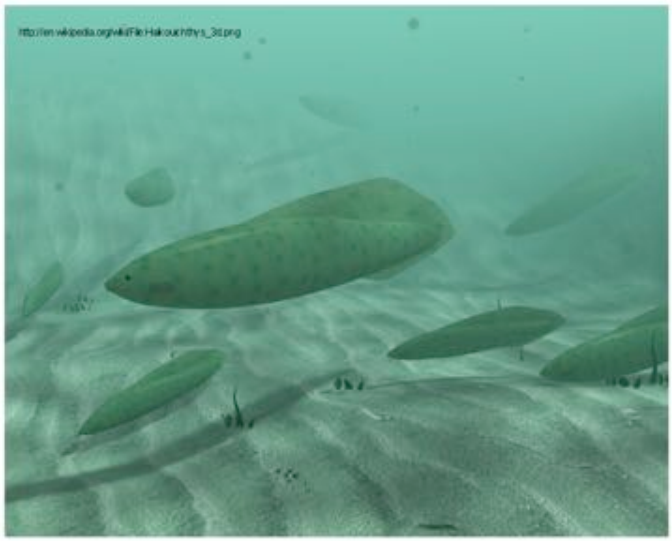
THE CAMBRIAN EXPLOSION



The Rise of the Animals

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Lecture Outline

- Diversity of Animals Today
  - General characteristics of Animals
  - Some major animal groups today
- Diversity of Life before the Cambrian Explosion
- The Timing of the Cambrian Explosion
  - Phase 1
  - Phase 2
  - Phase 3
- Causes of the Cambrian Explosion
  - Ocean Chemistry
  - Evolutionary Arms Race
  - A Time of Experimentation
- Windows into the Early Cambrian
  - The Chengjian Biota
  - The Burgess Shale

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DIVERSITY OF ANIMALS TODAY

- Q: What is the Cambrian Explosion?
- A: The SUDDEN diversification of the major phyla of life including animals.
- ANIMAL: Broadly used term
- Latin: *animalis* "having breath"

What is the Cambrian explosion?

.....the relatively rapid appearance, around 530 million years ago, of most major animal phyla, as demonstrated in the fossil record, accompanied by major diversification of organisms including animals and phytoplankton. Before about 580 million years ago, most organisms were simple, composed of individual cells occasionally organized into colonies. Over the following 70 or 80 million years, the rate of evolution accelerated by an order of magnitude and the diversity of life began to resemble that of today.

So this is a VERY significant part of the Earth System story.

The animals are an important (but not exclusive) past of the Cambrian explosion but just what is an animal? In latin in means "having breath." Misconceptions about animals include; humans are someway not animals or that any creature without a backbone are not an animal.

i>clicker: What is an animal?

a) Anything that is not human and not a plant
b) Anything with a backbone
c) Anything that breathes air
d) Any multicellular creature that is not a plant or algae
e) Any mammal

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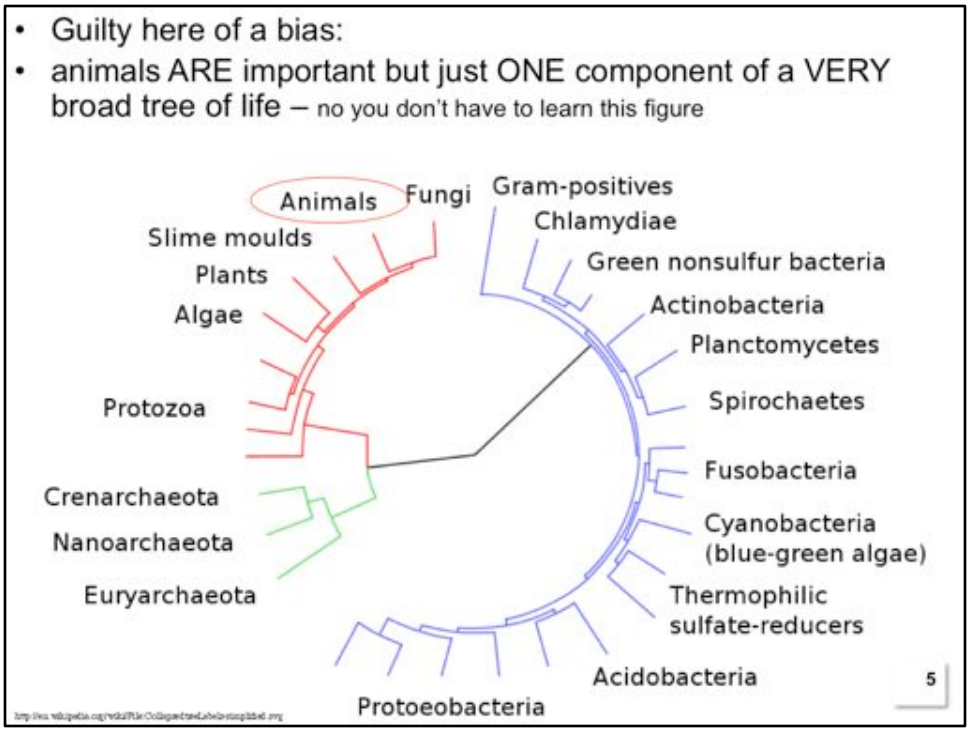
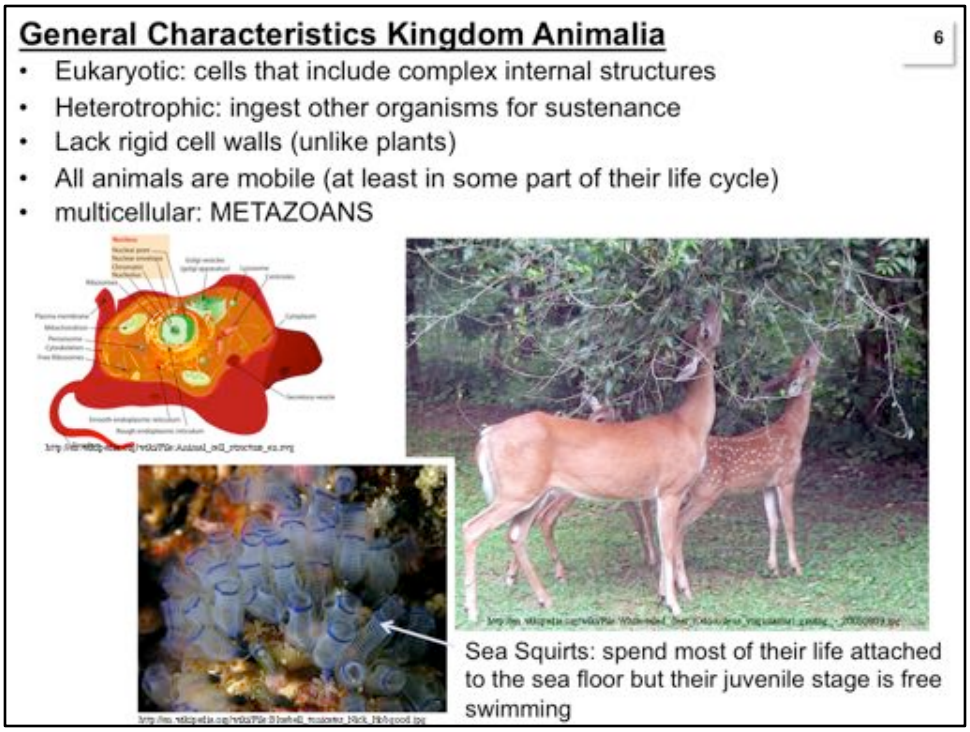


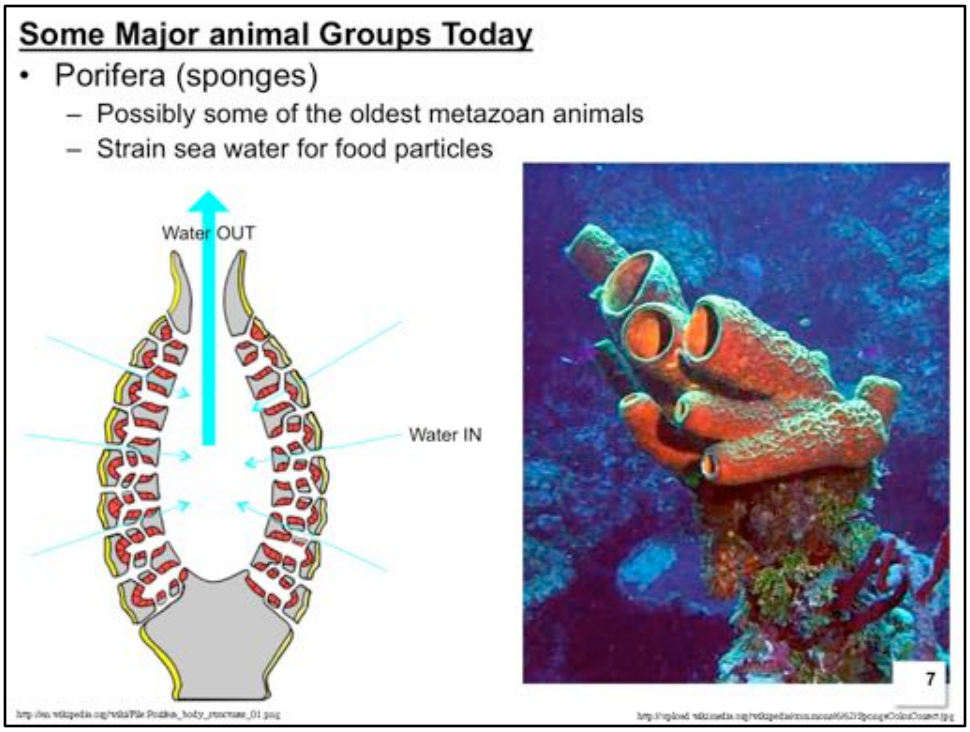
We must be aware of a bias here though. Although animals are an important part of the biosphere we must remember that they are but ONE Part of a very diverse tree of life.



What are the general characteristics of animals?

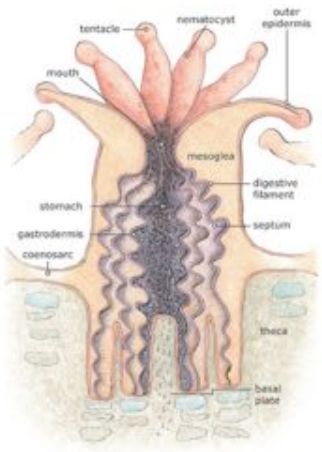
- Eukaryotic: cells that include complex internal structures like mitochondria and a nucleus (see previous lecture)
- Heterotrophic: mostly ingest other organisms for sustenance
- Lack rigid cell walls (unlike plants)
- All animals are mobile at least in some part of their life cycle. For example, although adult sea squirts spend most of their life attached to the sea floor their juvenile stage is free swimming

- MANY (not all) are multicellular: METAZOANS



The Poifera (sponges) are some of the most primitive metazoans living today. They are multicellular organisms which have bodies full of pores and channels allowing water to circulate through them from which they strain food particles.

- Cnidaria (corals and related animals)
  - Living part of a coral: the polyp



You do not need to know the details of this figure

- Some are important reef builders – secrete a calcium carbonate skeleton

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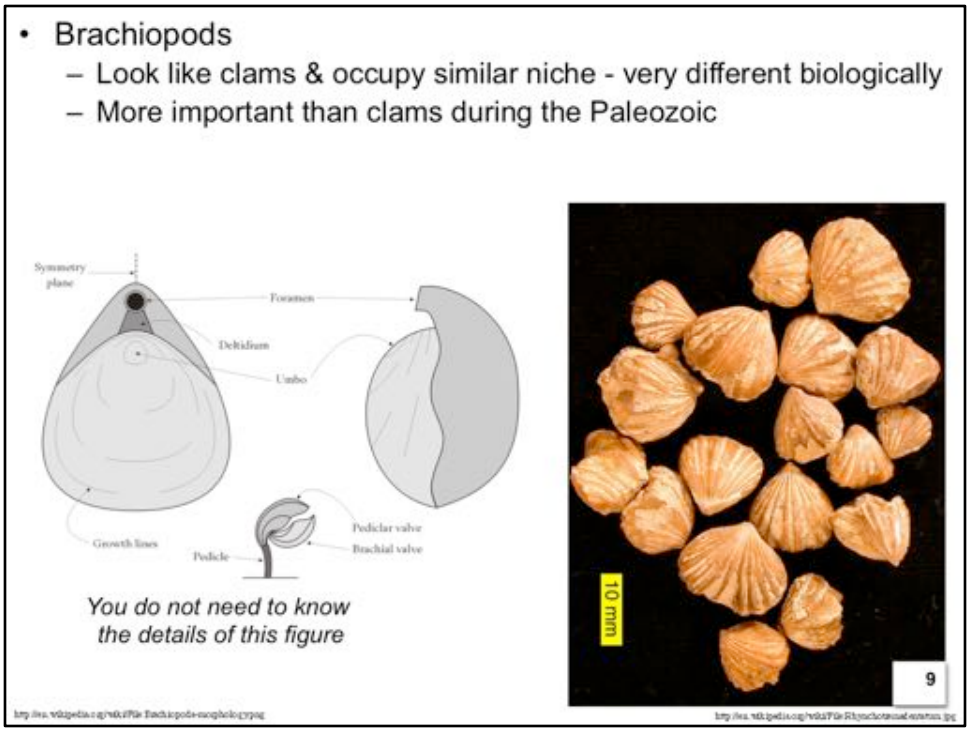
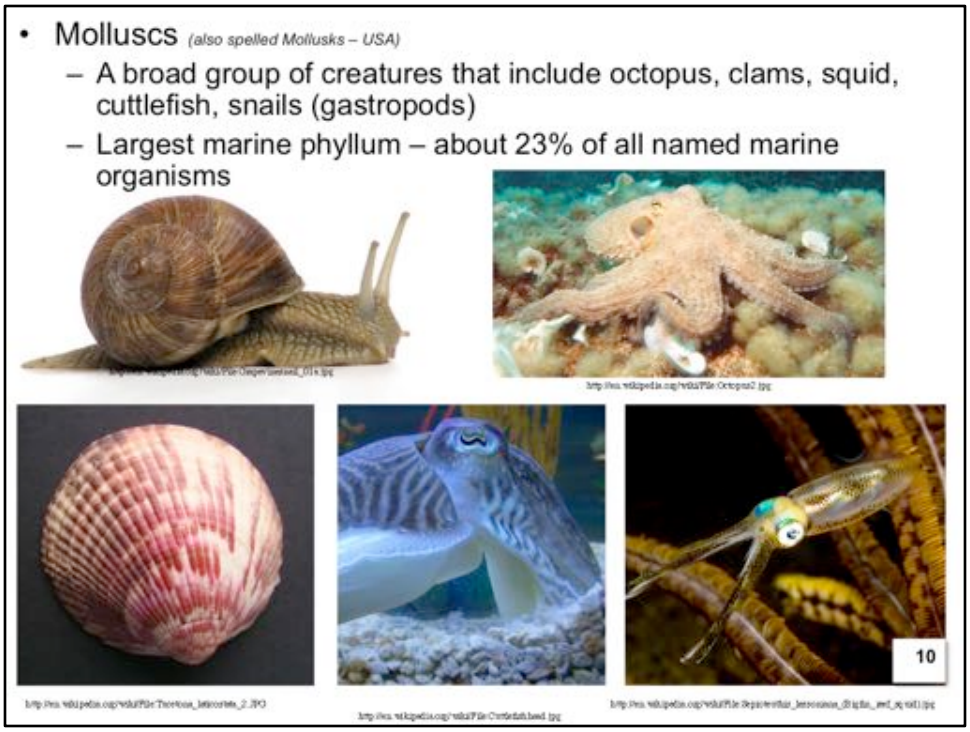
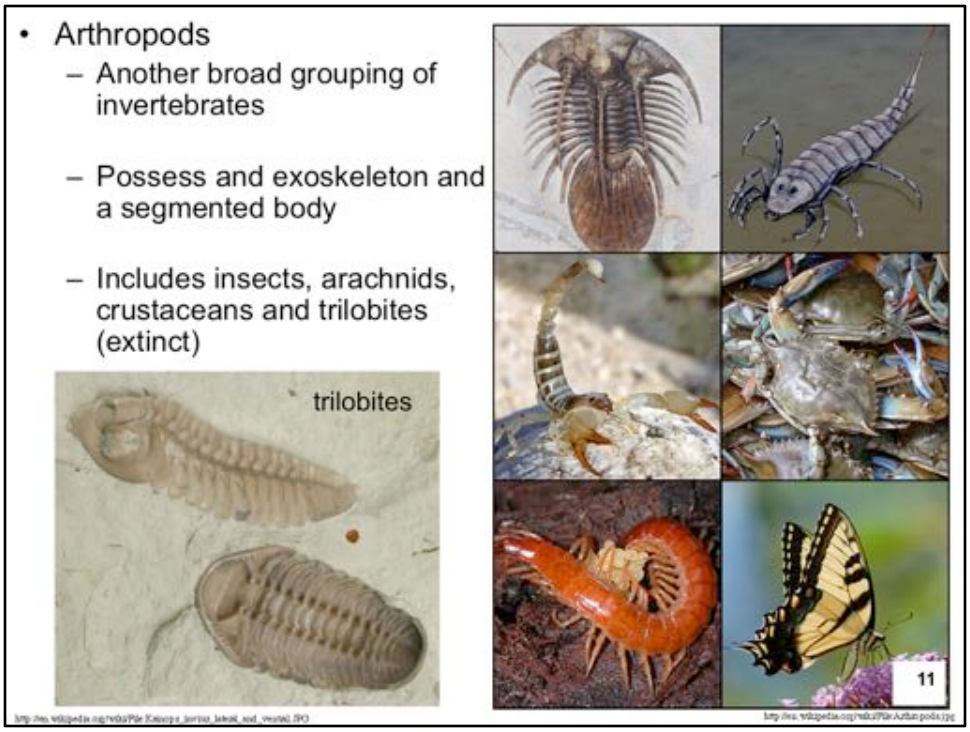
The cnidaria is a phylum containing over 10,000 species of animals found exclusively in aquatic and mostly marine environments. Their distinguishing feature is cnidocytes, specialized cells that they use mainly for capturing prey. Some cniderians secrete calcium carbonate skeletons (corals) and are important reef builders.



The Brachiopods (phylum Brachiopoda) are marine animals that have hard "valves" (shells) on the upper and lower surfaces, unlike the left and right arrangement in bivalve molluscs (clams). Brachiopod valves are hinged at the rear end, while the front can be opened for feeding or closed for protection. Brachiopods occupied similar niches to some modern day clams. They were very common in the Paleozoic but not so much today.



The molluscs or mollusks compose a large phylum of invertebrate animals, Mollusca. Around 85,000 extant species of molluscs are recognized. Molluscs are the largest marine phylum, comprising about 23% of all the named marine organisms. Numerous molluscs also live in freshwater and terrestrial habitats. The mollusks include octopus, cuttlefish and squid (cephalopods), clams (bivalves) and snails (gastropods)



An arthropod is an invertebrate animal having an exoskeleton (external skeleton), a segmented body, and jointed appendages. Arthropods are members of the phylum Arthropoda and include the insects, arachnids, and crustaceans. Arthropods are characterized by their jointed limbs and cuticles, which are mainly made of a substance called chitin; the cuticles of crustaceans are also biomineralized with calcium carbonate. The rigid cuticle inhibits growth, so arthropods replace it periodically by moulting. The arthropod body plan consists of repeated segments, each with a pair of appendages. Trilobites were an important arthropod group during the Paleozoic.

- Echinoderms
  - exoskeleton composed of calcium carbonate plates
  - Use a "water vascular system" to move tube feet
  - Body arranged into 5 (or groups of five) segments
  - Includes: starfish, sea urchins, crinoids, sea cucumbers

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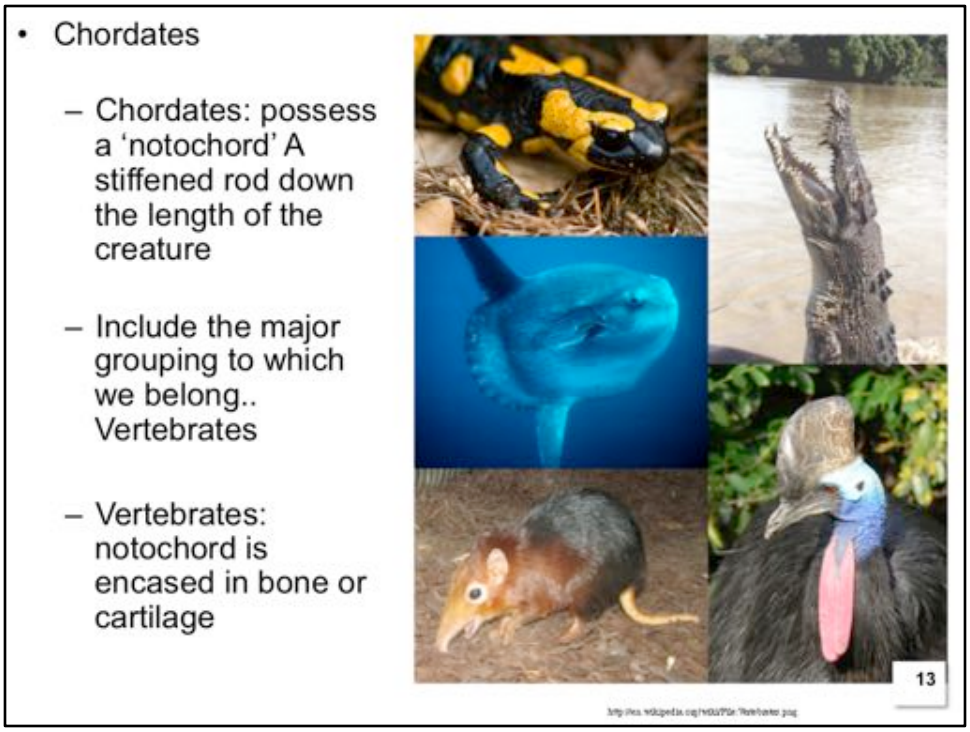
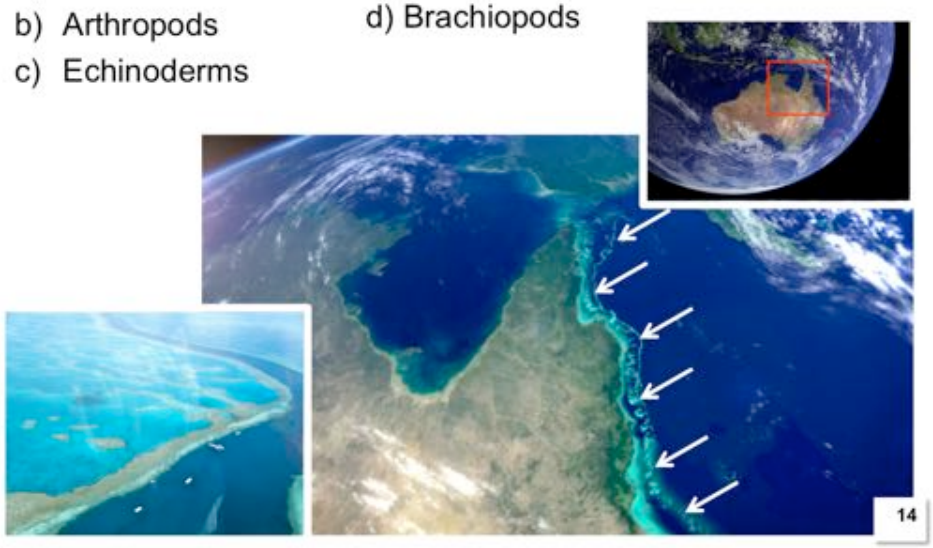
Echinoderms (Phylum Echinodermata) are a phylum of marine animals (not known in fresh water environments). The adults are recognized easily by their (usually five-point) radial symmetry, and include such well-known animals as starfish, sea urchins, sand dollars, and sea cucumbers. Echinoderms possess a unique water vascular system. This is a network of fluid-filled canals that function in gas exchange, feeding, and secondarily in locomotion of tube feet and spines.



Chordates, members of the phylum Chordata, are animals possessing a notochord, a hollow dorsal nerve cord. Taxonomically, the phylum includes the subphyla Vertebrata, including mammals (and thus humans), fish, amphibians, reptiles and birds all of which have a notochord encased in bone or cartilage.

i>clicker: What is this feature mostly composed of?

a) Cnidaria
b) Arthropods
c) Echinoderms
c) Chordates
d) Brachiopods



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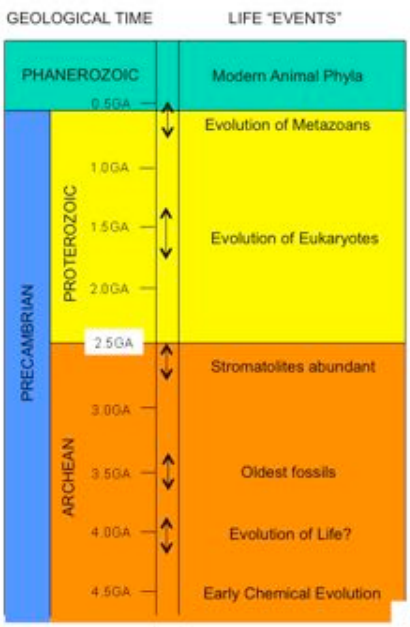
DIVERSITY OF LIFE BEFORE THE CAMBRIAN

- Earliest evidence of life 3.5GA
- Life probably evolved much earlier – possibly 4GA or earlier?
- Photosynthetic bacteria common by 2.5GA
- First multicellular life at least 1.2GA (*Bangiomorpha*)
- Earliest multicelluar animals about 600MA
- Majority of modern phyla appear RAPIDLY just after base of Cambrian



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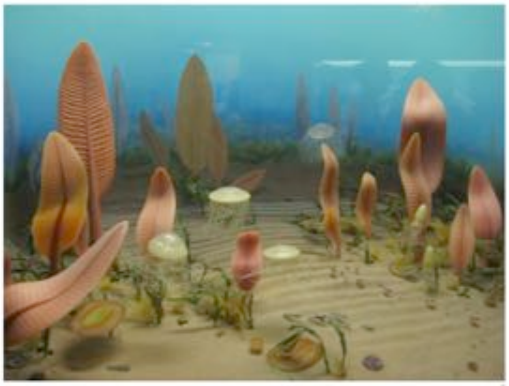
For more detail see the previous lecture.

- MUCH of Earth history life is pretty much bacteria or at best singled celled eukaryotes or VERY simple multicelluar algae
- Rapid evolution of microbes after the Great Oxygenation Event but then life "stalls"
- WHY? For details see EOSC 326 (general science credit) or EOSC 425 if you do an EOSC degree

Till we get to the period around the Cambrian explosion life had been pretty well bacterial slime or very simple mulicelluar creatures. We see an evolution or life around abut the time of the great oxygenation event but then life stalls till we get to the Cambrian explosion. To see why life did stall see EOSC326 or EOSC425.

- Life starts to get interesting with the evolution of the Ediacarans
- Definite metazoans with some possible ancestors of modern forms but NOTHING like modern diversity of today's phyla



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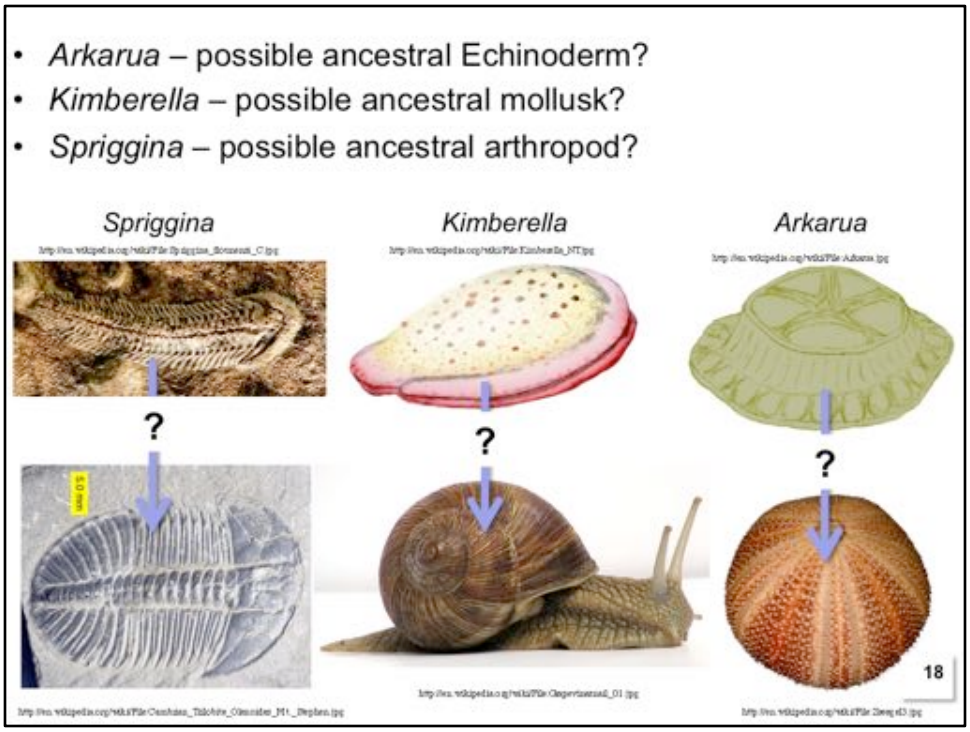
Some consider the Ediacarans to be the first "echo" of the big bang that was to come with the Cambrian explosion. We do see an increased diversity with the Ediacarans (and possibly some ancestors of today's animal groups) but nothing like the diversity that was to develop in the Cambrian.



Possible Ediacaran ancestors of later life forms include:

Arkarua – possible ancestral Echinoderm?

Kimberella – possible ancestral mollusk?

Spriggina – possible ancestral arthropod?

i>clicker: If kimberalla is an ancestral mollusk which of these seafood dishes might it be most closely related to?

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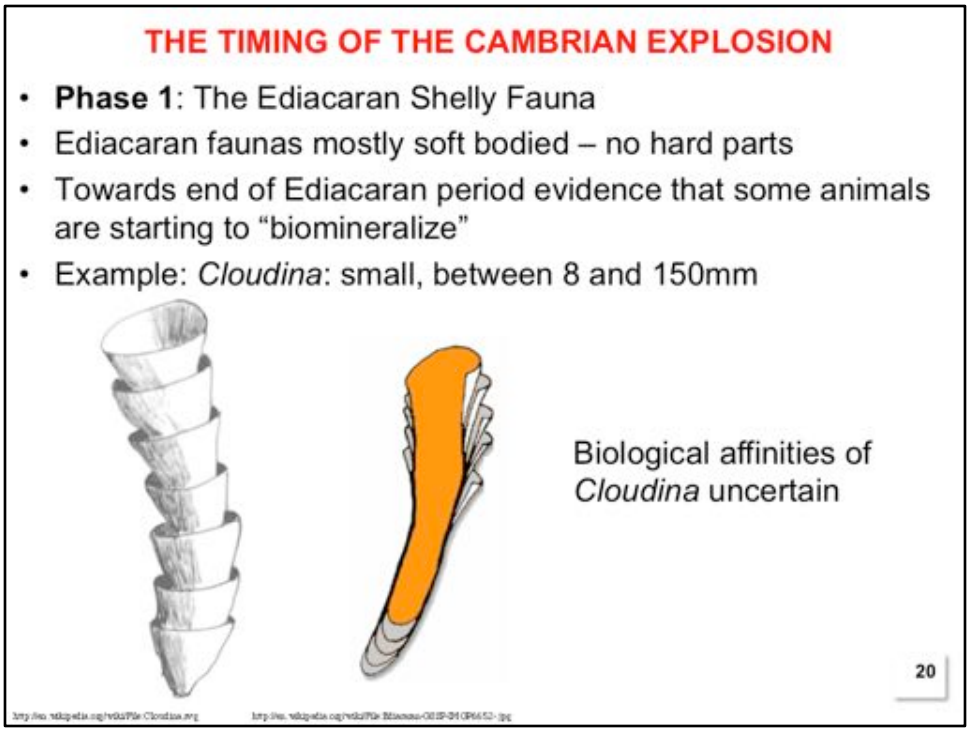
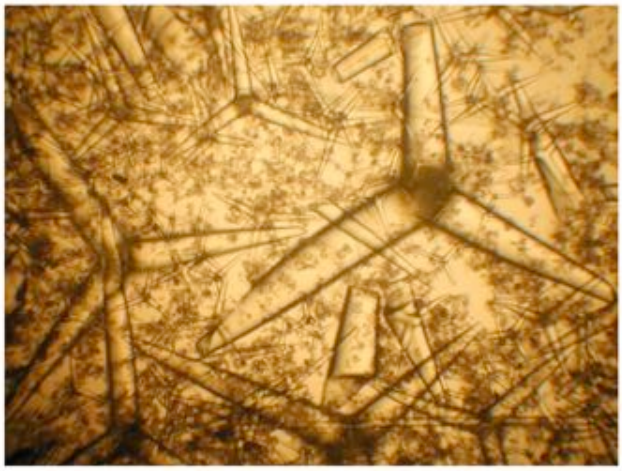


Phase 1: The Ediacaran Shelly Fauna

Ediacaran faunas mostly soft bodied and no hard parts like shells or an internal skeleteton. Towards end of Ediacaran period though you can find evidence that some animals are starting to "biomineralize." For example: *Cloudina* a small fossil small, between 8 and 150mm. They consist of calcareous cones nested within one another; the appearance of the organism itself remains unknown.

- The remains of sponges may have also been recovered along with *Cloudina*
- Sponge spicules: the internal framework elements that are the structural support of sponges



Sponge spicules

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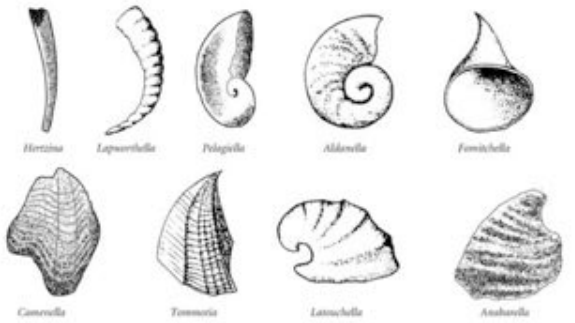
The remains of sponges may have also been recovered along with *Cloudina.* These are sponge spicules, the internal framework elements that are the structural support of sponges.

Phase 2: The Small Shelly Fauna

- Common in the early part of the Cambrian
- Contains some of the small mineralized material from phase 1 but also many new forms.
- Probably ancestral mollusks and brachiopods also many forms difficult to assign to any other phylum
- Skeletons composed of calcium carbonate and phosphate
- Rarely more than a few mm in size



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http://www.blackwellpublishing.com/paleobiology/figure.asp?chap=10&fig=Fig10-12&img=c10f012

Phase 2: The Small Shelly Fauna. These small fossils (rarely more than a few mm in size) are common in the early part of the Cambrian. The fauna contains some of the small mineralized material from phase 1 but there are many new forms. Within this fauna are likely primitive ancestors of the molluscs and brachiopods also many forms difficult to assign to any other phylum. The shells are composed of calcium carbonate and calcium phosphate.

Phase 3: Large animals with hard parts

- Some of the earliest: trilobites
  - Arthropods – VERY successful through the Paleozoic
  - Various life styles but mostly throught to have been grubbing about on the ocean floor processing sediment for organic material

One of the earliest Trilobites: order Olenellia

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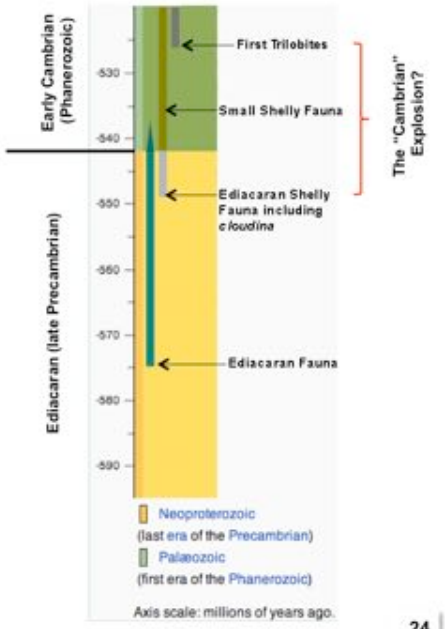
Phase 3:The appearance of large animals with hard parts. Some of the earliest large creatures with shells were the trilobites, a member of the arthropods and VERY successful through the Paleozoic. Trilobites had various life styles but mostly thought to have been scavenging around on the ocean floor processing sediment for organic material.

- Actual timing of Cambrian explosion poorly defined
- The “Roots” of the Cambrian explosion probably stretch back to the Ediacaran Fauna
- Still a remarkable event – From a low diversity biosphere SUDDENLY see the evolution of the majority of today’s modern phyla



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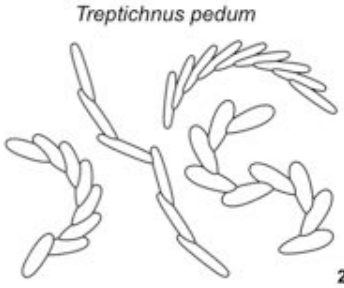
The actual timing of Cambrian explosion poorly defined. The “Roots” of the event probably stretch back to the Ediacaran Fauna but changes that occur around the base of the Cambrian are still remarkable. We see the Earth transformed from a low diversity biosphere VERY SUDDENLY with the evolution of the majority of today’s modern phyla.

- Explosion of life also associated with new niche exploitation
- See this in the sudden proliferation of trace fossils
- Evidence that animals are starting to INTERACT with their environment. Life is no longer "passive"
- Base of Cambrian defined by emergence of new behavior -
- Cambrian unique in that its base is defined by a TRACE FOSSIL rather than a body fossil: *Treptichnus pedum*



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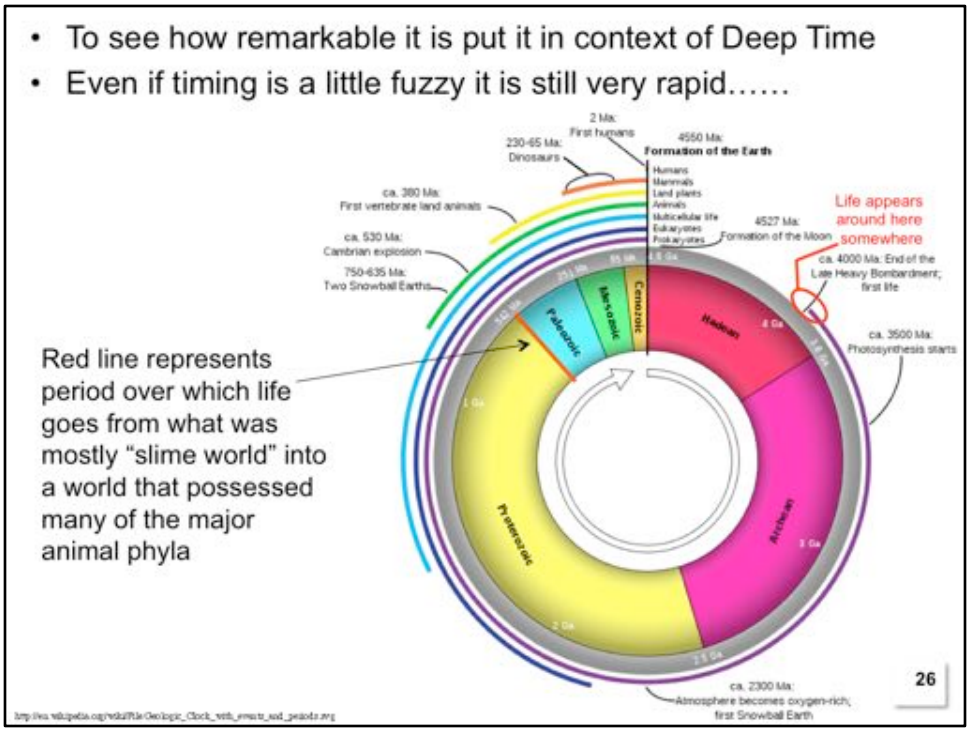
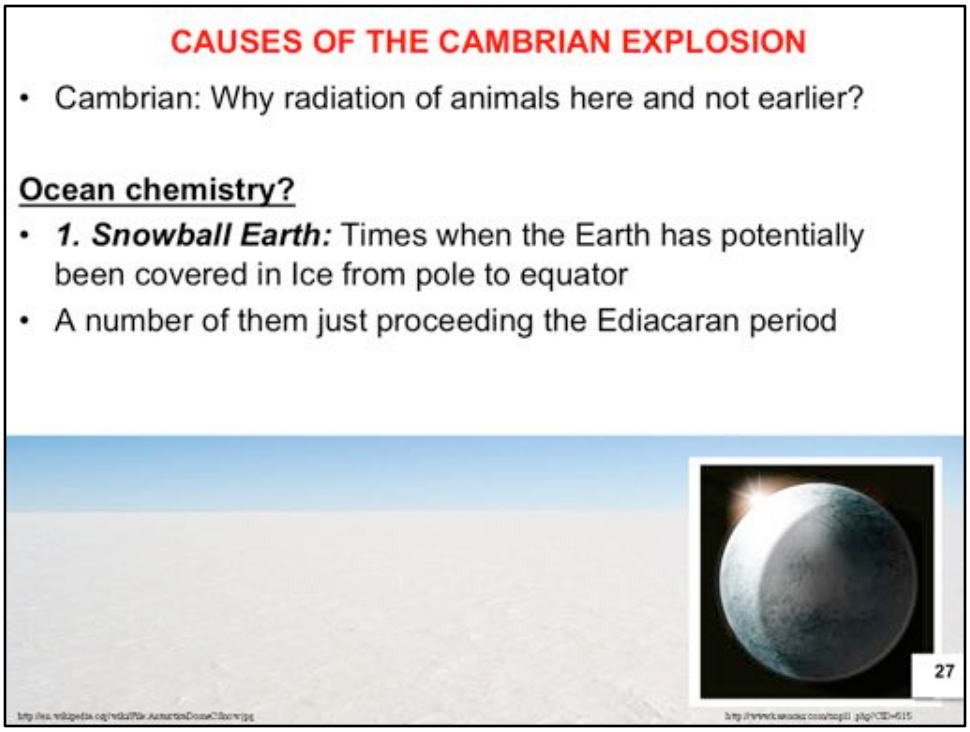
Base of the Cambrian GSSP: Fortune Head, SE Newfoundland

This explosion of life is also associated with new niche exploitation. You can see this in the sudden proliferation of trace fossils….. evidence that animals are starting to INTERACT in a big way with their environment. Life is no longer "passive" This is such a remarkable change that the base of Cambrian Period is defined by the emergence of this new behavior. The Cambrian is unique in that it's base is defined by a TRACE FOSSIL *Treptichnus pedum* rather than a body fossil. The section that contains the international reference section for the base of the Cambrian is at Fortune Head in SE Newfoundland.



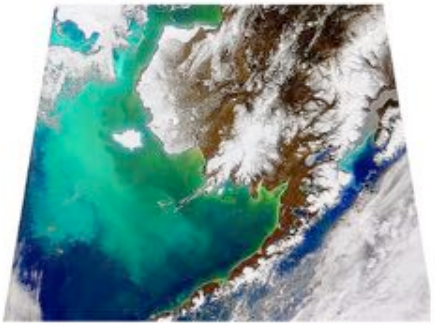
This diagram illustrates what a short period of time it took for life to proliferate into a rich and diverse biosphere.

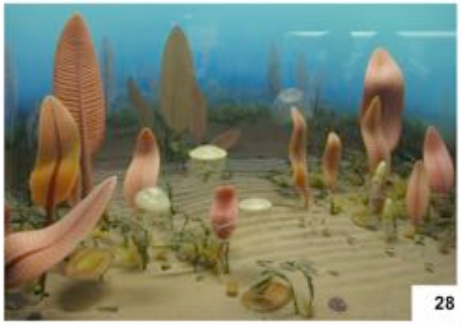


But what caused the Cambrian explosion? Why did it not occur earlier? Why, if life arose so long ago, has it only (relatively) recently got complex? There are many suggestions, here are some:

Perhaps ocean chemistry had to change. It is known that during the Precambrian the Earth suffered so called “snowball Earth” events. Periods when the land and the oceans were completely covered in ice. A number of them occurred just before the Ediacaran period.

- The end of a snowball period is thought to have been associated with “hyper hurricanes”
- Mixes up the Earth’s oceans with two effects:
  - 1. releases a flood of nutrients into the oceans and causes a bloom of photosynthetic algae = increased oxygen production
  - 2. mixes up and increases oxygen content of the oceans - makes certain key metabolic elements more available
- Result: Animals get larger.. greater oxygen availability, more complex and efficient metabolic systems





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When these glacial events ended (and they ended very rapidly!) it is thought global temperatures changed from about -50°C to +50°C over a very short period of time. Under such conditions it is likely that the globe experienced extreme weather in the form of “hyper hurricanes” many times the scale of hurricanes that we see today. It is thought that these hurricanes would mix up the now warm oceans with two effects:

1. The release of a flood of nutrients into the warm oceans from weathering on land and by churning up the ocean floor sediments. This would cause a bloom of photosynthetic algae leading to increased global oxygen production

2. This oxygen increase would mean that the oceans contained more oxygen and the severe hurricanes would ensure that the oxygen was thoroughly mixed them them.

It has been suggested that this sudden release of oxygen would change the chemistry of the oceans and make certain key metabolic elements more available to creatures.

The result? Animals can get larger due to the greater oxygen availability **and** develop more complex and efficient metabolic systems due to key metabolic elements now being available. For more information about Snowball Earth events and how it relates to the evolution of life see EOSC326 or EOSC425.

- ***2. Calcium:*** Recent research: an increase in calcium concentration at ocean ridges around the base of the Cambrian

- Does this allow for higher concentration of Ca in Earth's oceans and the development of creatures with hard parts ($CaCO_3$)?

Cloudina

Trilobite

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Recent research has also shown that there was an increase in calcium concentration at ocean ridges around the base of the Cambrian
Could this have allowed for higher concentration of Ca in Earth's oceans and the development of creatures with hard parts made from calcium carbonate ($CaCO_3$)?

Evolutionary Arms Race?

- The previous "causes" could possibly explain why things got "big" and why they developed hard parts. It does not explain why life diversified so rapidly.
- The development of hard parts would have given a selective advantage to some creatures
- Some evidence of predation in the Ediacaran (see yellow arrow)
- Could predation and defense from predation have accelerated evolution?

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The previous "causes" could possibly explain why things got "big" and why they developed hard parts. It does not explain why life diversified so rapidly.
The development of hard parts would have given a selective advantage to some creatures. Ultimately it is likely that it was a cascading explosion of competition that drove the Cambrian explosion.

Perhaps that competition centres around predation and defense from predation. There is some (but not very much) evidence of predation in the Ediacaran (see yellow arrow). It is suggested that this little round hole might have been caused by some creature boring into the shell of this *Cloudina* fossil.

- The evolution of senses such as vision may also help explain this “arms race” – eyes are a common feature of many trilobites.

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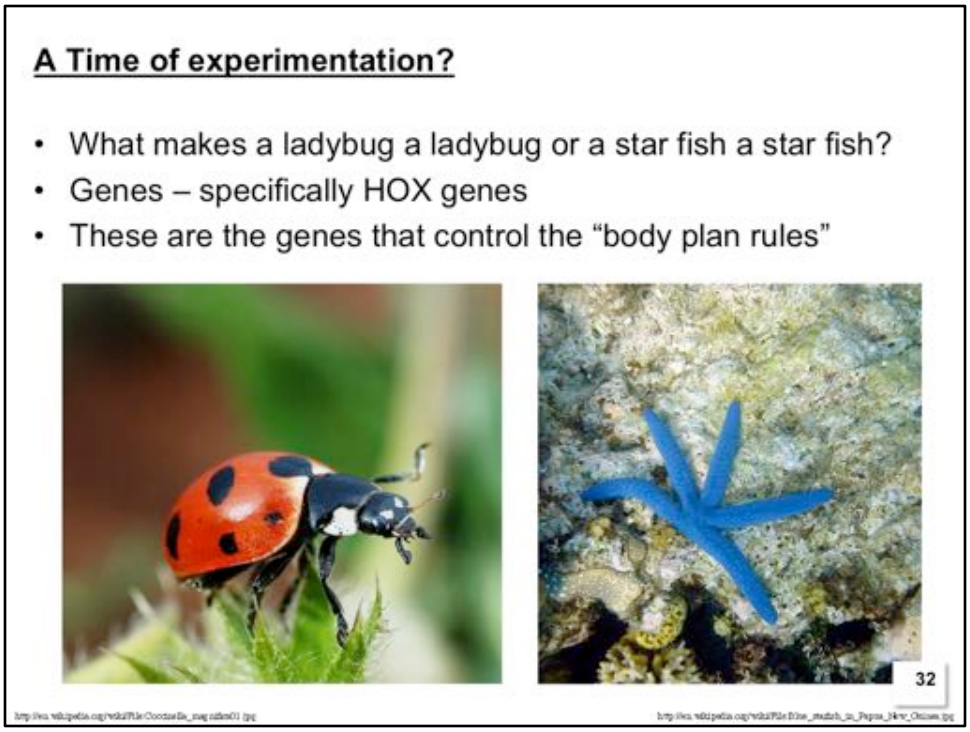
The evolution of senses such as vision may also help explain why this “arms race” really took off. Eyes are a common feature of many trilobites.



Perhaps it was also a time of evolutionary experimentation that led to the development of many different life forms. But why during this period and not since? Since the Cambrian explosion there has been no new emergence of major phyla. There has been the evolution of numerous species but they all fall into the categories of creatures that appeared during the Cambrian Explosion.

For that we may have to ask the question…. "what makes a ladybug a ladybug or a star fish a star fish?" The answer is "Genes" but specifically HOX genes…. the genes that control all "body plan rules."

To put this more technically: "Hox genes are a group of related genes that control the body plan of the embryo along the anterior-posterior (head-tail) axis. After the embryonic segments have formed, the Hox genes determine the type of segment structures (e.g. legs, antennae, and wings in fruit flies or the different vertebrate ribs in humans) that will form on a given segment."

- Were there less HOX control genes in the Cambrian?
- Would this explain why we see so many new / novel forms evolving?
- May at least explain why we so many weird creatures in the Cambrian that don't quite "fit the rules"

Opabinia: probably an arthropod but five eyes and a grasping trunk?

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It has been suggested that there may have been less HOX control genes in these early Cambrian creatures. Would this explain why we see so many new / novel forms evolving?

It may at least explain why we so many weird creatures in the Cambrian that don't quite "fit the rules" such as the very strange *Opabinia* which is kind of an arthropod but in reality is very difficult to place in any modern group exactly.

- Another example…. *Helicoplacus*:
- An Echinoderm:
  - Tube feet
  - Composed of calcium carbonate plates
- BUT does not follow echinoderm "rules" does not exhibit 5 fold symmetry

Helicoplacus guthi

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Another example of this is *Helicoplacus*. This is an Echinoderm. It had tube feet and was composed of calcium carbonate plates like modern echinoderms but it doesn't completely follow modern echinoderm "rules" as it does not exhibit 5 fold symmetry.

WINDOWS INTO THE EARLY CAMBRIAN WORLD

- By end of Early Cambrian all major modern phyla were present
- Of these only the Porifera (Sponges) and Cnideria (creatures that today include corals) had evolved before early Cambrian
- It is from these forms that all life we see today has proliferated.
- No new major phyla have evolved since this time

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By the end of the Early Cambrian all major modern phyla were present. Of the modern phyla only the Porifera (Sponges) and Cnideria (creatures that today include corals) had evolved before the early Cambrian. It is from the Creatures we see in the early Cambrian that the majority of the forms that all life we see today have proliferated. **No new major phyla have evolved since this time**

- We now know quite a lot about the Early Cambrian following the Cambrian explosion
- Thanks to Lagerstatten: "exceptional fossil preservation"
- Prior to discovery and appreciation of Cambrian Lagerstatten, Cambrian regarded as "Trilobite World"
- Probably due to the higher preservation potential of creatures with hard parts

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It is at times difficult to peer though time into ancient biospheres. Various creatures have different potentials to become a fossil depending on a whole bunch of factors, possibly giving us a skewed understanding of life in the past (see module E).

It is because of this that fossil bonanzas or *conservation Lagerstatten* (geological sections where certain environmental circumstances allow for unusual and unexpected preservation of life forms) become vital in adding depth and color to our understanding of the past. Prior to discovery and appreciation of Cambrian Lagerstatten, the Cambrian was regarded as "Trilobite World." A biosphere that was dominated by creatures with hard shells like trilobites. As we shall see, trilobites were only part of the picture. Even though they were very common life forms, their presence in large numbers in the fossil record probably has a lot to do with their higher preservation potential.

The Chengjiang Biota (Maotianshan Shales)

- Lower Cambrian: 525 – 520MA, Yunnan Province, China
- Much more than trilobites
- Only 3% of the Chengjiang Biota has substantial hard parts – the rest soft bodied – don't usually fossilize
- Fossilization probably aided by sudden sediment avalanches (turbidites) that covered and buried the creatures rapidly

Anomalocaris – Top Predator of the Cambrian

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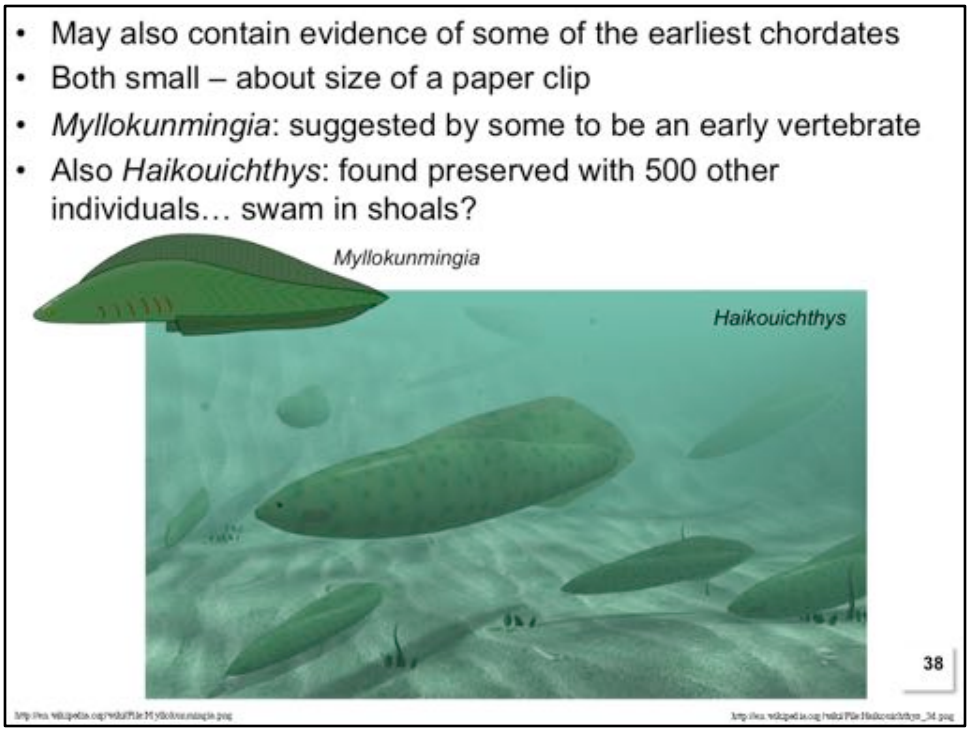
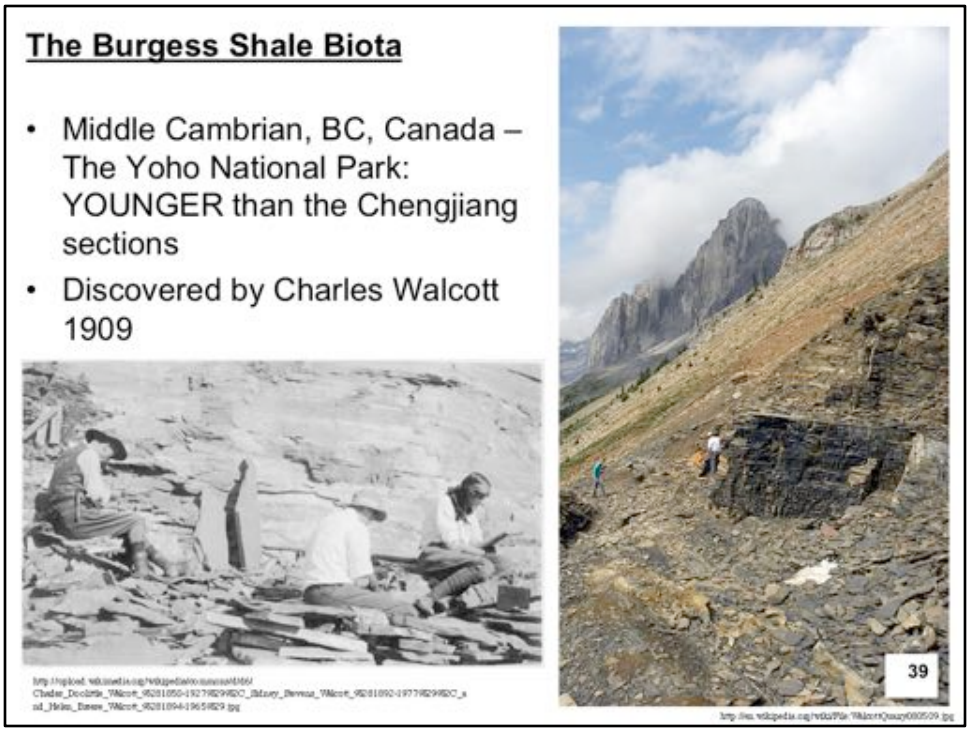
We now have some fantastic sections that really show that the Cambrian consisted of much more than trilobites (even though they were very common). The Lower Cambrian Chengjiang Biota (Maotianshan Shales) was deposted between 525 – 520MA, in what is today Yunnan Province, China.

Only 3% of the Chengjian Biota has substantial hard parts – the rest are soft bodied creatures that don't usually fossilize. Fossilization was probably aided by sudden sediment avalanches (turbidites) that covered and buried the creatures rapidly.

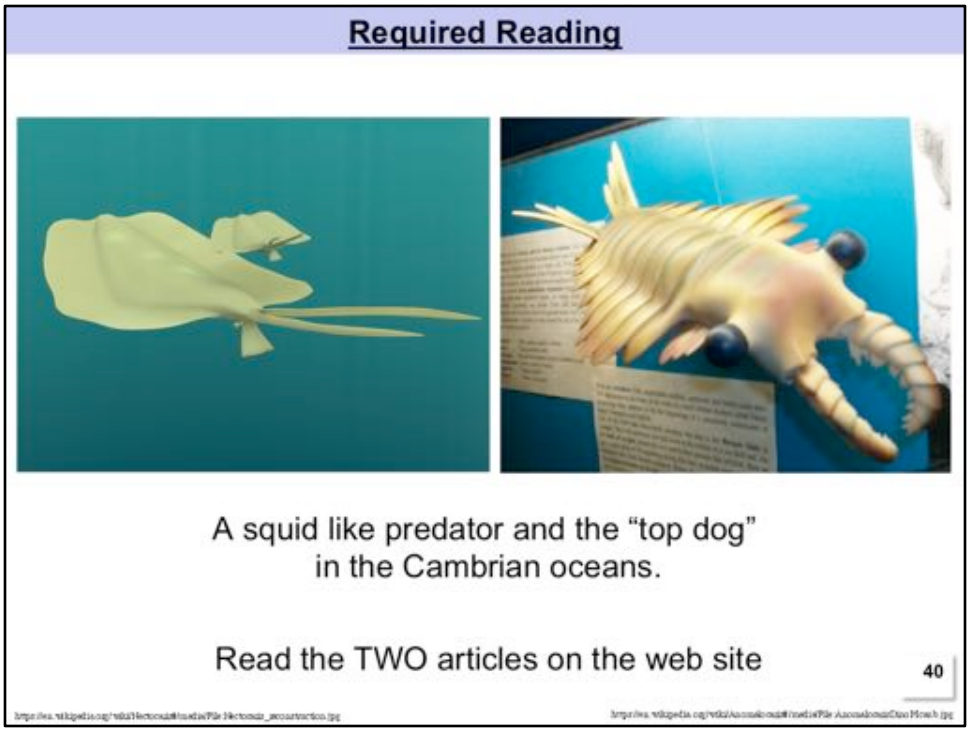


This section may also contain evidence of some of the earliest chordates. Two fossils, both small, about size of a paper clip, have been discovered:

Myllokunmingia: suggested by some to be an early vertebrate AND *Haikouichthys*: found preserved with 500 other individuals suggesting that it probably swam in large shoals like some modern fish do today.



Perhaps the most famous Cambrian Lagerstatten though is a section that is younger than that from Chengjiang, the Middle Cambrian Burgess Shale of the Yoho National Park in BC. It was discovered by Charles Walcott in 1909.



As we have noted already, back in the Cambrian there may have been less "fail-safe HOX genes" resulting in the possibility of more "bizarre forms" being expressed – most of these forms would have never survived but perhaps just a few would have been viable to survive, breed and pass on their genes resulting in these odd species. Perhaps this explains why the Cambrian appears to be a period of evolutionary experimentation before the "animal rules" we see today became entrenched in the genetic code of the Metazoa.

So what happened to all the "odd stuff'? Some of it just didn't make the grade, they failed in an increasingly competitive biosphere. Another factor could be the evolution of new predators.