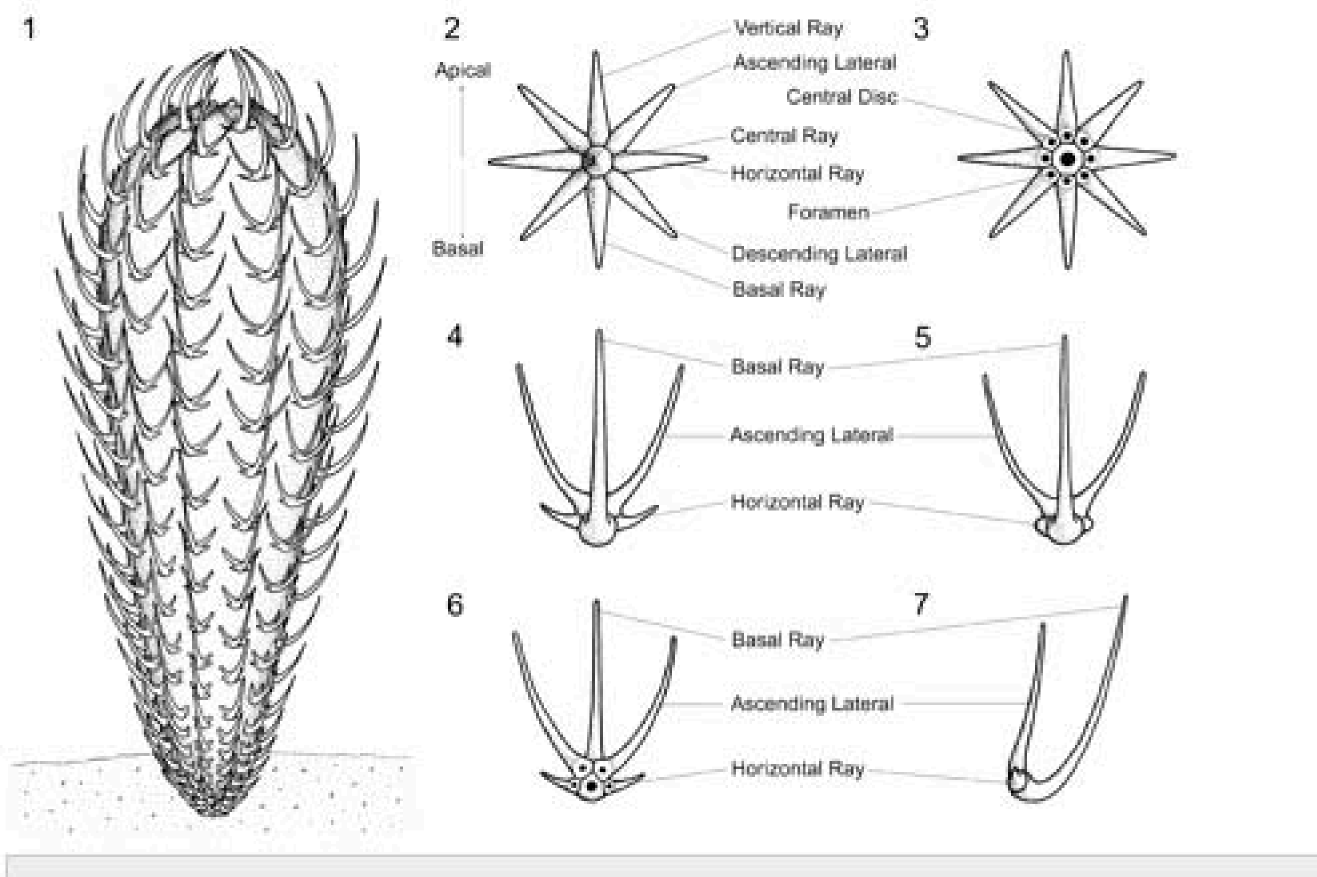


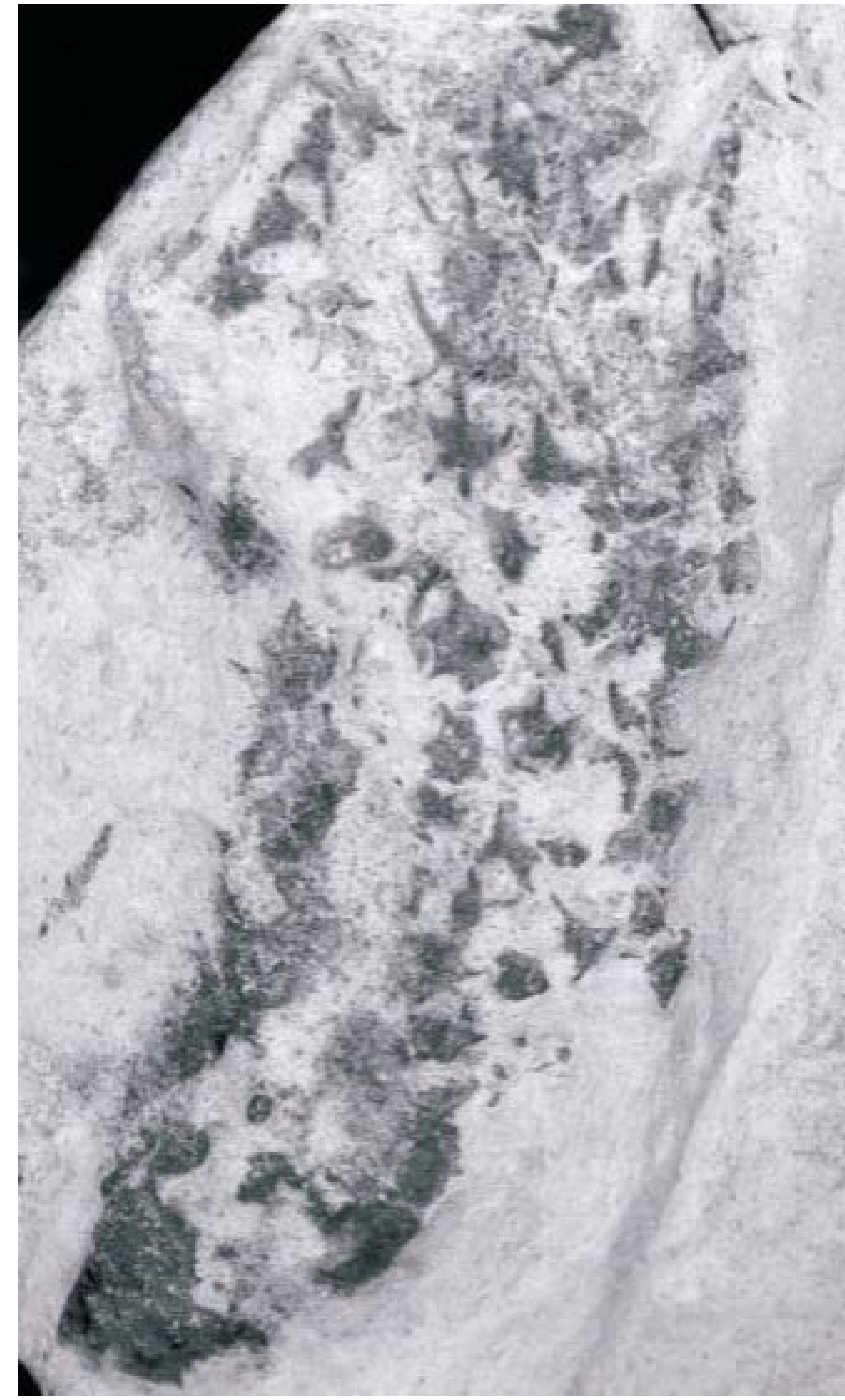
FIGURE 1—Times of first appearance in the fossil record of body fossils of living phyla. The times are conservative, in that questionable records and all data from trace fossils are excluded. Data from Valentine, in preparation.



Source: Porter, Susannah M. "Halkieriids in Middle Cambrian Phosphatic Limestones from Australia." *Journal of Paleontology* 78, no. 3 (2004).

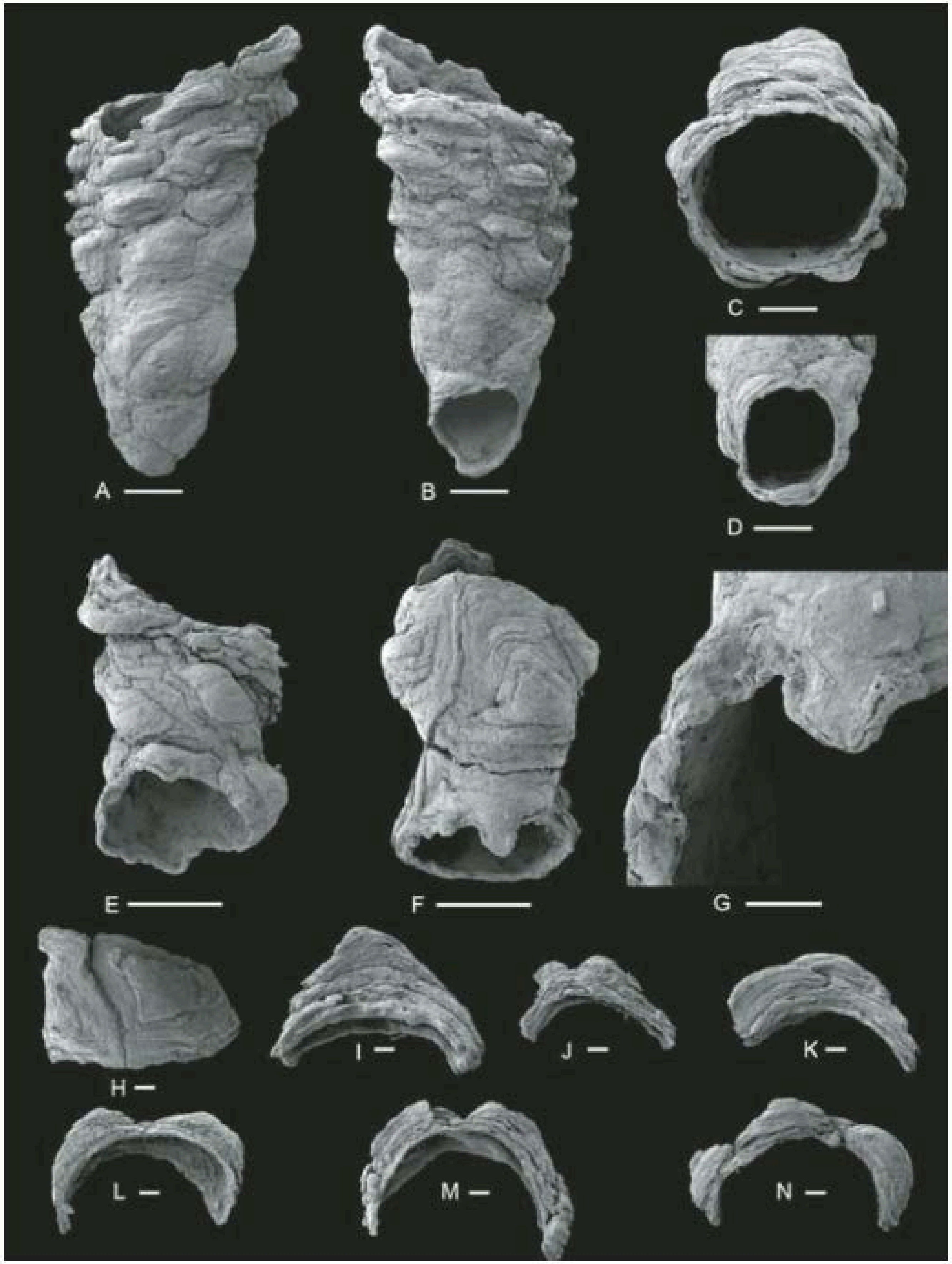
NEW CHANCELLORIIDS FROM THE EARLY CAMBRIAN SEKWI FORMATION WITH A COMMENT ON CHANCELLORIID AFFINITIES



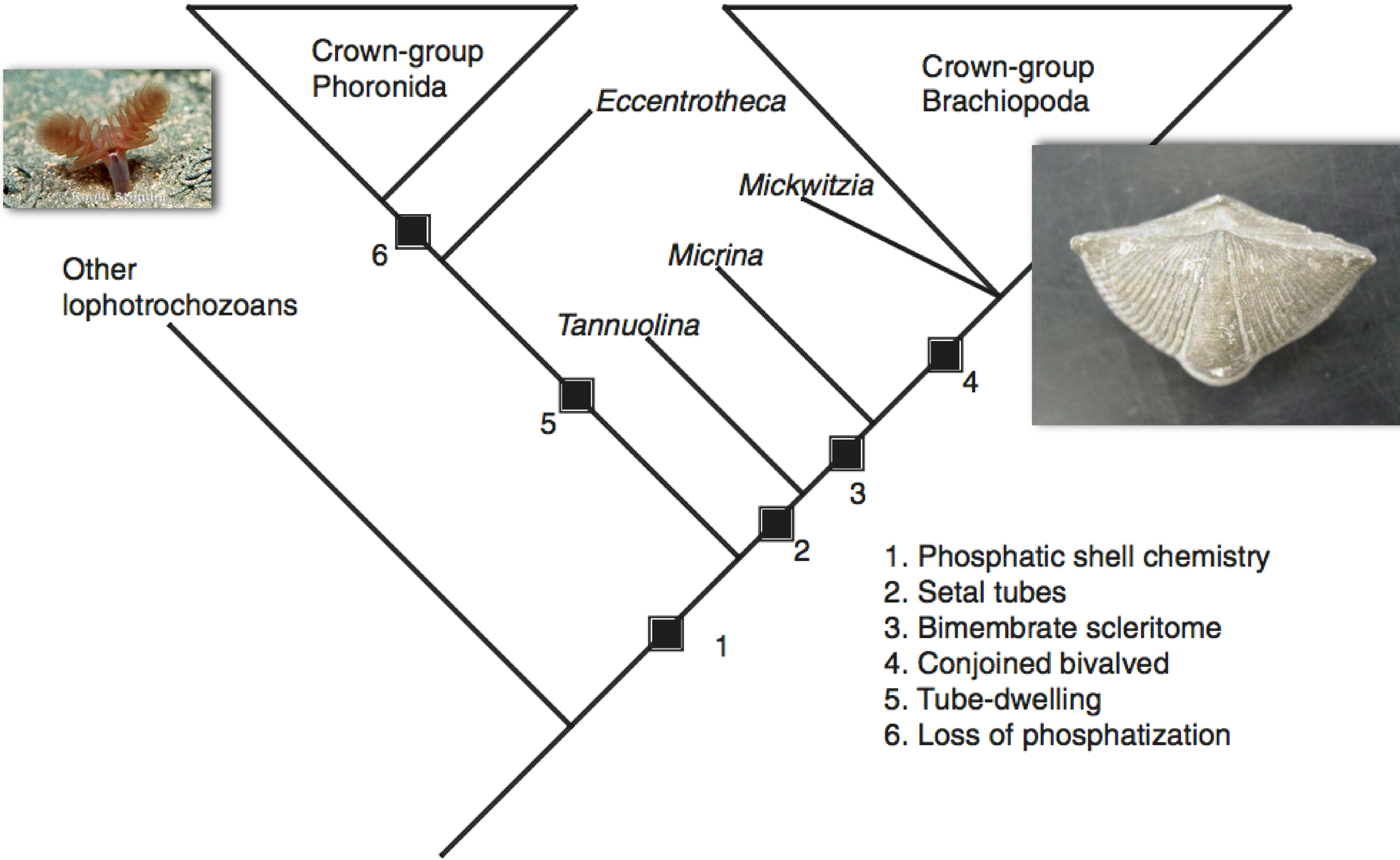


NEW CHANCELLORIIDS FROM THE EARLY CAMBRIAN SEKWI FORMATION WITH A COMMENT ON CHANCELLORIID AFFINITIES

ROBERT D. RANDELL,[1] BRUCE S. LIEBERMAN,[1] STEPHEN T. HASIOTIS,[1] AND MICHAEL C. POPE[2]

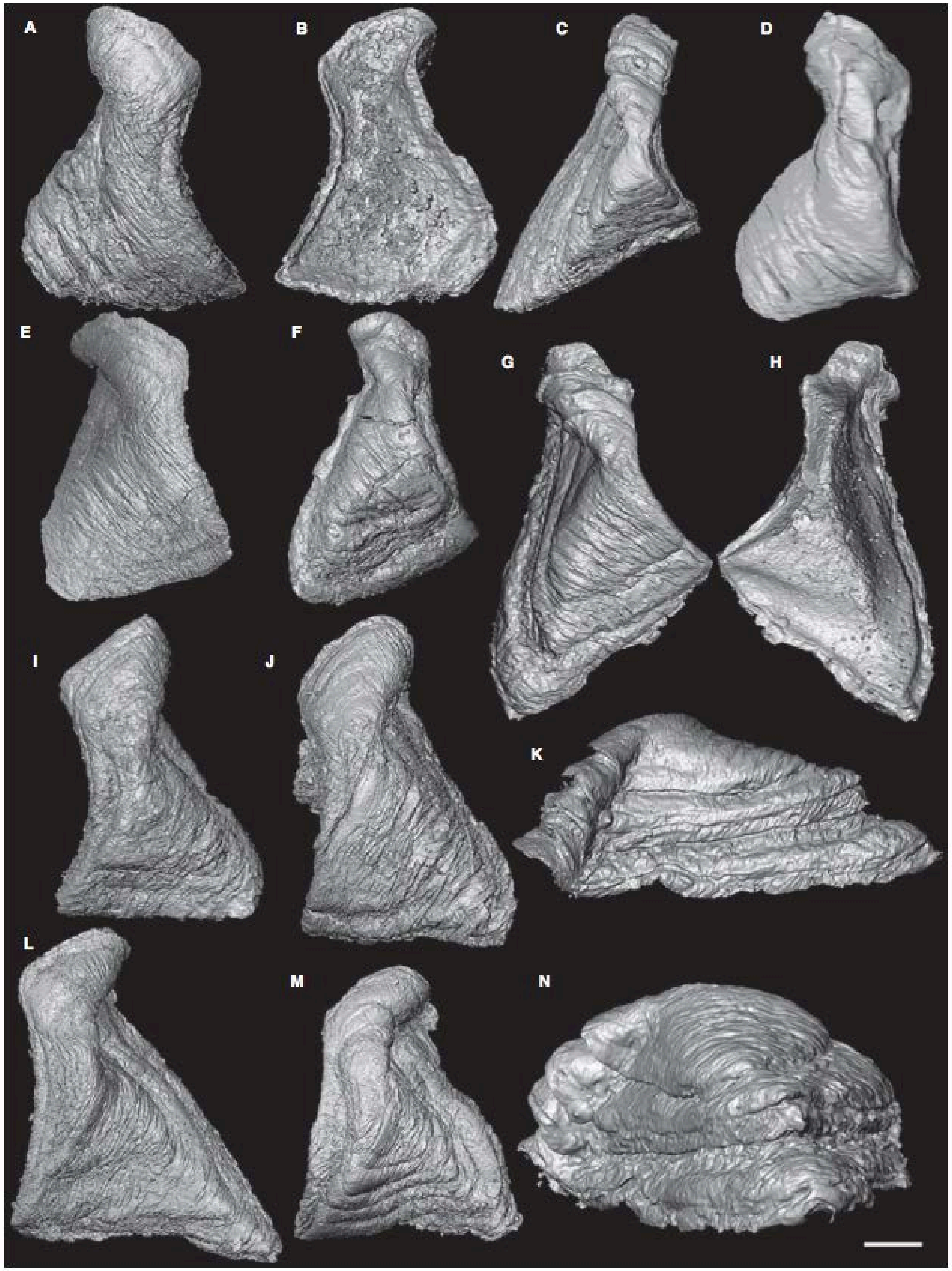


Lower Cambrian of South Australia



The scleritome of *Eccentrotheca* from the Lower Cambrian of South Australia: Lophophorate affinities and implications for tommotiid phylogeny

Christian B. Skovsted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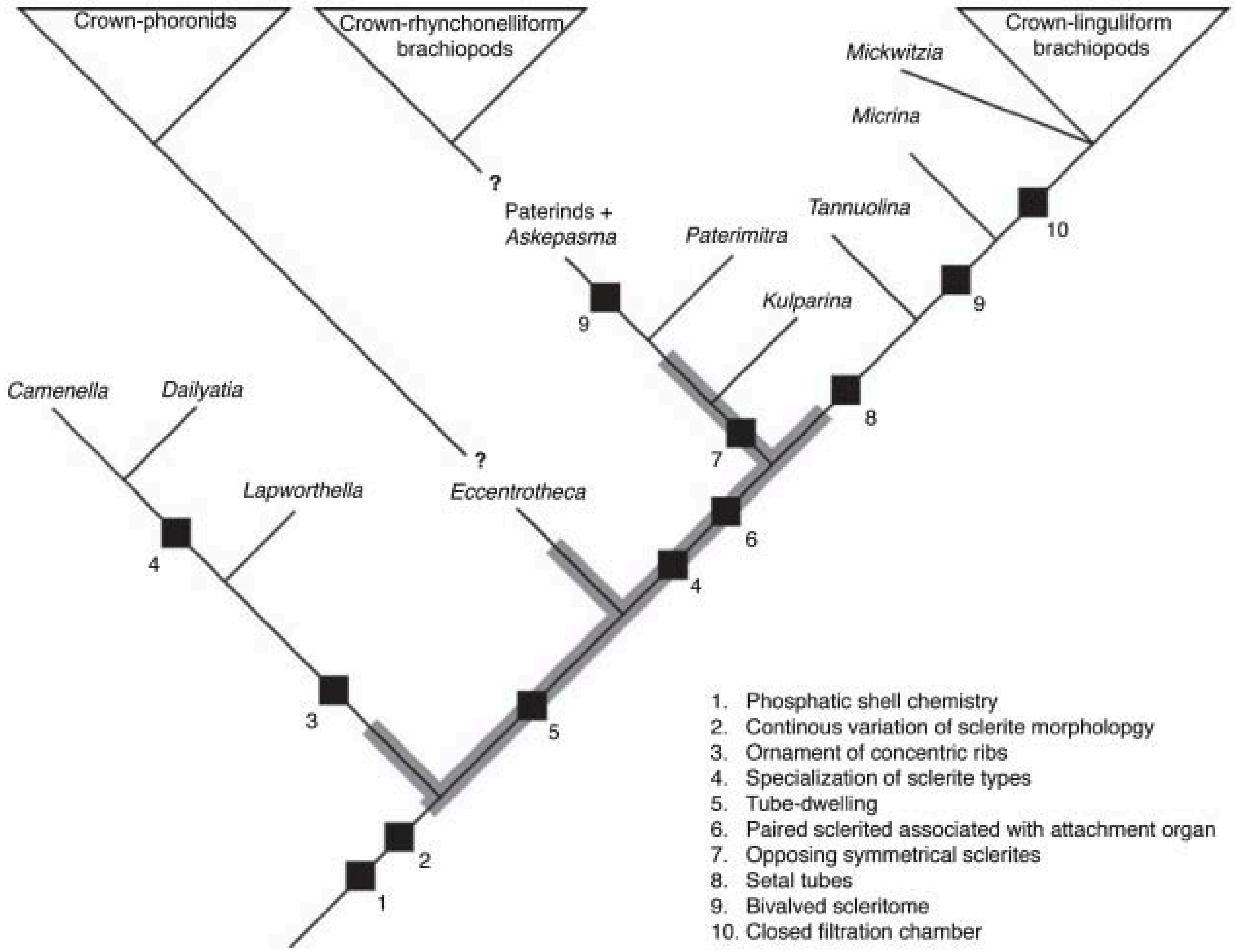


FIG. 9. Hypothetical reconstruction of the phylogenetic relationships between the tommotiids and crown-brachiopods, based on Skovsted *et al.* (2009*a*; 2011) modified by Holmer *et al.* (2011). Phylogenetic positions for *Sunnaginia* consistent with the data presented here and characters suggested by Skovsted *et al.* (2009*a*; 2011) shown in the grey box. *Sunnaginia*, like all tommotiids, possessed phosphatic sclerites [1] and shares continuous variation in shell morphology [2] with *Eccentrotheca*, but lacks the ornamented concentric ribs [3] of the camenellans [3,4], linguliform brachiopods [8–10] or paterinid brachiopods [9]. As no articulated scleritomes for *Sunnaginia* are known, it is uncertain whether characters [5], [6] and [7] were present or absent for that genera, and it has been suggested the *Sunnaginia* scleritome may have possessed differentiated sclerites [4] (Landing 1995).

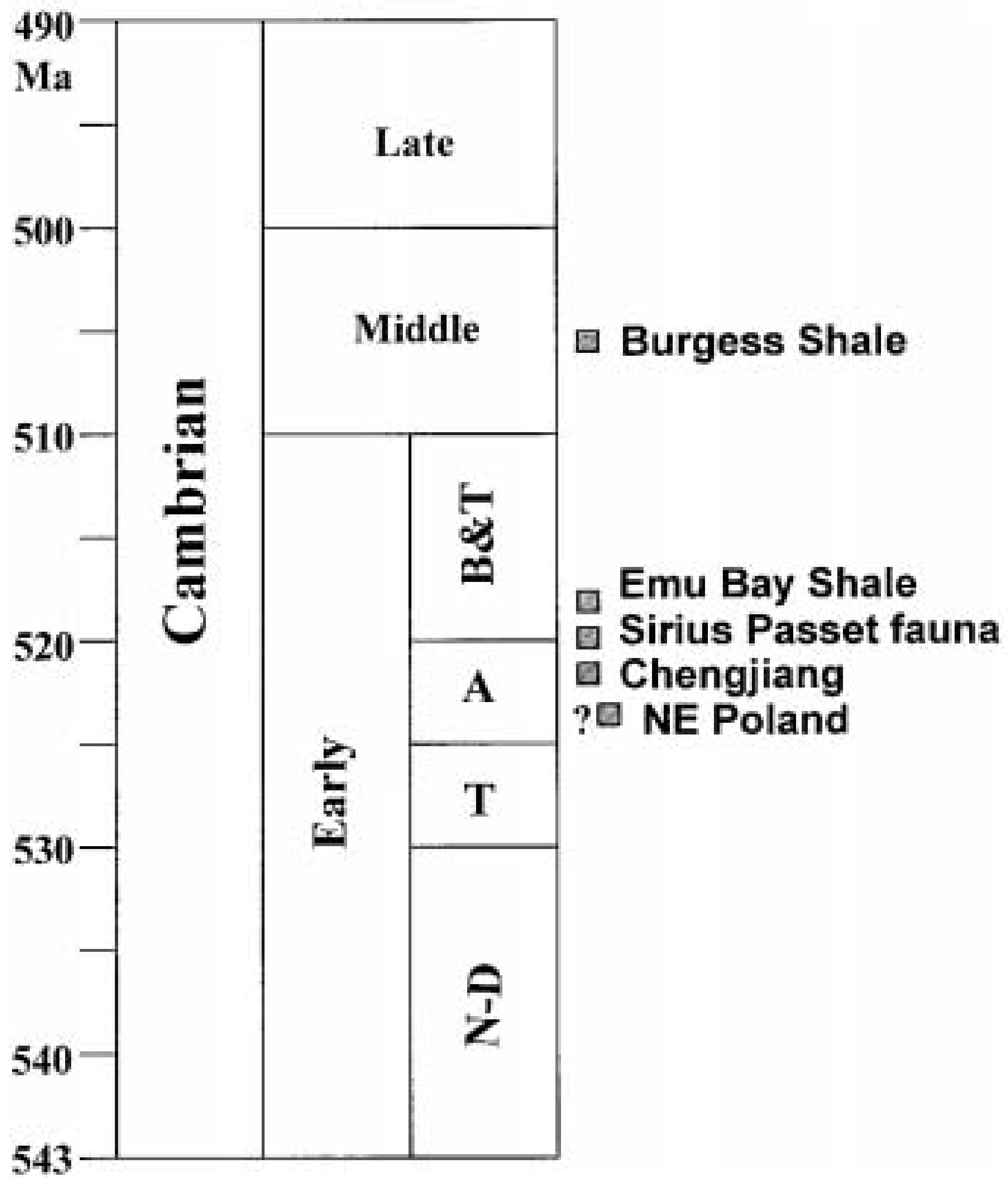


Fig. 2. Time scale showing several well-known Cambrian fossil Lagerstätten. Regional Siberian Stage names are as follows: N-D, Nemakit-Daldynian; T, Tommotian; A, Atdabanian; B & T, Botomian and Toyonian.

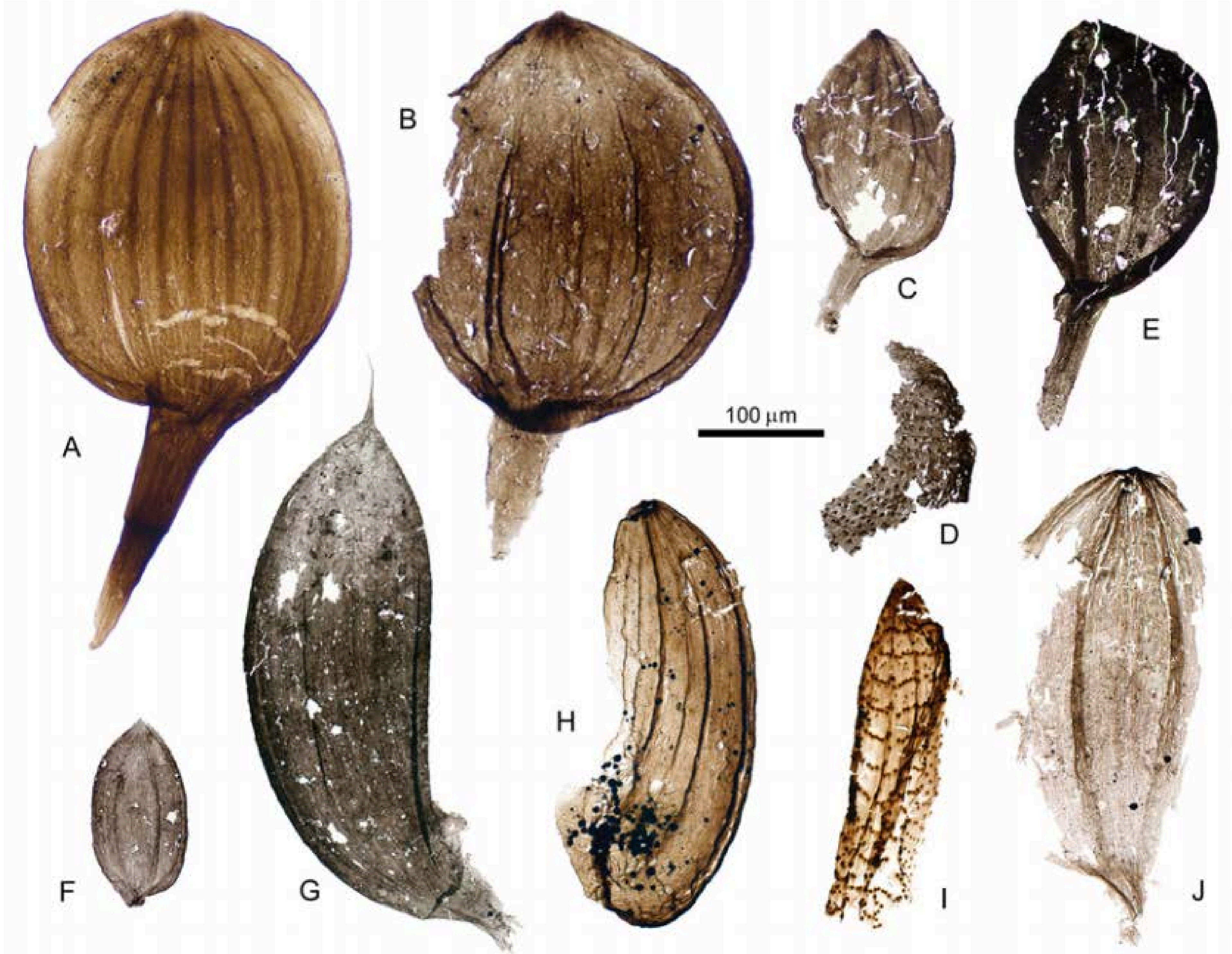
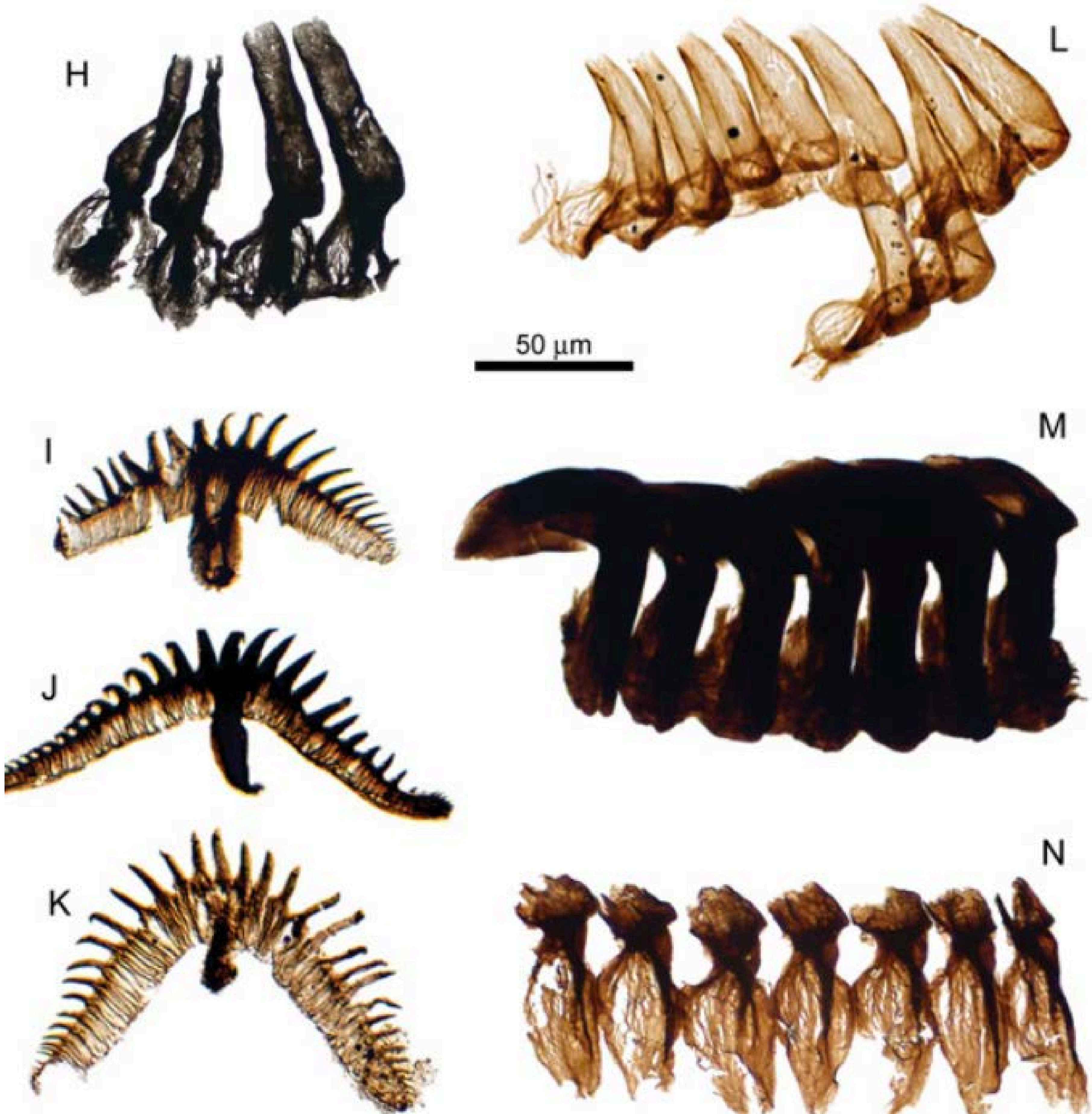


Figure 1. ***Wiwaxia*** **sclerites. A: Mount Cap Formation (Colville Hills), late early Cambrian, Northwest Territories, Canada. B: Kaili Formation, early middle Cambrian, Guizhou, China. C: Pika Formation, latest middle Cambrian, Alberta, Canada. D: Mahto Formation, late early Cambrian, Alberta. E: Burgess Shale, middle Cambrian, British Columbia, Canada. F, G: Hess River Formation, early middle Cambrian, Northwest Territories. H, I: Earlie Formation, late middle Cambrian, Saskatchewan, Canada. J: Forteau Formation, late early Cambrian, Newfoundland, Canada.**


H
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50 μm
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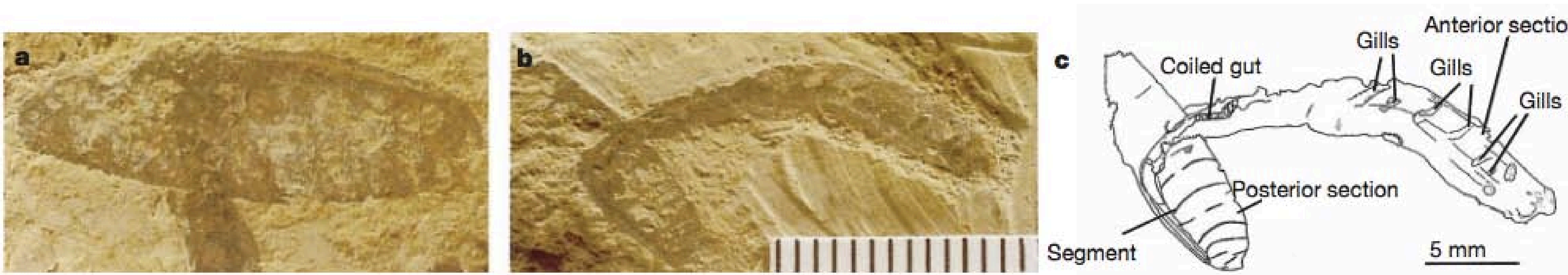


Figure 6 The Lower Cambrian *Yunnanozoon lividum* from Chengjiang, Yunnan. **a**, Part, complete specimen, Specimen NWU93-1406A. **b**, Counterpart, detail of posterior section and its attachment to anterior section, NWU93-1406B. **c**, Camera-lucida drawing wi details of part and counter-part combined. In **b**, a millimetric scale bar is shown.

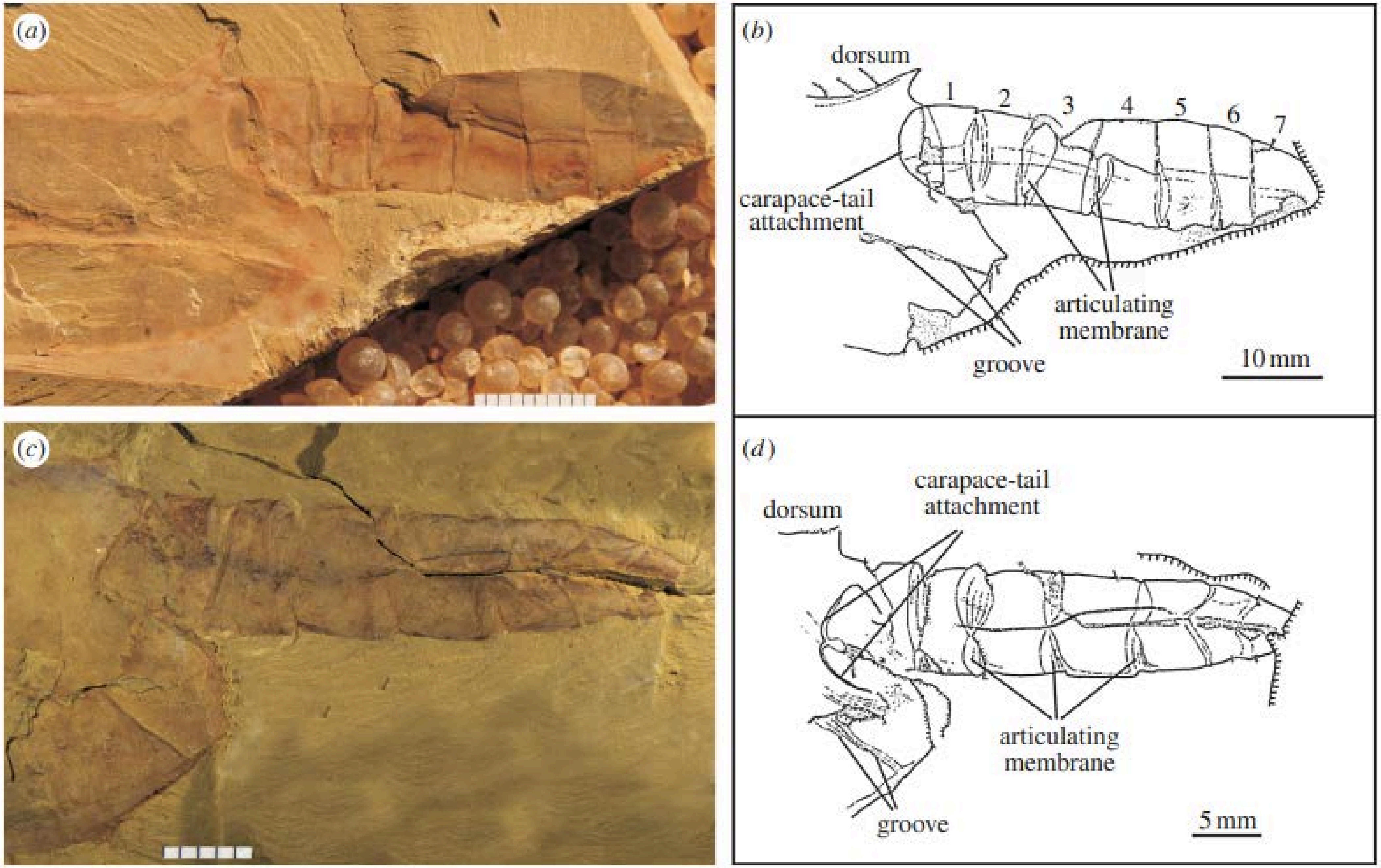
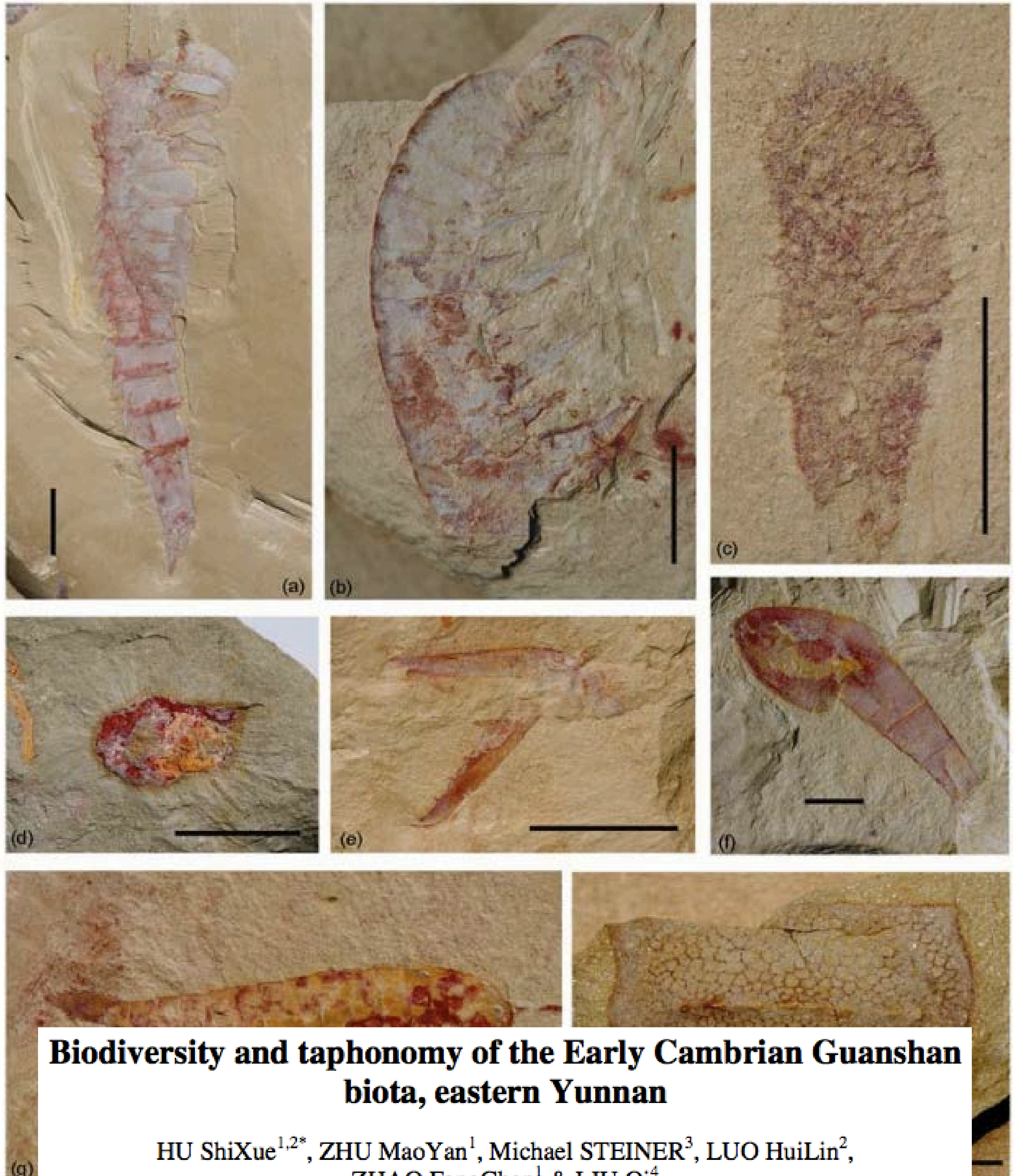
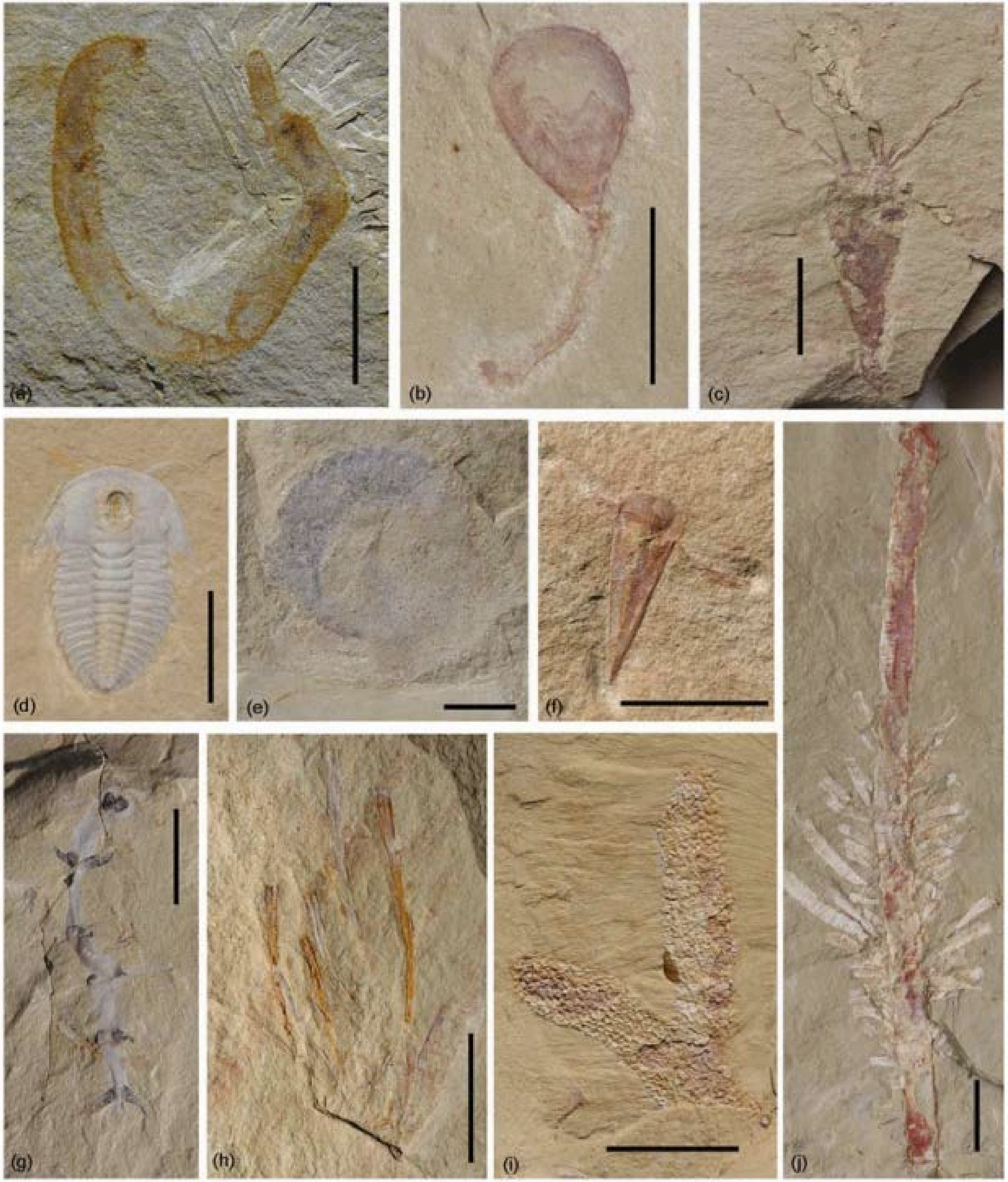


Figure 1. *Vetulicola cuneata*: possible stem-group Deuterostomia. (*a–d*) Details of the posterior body. ELI-0000301, posterior of body to show (*a*) articulation of the tail, (*b*) with camera-lucida interpretation; ELI-0000302, (*c*) tail in approximately ventral orientation; note absence of fin, (*d*) with camera-lucida interpretation. All scale bars millimetric. Abbreviation in this and figure 2: ELI, Early Life Institute, Northwest University, Xi'an, China.



Biodiversity and taphonomy of the Early Cambrian Guanshan biota, eastern Yunnan

HU ShiXue[1,2*], ZHU MaoYan[1], Michael STEINER[3], LUO HuiLin[2], ZHAO FangChen[1] & LIU Qi[4]


(a)
(b)
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(e)
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(g)
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NEW ARTIOPODAN ARTHROPODS FROM THE EARLY CAMBRIAN EMU BAY SHALE KONSERVAT-LAGERSTÄTTE OF SOUTH AUSTRALIA

JOHN R. PATERSON,[1] DIEGO C. GARCÍA-BELLIDO,[2] AND GREGORY D. EDGECOMBE[3]

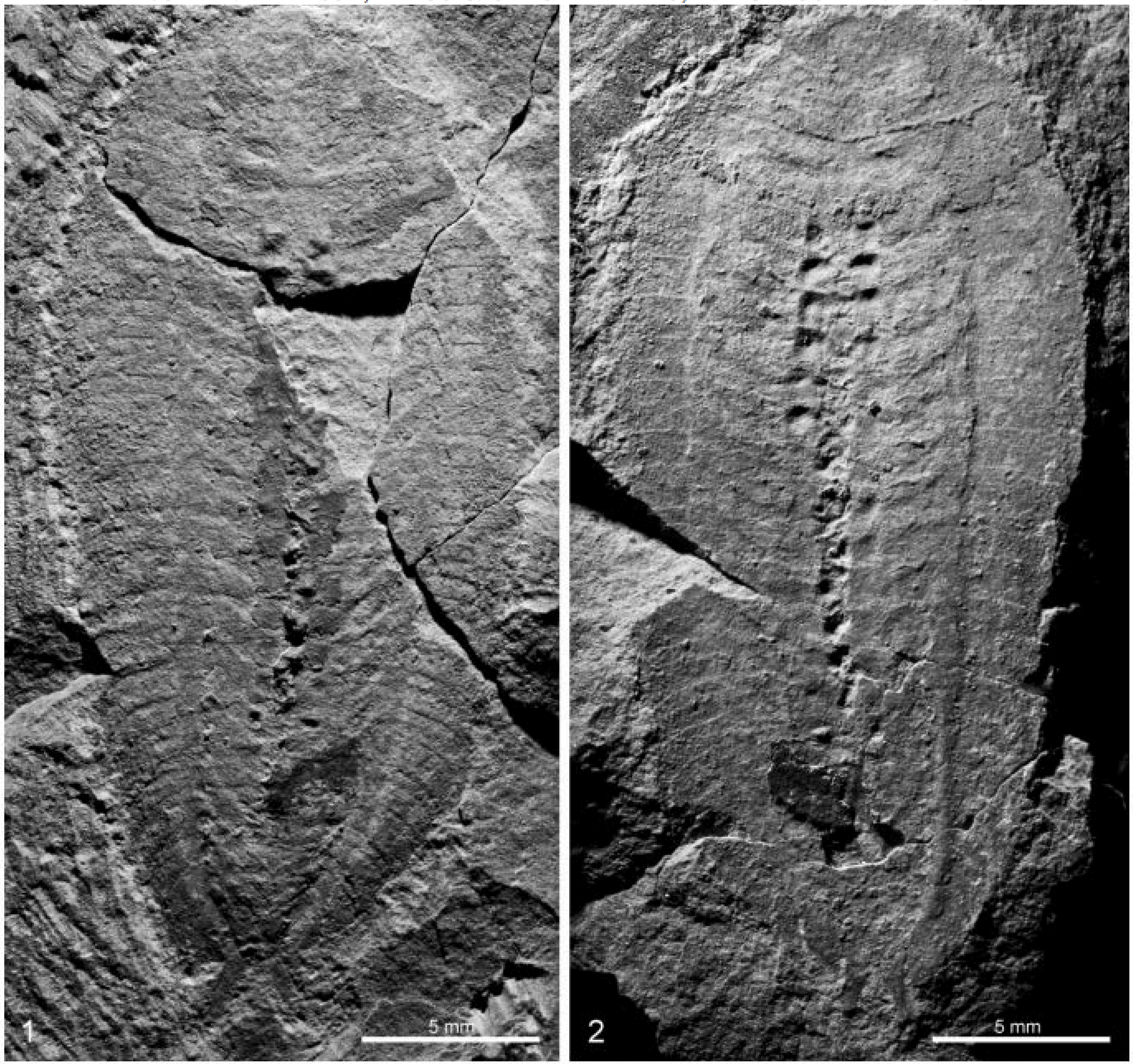
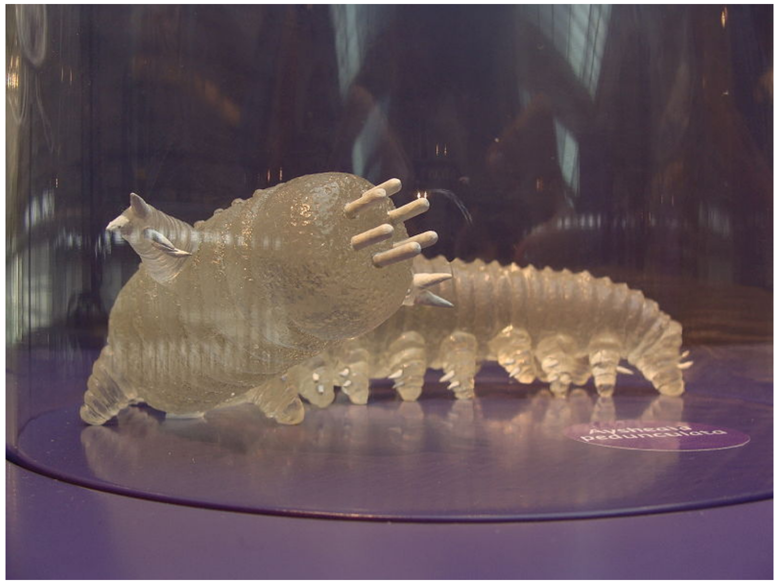


FIGURE 10—Holotype of *Australimicola spriggi* n. gen. n. sp., SAM P44482. *1*, *2*, part (SAM P44482a) and counterpart (SAM P44482b), respectively, of near complete specimen showing impression of hypostome, 3D mineralized midgut glands, faint endopod impressions, and pygidium with a pair of

Burgess Shale Fauna

Photgraph is by Charles D. Walcott and is in the public domain.



Courtesy of Eduard Sola Vazquez. CC-BY.

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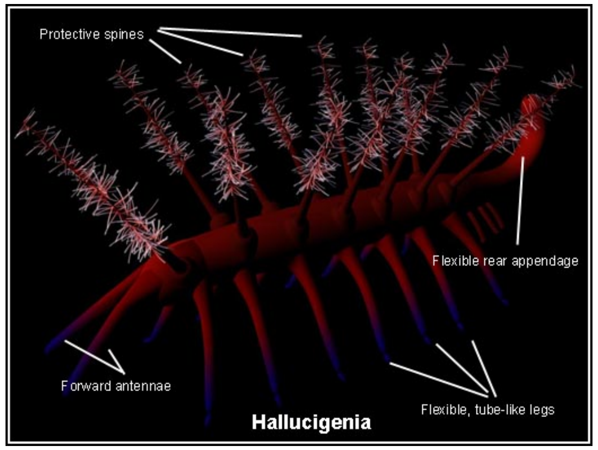
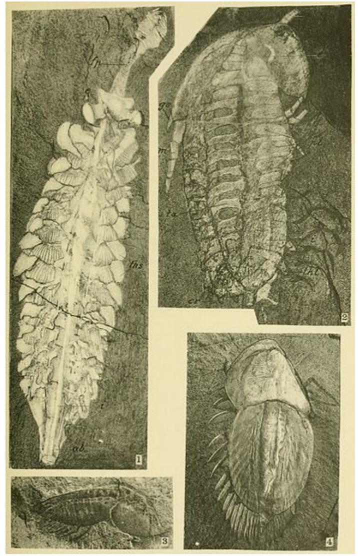




Photgraph is by Charles D. Walcott and is in the public domain.

Courtesy of Nobu Tamura. CC-BY.

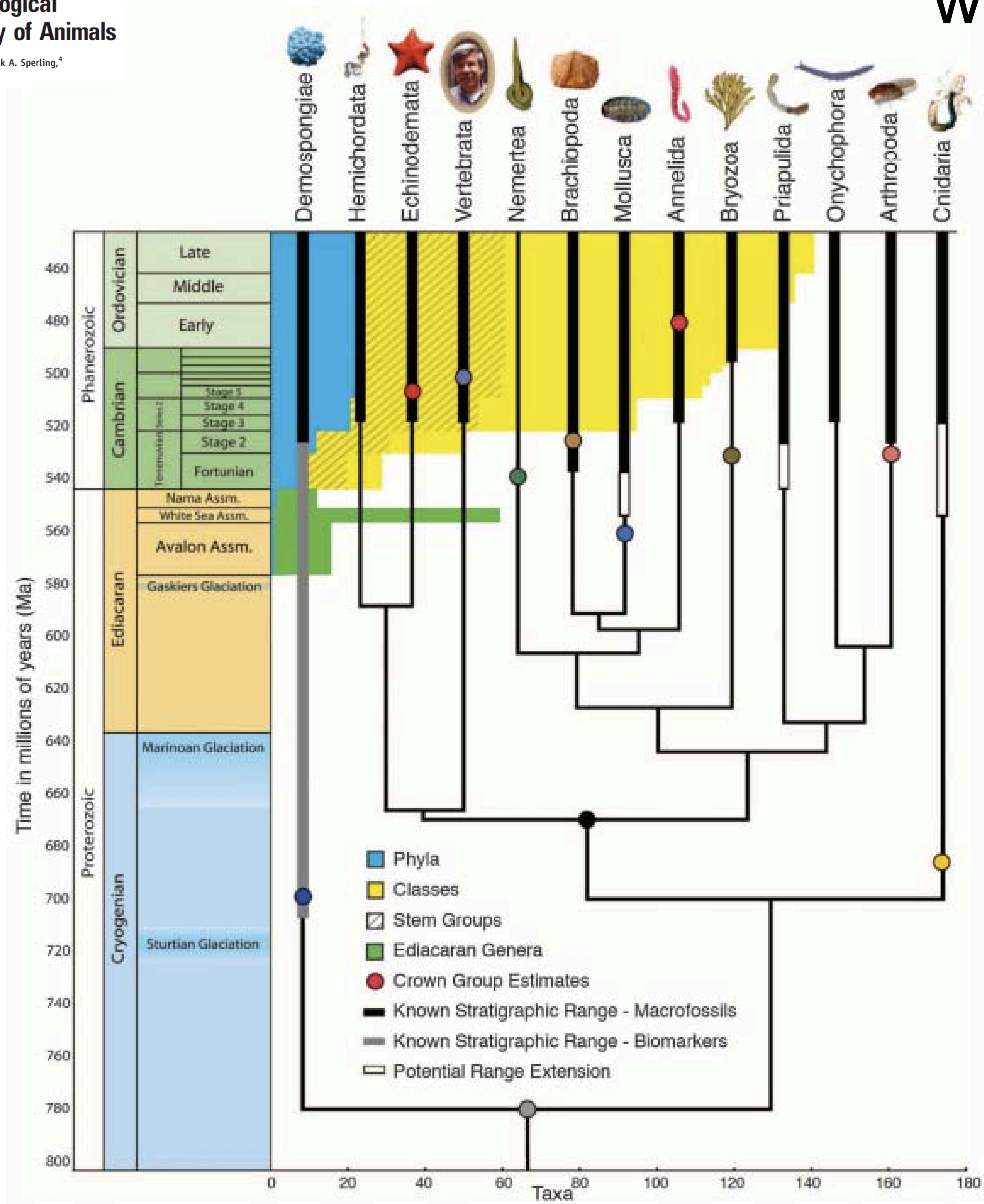
Cambrian Radiation & its Causes

- What causes complexity?
- Environment - oxygen / hydrogen sulfide
- Genomic requirements
- Ecological interactions / predation

The Cambrian Conundrum: Early Divergence and Later Ecological Success in the Early History of Animals

Douglas H. Erwin,[1,2*] Marc Laflamme,[1] Sarah M. Tweedt,[1,3] Erik A. Sperling,[4] Davide Pisani,[5] Kevin J. Peterson[6*]

why does this lag exist?



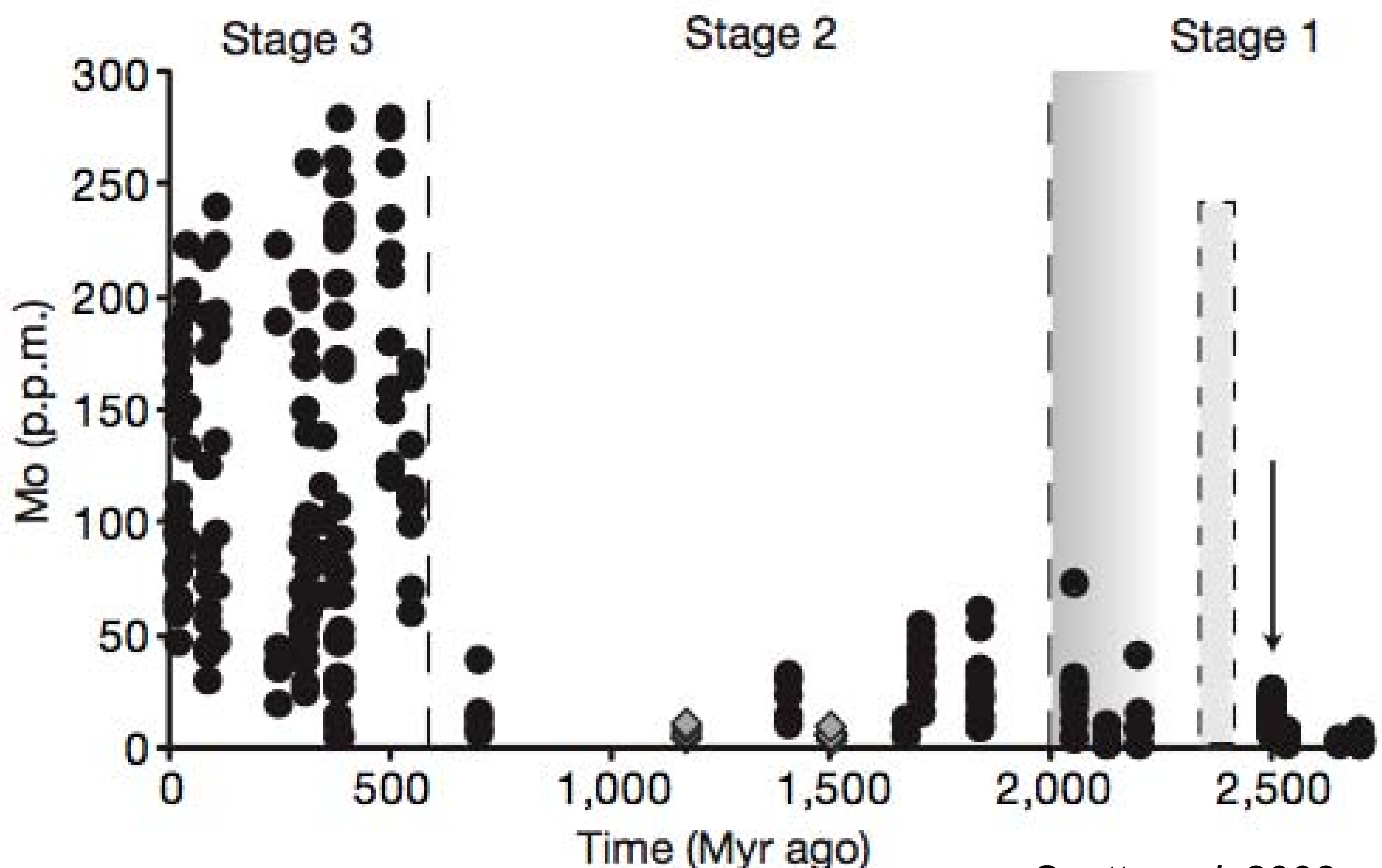
 Source: Erwin, D. H., et al. "The Cambrian Conundrum: Early Divergence and Later Ecological Success in the Early History of Animals." *Science* 334, no. 6059 (2011): 1091-7.

Redox

- Animals require oxygen in varying amounts
- H_2S is toxic to pretty much all animals, algae, etc - shuts down cellular respiration by complexing w/ iron in mitochondria (ouch)

Ediacaran/Cambrian Rise in Oxygen (sometimes)

Redox sensitive metals show a change in the late Ediacaran



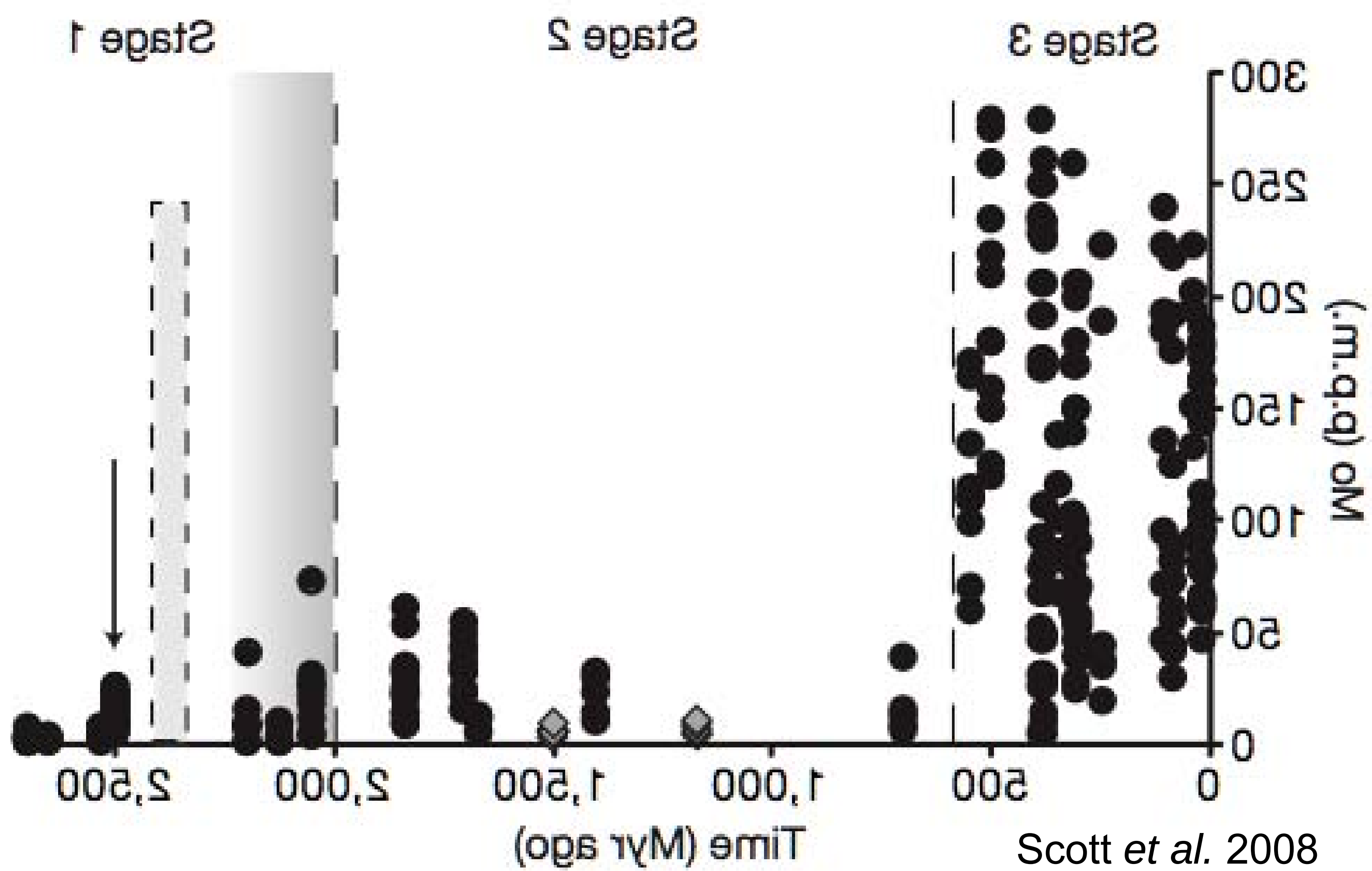
Scott *et al.* 2008

Ediacaran/Cambrian Rise in Oxygen (sometimes)

Euxinia (no O_2, lots of H_2S) ↓ → Mo ↑

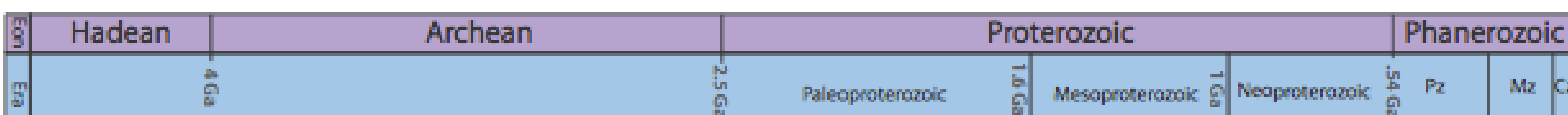
Less Oxygen

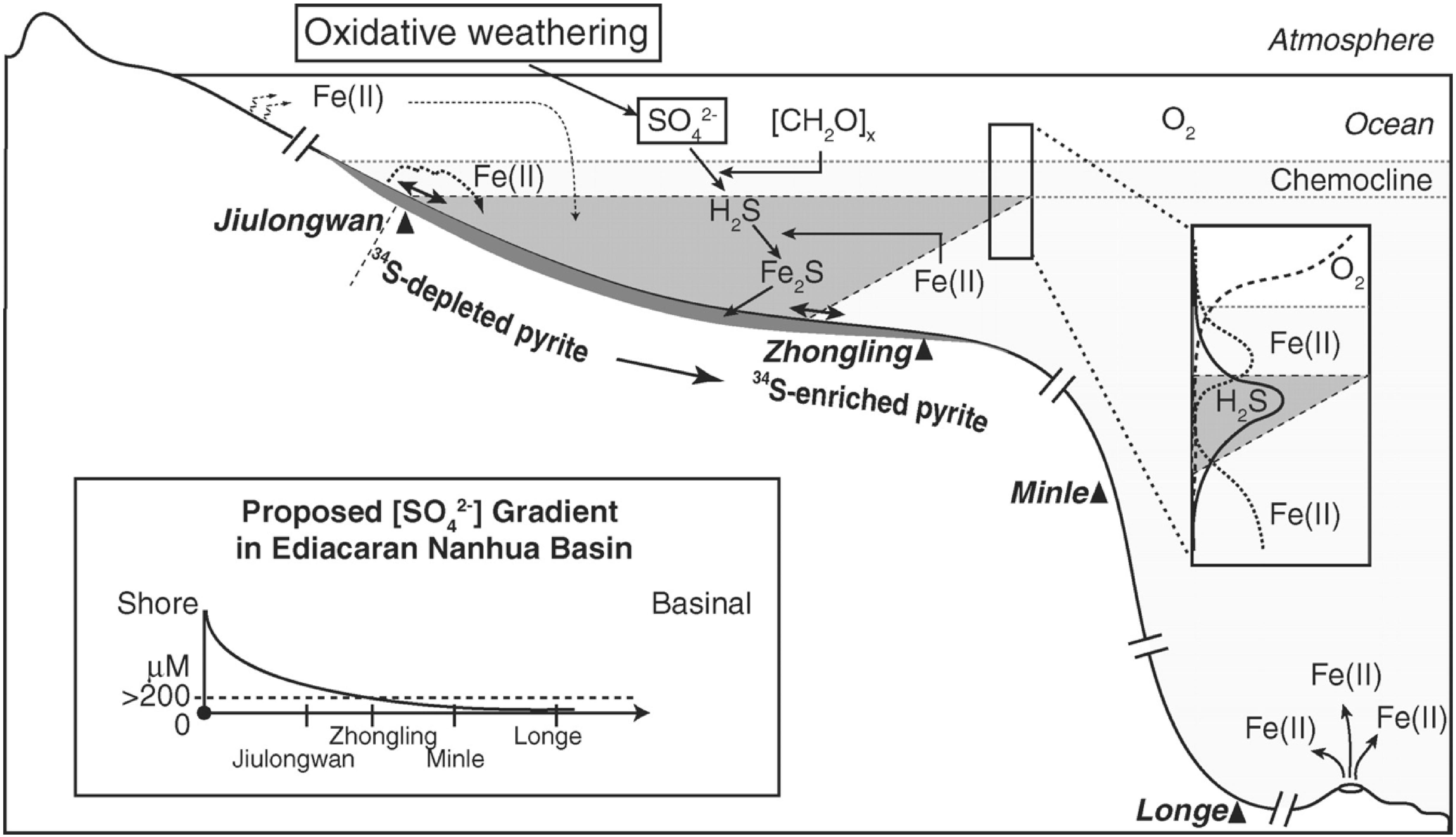
More Oxygen



Scott *et al.* 2008

Courtesy of Nature Publishing Group. Used with permission. Source: Scott, C., et al. "Tracing the Stepwise Oxygenation of the Proterozoic Ocean." *Nature* 452, no. 7186 (2008): 456-9.





A Stratified Redox Model for the Ediacaran Ocean

Chao Li[1,*], Gordon D. Love[1], Timothy W. Lyons[1], David A. Fike[2], Alex L. Sessions[3] and Xuelei Chu[4]

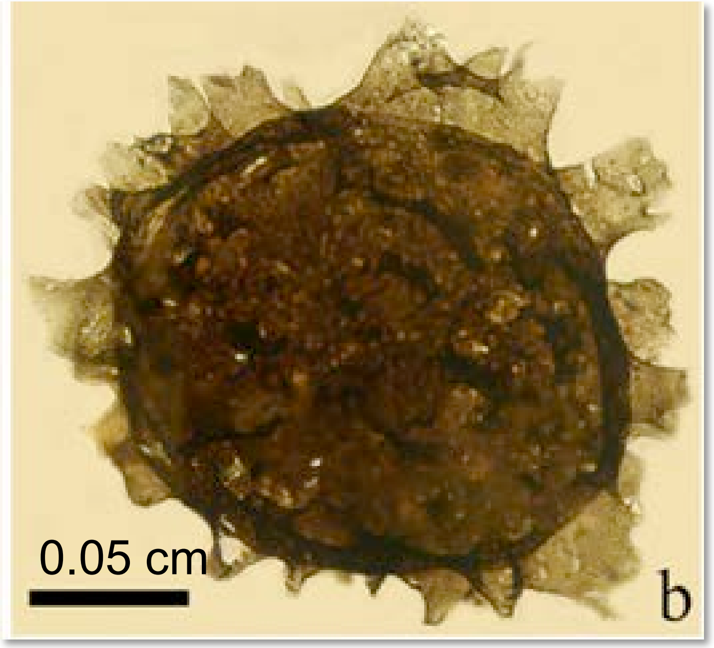
Changing Redox conditions: Testing the Hypothesis

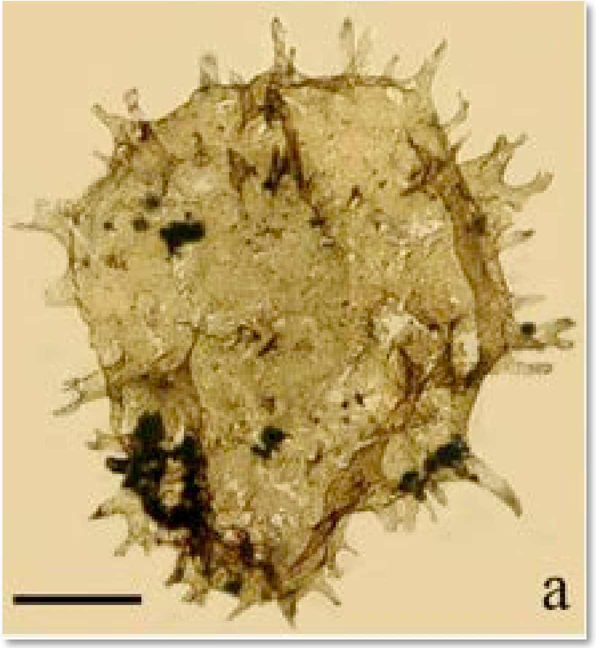
Expect changes in the distribution of fossils in the Ediacaran relative to proxies for oxygenation

i.e. LOEM's in lower oxygen settings, and macroscopic organisms in higher oxygen settings

Test Site: Kelt'ma -1 drillcore (modern day Russia)

macroscopic

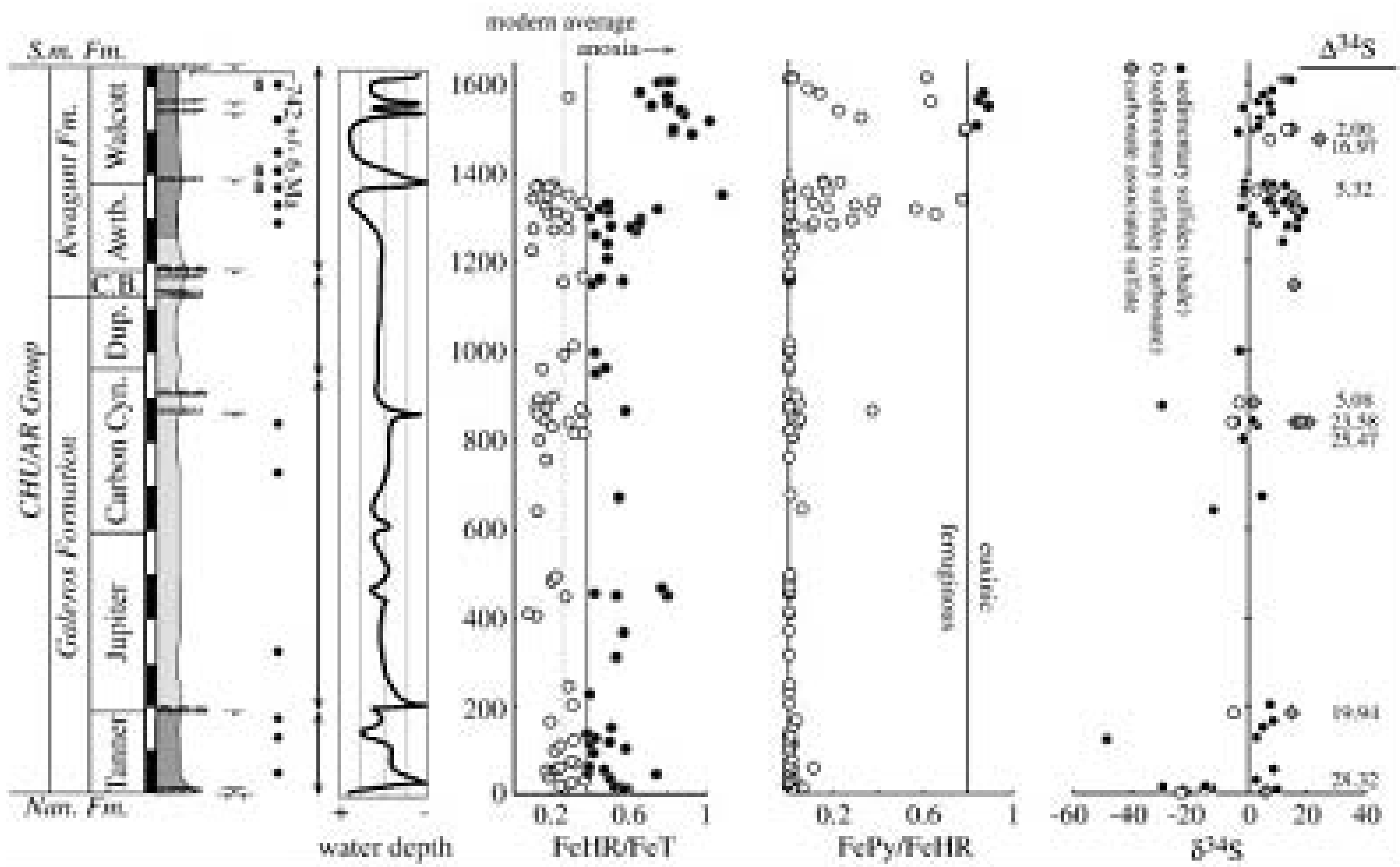




microscopic

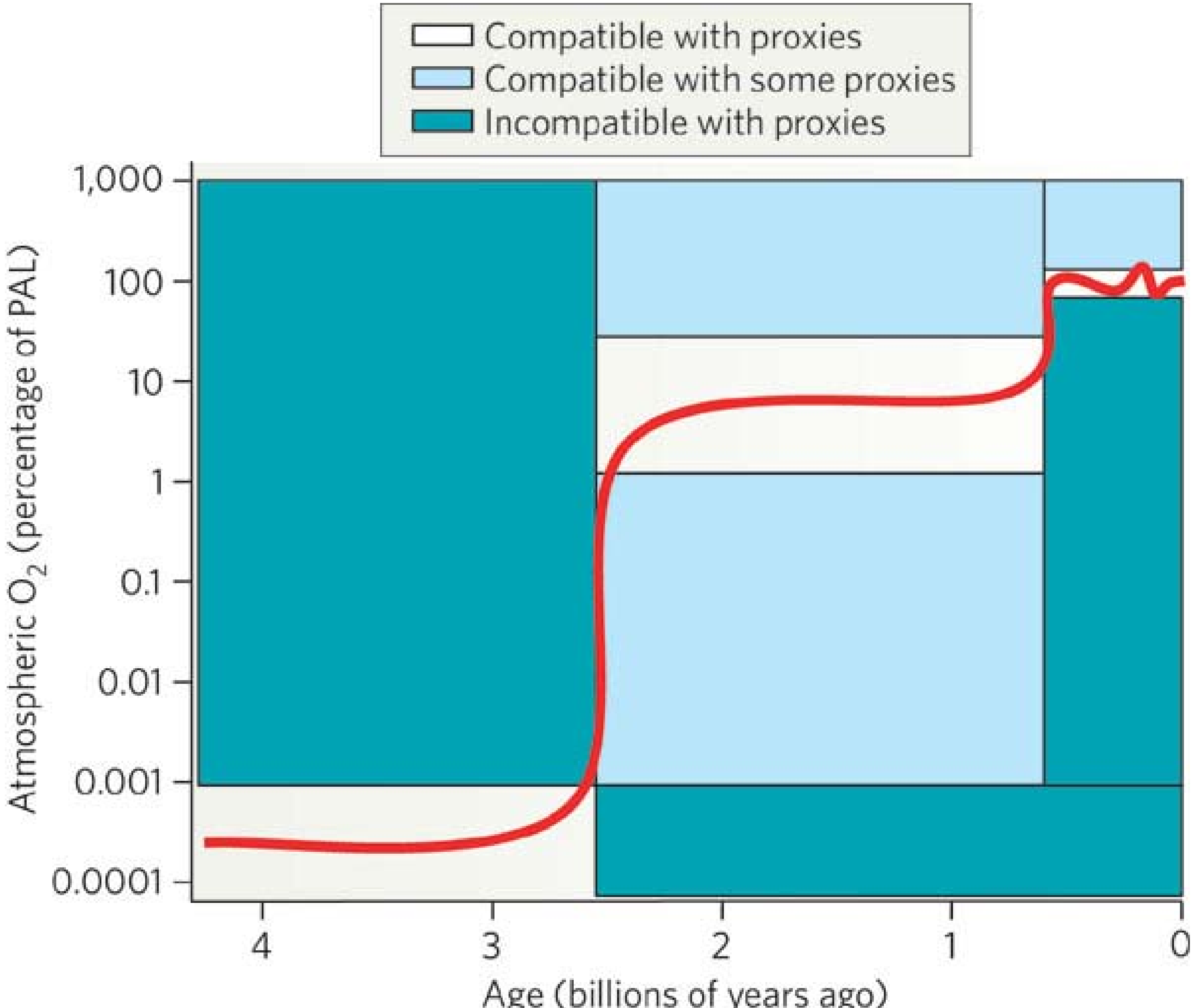
Vorob'eva et al., 2009

Eastern European Platform

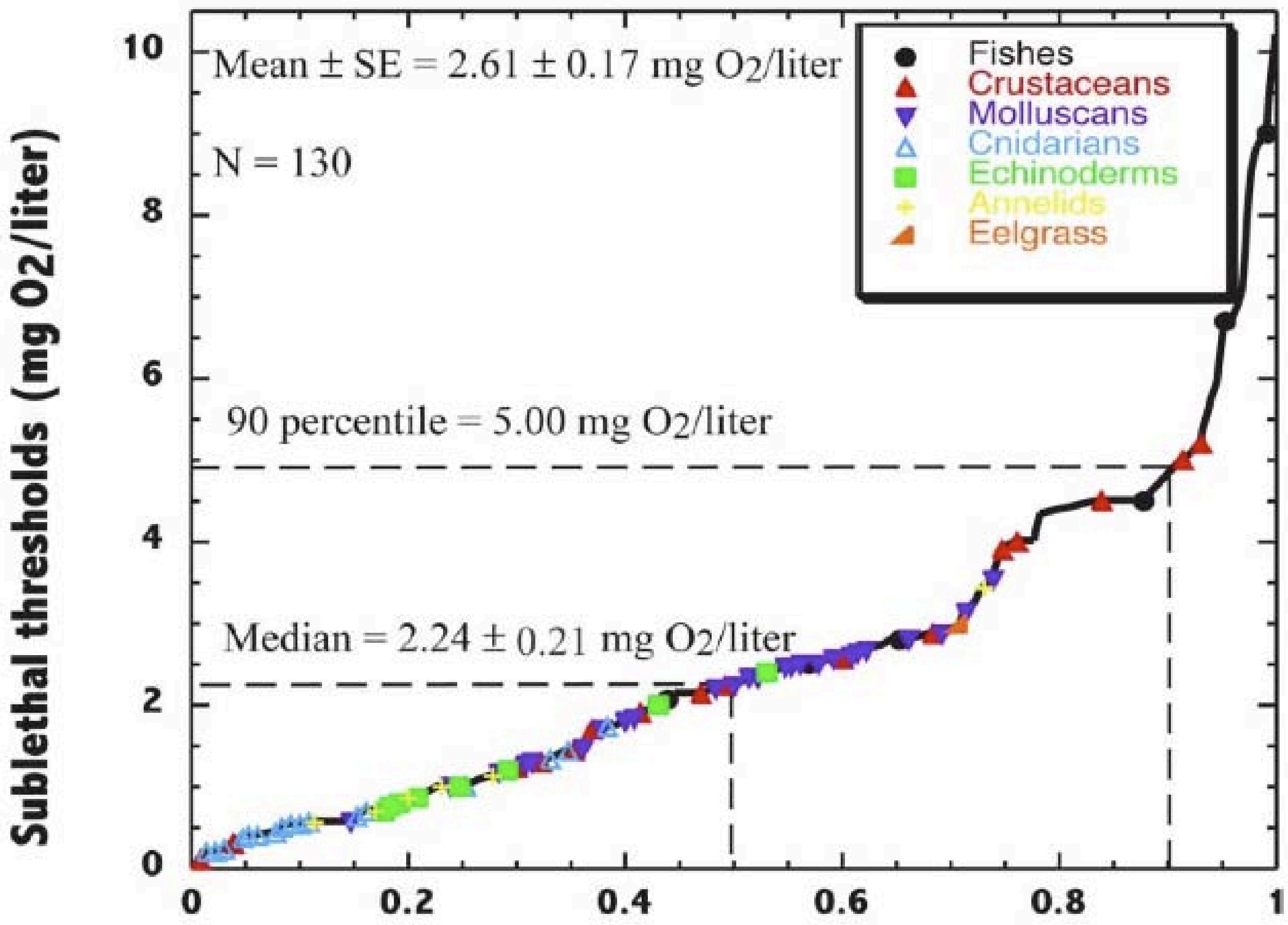


Johnston *et al.* in prep

MAJOR Challenge

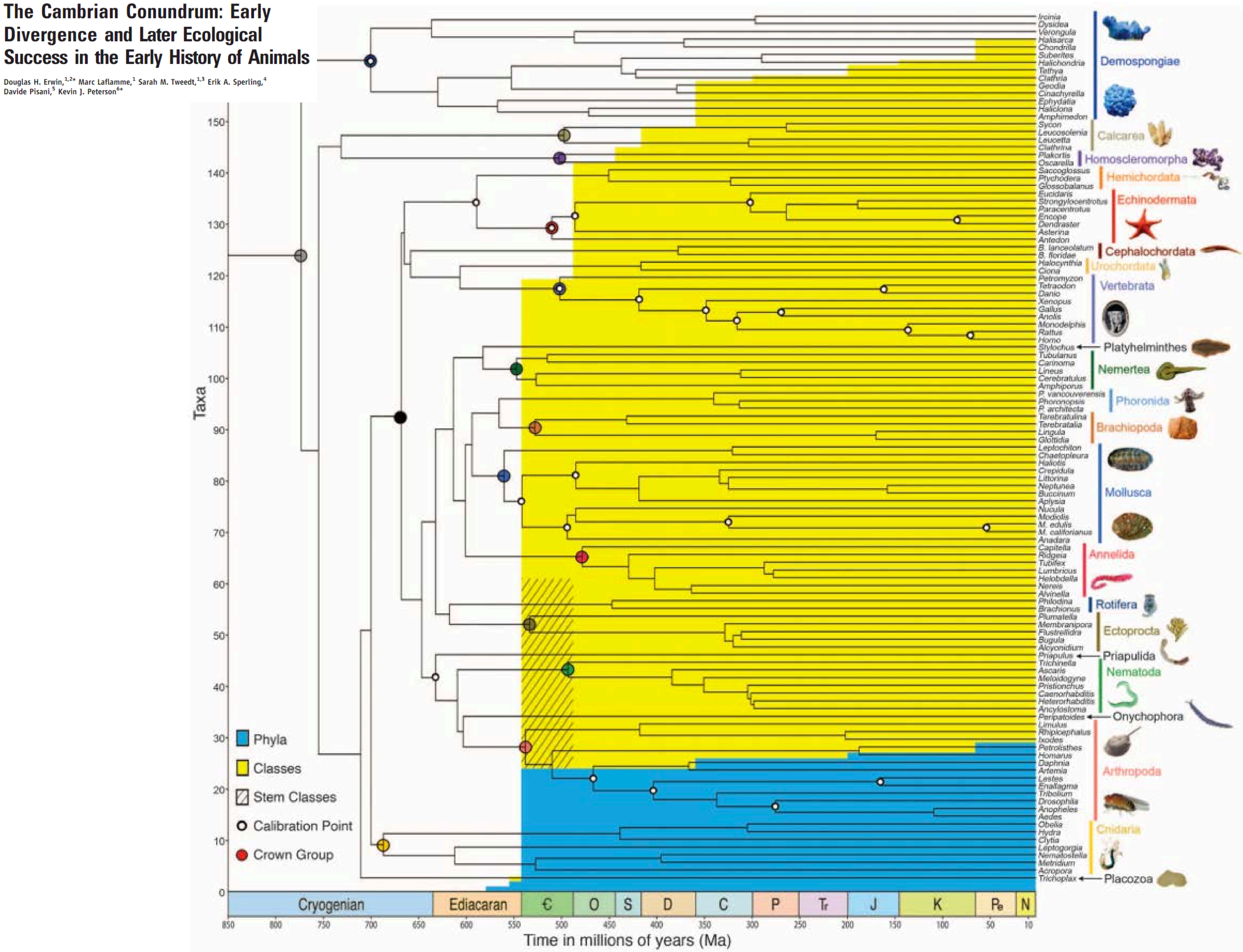


Lee R. Kump

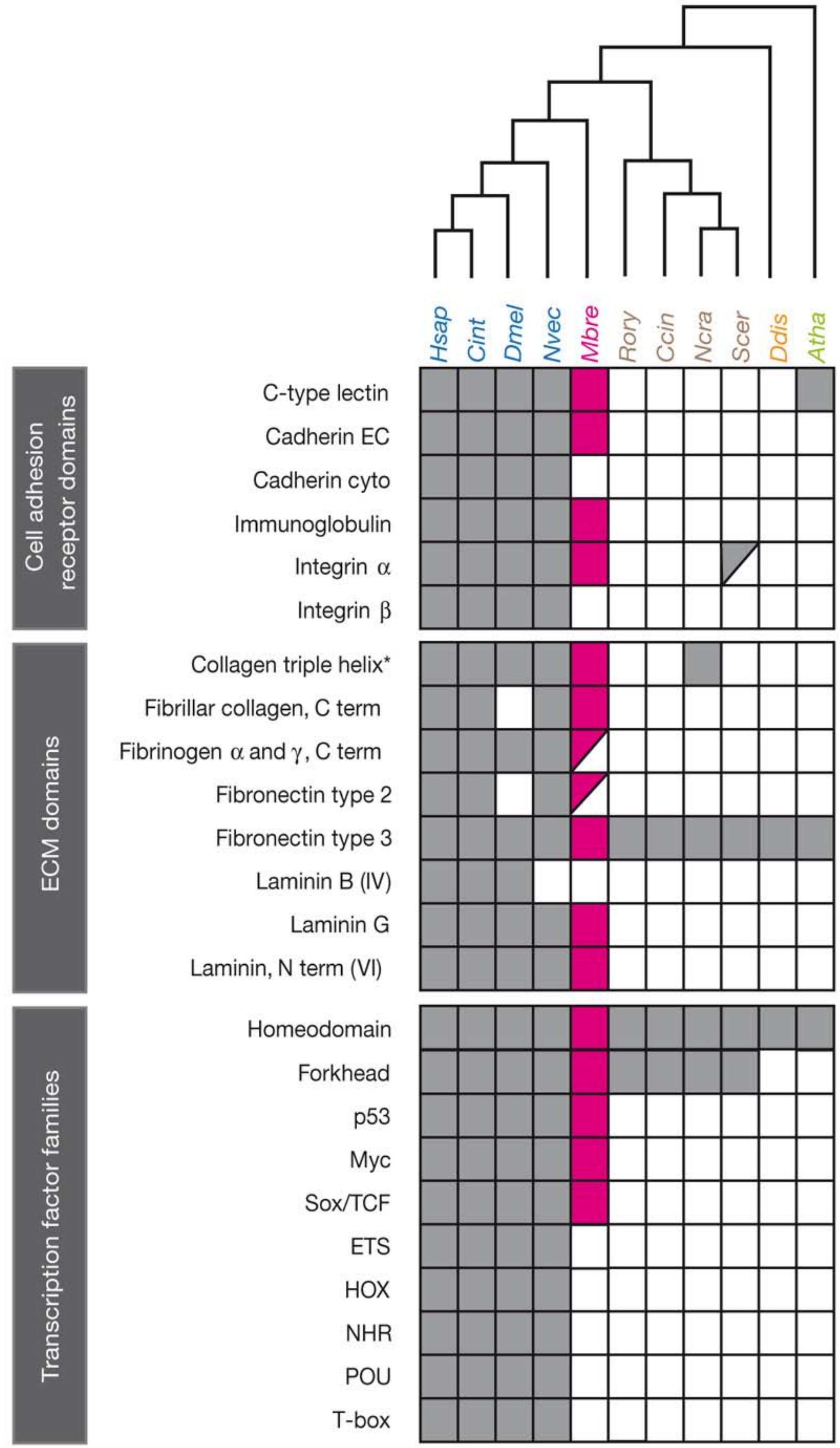


Thresholds of hypoxia for marine biodiversity

Raquel Vaquer-Sunyer* and Carlos M. Duarte



 Source: Erwin, D. H., et al. "The Cambrian Conundrum: Early Divergence and Later Ecological Success in the Early History of Animals." *Science* 334, no. 6059 (2011): 1091-7.



 Source: King, N. M., et al. "The Genome of the Choanoflagellate Monosiga Brevicollis and the Origin of Metazoans." *Nature* 451, no. 7180 (2008): 783-8.

Explaining the Cambrian "Explosion" of Animals

Charles R. Marshall

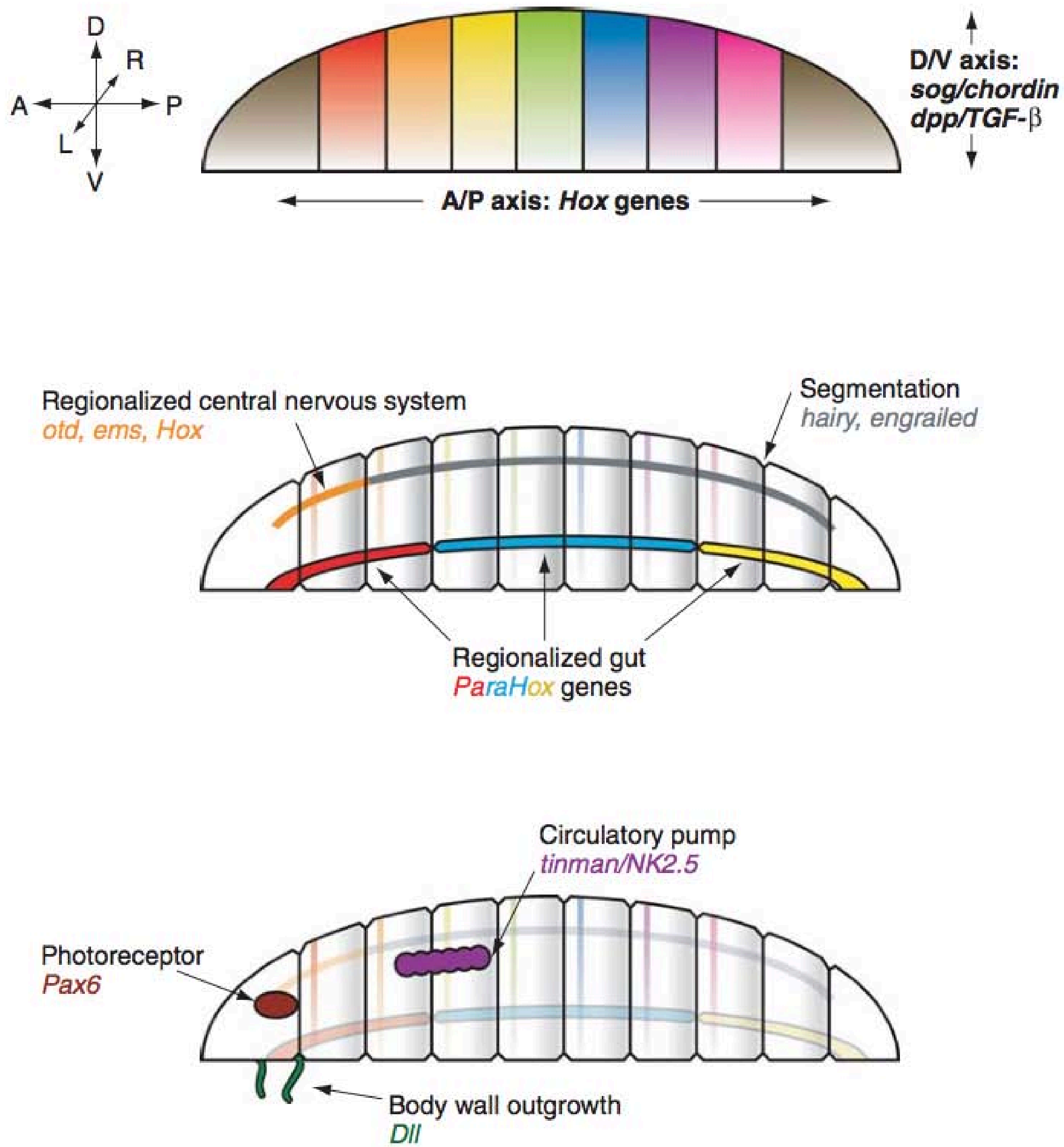


Figure 2

A few of the key developmental genes, and the morphologies they may have conferred, inferred to have been present in the last common ancestor of all the bilaterian phyla (the *ur*-bilaterian), based on the phylogenetic distribution of developmental genes in mouse and fly. Top: The anterior/posterior (A/P) axis may have been subdivided by nested, overlapping domains of *Hox* gene expression. The dorsal/ventral (D/V) axis may have been controlled by ancestral genes of the *short gastrulation* (*sog*)/*chordin* and TGF-β families. Middle: Different tissue layers were regionally patterned along the A/P axis, including the gut (*paraHox* gene cluster) and nervous system [*orthodenticle* (*otd*), *empty spiracles* (*ems*), *Hox* genes). Segmentation (seriation) may have been present through the action of the genes ancestral to *engrailed* and *hairy*. Bottom: Ancestral photoreceptor organs (*Pax6*), circulatory pump (*tinman/NK2.5*) and outgrowths/ingrowths of the body wall [*Distal-less* (*Dll*)] are also inferred to have been part of the morphogenetic potential of the *ur*-bilaterian. From Carroll et al. (2001), published with permission.

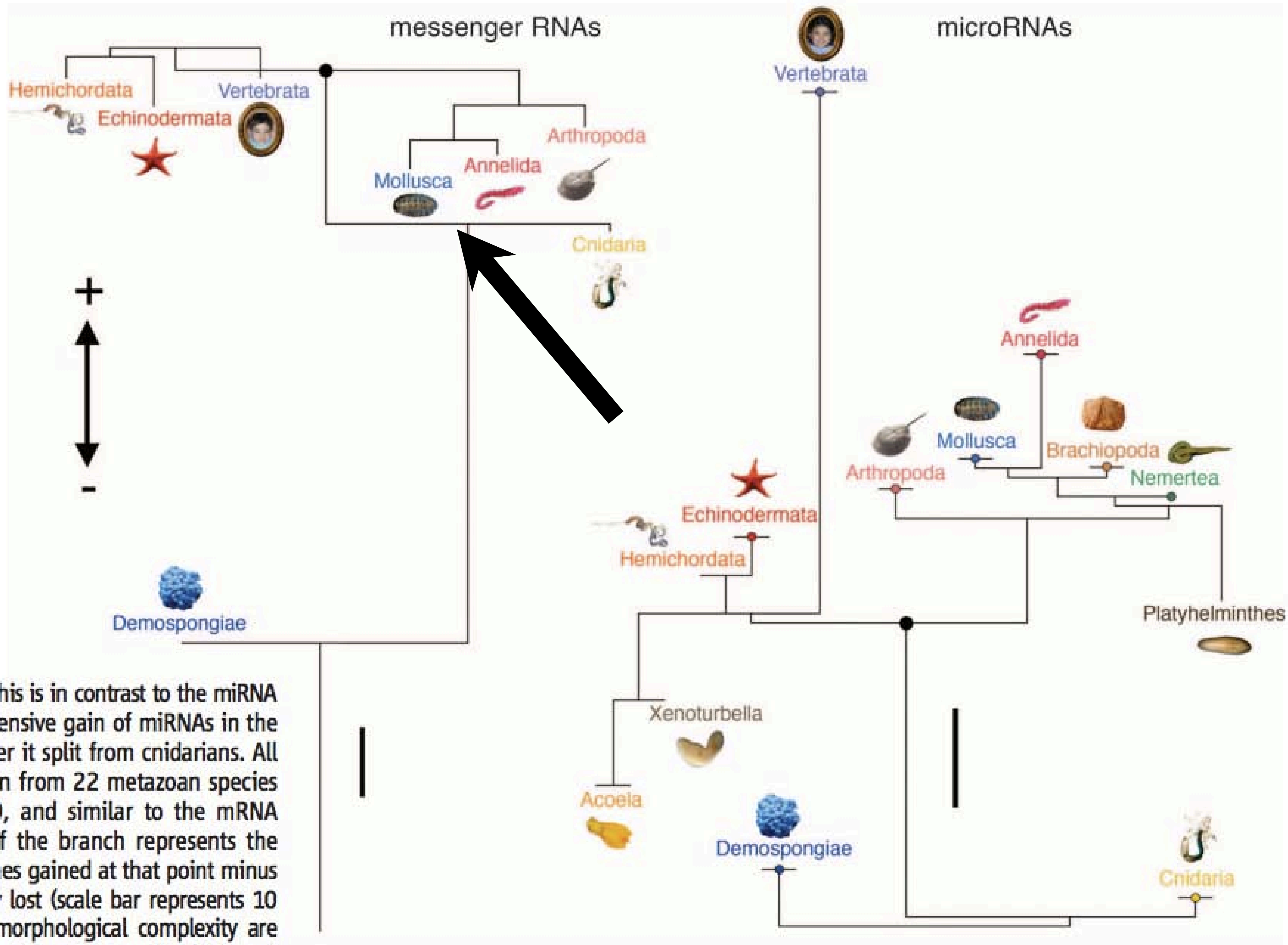
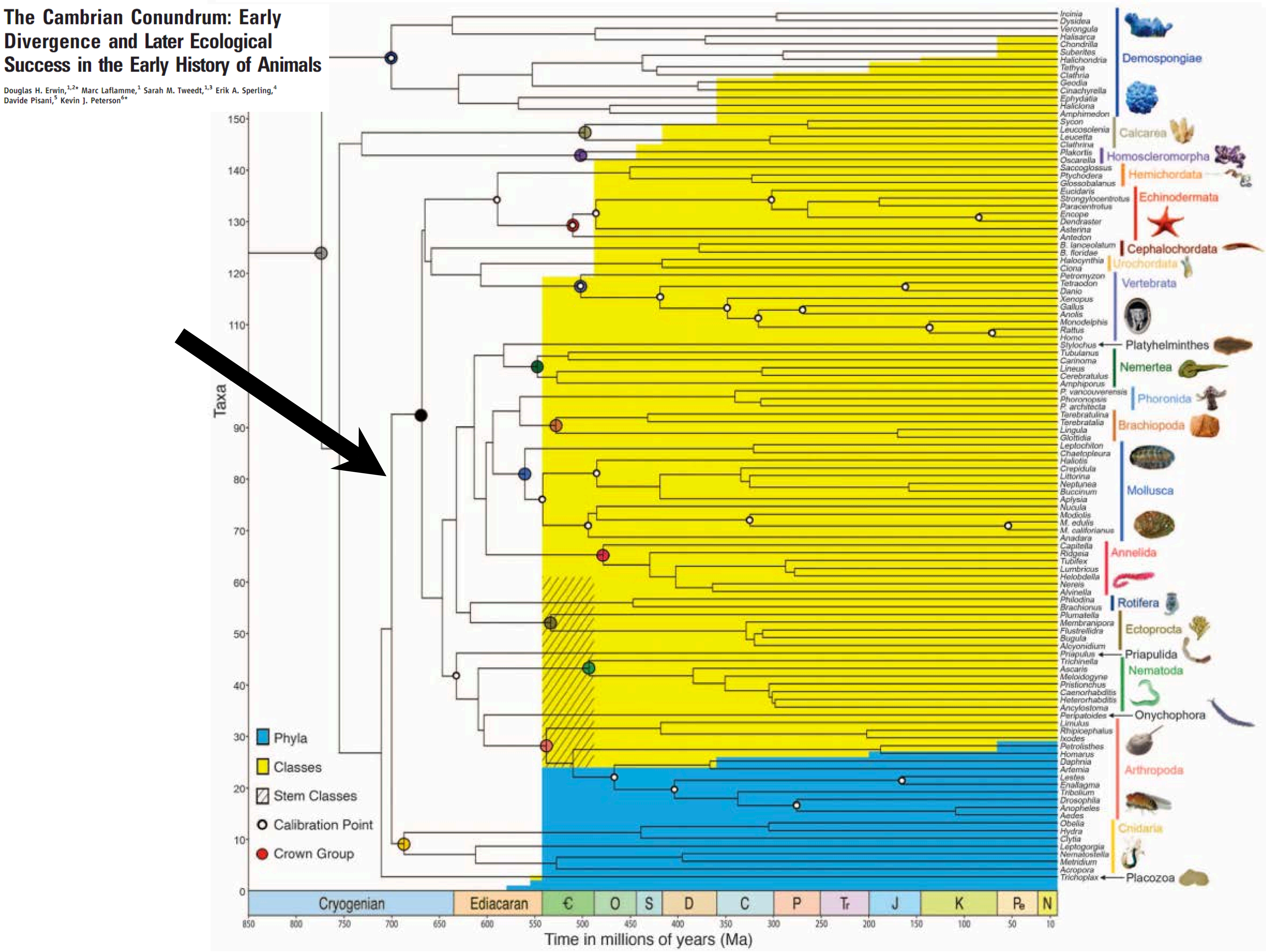


Fig. 4. Acquisition and secondary loss of messenger RNAs (mRNAs, **left**) and microRNAs (miRNAs, **right**) in selected taxa. One hundred and thirty-one representative transcription factors and signaling ligands were coded for eight metazoan taxa (database S3) and mapped onto a widely accepted metazoan topology (*15*, *16*). The length of the branch represents the total number of mRNA genes acquired minus those that were lost (scale bar represents 10 genes total). Much of the developmental mRNA toolkit was acquired before the last common ancestor of cnidarians and bilaterians. This is in contrast to the miRNA repertoire that displays extensive gain of miRNAs in the bilaterian stem lineage after it split from cnidarians. All 139 miRNA families known from 22 metazoan species were coded (database S4), and similar to the mRNA figure (left), the length of the branch represents the total number of miRNA genes gained at that point minus those that were secondarily lost (scale bar represents 10 genes total). Increases to morphological complexity are correlated with increases to the miRNA toolkit (*60*), and secondary simplifications in morphology correlate with a relatively high level of secondary miRNA loss (*20*).



The Cambrian Conundrum: Early Divergence and Later Ecological Success in the Early History of Animals
Douglas H. Erwin,[1,2*] Marc Laflamme,[1] Sarah M. Tweedt,[1,3] Erik A. Sperling,[4] Davide Pisani,[5] Kevin J. Peterson[6*]
Taxa
Demospongiae
Calcarea
Homoscleromorpha
Hemichordata
Echinodermata
Cephalochordata
Urochordata
Vertebrata
Platyhelminthes
Nemertea
Phoronida
Brachiopoda
Mollusca
Annelida
Rotifera
Ectoprocta
Priapulida
Nematoda
Onychophora
Arthropoda
Cnidaria
Placozoa
Phyla
Classes
Stem Classes
Calibration Point
Crown Group
Cryogenian
Ediacaran
€
O
S
D
C
P
Tr
J
K
Pe
N
Time in millions of years (Ma)

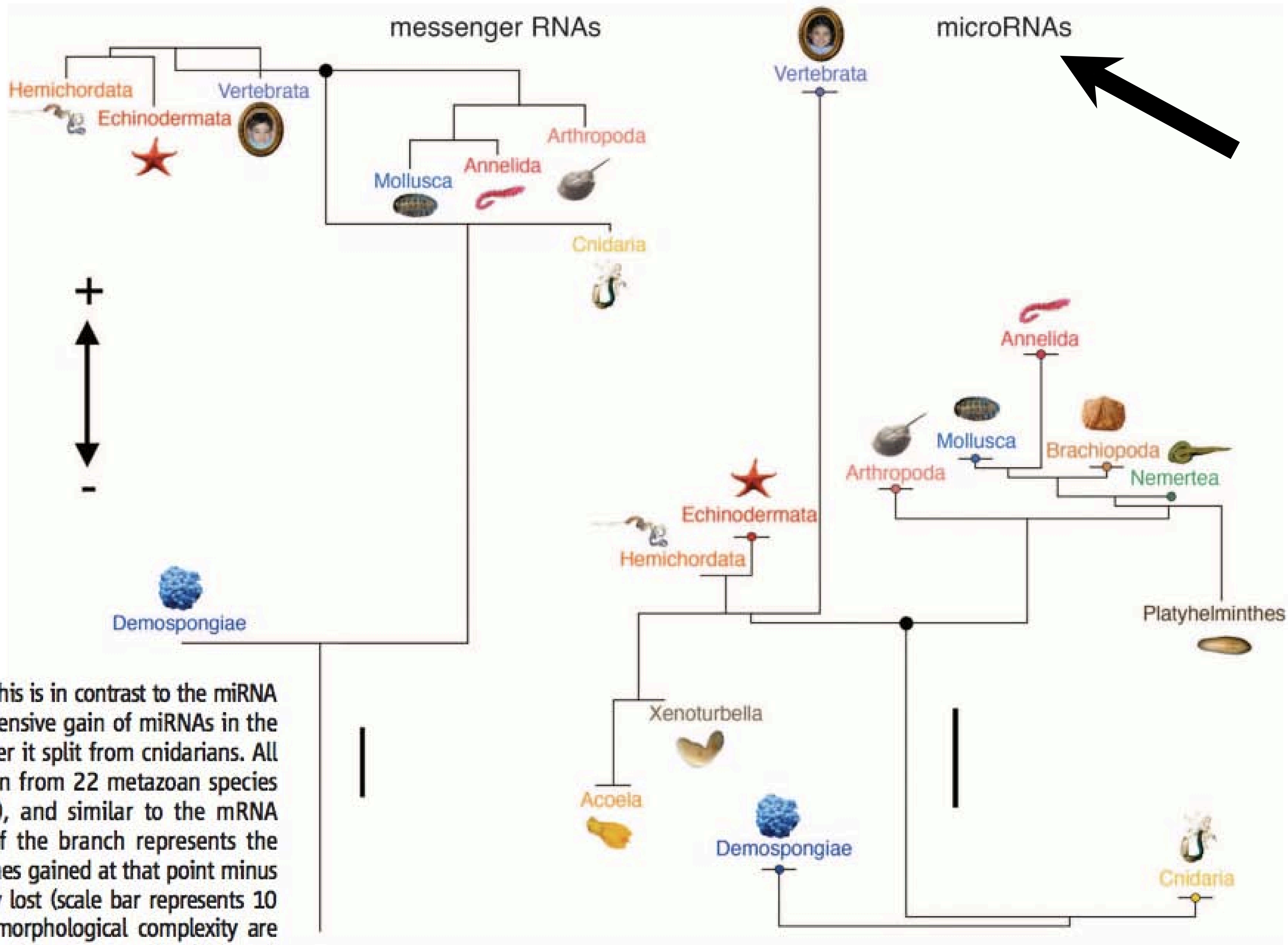
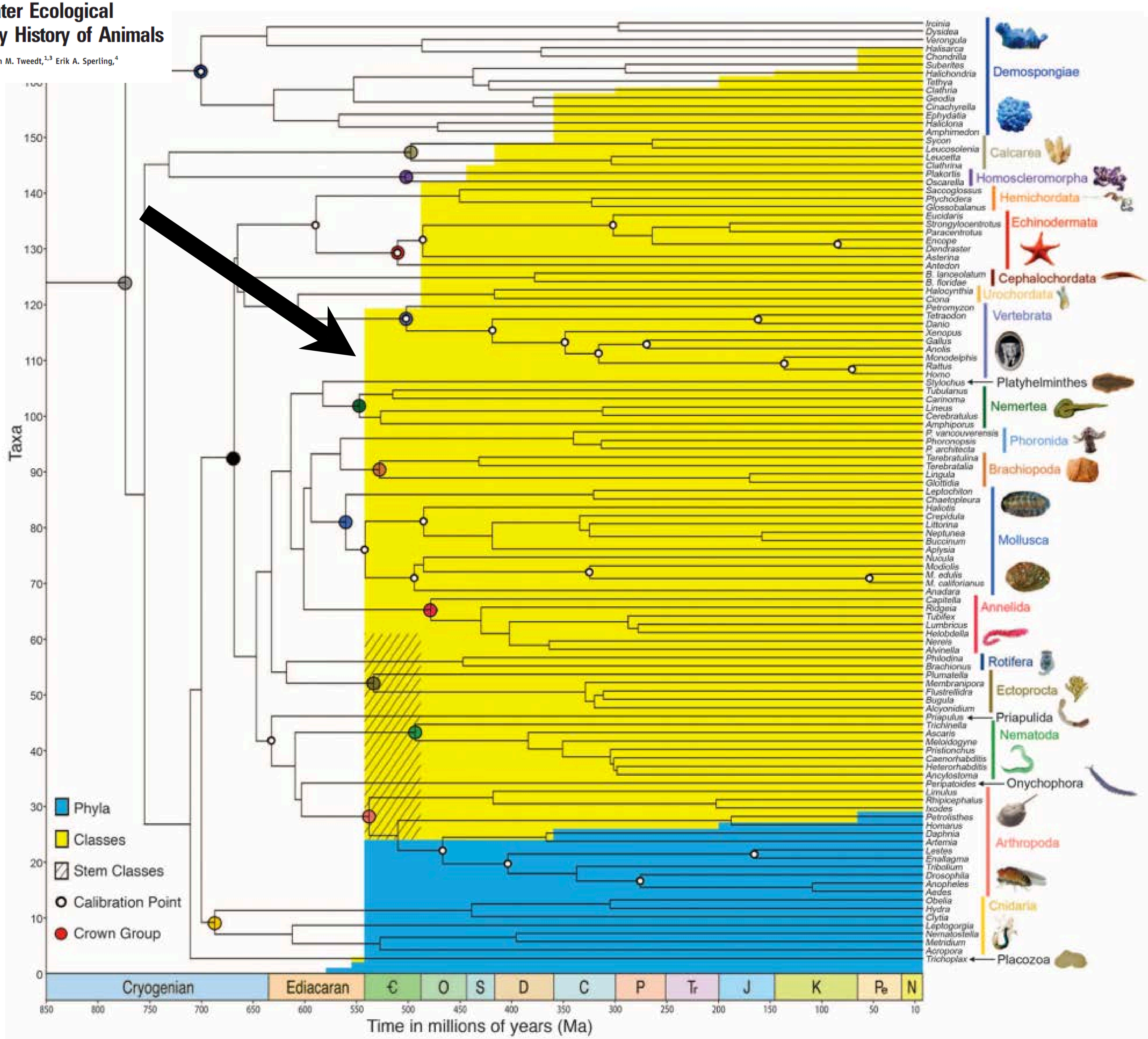


Fig. 4. Acquisition and secondary loss of messenger RNAs (mRNAs, **left**) and microRNAs (miRNAs, **right**) in selected taxa. One hundred and thirty-one representative transcription factors and signaling ligands were coded for eight metazoan taxa (database S3) and mapped onto a widely accepted metazoan topology (*15*, *16*). The length of the branch represents the total number of mRNA genes acquired minus those that were lost (scale bar represents 10 genes total). Much of the developmental mRNA toolkit was acquired before the last common ancestor of cnidarians and bilaterians. This is in contrast to the miRNA repertoire that displays extensive gain of miRNAs in the bilaterian stem lineage after it split from cnidarians. All 139 miRNA families known from 22 metazoan species were coded (database S4), and similar to the mRNA figure (left), the length of the branch represents the total number of miRNA genes gained at that point minus those that were secondarily lost (scale bar represents 10 genes total). Increases to morphological complexity are correlated with increases to the miRNA toolkit (*60*), and secondary simplifications in morphology correlate with a relatively high level of secondary miRNA loss (*20*).

The Cambrian Conundrum: Early Divergence and Later Ecological Success in the Early History of Animals

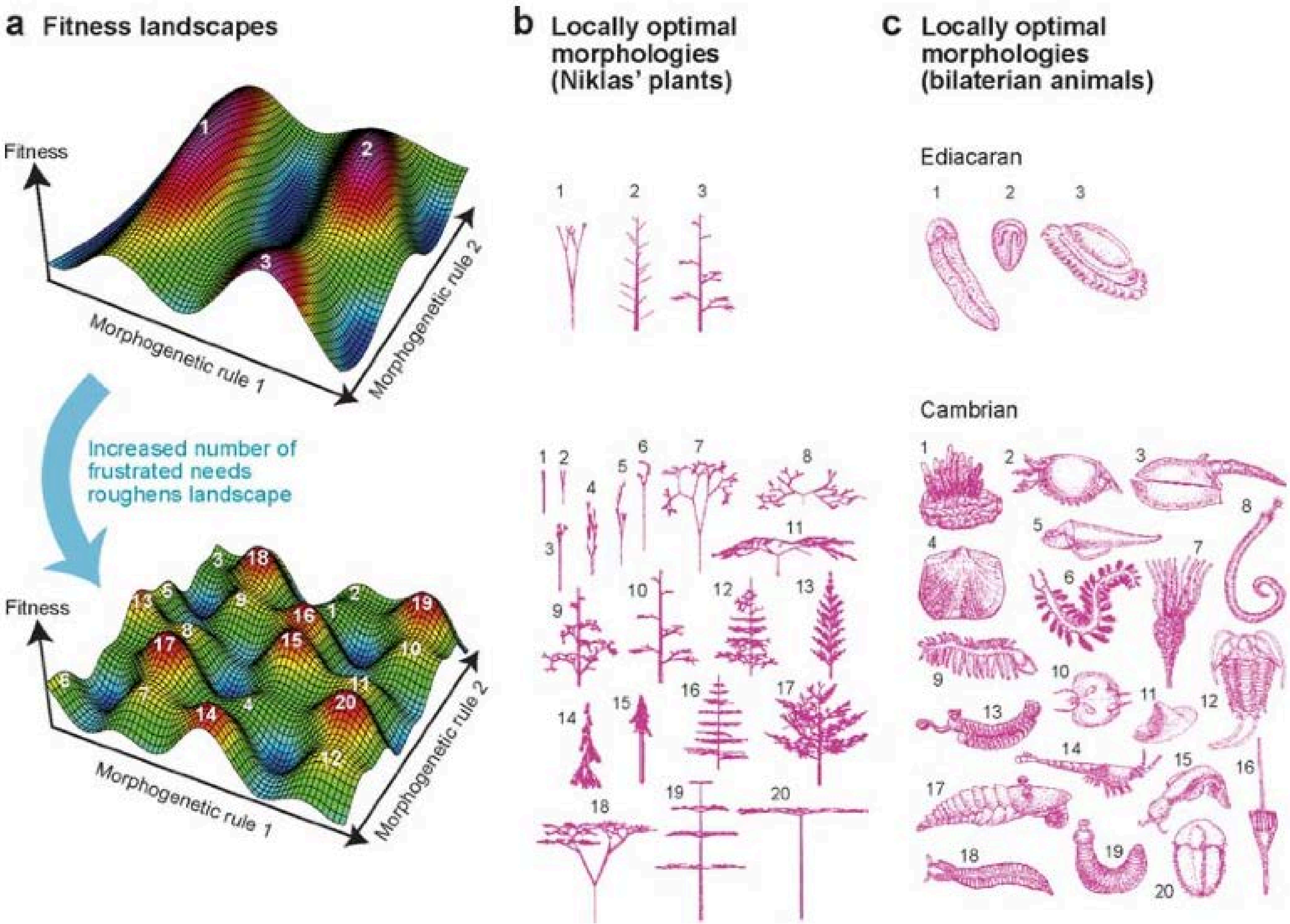
Douglas H. Erwin,[1,2]* Marc Laflamme,[1] Sarah M. Tweedt,[1,3] Erik A. Sperling,[4] Davide Pisani,[5] Kevin J. Peterson[6]*



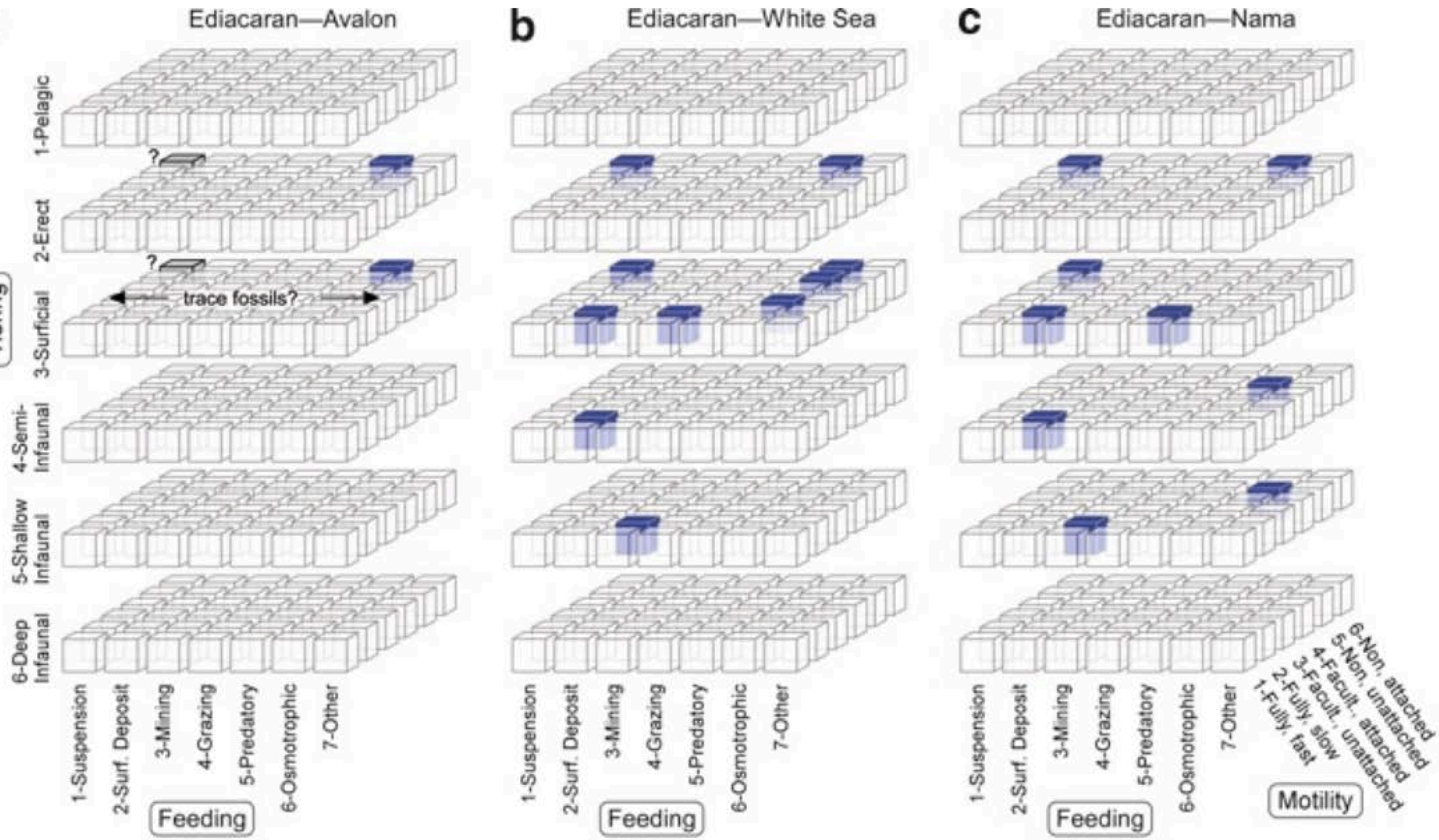
 Source: Erwin, D. H., et al. "The Cambrian Conundrum: Early Divergence and Later Ecological Success in the Early History of Animals." *Science* 334, no. 6059 (2011): 1091-7.

Explaining the Cambrian "Explosion" of Animals

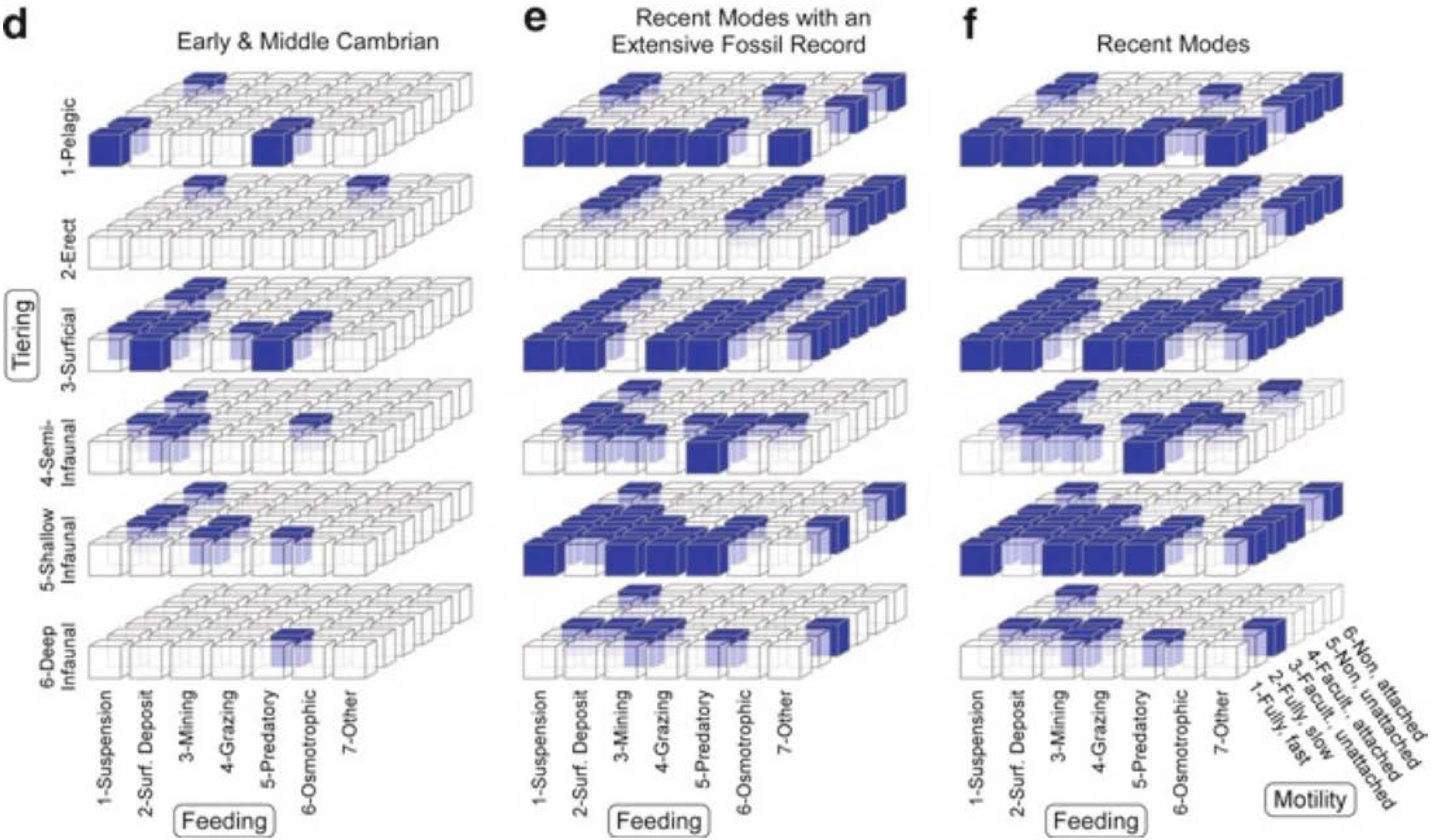
Charles R. Marshall



 Source: Marshall, C. R. "Explaining the Cambrian "Explosion" of Animals." *Annu. Rev. Earth Planet. Sci.* 34 (2006): 355-84.



 Source: Page 17 of Bush, A. M., et al. "Ecospace Utilization during the Ediacaran Radiation and the Cambrian Eco-Explosion." In *Quantifying the Evolution of Early Life*, Springer Netherlands, 2011, pp. 111-33.



 Source: Page 17 of Bush, A. M., et al. "Ecospace Utilization during the Ediacaran Radiation and the Cambrian Eco-Explosion." In *Quantifying the Evolution of Early Life*, Springer Netherlands, 2011, pp. 111-33.

Role of Predation

A Perfect Storm

- Changing Redox Conditions
- Genetic innovation
- Changing ecological landscapes

Complexity is not limited to the animals!

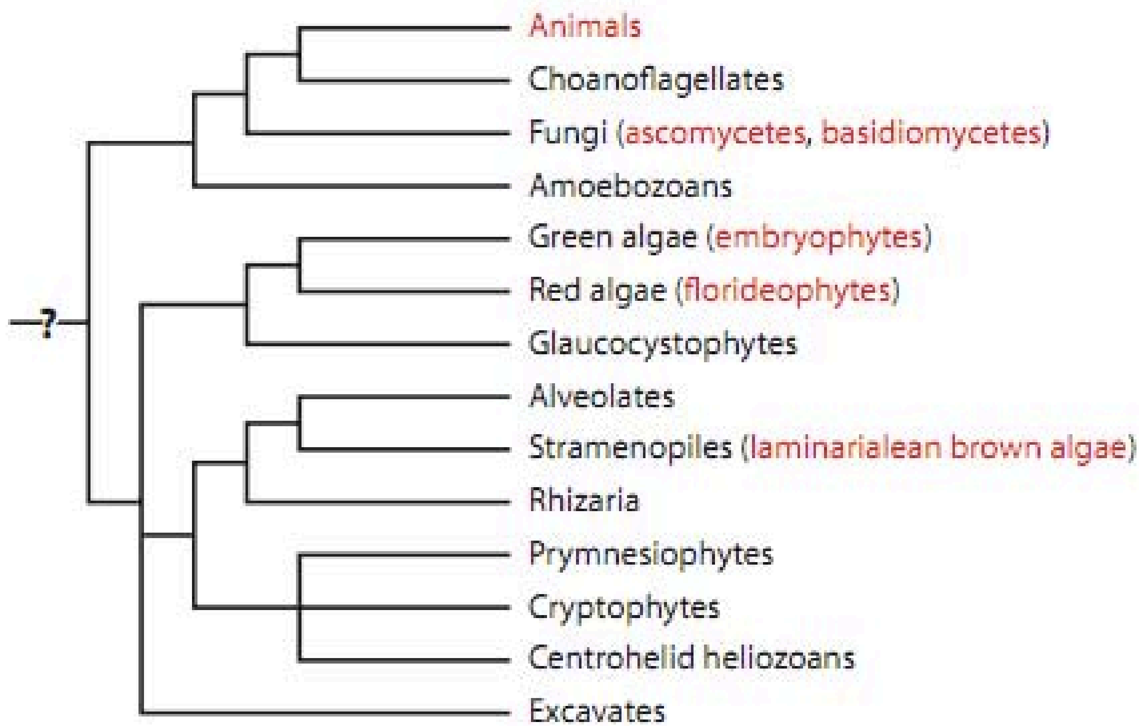


Figure 1

Eukaryotic phylogeny, showing the positions of complex multicellular organisms (*red*).

Knoll 2011 Annual Reviews

What really changed?

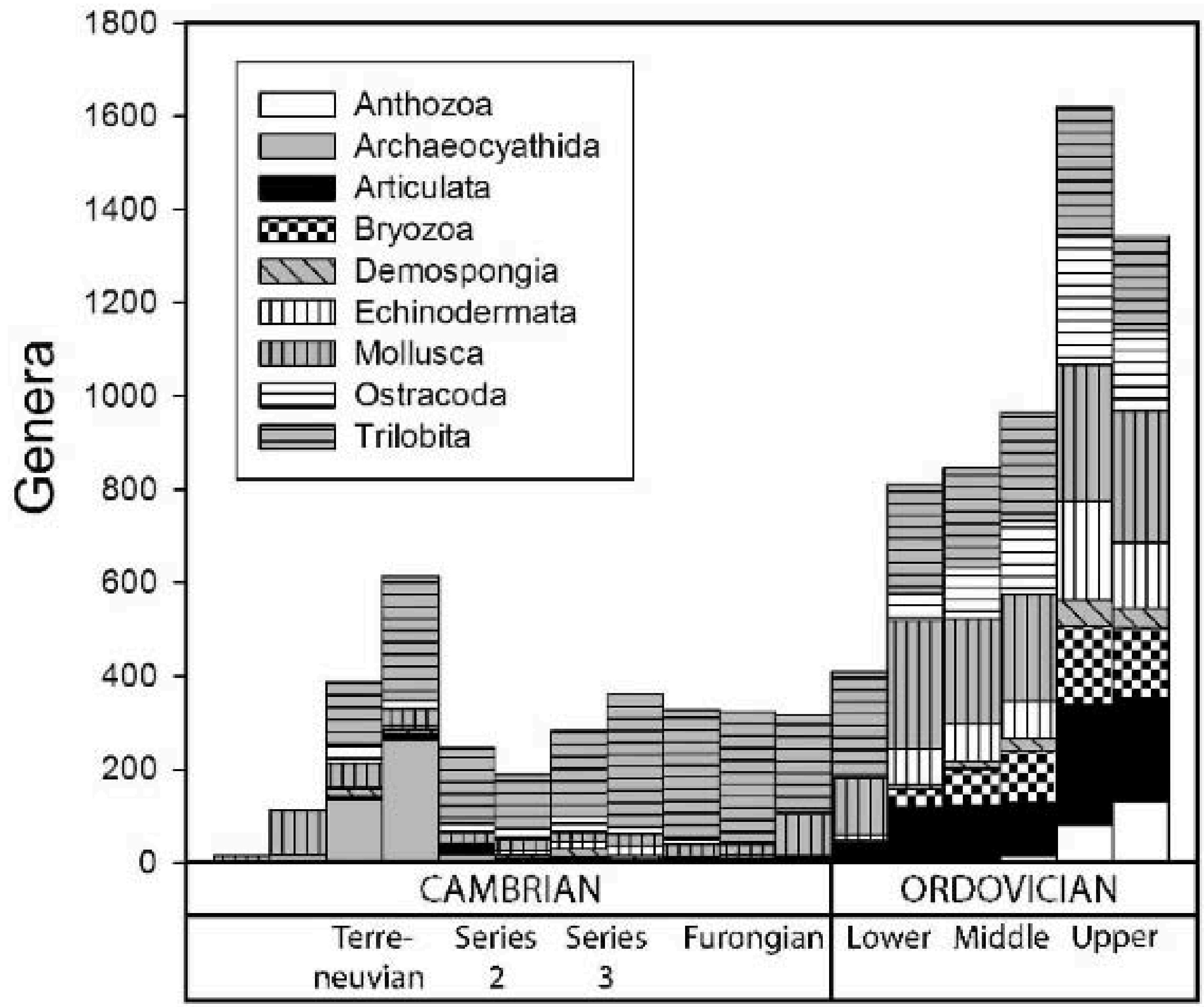


FIGURE 8—Generic diversity of calcifying animal groups from the Cambrian into the Ordovician (Peters [2005a] database, using Sepkoski's [2002] data).

Pruss et al. 2010

Ordovician Radiation

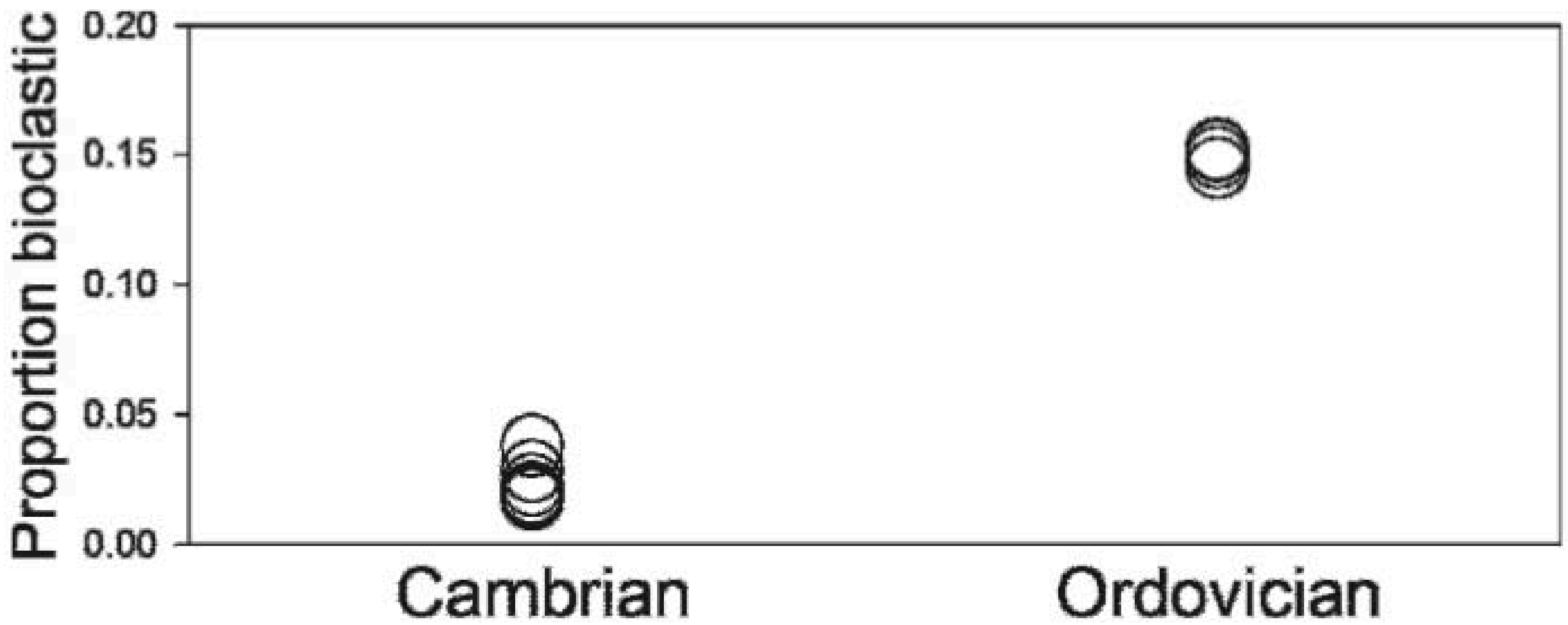
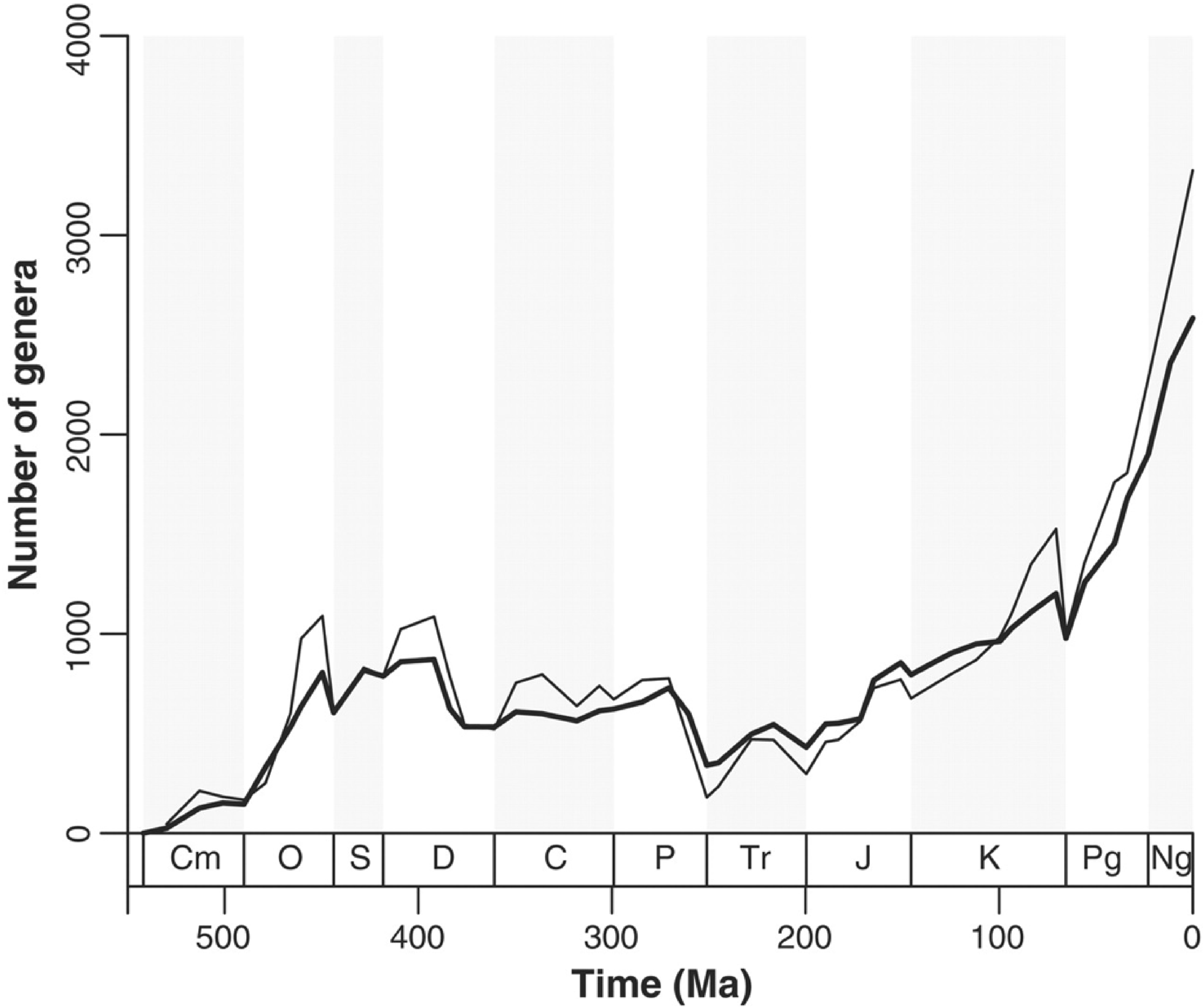


FIGURE 5—Abundance of skeletal material as a fraction of lithofacies volume for the Cambrian of Newfoundland and Ordovician of the Ibex Area, Utah (see text for further explanation).

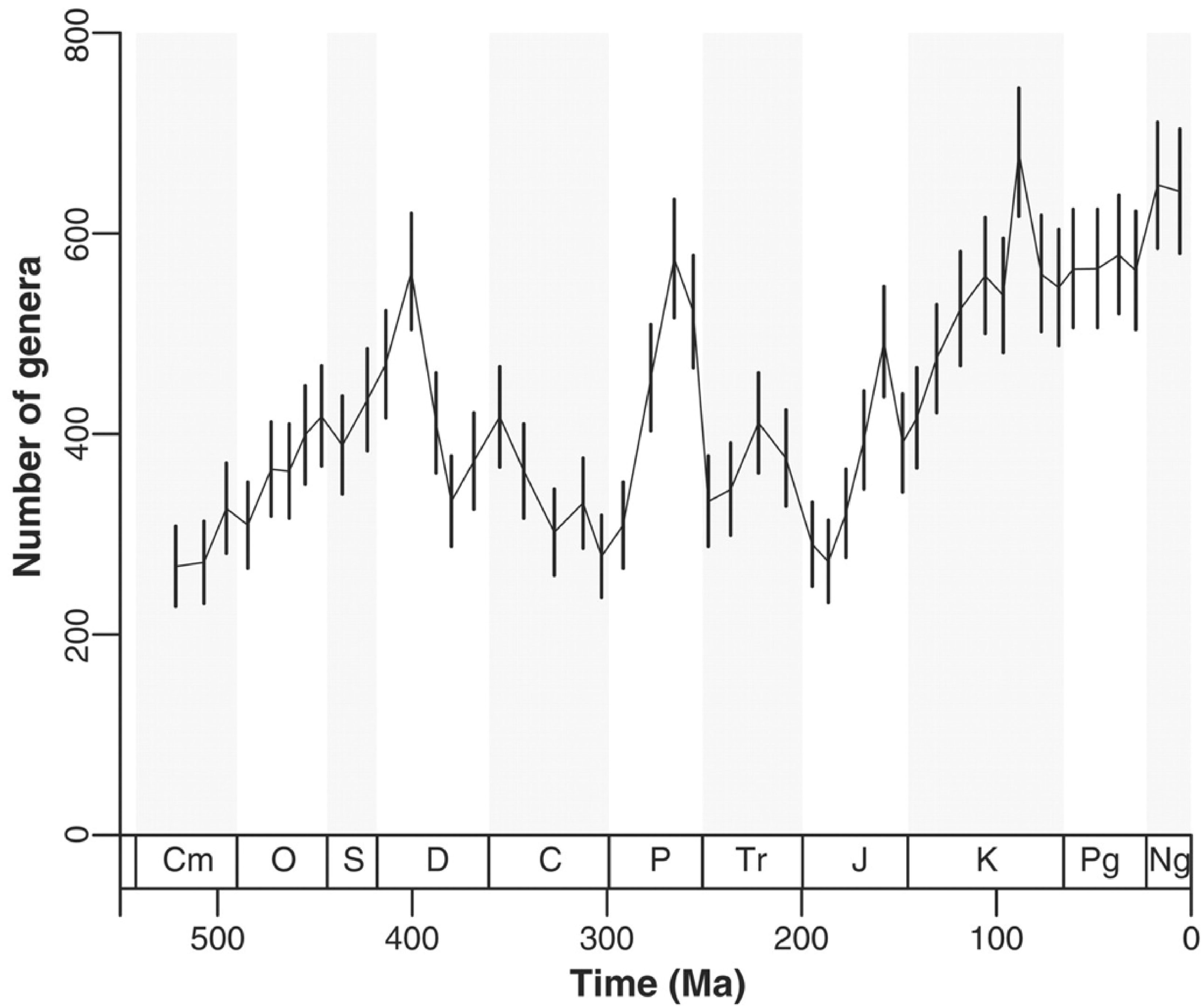
Pruss et al. 2010



Phanerozoic Trends in the Global Diversity of Marine Invertebrates

Science 4 July 2008:
vol. 321 no. 5885 97-100

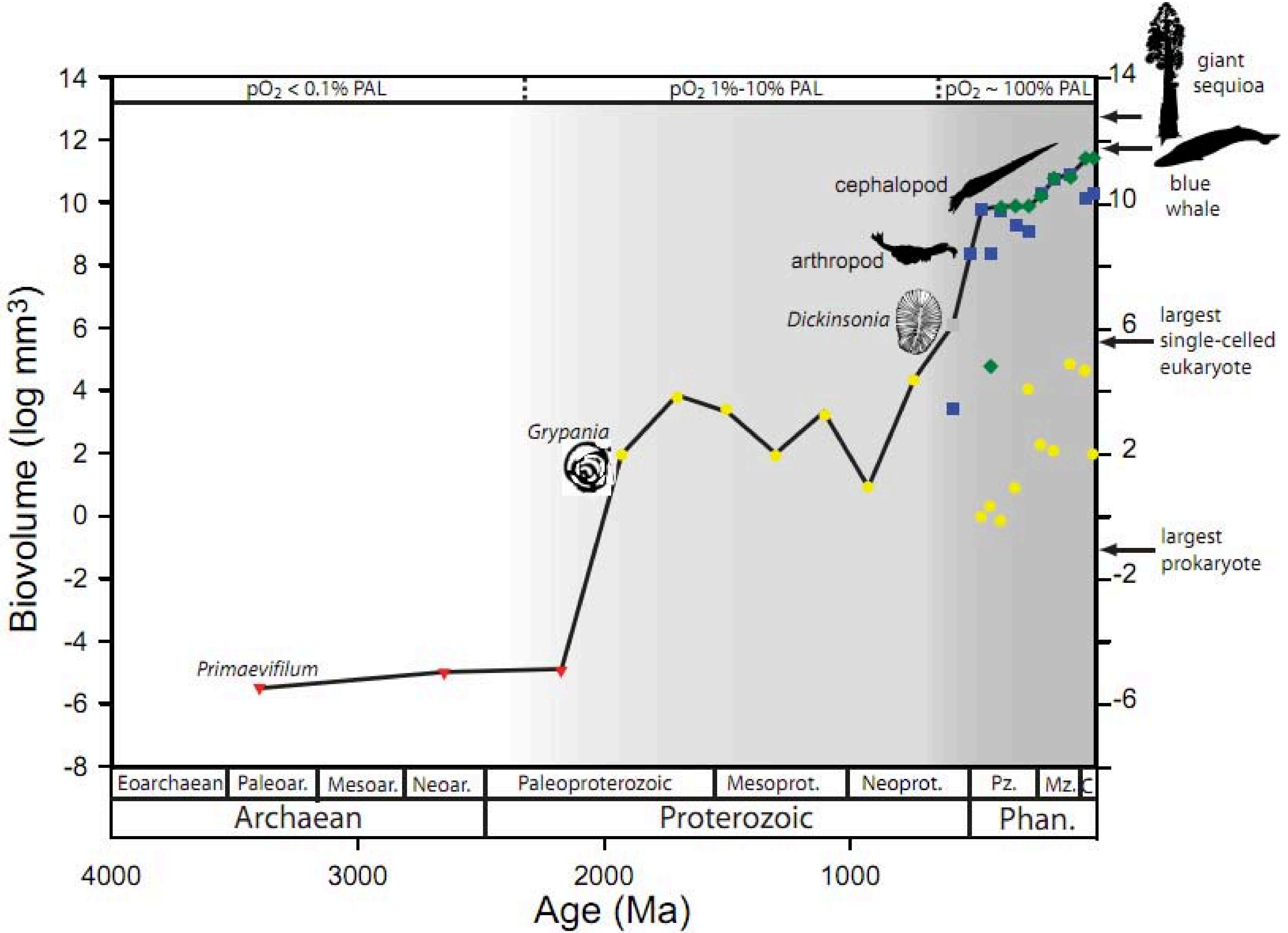
Genus-level diversity curves based on Sepkoski's compendium [thin line (5)] and our new data (thick line). Counts are of marine metazoan genera crossing boundaries between temporal bins (boundary crossers) and exclude tetrapods. Ranges are pulled forward from first fossil appearances to the Recent, instead of ending at the last known fossil appearance. Extant genera are systematically marked as such based on Sepkoski's compendium and the primary literature. There is no correction for sampling, and genera are assumed to be sampled everywhere within their ranges because Sepkoski's traditional synoptic data (5) do not record occurrences within individual collections.



Phanerozoic Trends in the Global Diversity of Marine Invertebrates

Science 4 July 2008:
vol. 321 no. 5885 97-100

Genus-level diversity of both extant and extinct marine invertebrates (metazoans less tetrapods) during the Phanerozoic, based on a sampling-standardized analysis of the Paleobiology Database. Points represent 48 temporal bins defined to be of roughly equal length (averaging 11 My) by grouping short geological stages when necessary. Vertical lines show the 95% confidence intervals based on Chernoff bounds, which are always conservative regardless of the number of genera that could be sampled or variation in their sampling probabilities (18). Data are standardized by repeatedly drawing collections from a randomly generated set of 65 publications until a quota of 16,200 specimens has been recovered in each bin.



Courtesy of the authors and the National Academies and Sciences. Used with permission. Source: Payne, J. L., et al. "Two-phase Increase in the Maximum Size of Life over 3.5 billion years Reflects Biological Innovation and Environmental Opportunity." *Proceedings of the National Academy of Sciences* 106, no. 1 (2009): 24-7.

fossil timeline challenge

The last 543 million years (yawn)