THE FOSSIL RECORD AND THE CAMBRIAN "EXPLOSION": AN UPDATE

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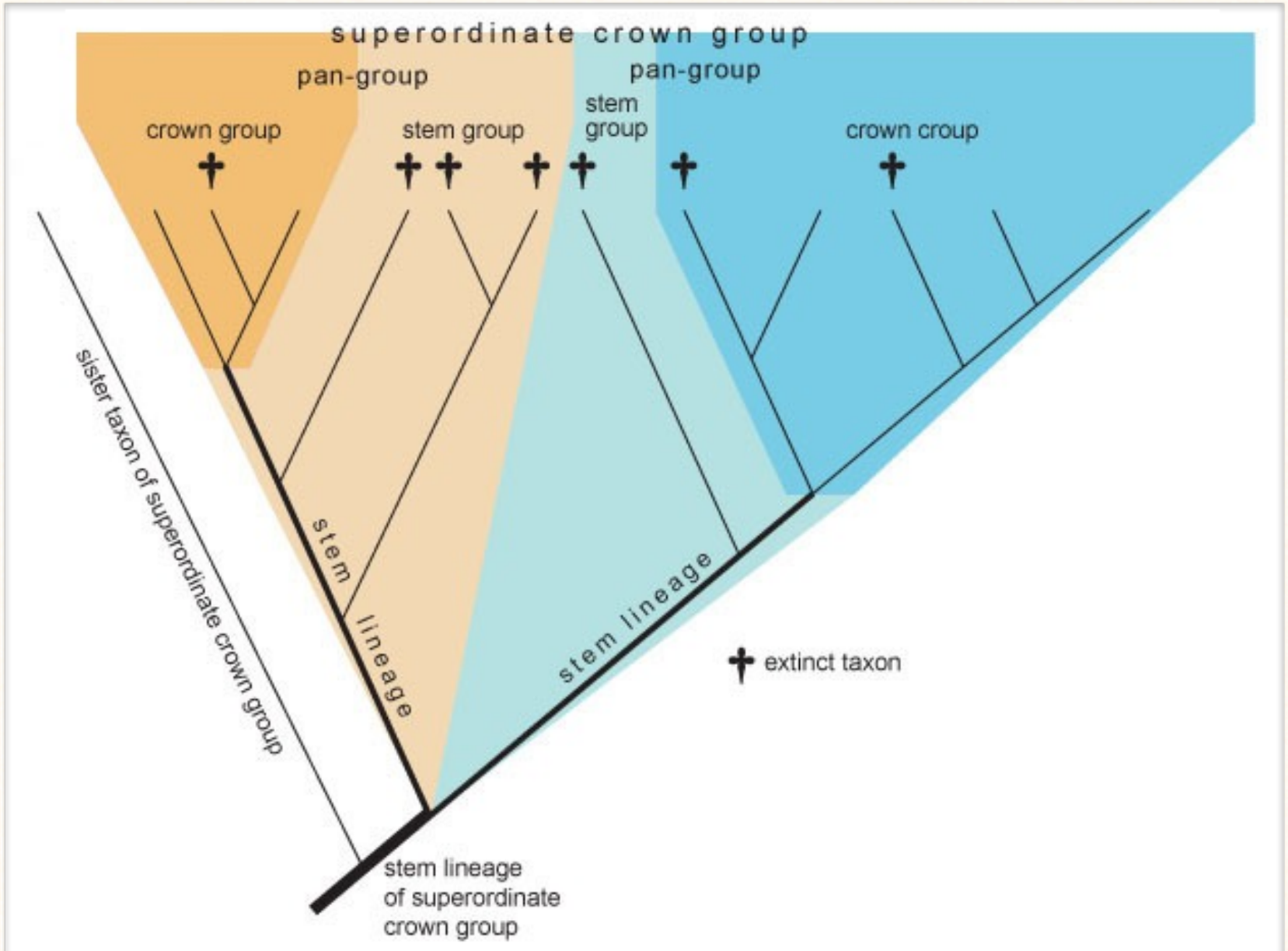
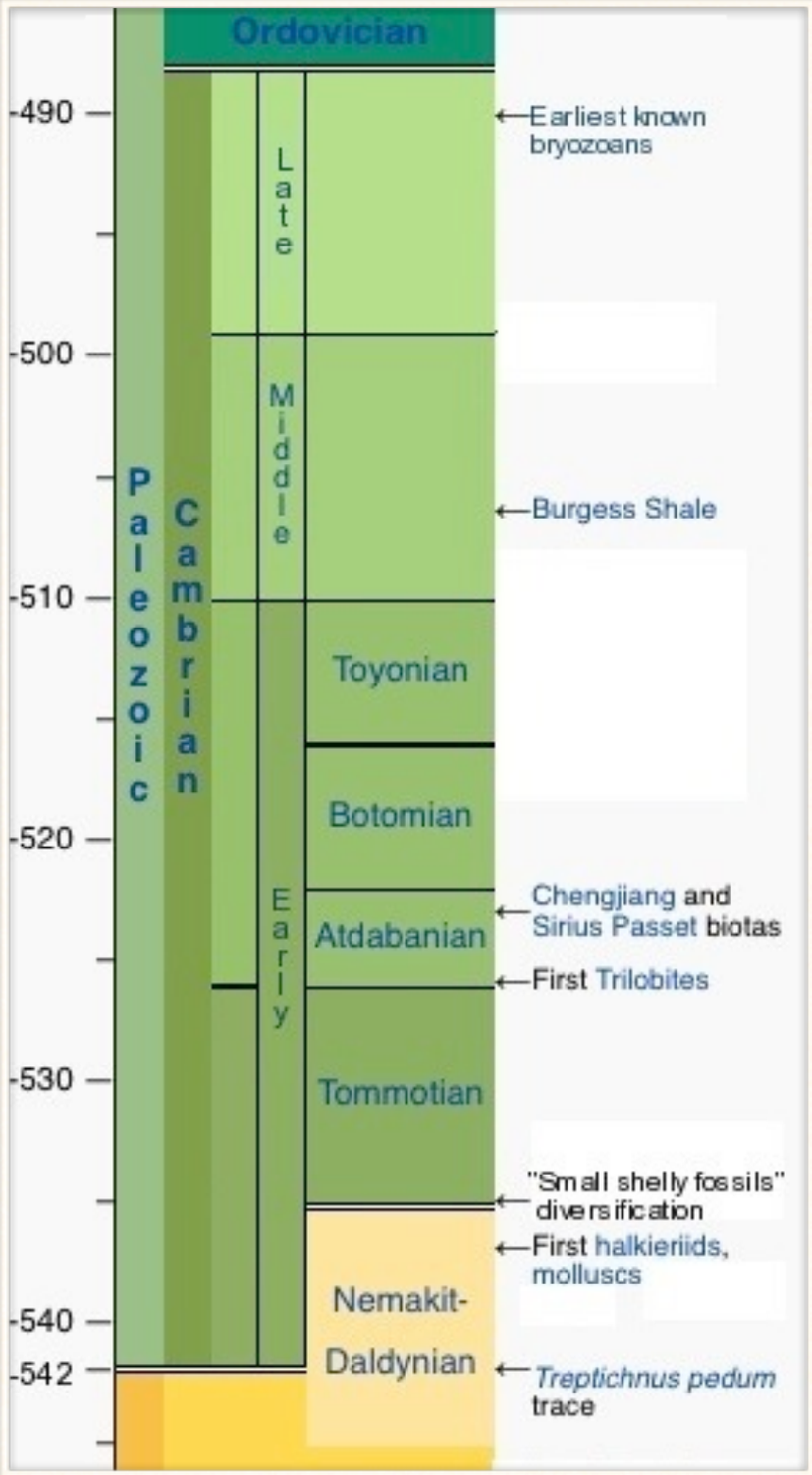
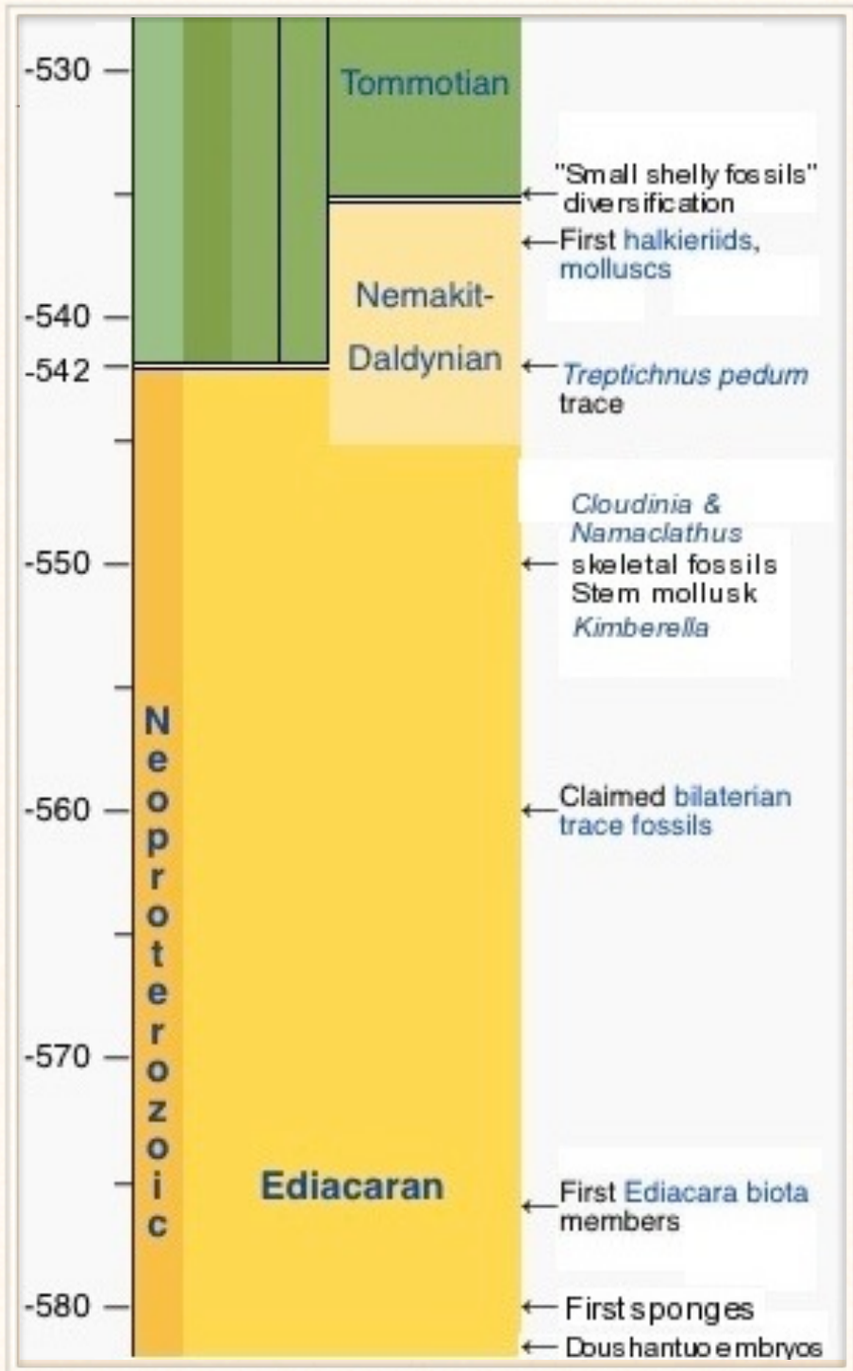
Crown Groups, Stem Groups, and Sister Groups



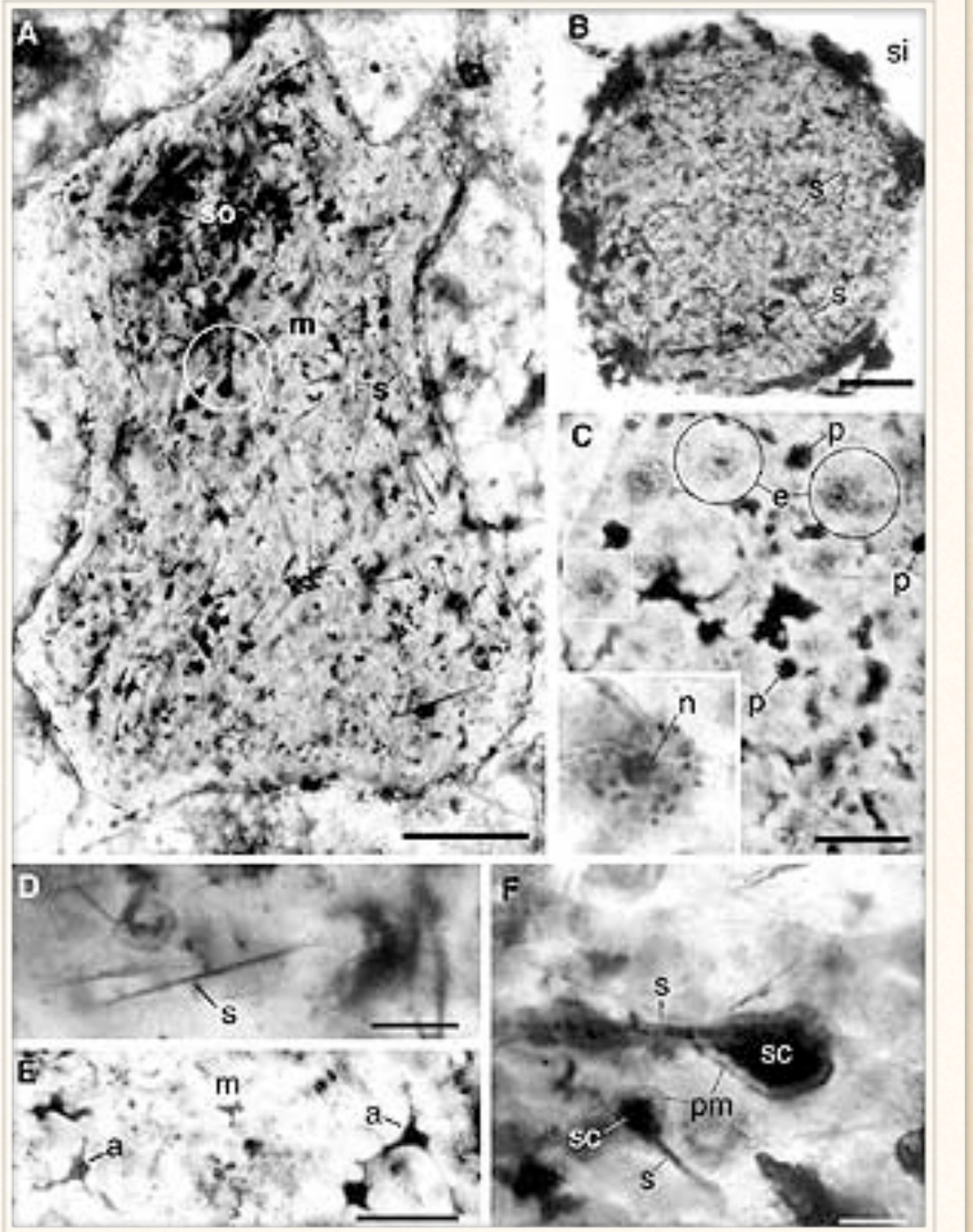
Cambrian "Explosion" Timeline



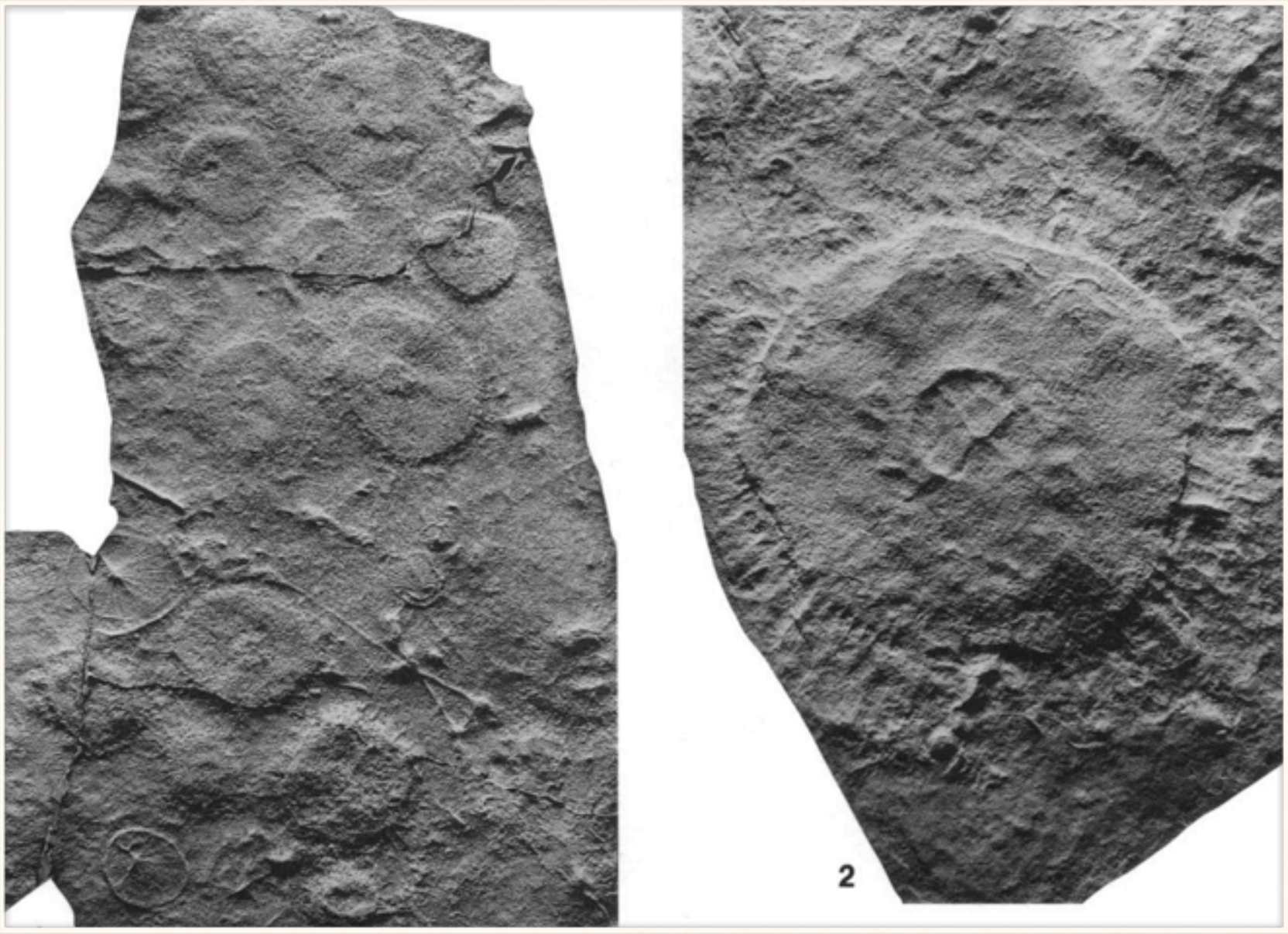


Ediacaran Doushantuo – 580 my Demosponges

Presence of sponges extended to 700 my by biomarkers



Ediacaran Hexactinellid Sponges



Ediacaran Cnidaria (?)

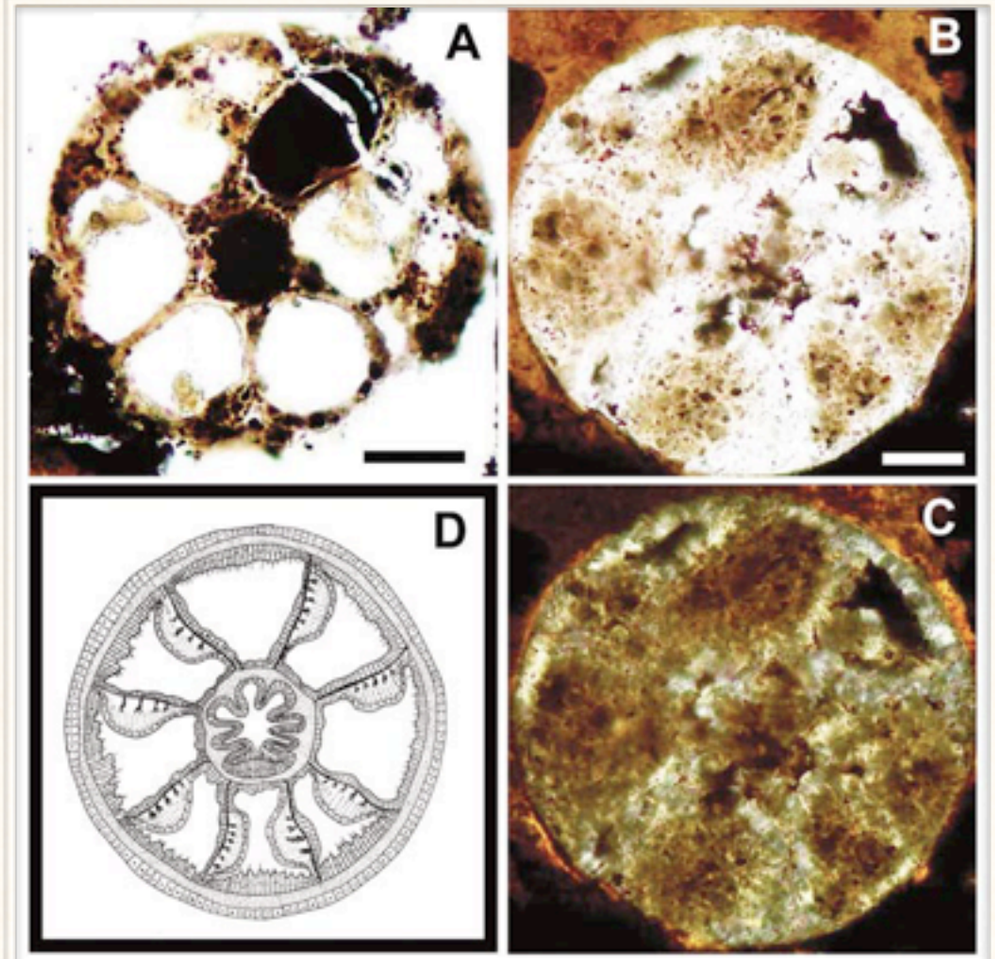
"Jellyfish-like" Organisms

Mawsonites

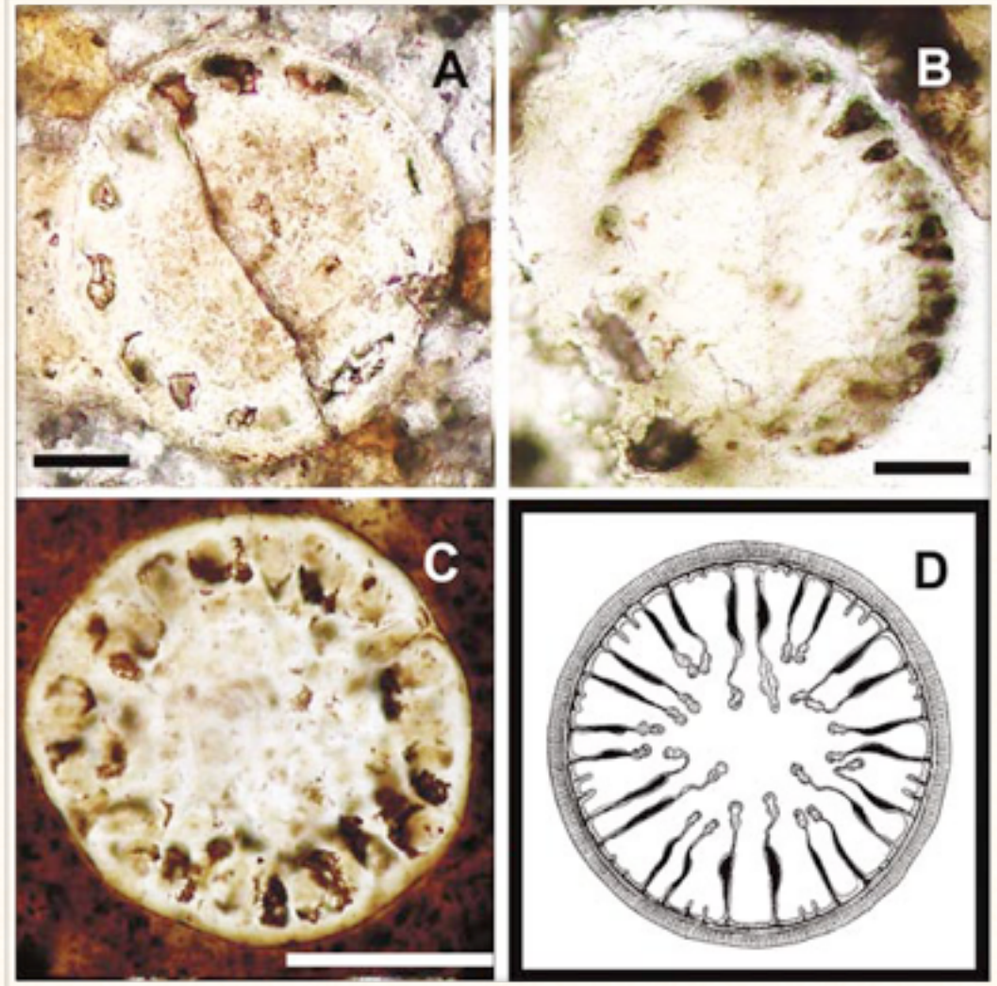
Nemaia 600 my

Neoproterozoic Cnidarian (Anthozoan)

polyps and stalks



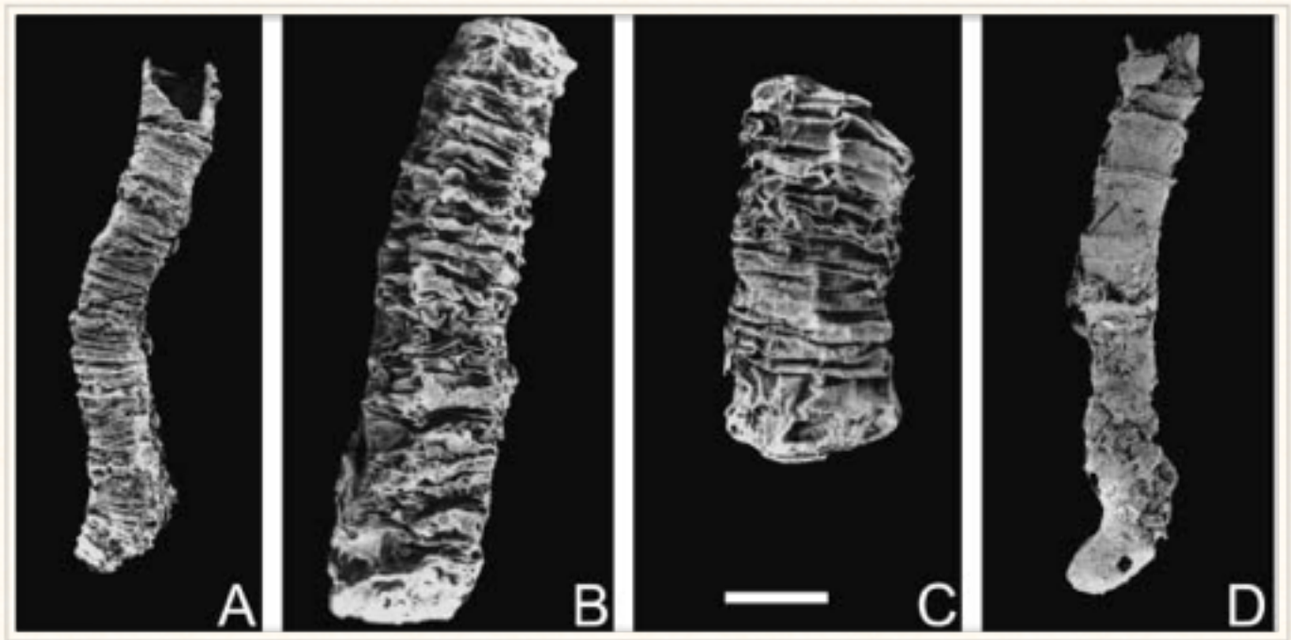
Octocoral?

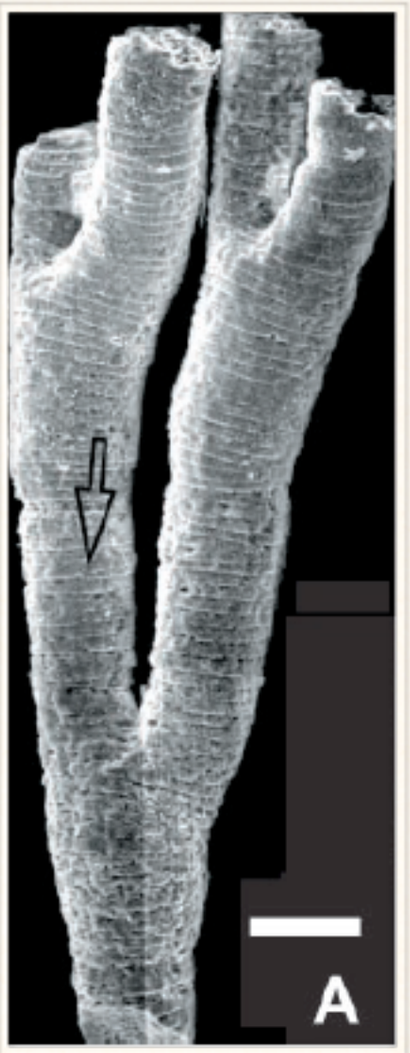


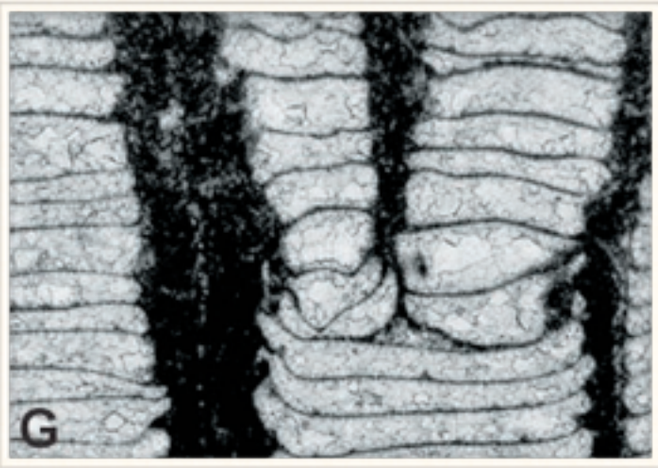
Zoantharian?

Ediacaran Calcified Metazoans

Sinotubulites and *Cloudinia*

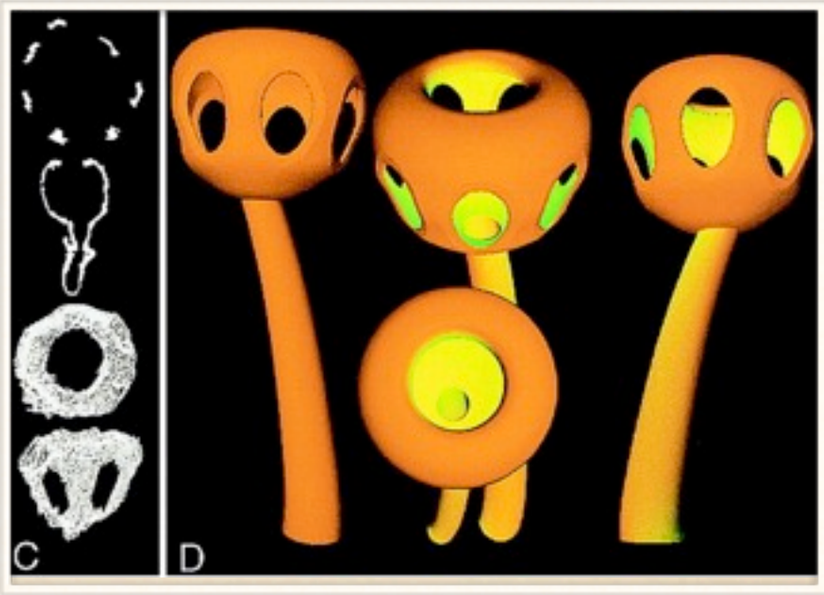




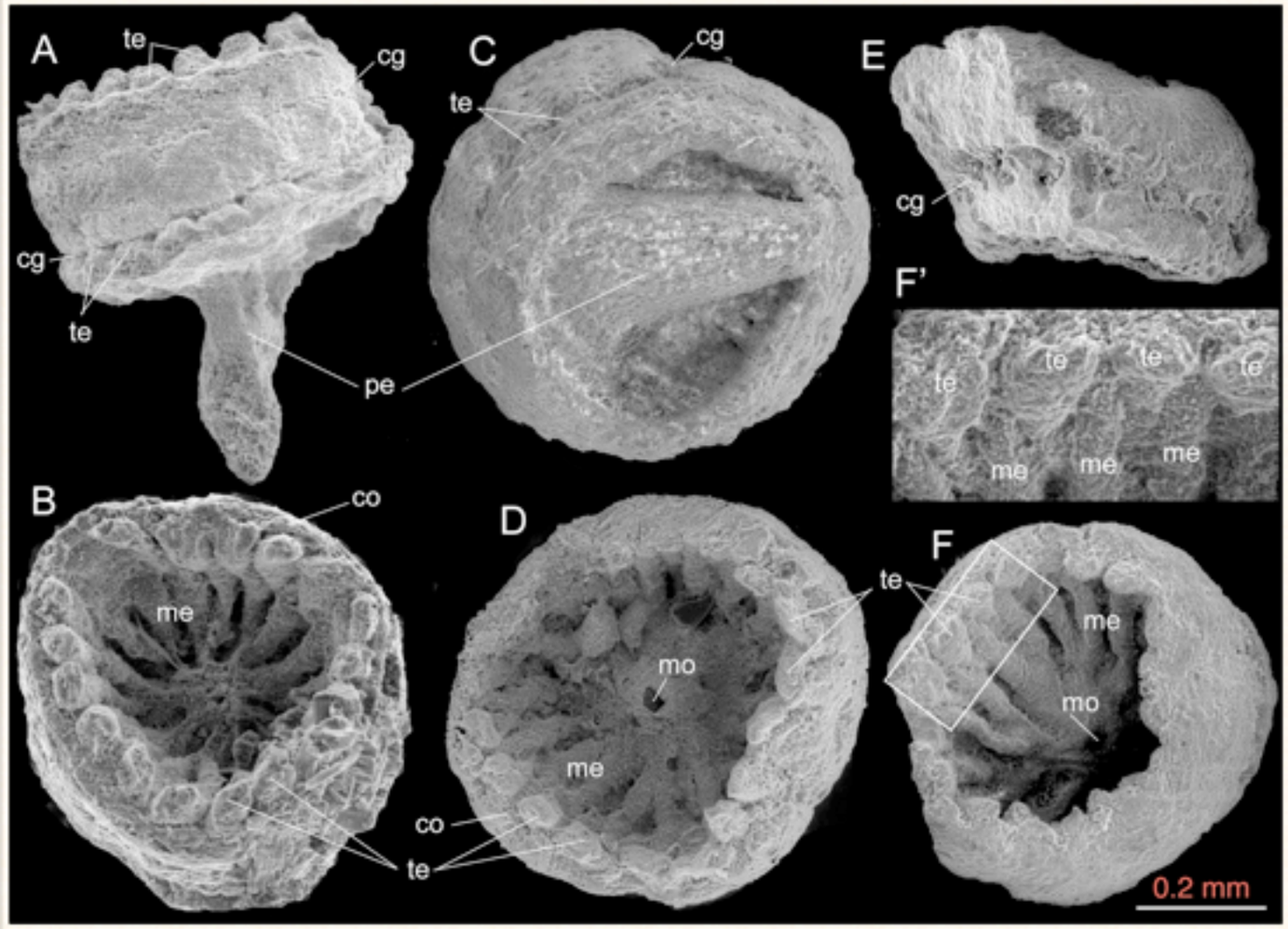


Sinocyclocyclicus

Namacalathus



Early Cambrian Anemone-like Anthozoans



Eolympia

Ediacaran Algal Mats

Wrinkled Microbial Mat

Mat Ground with Vendian Fossils

Ediacaran Bilaterian

Spriggina

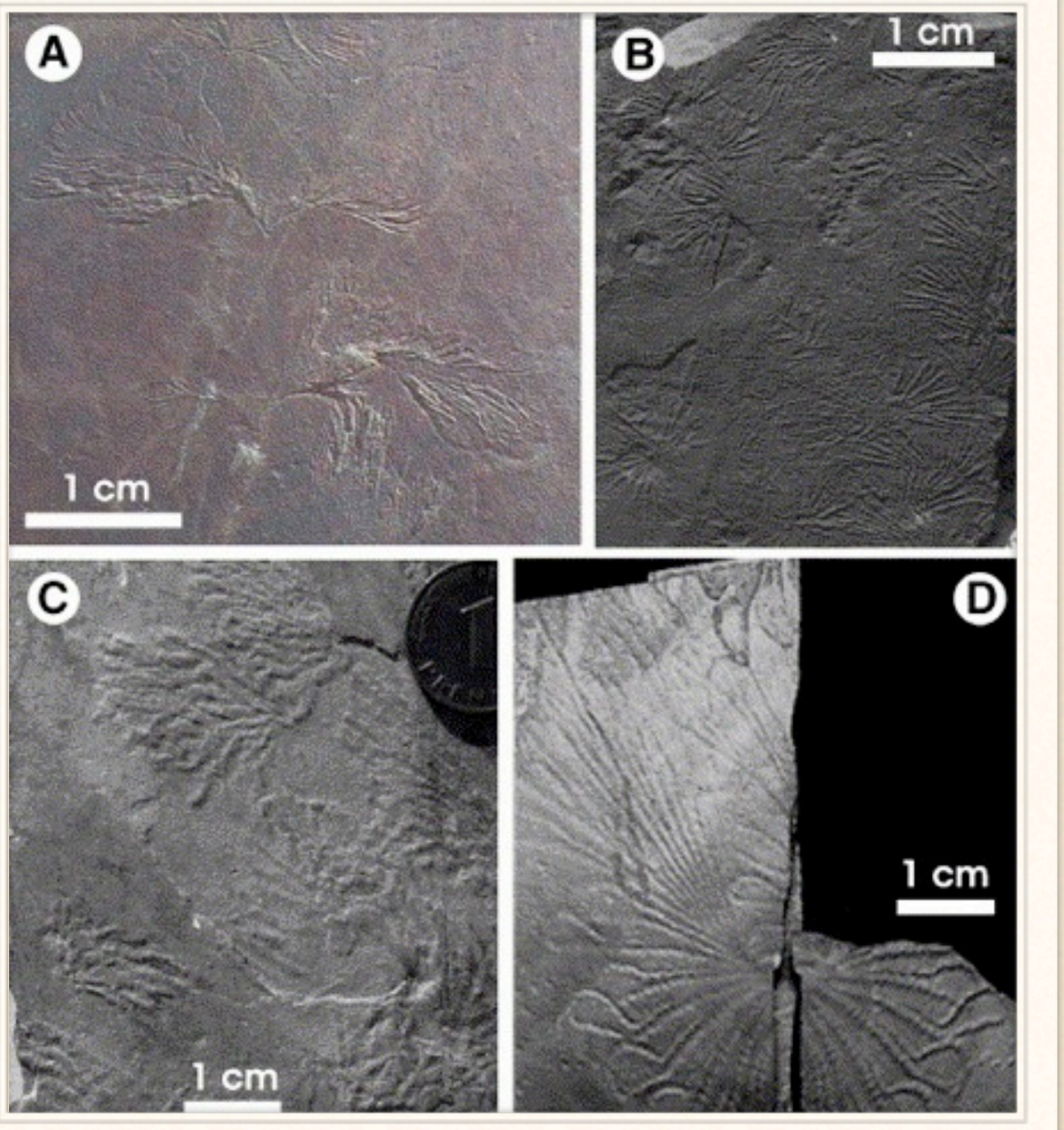
Marywadea

Yorgia and *Dickinsonia*

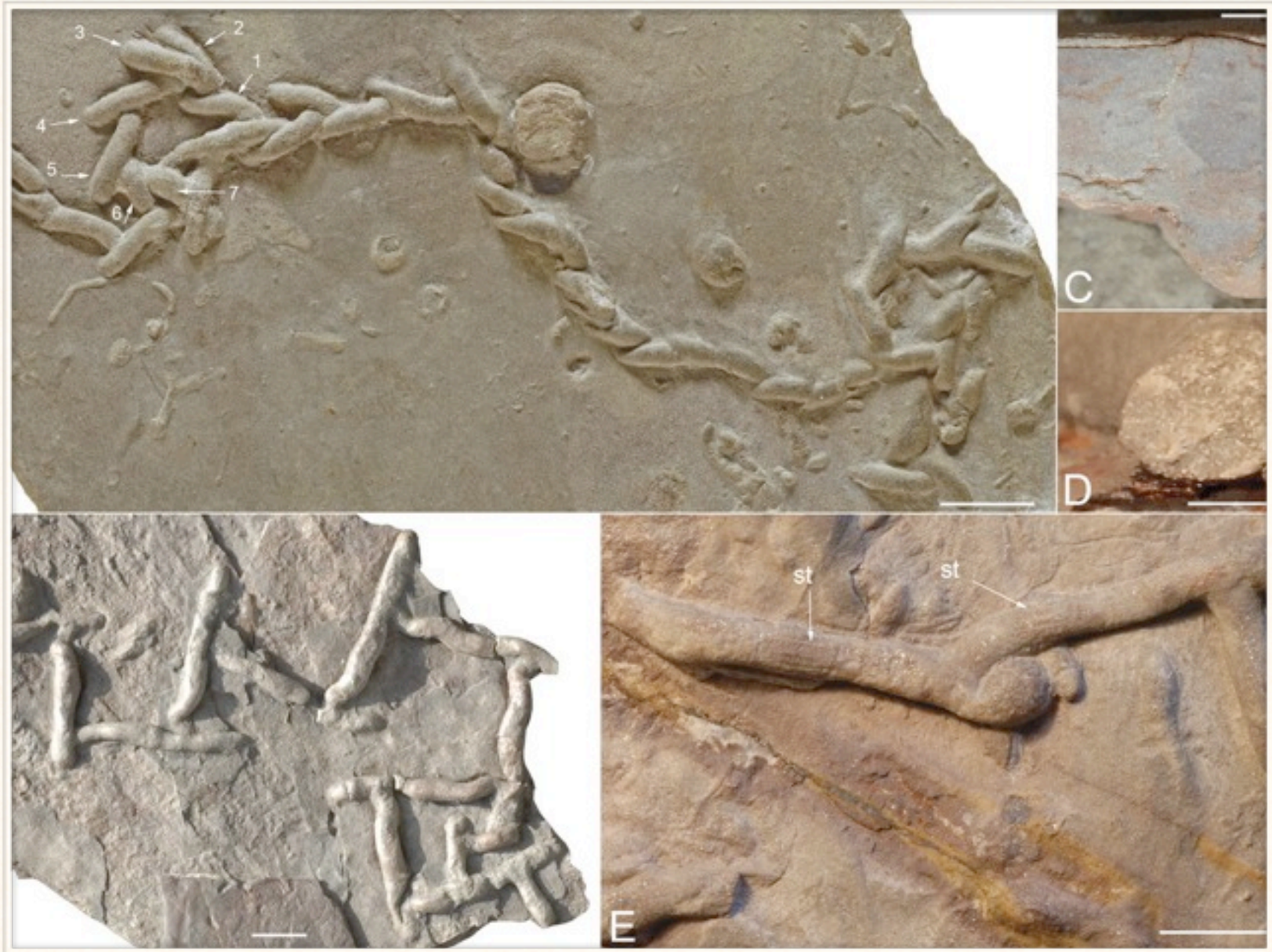
Ediacaran Stem Mollusk *Kimberella* with grazing tracks

Ediacaran horizontal burrows
Helminthopsis, *Helminthoidichnites* and *Gordia*

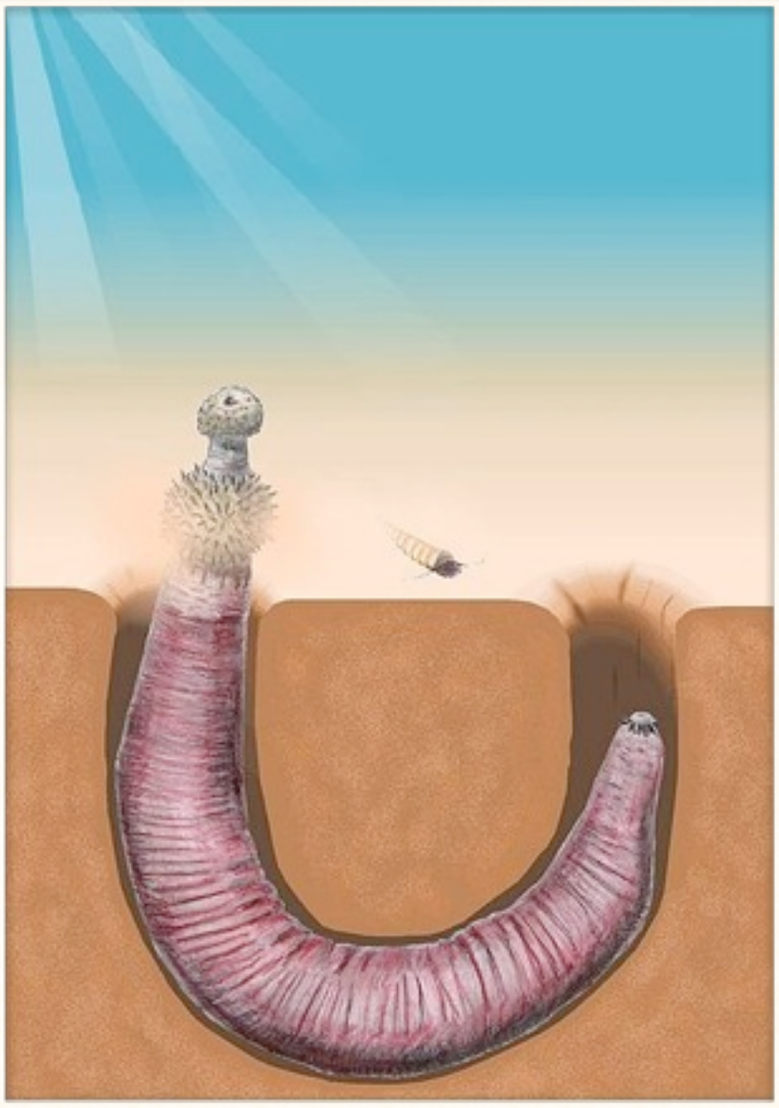
Below-mat Miners: *Oldhamia*



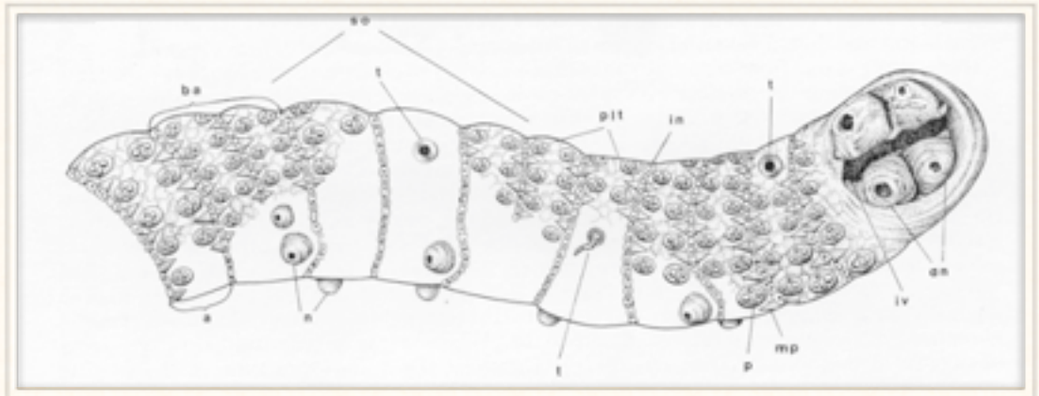
Trepichnus pedum
basal Cambrian burrows

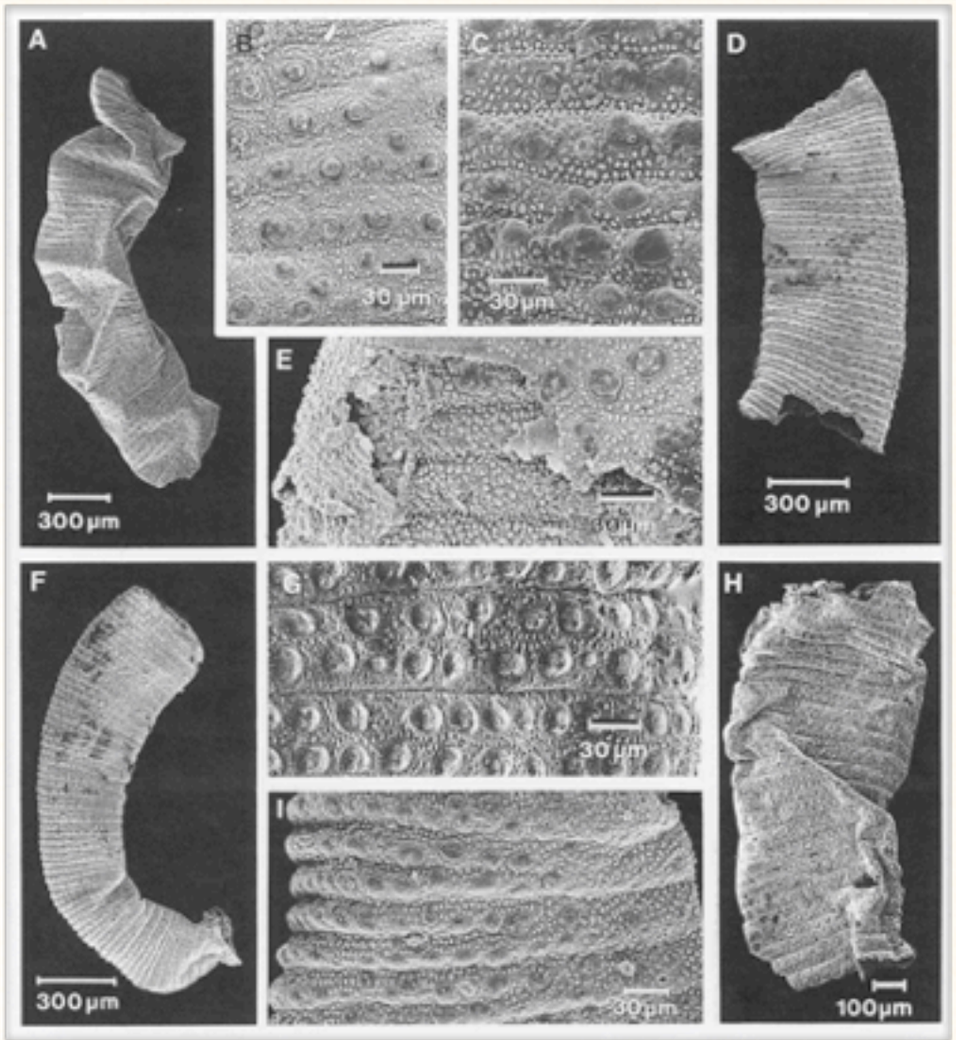


Cambrian
Priapulid worms



Palaeoscolecid Worms

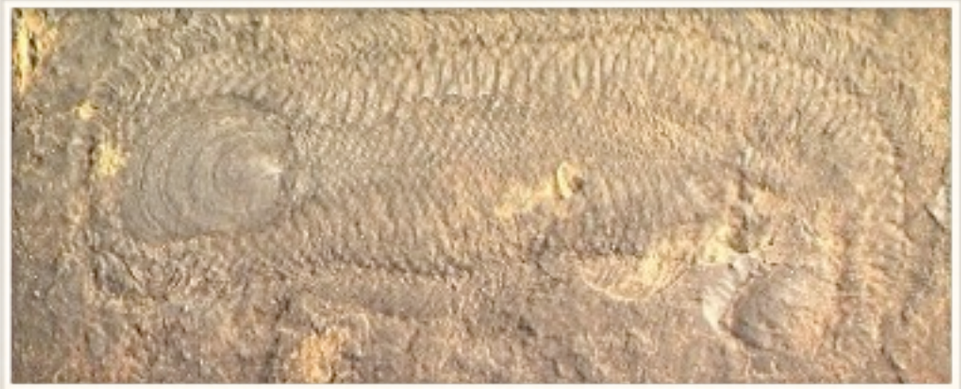




Stem Mollusks, Annelids and Sister Taxa

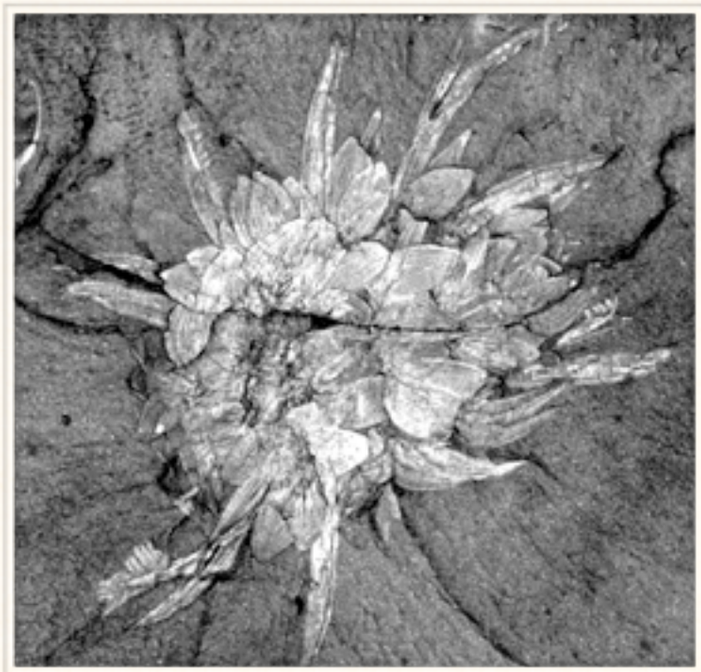
Canadia

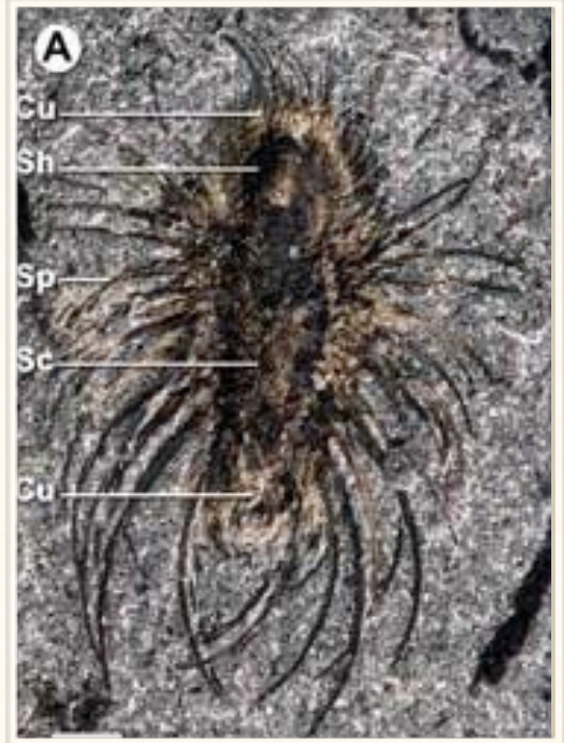
Halkieria



Odontogriphus

Wiwaxia



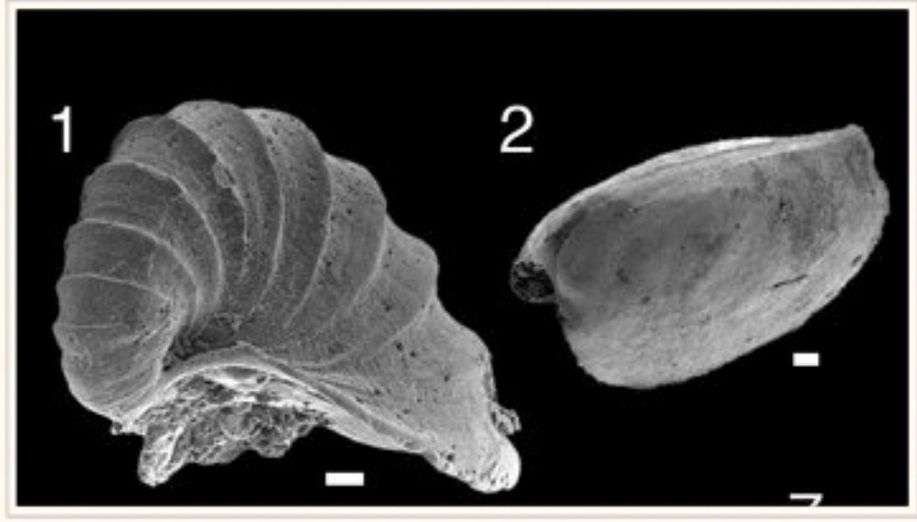


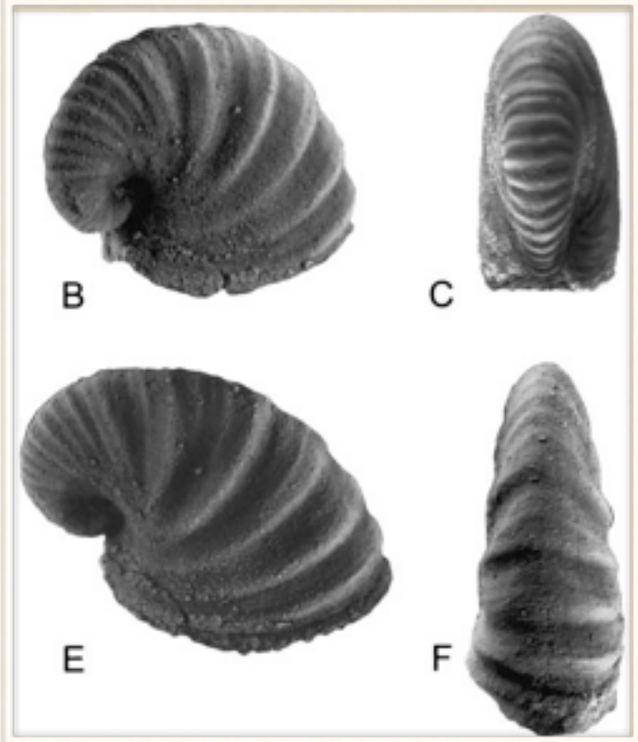
Orthozanclus

Mollusk Classes

Helcionelloids as stem mollusks

Archaeospira and *Watsonella*



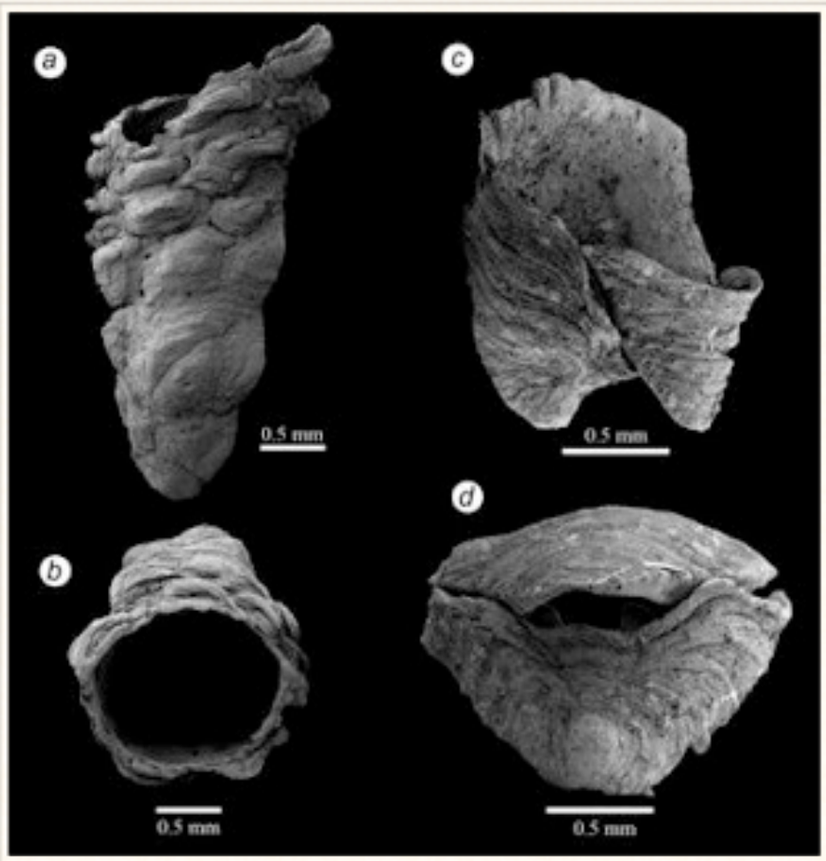


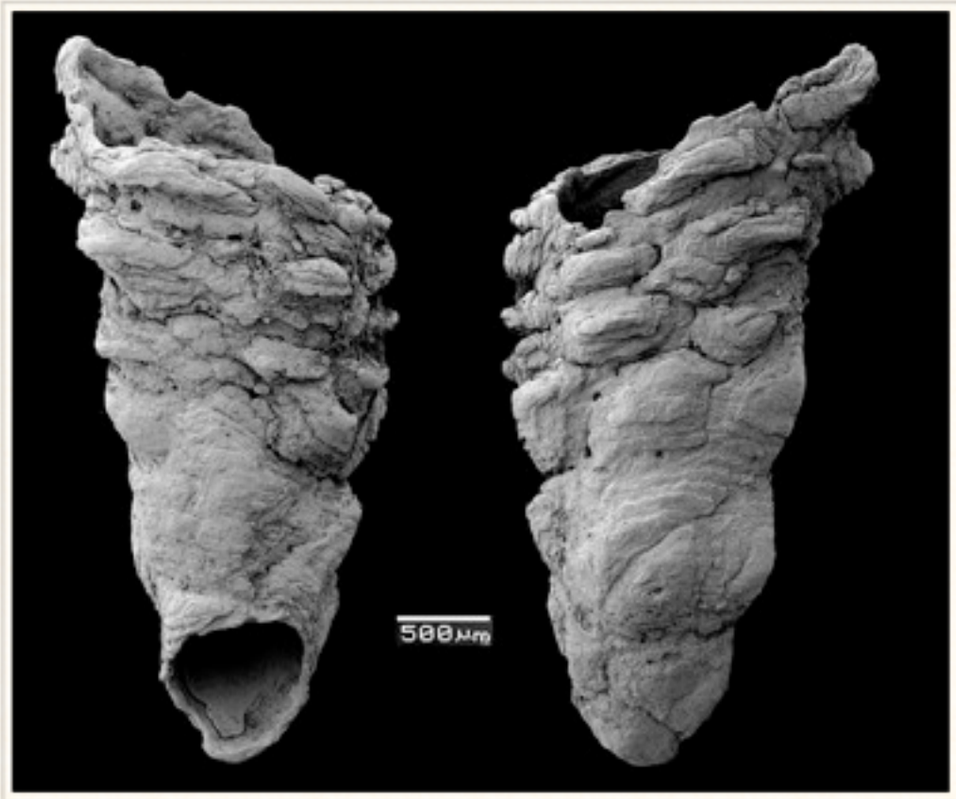
Oelandiella

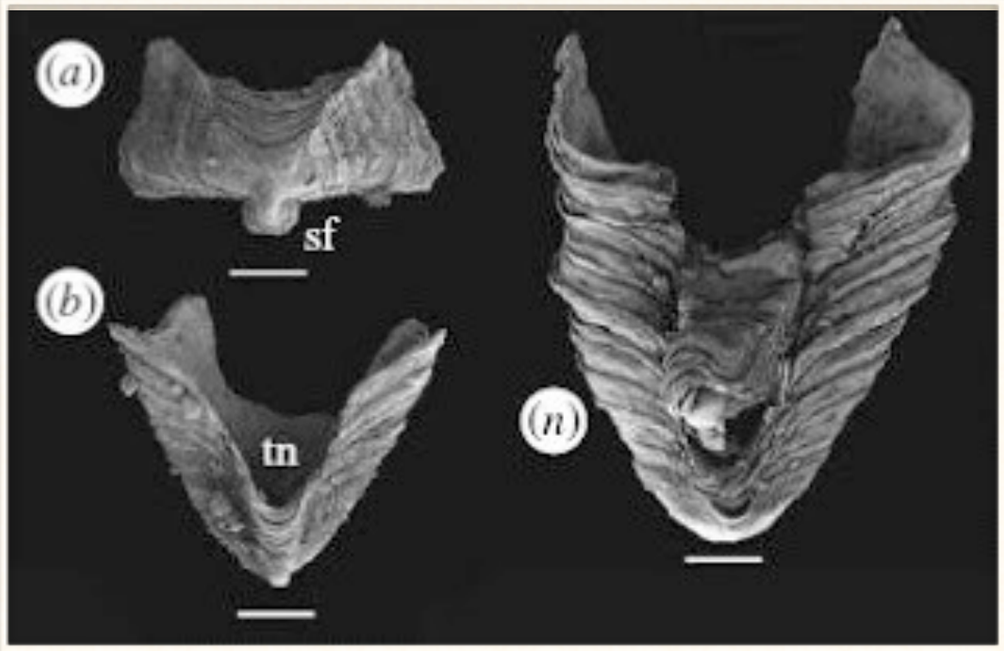
Aldanella

Fordilla

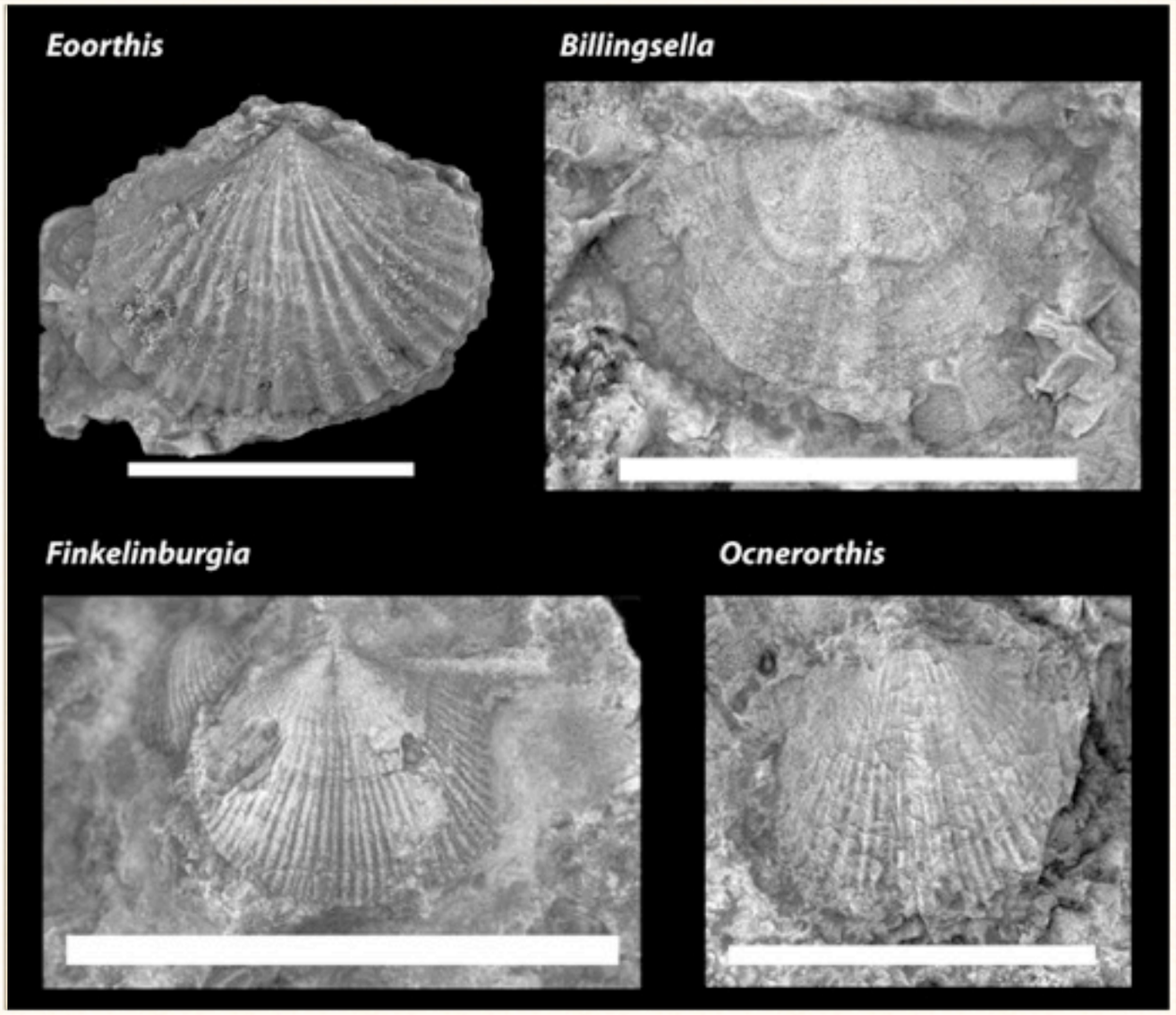
Early Cambrian Tommotids as Stem Brachiopods



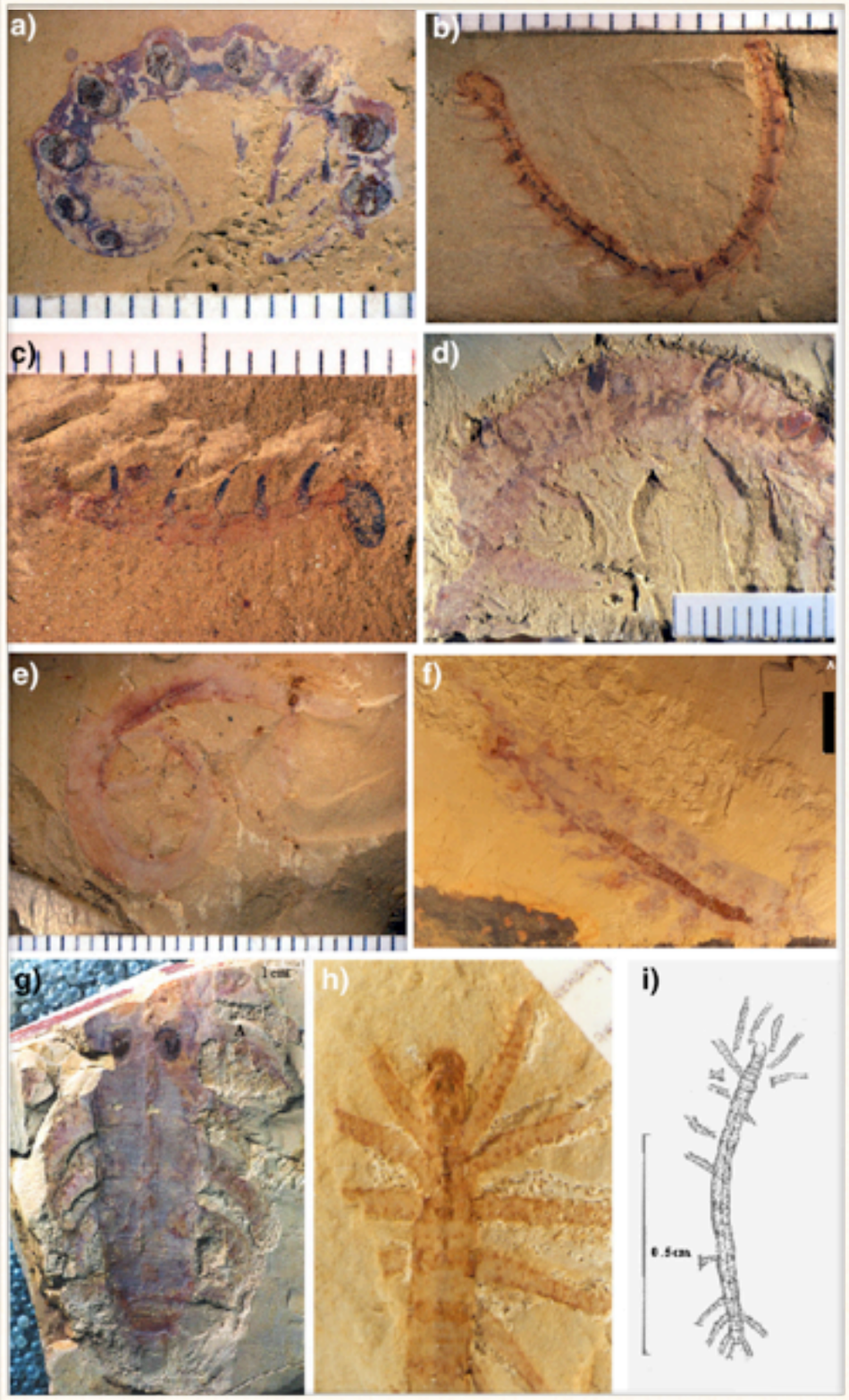




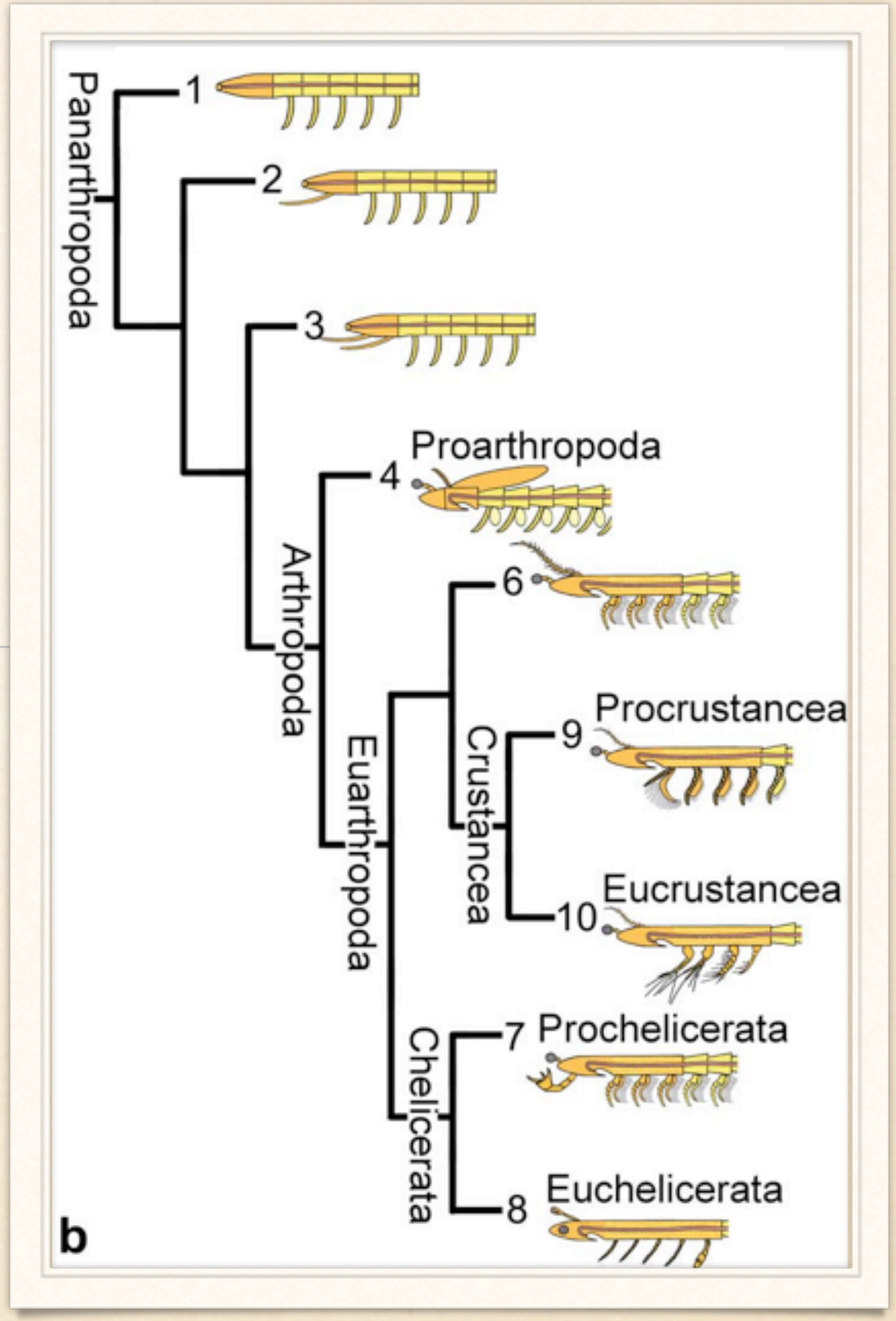
Cambrian Brachiopods



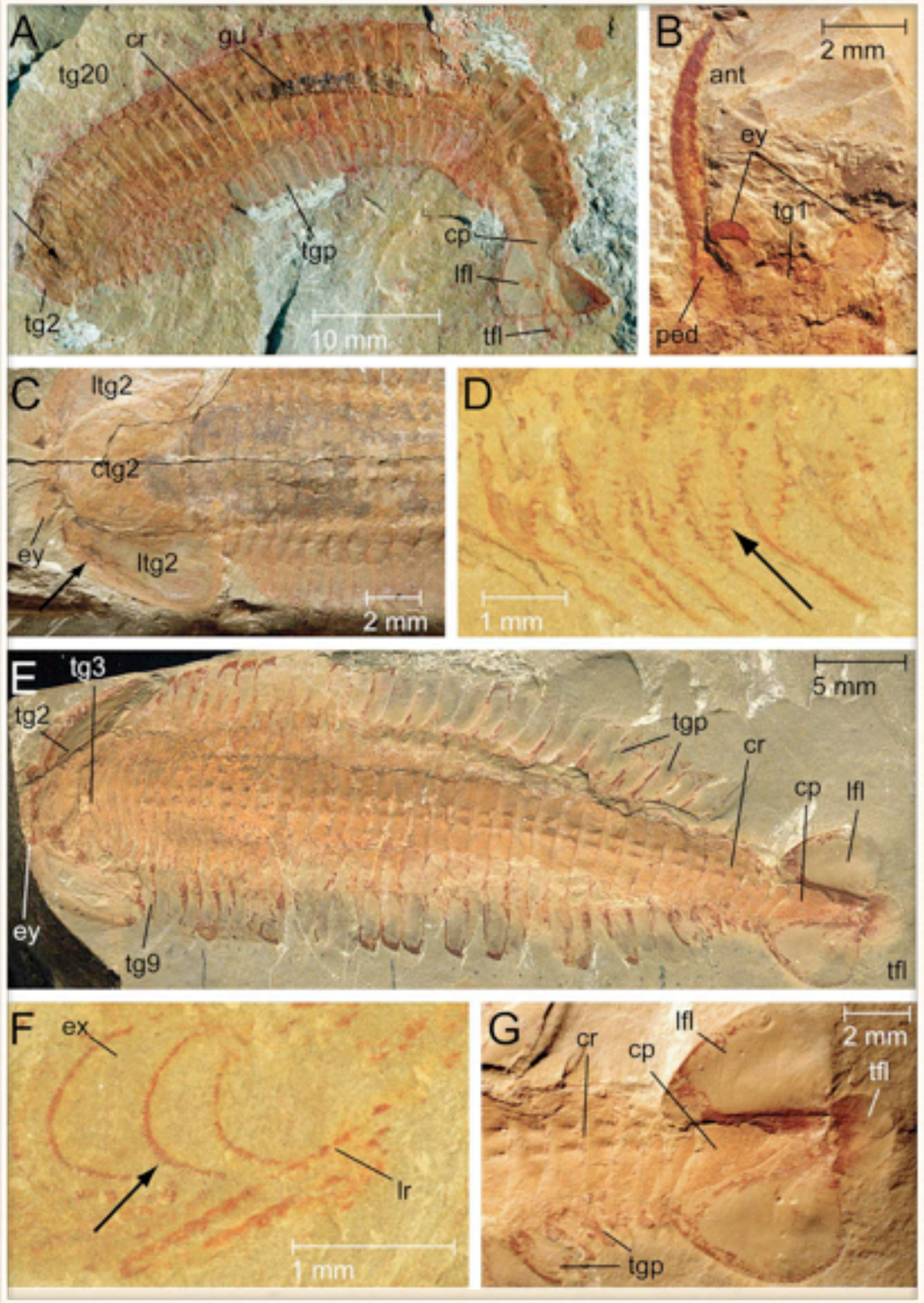
Cambrian Lobopods



Evolution of Arthropod Body Plan

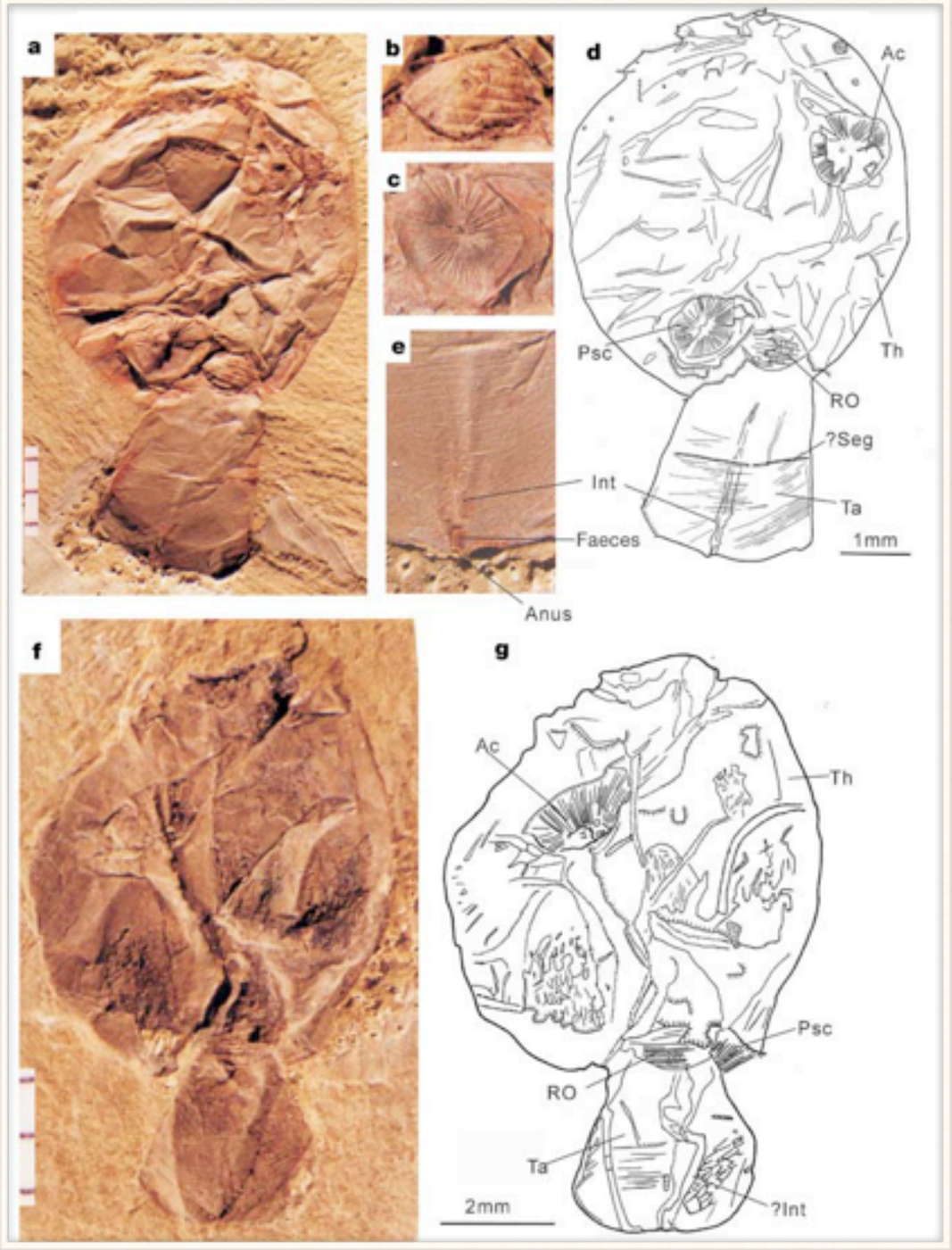


Early Cambrian Stem Arthropod *Shankouia*



Anomalocarid Stem Arthropod

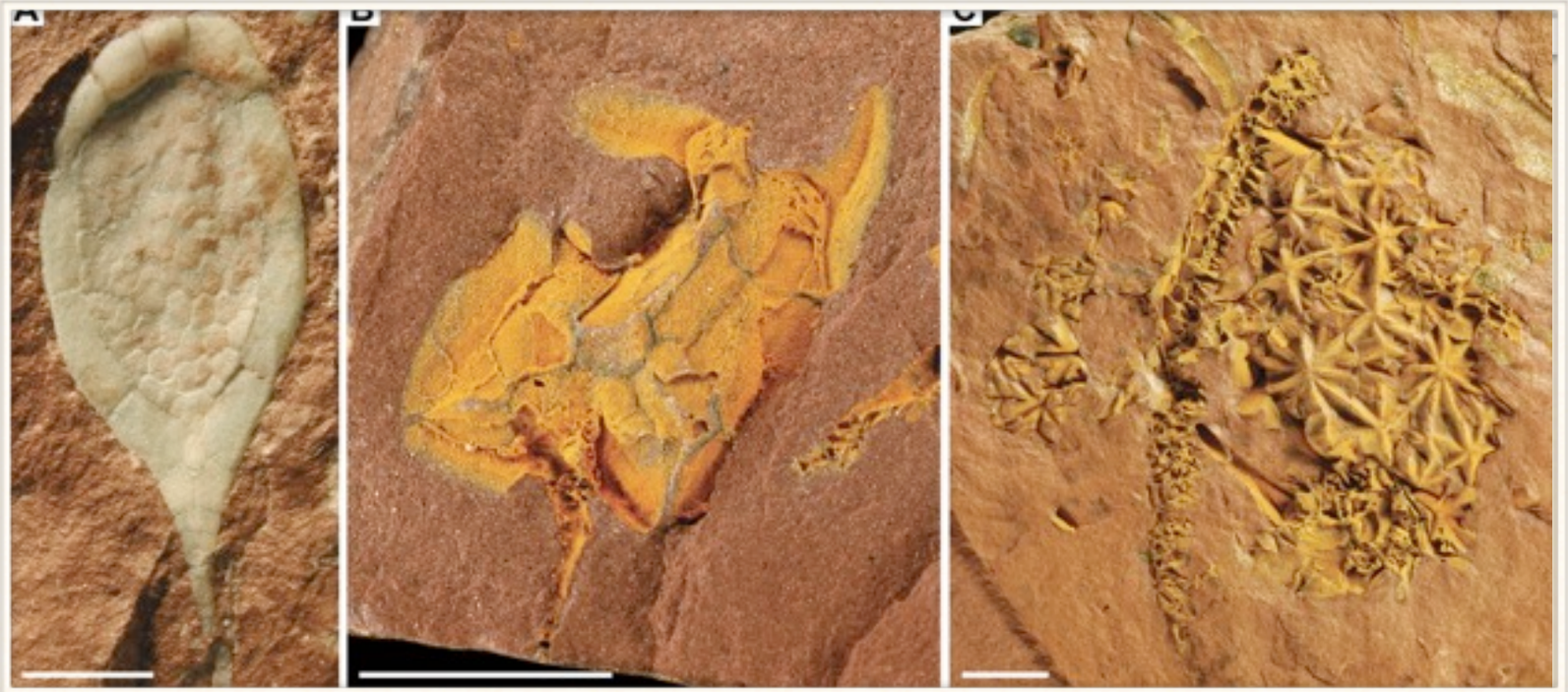
Early Cambrian Ventulocystids Stem Echinoderms



Ctenoimbricata

Cambrian Echinoderms

Cinctan, Stylophoran, Eocystitid



Basal Echinoderms

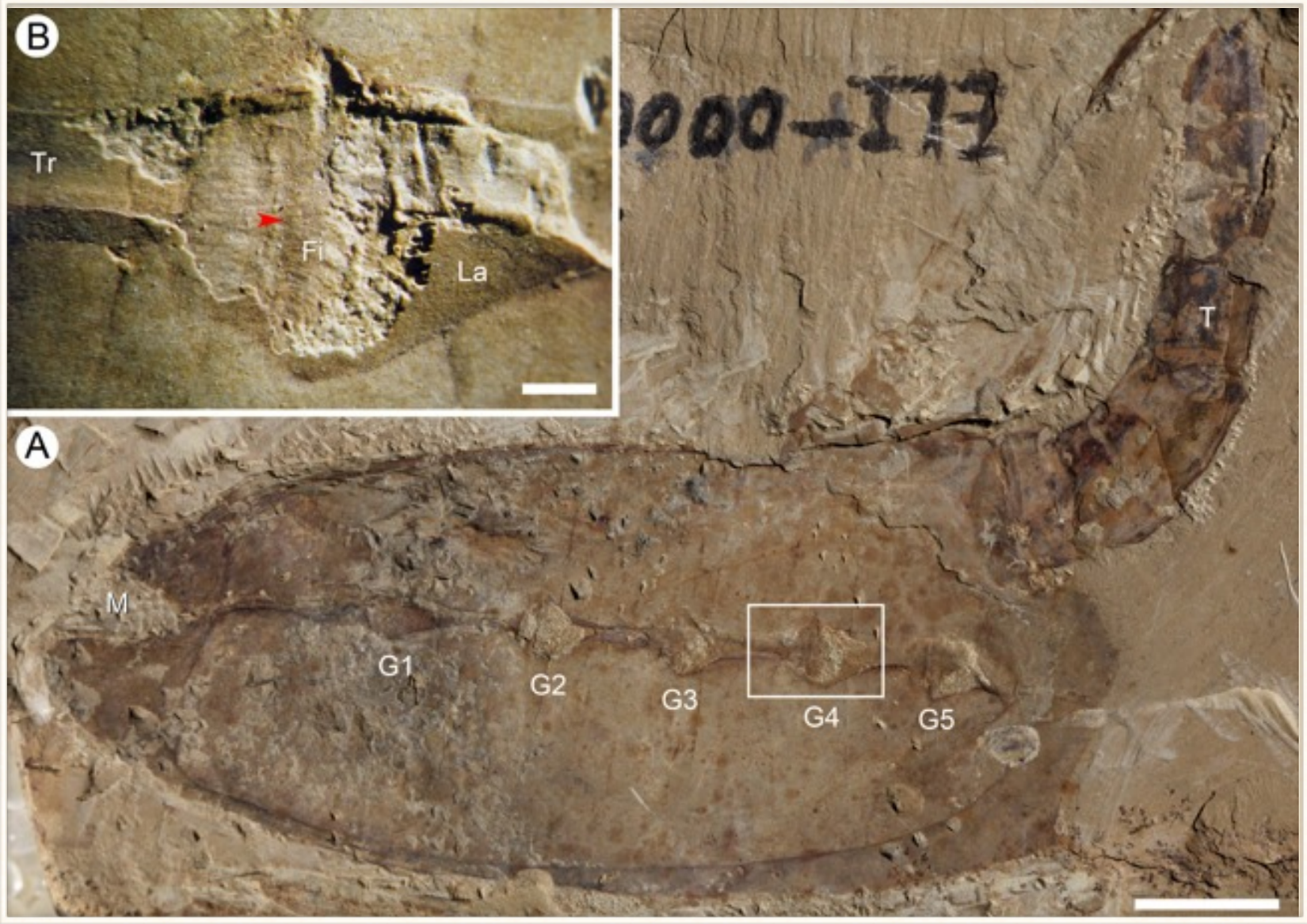
Helicoplacoids

Edrioasteroids

Eocrinoid
Golgia

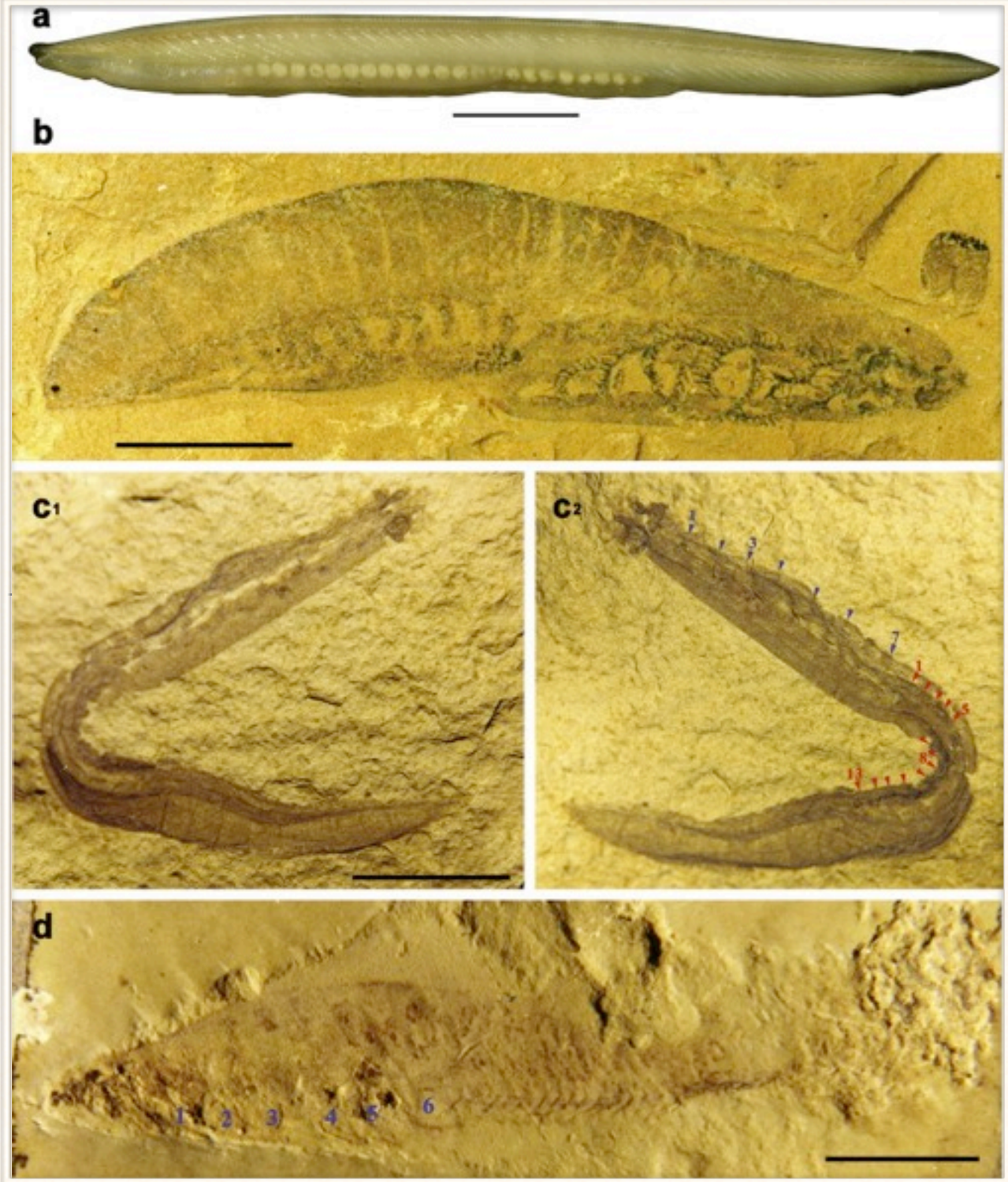
Early Cambrian Stem Deuterostomes

Vetulicolians



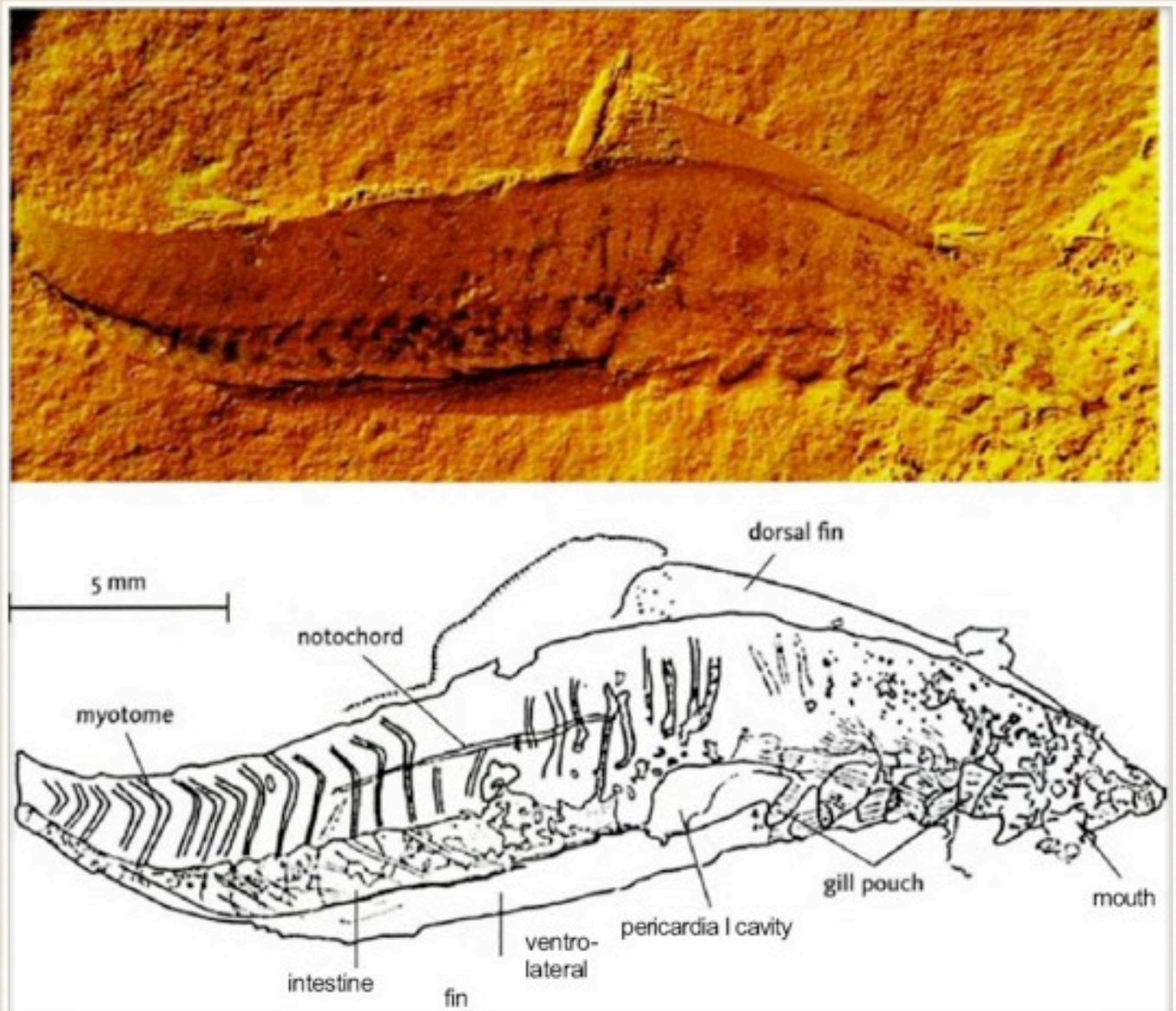
Cambrian Cephalochordates Craniate

Haikouella
Yunnanzoon
Haikouichthys

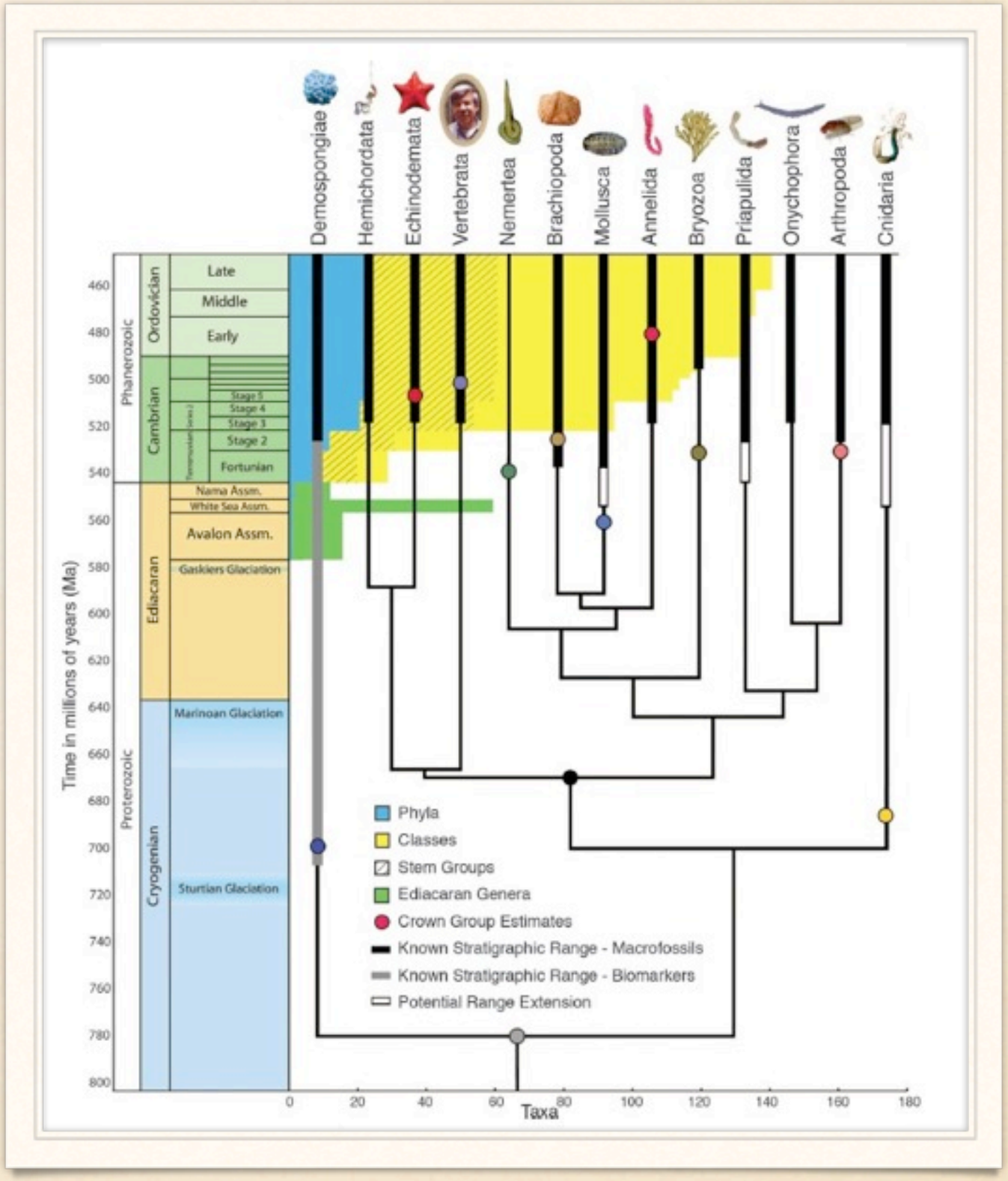


Cambrian Craniate Chordate (Stem Vertebrate?)

Myllokunmingia



Molecular vs Fossil Record



SOURCES OF ILLUSTRATIONS

- Side 2 & 3
  - Miller, K. B., 2011, “The Cambrian “explosion,” transitional forms, and the tree of life,” BioLogos White Paper.

SOURCES OF ILLUSTRATIONS

- Slide 4
  - Li, C-W., et al., 1998, "Precambrian sponges with cellular structures," Science 279: 879-882.
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  - Gehling, J. G., and Rigby, J. K., 1996, Long expected sponges from the Neoproterozoic Ediacara fauna of South Australia," Journal of Paleontology 70 (2): 185-195.
- Slide 6
  - *Mawsonites* image from Natural History Museum of London posted on Wikimedia Commons, 2007. Source: Nordelch.
  - *Nemaia* image from the Virtual Fossil Museum at http://www.fossilmuseum.net/fossils/Cnidaria/Nemaia-simplex/Nemaia.htm

SOURCES OF ILLUSTRATIONS

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  - Chen, Z., et al., 2008, "Tube structure and original composition of *Sinotubulites*: shelly fossils from the late Neoproterozoic in southern Shaanxi, China," Lethaia 41: 37-45.
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SOURCES OF ILLUSTRATIONS

- Slide 9
  - Han J., et al., 2010, "Tiny sea anemone from the Lower Cambrian of China," PLoS ONE 5(10): e13276.
- Slide 10
  - Mistaken Point Ediacaran image by G. M. Narbonne from online exhibits of Miller Museum of Geology, Queens Univ., Kington, ON, CA. http://geol.queensu.ca/museum/
  - Wrinkled microbial mat image from http://www.gondwanaresearch.com/hp/wrinkle.jpg
- Slide 11
  - *Spriggina* image from Wikimedia Commons, 2007. Attribution: Verisimilus at en.wikipedia.
  - *Marywadea* image from Peterson, K. J., et al., 2008, "The Ediacaran emergence of bilaterians: congruence between the genetic and the geological fossil records," Philosophical Transactions Royal Society B 363: 1435-1443.

SOURCES OF ILLUSTRATIONS

- Slide 12
  - *Dickinsonia Costata* image from Wikimedia Commons, 2007. Attribution: Verisimilus at en.wikipedia.
  - *Yorgia* image and resting traces from Wikimedia Commons, 2009. Source: Arkhangelsk Regional Museum. Author: Aleksey Nagovitsyn.
- Slide 13
  - Fedonkin, M. A., 2003, "The origin of the Metazoa in the light of the Proterozoic fossil record," Paleontological Research 7: 9-41.
- Slide 14
  - *Helminithopsis* image from online exhibits of Miller Museum of Geology, Queen University, Kington, Ontario, CA. http://geol.queensu.ca/museum/
  - *Helminthoidichnites* and *Gordia* images from http://www3.amherst.edu/~jwhagadorn/research/UpperCambrian/TraceFossils/

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- Slide 15
  - Seilacher, A., et al., 2005, "Trace fossils in the Ediacaran-Cambrian transition: Behavioral diversification, ecological turnover and environmental shift," Palaeogeography, Palaeoclimatology, Palaeoecology 227: 323-356.
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  - Vannier J., et al., 2012, "Priapulid worms: Pioneer horizontal burrowers at the Precambrian-Cambrian boundary," Geology 38: 711-714.
- Slide 17
  - Priapulid burrow reconstruction from Wikimedia Commons, 2008. Author: Smokeybjb.
  - Burgess shale priapulid *Ottia* from Royal Ontario Museum. http://burgess-shale.rom.on.ca/en/fossil-gallery/list-species.php
- Slide 18
  - Müller, K., and Hinz-Schallreuter, 1993, "Palaeoscolecid worms from the Middle Cambrian of Australia," Palaeontology 36 (3): 549-592.

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- Slide 19
  - *Odontogriphus* image from Caron, J. B., et al., 2006, "A soft-bodied mollusc with radula from the Middle Cambrian Burgess Shale," Nature 442: 159-163.
  - *Halkeria* image from Wikimedia Commons, photo by Jakob Vinther. Source: en.wikipedia.org
  - *Orthozanchus* image from Conway Morris, S., and Caron, J. B., 2007, Halwaxiids and the early evolution of the Lophotrochozoans," Science 315: 1255-1258.
  - *Wiwaxia* image from Smithsonian National Museum of Natural History at http://paleobiology.si.edu/burgess/wiwaxia.html
  - *Canadia* image from Smithsonian National Museum of Natural History at http://paleobiology.si.edu/burgess/canadia.html

SOURCES OF ILLUSTRATIONS

- Slide 20
  - *Oelandiella* image from Gubanov, A. P., and Peel, J. S., 1999, "*Oelandiella*, the earliest Cambrian helcionelloid mollusc from Siberia," Palaeontology 42(pt 2): 211-222.
  - *Archaeospira* and *Watsonella* images from the Burgess Shale website at http://burgess-shale.rom.on.ca/en/science/origin/04-cambrian-explosion.php
  - *Fordilla* image from Charles Doolittle Walcott (1886) Second contribution to the studies on the Cambrian faunas of North America, Geological Survey bulletin issue 30 , Govt. Print. Off., pp.369
  - *Aldanella* image from Parkhaev, P. Yu., 2007, "Shell chirality in Cambrian gastropods and sinistral members of the genus *Aldanella* Vostokova, 1962," Paleontological Journal 41(3): 233-240.

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  - Skovsted, C. B., et al., 2008, " The scleritome of *Eccentrotheca* from the Lower Cambrian of South Australia: Lophophorate affinities and implications for tommotid phylogeny," Geology 36: 171-174.
  - Skovsted, C. B., et al., 2009, "The scleritome of *Paterimitra*: an Early Cambrian stem group brachiopod from South Australia," Proceedings of the Royal Society B 276: 1651-1656.
- Slide 22
  - Cambrian brachiopods from Oklahoma illustrated in Sam Noble Museum of Natural History, Norman, OK. http://commonfossilsofoklahoma.snomnh.ou.edu/cambrian-fossil-gallery

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- Slide 23
  - Liu J., et al., 2008, "Origin, diversification, and relationships of Cambrian lobopods," Gondwana Research 14: 277-283.
- Slide 24
  - Chen, J-Y., 2011, "The origins and key innovations of vertebrates and arthropods," Paleoworld 20: 257-278.
- Slide 25
  - Waloszek, D., et al., 2005, "Early Cambrian arthropods - new insights into arthropod head and structural evolution," Arthropod Structure & Development 34: 189-205.
- Slide 26
  - Burgess shale *Anomalocaris canadensis* from Royal Ontario Museum. http://burgess-shale.rom.on.ca/en/fossil-gallery/list-species.php

SOURCES OF ILLUSTRATIONS

- Slide 27
  - Shu, D-G., et al., 2002, "Ancestral echinoderms from the Chengjiang deposits of China," Nature 430: 422-428.
- Slide 28
  - Cinctan, stylophoran, and eocystitid images from Zamora, S., 2010, "Middle Cambrian echinoderms from north Spain show echinoderms diversified earlier in Gondwana," Geology 38(6): 507-510.
  - *Ctenoimbricata* image from Zamora, S., et al., 2012, "Plated Cambrian biolaterians reveal the earliest stages of echinoderm evolution," PLoS One 7(6): e38296.
- Slide 29
  - Helicoplacoid image from palaeobiology page of Uppsala University at http://www.palaeontology.geo.uu.se/Mainpages/fom2009.html
  - Edrioasteroid image from http://www.geol.umd.edu/~tholtz/G331/lectures/331echin1.html
  - Eocrinoid *Golgia* image from Wikimedia Commons, 2009. Author: Kevmin.

SOURCES OF ILLUSTRATIONS

- Slide 30
  - Ou, Q., et al., 2012, Evidence of gill slits and a pharynx in Cambrian vetulicolians: Implications for the early evolution of deuterostomes," BMC Biology 10: 81
- Slide 31
  - Chen, J-Y., 2011, "The origins and key innovations of vertebrates and arthropods," Paleoworld 20: 257-278.
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  - Chen, J-Y., et al., 1999, An early Cambrian craniate-like chordate," Nature 402:518-522.
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  - Erwin, D.H., et al., 2011, "The Cambrian conundrum: Early divergence and later ecological success in the early history of animals," Science 334: 1091-1097.