Concepts of Biology: BIOL 111
Study guide for Exam 2

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Lectures 8–16

Contents

1 Questions and answers

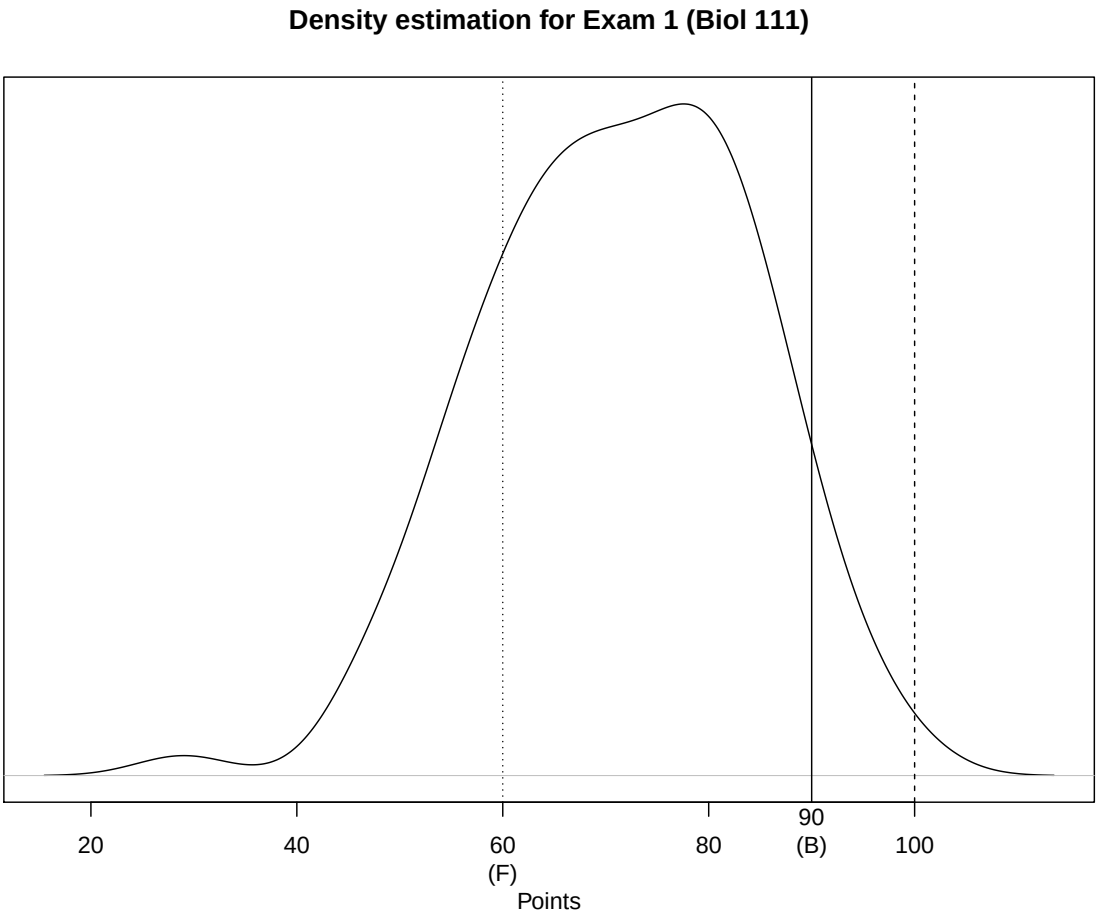
1.1 Exam 1

Results of Exam 1: statistic summary

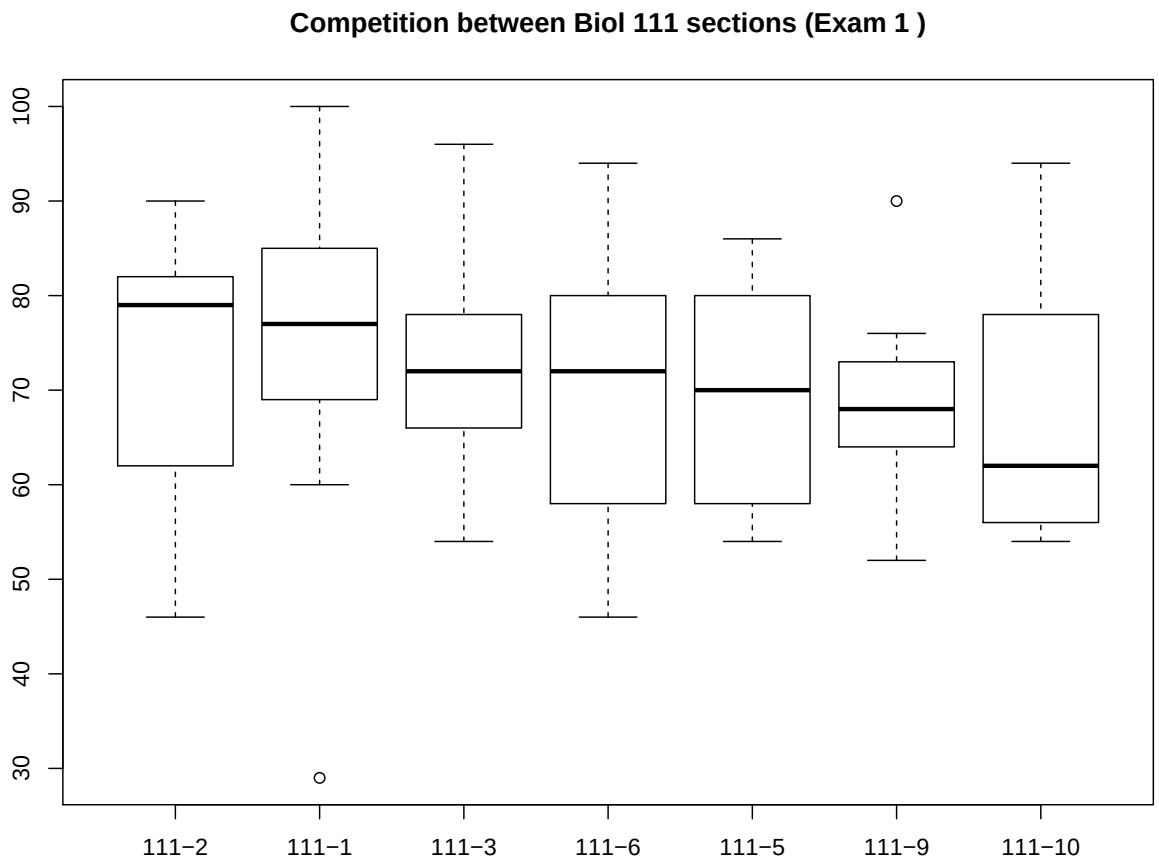
```
Summary:
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's
  29.00   63.00   72.00   71.41   81.00  100.00       7
Grades:
   F    D    C    B  max
```

< 60 < 70 < 80 < 90 100

Results of Exam 1: the curve



Results of Exam 1: sections



Results of Exam 1: some questions

6. Who told that "*Nothing in Biology Makes Sense Except in the Light of Evolution*"?

   A. Bertrand Russel

   B. Charles Darwin

   C. **Theodosius Dobzhansky**

29. How many grams of phosphoric acid we should dilute in 1 liter of water to obtain 1 M concentration?

   A. 7 g

   B. 48 g

   C. **98 g**

47. What is a most striking difference between carbohydrates and amino acids?

   A. Carbohydrates are sweet, amino acids are not

   B. **Amino acids contain nitrogen, carbohydrates do not**

   C. Carbohydrates are hydrophobic, amino acids are not

49. Which basic feature of life is modeled in coacervates?

   A. DNA $\rightarrow$ RNA $\rightarrow$ proteins

   B. **Semi-permeable membrane**

2 Where we are?

2.1 Molecules of life

Four types of biomolecules form biological polymers

- Lipids
- Sugars make polysaccharides
- Amino acids make proteins
- Nucleotides make nucleic acids

Abiogenesis is the most feasible theory of life origin

- Primordial soup
- RNA world
- Proteins
- Cells: last universal common ancestor (LUCA)

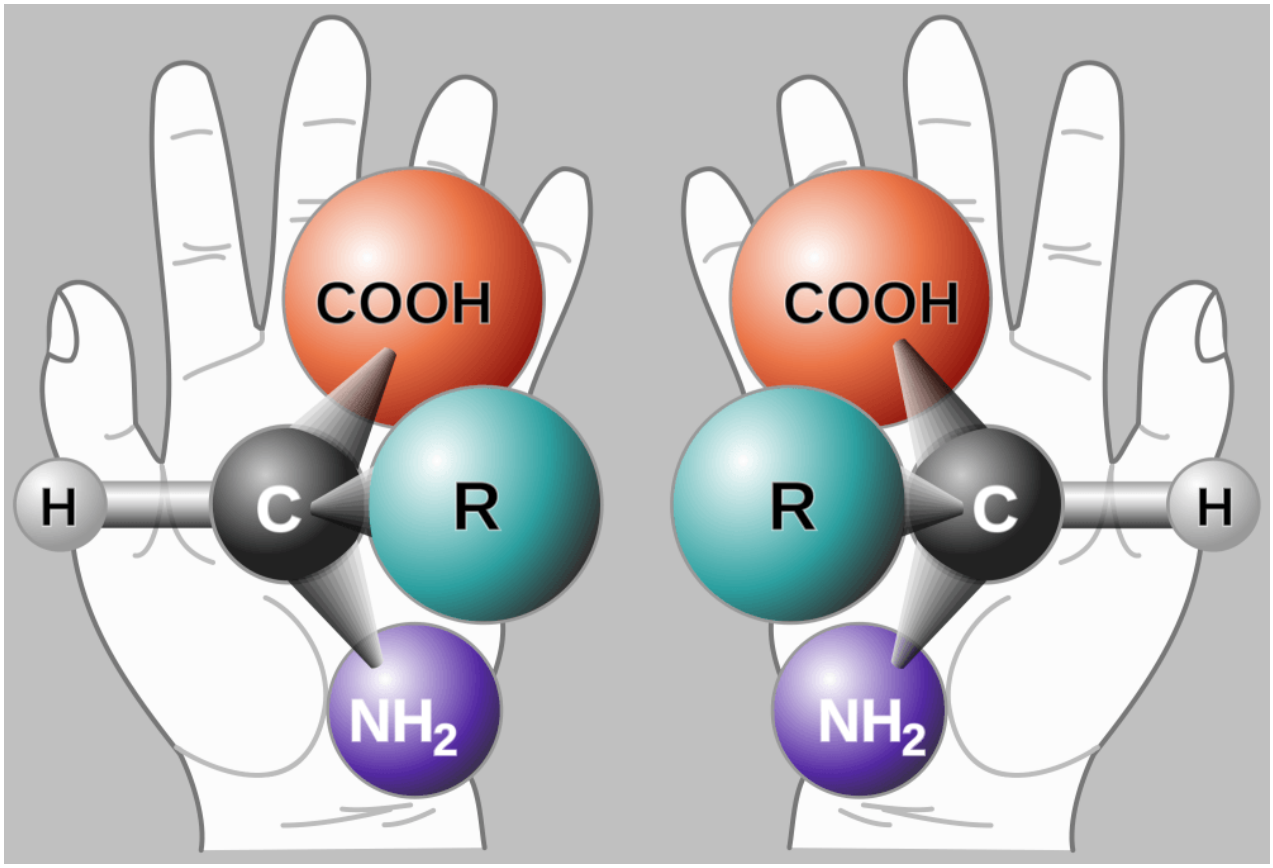
3 Origin of life

3.1 Alternatives and amendments to abiogenesis

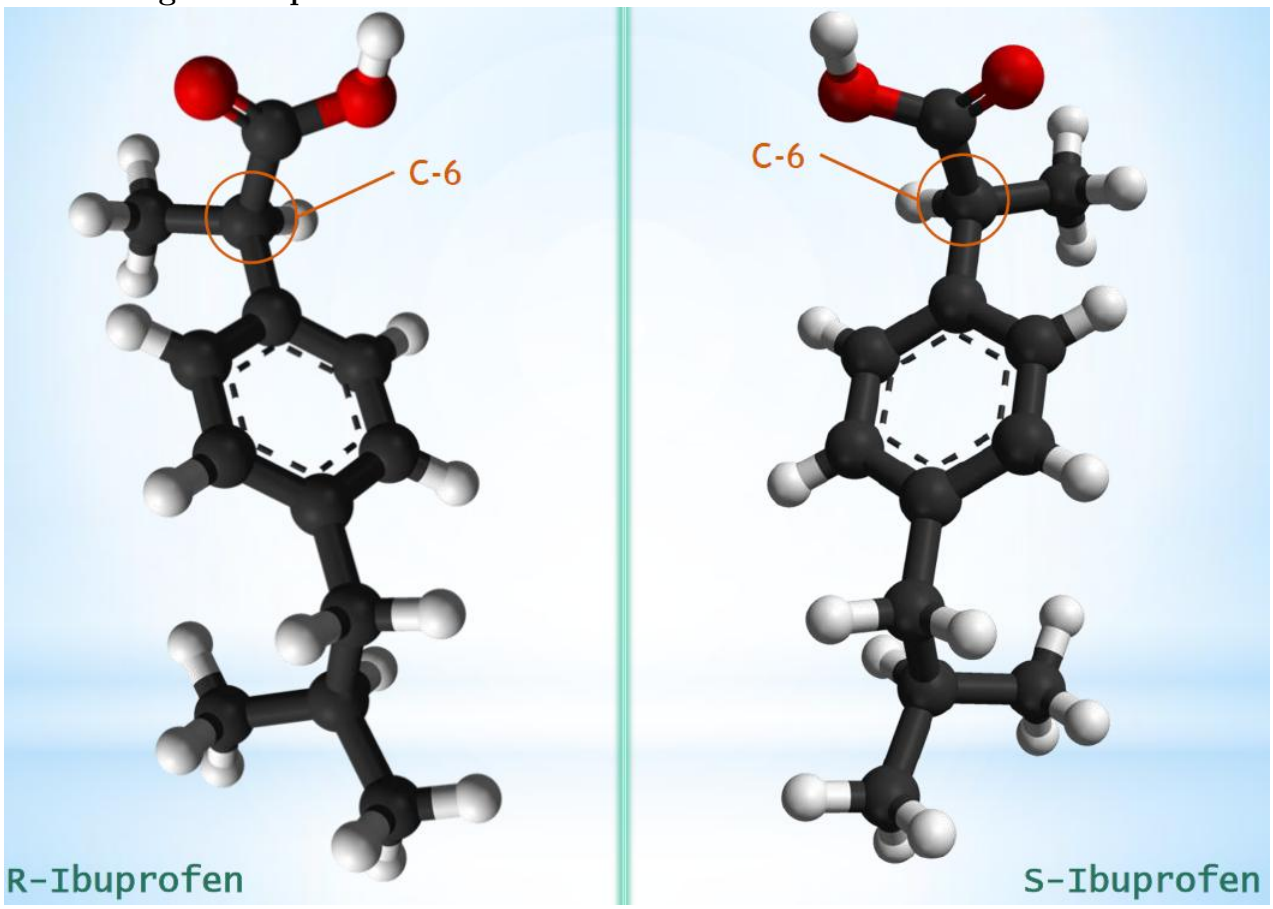
Problems of abiogenesis: chiral purity of life

- Most of amino acids and other biological molecules are **chiral**: they have "left" and "right" forms
- *All proteins from living organisms contain only "left" amino acids*
- Sugars (carbohydrates) could also be "left" and "right"
- *Nucleic acids contain only "right" sugars*

"Left" and "right" amino acids



“Left” and “right” ibuprofen



First is a drug, second is almost useless!

Panspermia theory

- Life is a fundamental feature of Universe
- It always exists and constantly spreading

Self-organization

- Lovelock's (1982) Gaia hypothesis: Earth is a living being
- Life is a way of stabilizing geological cycles on Earth
- Self-organization was based on the principles of Prigogine's **non-equilibrium thermodynamics**
- Life first, organisms second

4 First life

4.1 Hadean and Archean eons

First evidences of life

- Earth age is usually estimated as 4600 Mya (million years ago), Hadean eon was the first epoch
- First minerals are ≈4000 Mya, they mark Archean eon

Oldest evidences of life and photosynthesis

- The oldest organic carbon is ≈3800 Mya (Greenland, Mesoarchean)
- Organic carbon: carbon with $^{13}C/^{14}C$ ratio like in living plants
- Oldest remnants of chlorophyll: 3100 Mya (Mesoarchean)

Photosynthesis

- $CO_2 + H_2O \xrightarrow{\text{light, chlorophyll}} \text{carbohydrates} + O_2$
- Two stages:

  A. Light-dependent: production of energy (ATP) and photolysis of water

  B. Light-independent: assimilation of CO_2 into carbohydrates

- Then carbohydrates are partly converting into lipids; with addition of N—into amino acids; with addition of N and P—into nucleotides

Summary

- Photosynthesis changed the atmosphere of Earth

For Further Reading

References

[1] Photosynthesis. `http://en.wikipedia.org/wiki/Photosynthesis` (introduction)

Outline

5 Where we are?

5.1 Photosynthesis

Photosynthesis

- $CO_2 + H_2O \xrightarrow{\text{light, chlorophyll}} \text{carbohydrates} + O_2$
- Two stages:
  A. Light-dependent: production of energy (ATP) and photolysis of water
  B. Light-independent: assimilation of CO_2 into carbohydrates
- Then carbohydrates are partly converting into lipids; with addition of N—into amino acids; with addition of N and P—into nucleotides

ATP

- Universal energy source in the cell, "universal currency"
- ATP $\rightarrow$ ADP + P + energy

6 Archean eon

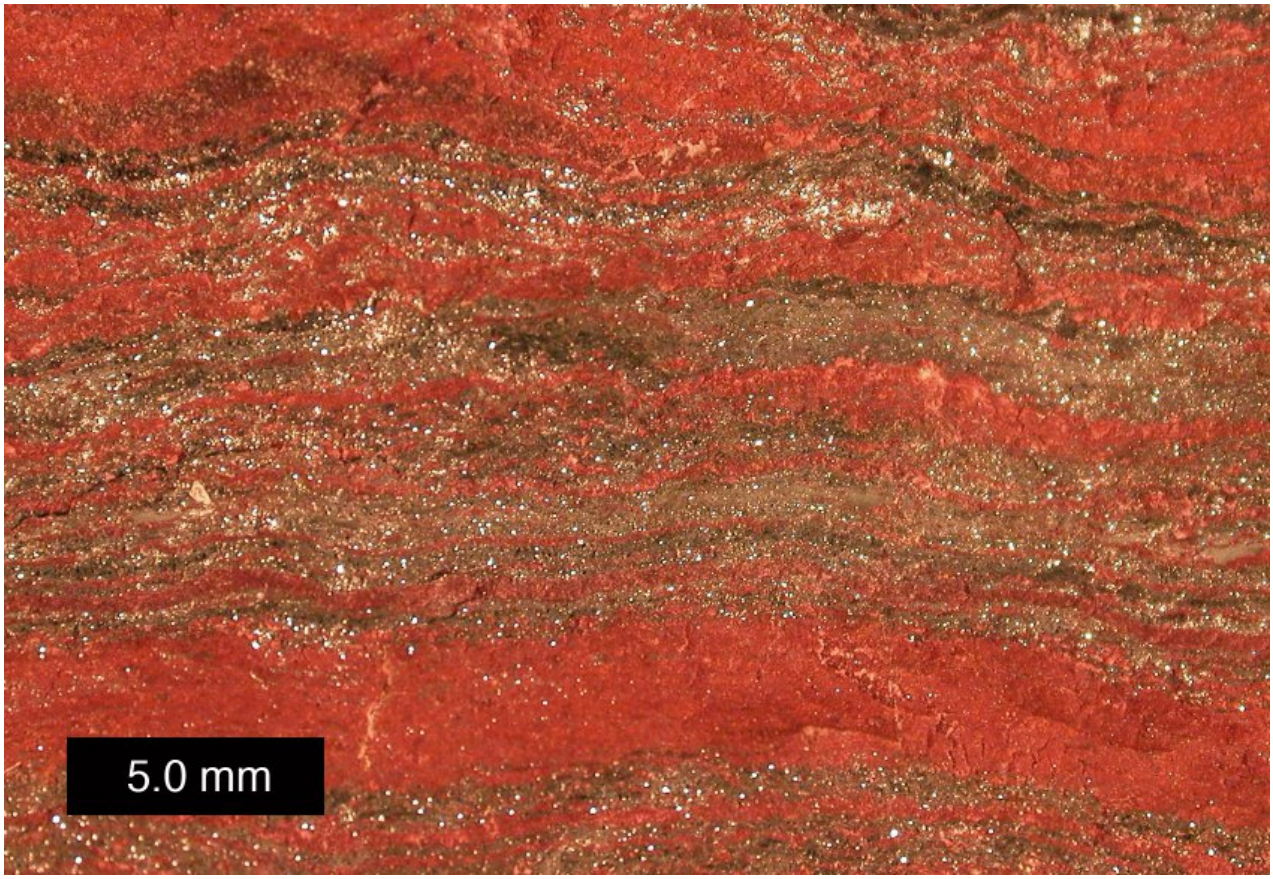
6.1 First Life

Oxygen and iron

- Initially, Earth atmosphere contained no oxygen
- Photosynthetic oxygen oxidized free iron into quartzite-like rocks contained hematite and other iron minerals
- New iron was always replenished from ocean water
- However, $\approx$2000 Mya, when Proterozoic eon started, almost all iron went deeper into mantle and core

Wheeler Peak, NV

Hematite



From oxygen oases to oxygen revolution

- In Archean, photosynthesis could only produce local "oxygen oases"
- But when no free iron was available anymore, atmosphere started to accumulate oxygen
- When oxygen reached 1% (Pasteur point), *aerobic life* started
- This was the **oxygen revolution** which allowed cells to obtain energy via *respiration*

Fermentation *versus* respiration

- carbohydrates $\rightarrow$ CO_2 + ethanol + 2 ATP
- carbohydrates + O_2 $\rightarrow$ CO_2 + H_2O + 38 (!!!) ATP

Which is better? Do not forget however that oxygen is highly poisonous and destructive molecule.

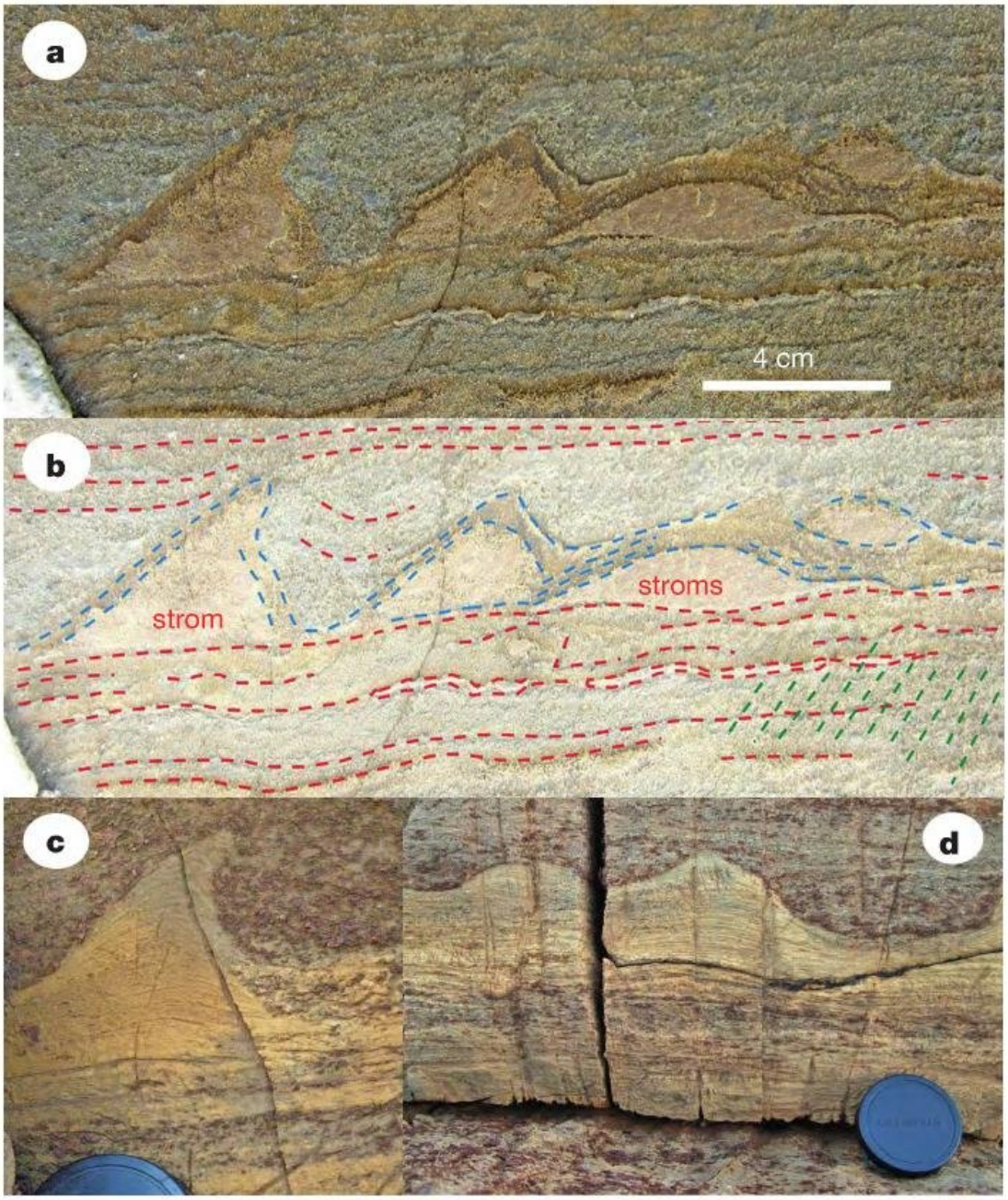
6.2 First fossil cells

First and second

- Stromatolites: microbial mats from (mostly) cyanobacteria (photosynthetic bacteria)
- *Metallogenium* and others: proteobacteria (e.g., aerobic metal-oxidizing bacteria)

Fossil stromatolite

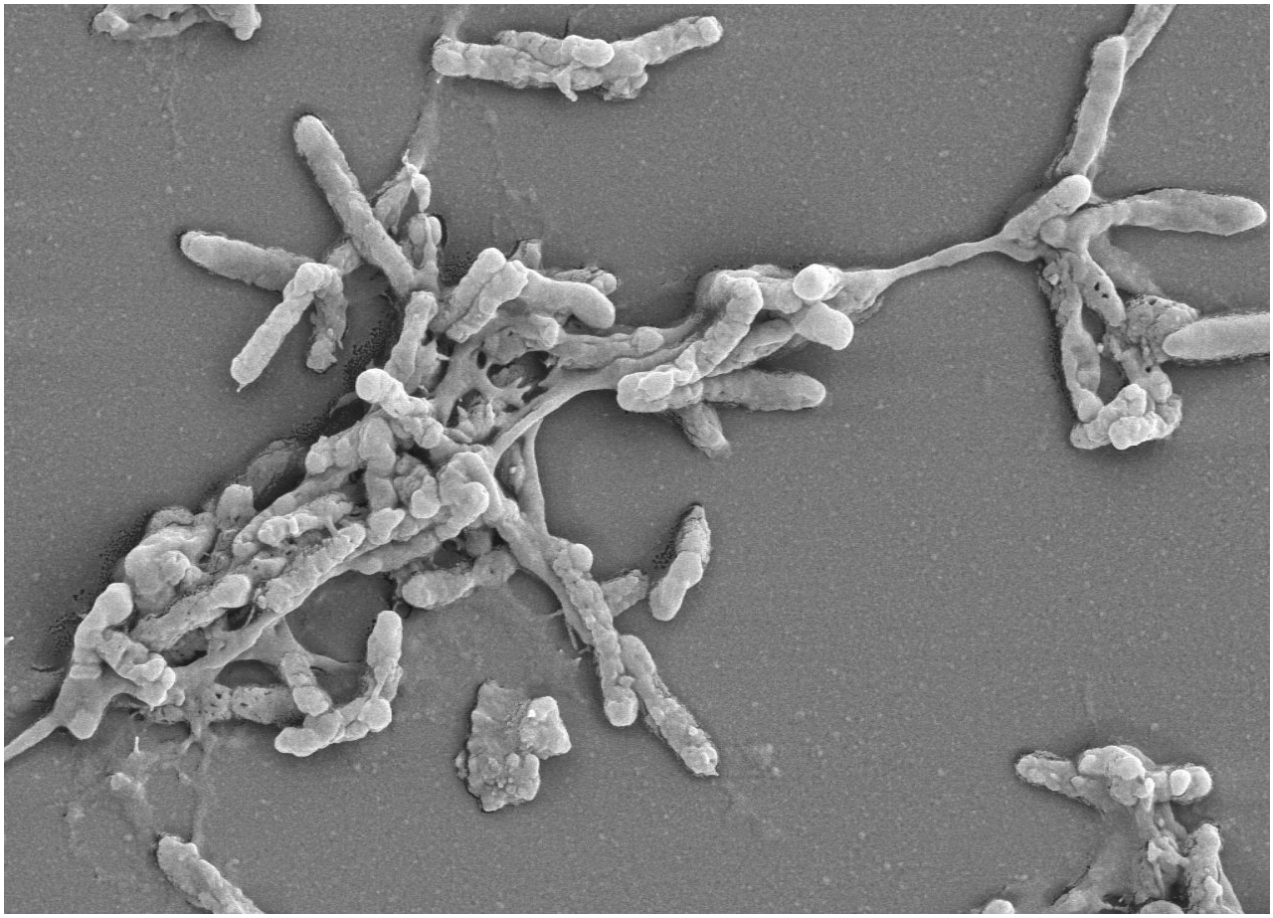
Oldest stromatolite: Isua, Southern Greenland



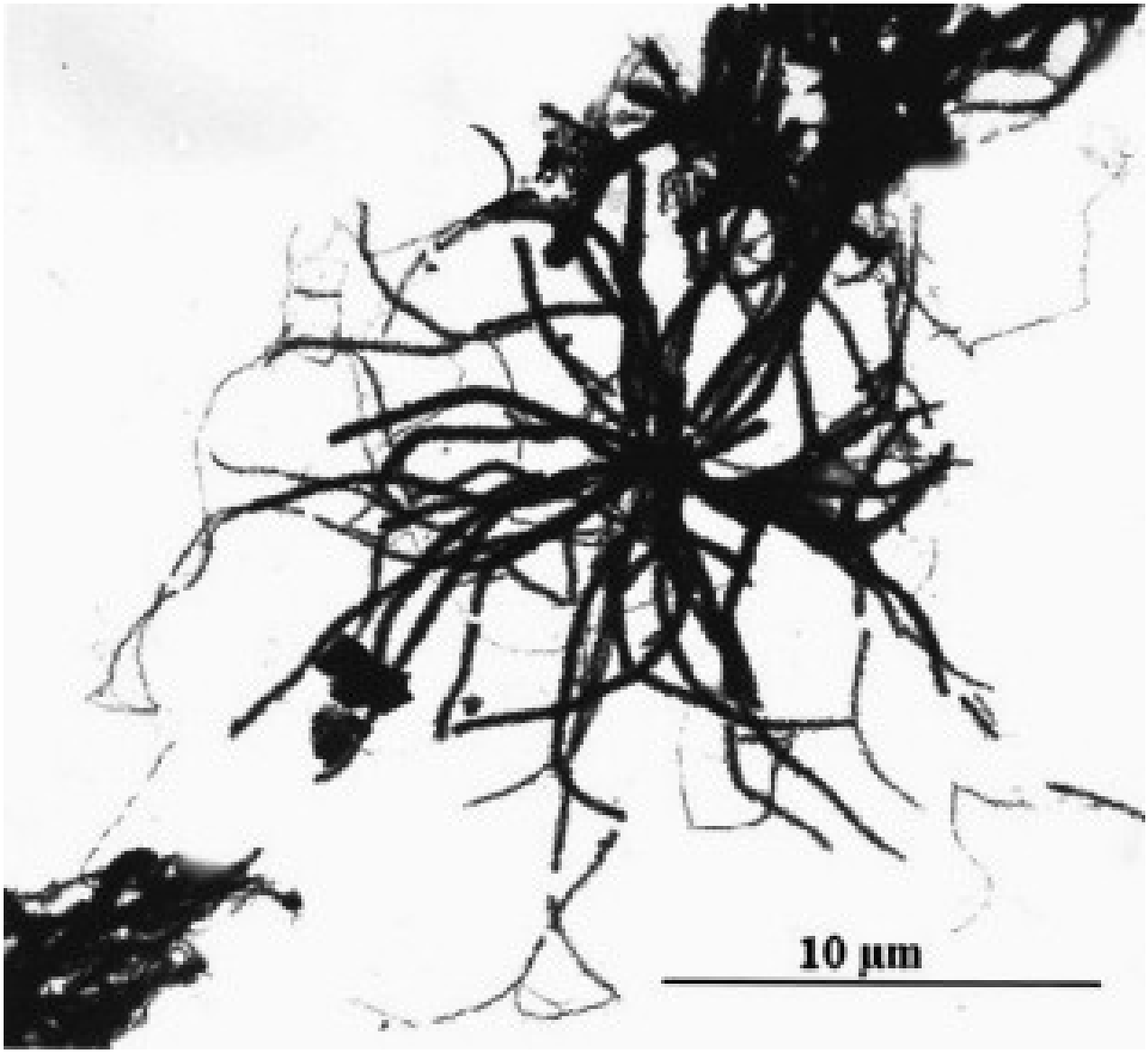
3.7 Myr!

Pesent-day stromatolite (Shark Bay, Australia)

Present-day iron-oxidizing bacteria



Fossil *Metallogenium*



First life

- In Archaean, cyanobacteria (fossilized as stromatolites) were first
- Photosynthesis changed the atmosphere
- Aerobic life respires to obtain more ATP

7 Cell

7.1 Prokaryotic cell

Prokaryotic cell

Main components of prokaryotic cell

- Cell wall

- Membrane
- Cytoplasm
- DNA
- Ribosomes
- Membrane folds and pockets
- Vesicles
- Flagella

7.2 How to be a prokaryote

How to make energy

Two ways:

- Cell respiration and other destructive processes make ATP for all cell
- Photosynthesis and other synthetic processes make ATP (but later, they spend it)

How to make proteins

To build factory, we need energy (see before) and also need *machines*. These are *proteins*. To build machines from scratch, we need *instruction* books. This is *DNA*. To work with instructions, it is better to keep them in library but copy only some *pages* for immediate use. These are *RNAs*.

- DNA and RNA contain four types of nucleotides
- The sequence of nucleotides is a cypher
- Each tree nucleotides will encode amino acid ("genetic code")
- Ribosomes translate triplets into amino acids and make proteins

Summary

- Bacteria were first
- Photosynthesis changed the atmosphere
- Aerobic life respires to obtain more ATP
- Prokaryotic cells are simplest cells

For Further Reading

References

[1] Photosynthesis. `http://en.wikipedia.org/wiki/Photosynthesis` (introduction)

[2] Cellular respiration. `http://en.wikipedia.org/wiki/Cellular_respiration` (introduction)

Outline

8 Where we are?

8.1 How to be a cell

Main duties

- Making energy: fermentation/respiration or photosynthesis
- Making proteins
- Digesting food
- Constructing body
- Multiplying
- Making sex

How to make proteins

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How to take food

- Digestive proteins are transported outside membrane
- They destroy polymers into monomers
- Monomers then are pumping through membrane into the cell
- If cell is photosynthetic, it produce monomers itself

How to make body

- Monomers could be spend:
  - in destructive reactions to obtain ATP, **or**
  - in synthetic reactions to make new polymers. These reactions are using ATP

How to multiply

- DNA is a double helix which may copy itself
- Two copies of DNA untangled and separated, then cytoplasm and membrane divide
- Of course, these processes spend lots of ATP

9 How to make proteins

9.1 More details

How to make proteins I

- Proteins are chemical machines of cell
- Each machine is described in gene
- The only way to make them is DNA $\rightarrow$ RNA $\rightarrow$ proteins
- DNA is a folded double spiral; it has two chains
- Every chain consists of four "letters"—nucleotides (A, T, G, C)
- Two chains are complimentary, and only A–T and G–C pairs are possible

How to make proteins II

- DNA may duplicate, then new DNAs will build complimentary chains and become exact copies
- DNA may also "produce" RNA: one of chains serves as matrix for new RNA
- RNA also has four letters (A, U, G, C)
- When RNA is building on DNA, RNA's "U" will be complimentary with DNA's "A"; all other rules are the same

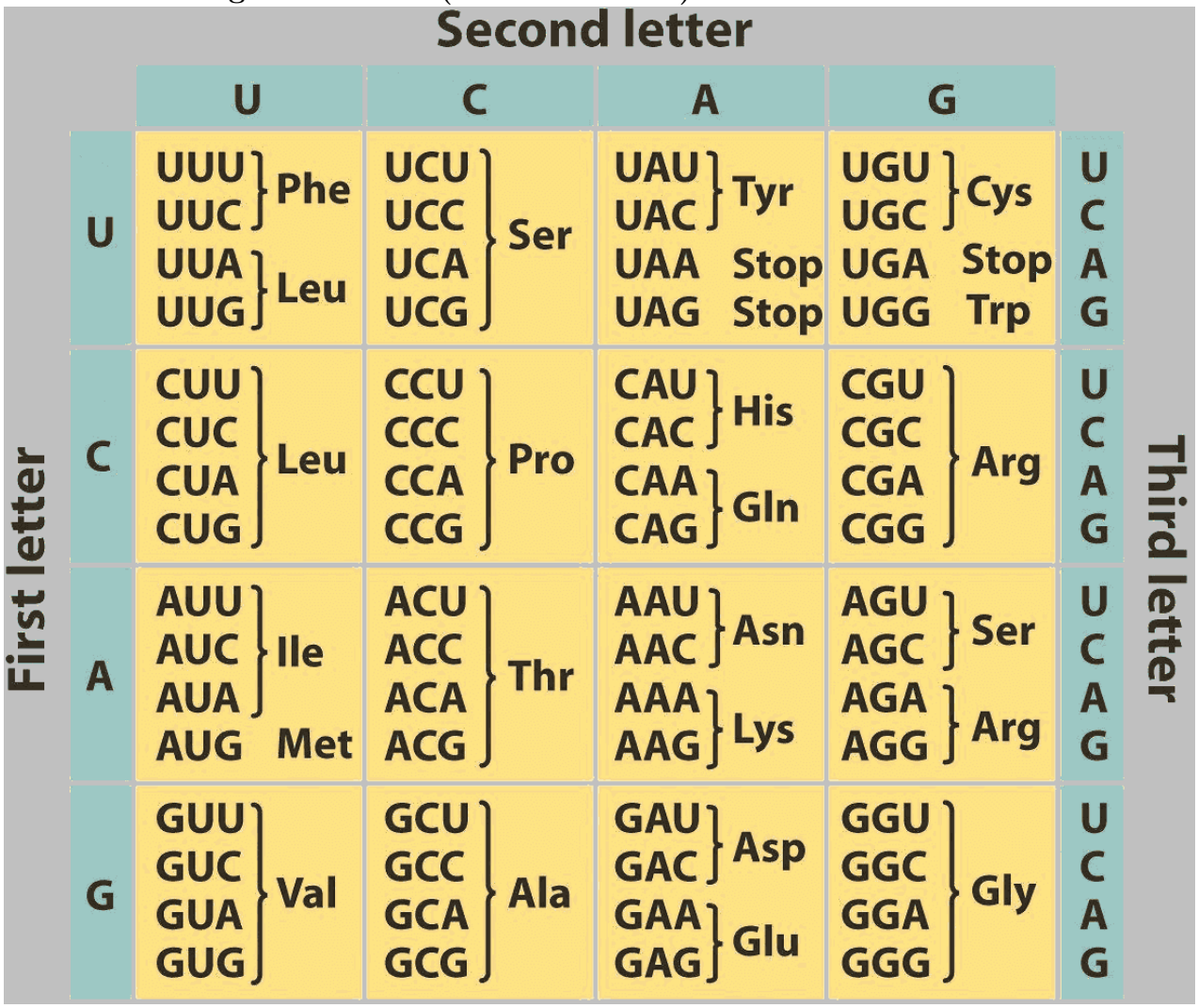
How to make proteins III

- New RNA is a messenger RNA (mRNA)
- It will come into ribosome, and ribosome will translate every three letters (triplet) into amino acid
- mRNA moves within ribosome, and new amino acids are joining into growing protein
- Translation rules are known as "genetic code"
- There are 64 possible triplets and only 20 amino acids—genetic code is redundant

Translation rules: "genetic code"

	U		C		A		G		
U	UUU	Phe	UCU	Ser	UAU	Tyr	UGU	Cys	U
	UUC	Phe	UCC	Ser	UAC	Tyr	UGC	Cys	C
	UUA	Leu	UCA	Ser	UAA	*STOP*	UGA	*STOP*	A
	UUG	Leu	UCG	Ser	UAG	*STOP*	UGG	Trp	G
C	CUU	Leu	CCU	Pro	CAU	His	CGU	Arg	U
	CUC	Leu	CCC	Pro	CAC	His	CGC	Arg	C
	CUA	Leu	CCA	Pro	CAA	Gln	CGA	Arg	A
	CUG	Leu	CCG	Pro	CAG	Gln	CGG	Arg	G
A	AUU	Ile	ACU	Thr	AAU	Asn	AGU	Ser	U
	AUC	Ile	ACC	Thr	AAC	Asn	AGC	Ser	C
	AUA	Ile	ACA	Thr	AAA	Lys	AGA	Arg	A
	AUG	Met	ACG	Thr	AAG	Lys	AGG	Arg	G
G	GUU	Val	GCU	Ala	GAU	Asp	GGU	Gly	U
	GUC	Val	GCC	Ala	GAC	Asp	GGC	Gly	C
	GUA	Val	GCA	Ala	GAA	Glu	GGA	Gly	A
	GUG	Val	GCG	Ala	GAG	Glu	GGG	Gly	G

Translation rules: "genetic code" (another variant)



Summary

- Prokaryotic cells are simplest cells. They produce energy, obtain monomers, synthesize polymers, e.g. proteins from DNA and RNA, and sometimes also make monomers themselves (with photosynthesis), divide and even perform a sexual process (recombine DNA between cells)

For Further Reading

References

[1] Genetic code. `http://en.wikipedia.org/wiki/Genetic_code`

[2] Protein biosynthesis. `http://en.wikipedia.org/wiki/Protein_biosynthesis`

Outline

10 Where we are?

10.1 How to be a cell

Main duties

- Making energy
- Making proteins
- Digesting food and constructing body
- Multiplying
- Making sex

How to make proteins III

- RNA synthesized from DNA is a *messenger RNA* (mRNA)
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U	UUU	Phe	UCU	Ser	UAU	Tyr	UGU	Cys	U
	UUC	Phe	UCC	Ser	UAC	Tyr	UGC	Cys	C
	UUA	Leu	UCA	Ser	UAA	*STOP*	UGA	*STOP*	A
	UUG	Leu	UCG	Ser	UAG	*STOP*	UGG	Trp	G
C	CUU	Leu	CCU	Pro	CAU	His	CGU	Arg	U
	CUC	Leu	CCC	Pro	CAC	His	CGC	Arg	C
	CUA	Leu	CCA	Pro	CAA	Gln	CGA	Arg	A
	CUG	Leu	CCG	Pro	CAG	Gln	CGG	Arg	G
A	AUU	Ile	ACU	Thr	AAU	Asn	AGU	Ser	U
	AUC	Ile	ACC	Thr	AAC	Asn	AGC	Ser	C
	AUA	Ile	ACA	Thr	AAA	Lys	AGA	Arg	A
	AUG	Met	ACG	Thr	AAG	Lys	AGG	Arg	G
G	GUU	Val	GCU	Ala	GAU	Asp	GGU	Gly	U
	GUC	Val	GCC	Ala	GAC	Asp	GGC	Gly	C
	GUA	Val	GCA	Ala	GAA	Glu	GGA	Gly	A
	GUG	Val	GCG	Ala	GAG	Glu	GGG	Gly	G

11 Sexual process

11.1 Prokaryotic sex

How to make sex

- If DNA will stay unchanged, cells cannot evolve
- To make evolution possible, there are processes which modify DNA:
  - Mutations
  - Recombinations
- Sexual process allows DNA recombination
- Prokaryotic cells simply connect and exchange pieces of DNA ("bacterial conjugation")

12 Basics of ecology

12.1 Ways of life

Ways of life

- How to obtain energy?
  A. From sun light: **phototrophy**
  B. From chemical reactions with inorganic matter ("rocks"): **lithotrophy**
  C. From breaking organic molecules into inorganic (typically, carbon dioxide and water): **organotrophy**
- How to obtain building blocks?
  A. From assimilation of carbon dioxide: **autotrophy**
  B. From other living beings: **heterotrophy**

Six life styles

	Phototrophs	Lithotrophs	Organotrophs
Autotrophs	...	...	...
Heterotrophs	...	...	...

12.2 Ecological interactions

Two-species model

- Species I and species II may influence each other differently
- For example, species I may facilitate the increase the number of species II individuals (+ interaction)
- At the same time, species II could be neutral to species I (0 interaction)

Six basic ecological interactions

	+	0	−
+	mutualism	commensalism[1]	exploitation[2]
0	...	neutralism	amensalism
−	...	...	interference[3]

[1] Includes phoresy (transportation), inquilinism (housing) and "sponging"
[2] Includes predation, parasitism and phytophagy
[3] Includes competition, allelopathy and aggression

Summary

- Prokaryotic cells are simplest cells. They produce energy, obtain monomers, synthesize polymers, e.g. proteins from DNA and RNA, and sometimes also make monomers themselves (with photosynthesis), divide and even perform a sexual process (recombine DNA between cells).
- Sexual process is the requirement for evolution.

For Further Reading

References

[1] Genetic code. `http://en.wikipedia.org/wiki/Genetic_code`

[2] Bacterial conjugation. `http://en.wikipedia.org/wiki/Bacterial_conjugation`

Outline

13 Where we are?

13.1 Ways of life

Ways of life

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  A. From sun light: **phototrophy**
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  C. From breaking organic molecules into inorganic (typically, carbon dioxide and water): **organotrophy**
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  A. From assimilation of carbon dioxide: **autotrophy**
  B. From other living beings: **heterotrophy**

14 Basics of ecology

14.1 Ecological interactions

Two-species model

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Six basic ecological interactions

	+	0	−
+	mutualism	commensalism[1]	exploitation[2]
0	...	neutralism	amensalism
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[1] Includes phoresy (transportation), inquilinism (housing) and "sponging"
[2] Includes predation, parasitism and phytophagy
[3] Includes competition, allelopathy and aggression

15 Origin of eukaryotes

15.1 Microbial mats

Microbial mats complexity

- Mats were not only cyanobacteria (aerobic photosynthetic autotrophs), but also
- anaerobic photosynthetic bacteria and
- heterotrophic and chemotrophic bacteria
- All these bacteria form the first **ecosystem**

Layers in microbial mat

15.2 First eukaryotes = first predators

Bdellovibrio

- Bacteria are small an rigid, there is only one example of bacteria which can "eat" others
- However, this *Bdellovibrio* will only eat in the space between membrane an cell wall

***Bdellovibrio* invading the prey**

Antibiotics

- The other problem was chemicals which bacteria are using to win a competition: antibiotics
- Most of antibiotics change the process of protein synthesis or cell wall construction

Proterozoic challenge

- Archean ecosystems were based on "clone wars" using antibiotics, horizontal transfer of genes and splitting jobs. However, they were incomplete: no predators.
- To predate, one need to *make large cell and invent the phagocytosis* (cellular "swallowing")
- To escape from antibiotics, one need a different chemical machines for protein biosynthesis

However,

- Large and complicated cell needs more DNA—but how to divide it equally?
- Horizontal transfer will hinder evolution towards something unusual—but how to stop it?
- Large and complicated cells need much more ATP—how to make it?

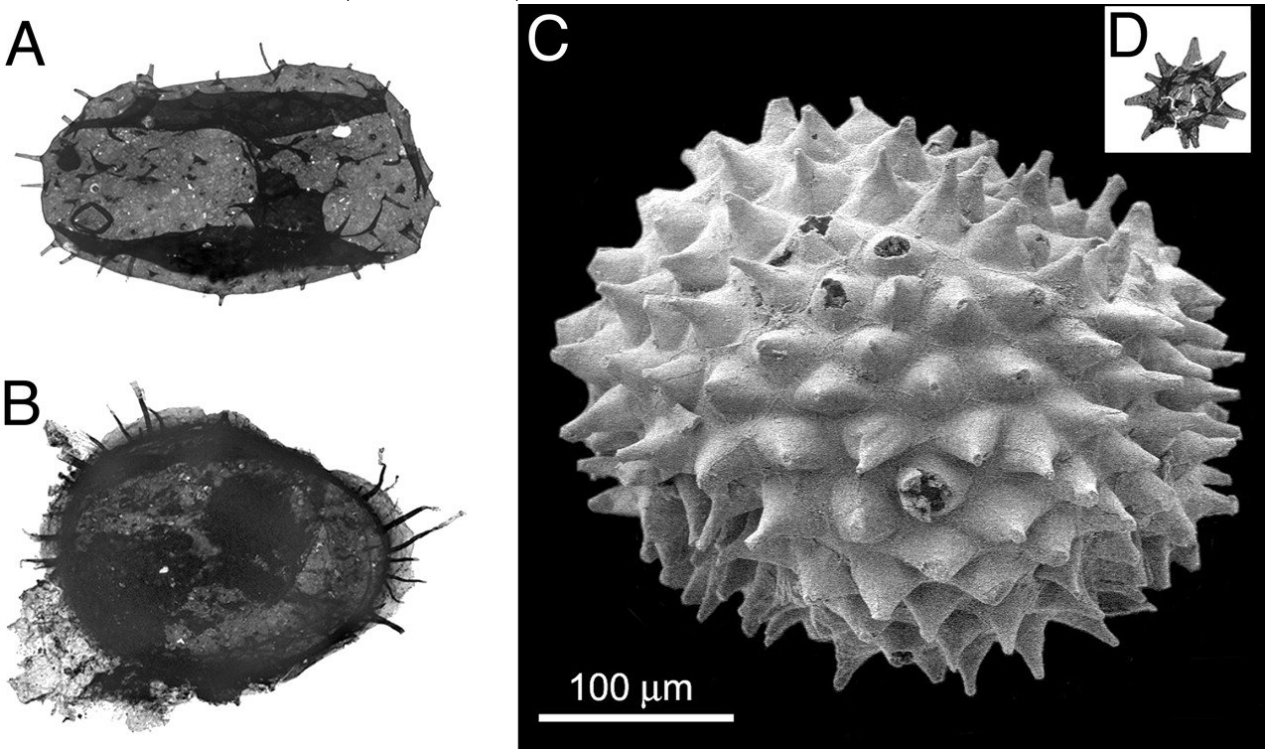
Two most essential problems

- How to escape from antibiotics?
- How to predate?

Eukaryotic cell as a response to Proterozoic challenge

- Predators
- New pathways of protein synthesis
- Cytoskeleton allows for cytoplasm motility
- Nucleus for DNA security and distribution
- Mitochondria make ATP

Acritarchs in Proterozoic (1,900 Mya)



16 Eukaryotic cell

16.1 Organelles and their functions

Eukaryotic cell

Membrane and cytoplasm

- Cytoplasm is constantly flowing
- Membranes are using for construction of multiple internal organelles

Summary

- All life styles were exist before eukaryotic origin
- The only interaction absent in prokaryotic communities was predation
- Microbial mats were first ecosystems
- To predate, bacteria must develop the enhanced cell
- Eukaryotic cell is a "second-level", enhanced cell

For Further Reading

References

[1] Ecological interactions. `http://en.wikipedia.org/wiki/Biological_interaction`

[2] Eukaryote. `http://en.wikipedia.org/wiki/Eukaryote`

Outline

17 Where we are?

17.1 Eukaryotic cell

Eukaryotic cell

- *Cytoplasm is constantly flowing*
- *Membranes are using for construction of multiple internal organelles*

18 Eukaryotic cell

18.1 Organelles and their functions

Cytoskeleton

- Microtubules and microfilaments
- Phagocytosis
- Motility
- No cell wall (but note that plants and fungi developed cell wall again)
- Flagella "oar" which has no similarity with "rotor" flagella of prokaryotes

Nucleus

- Transcription and translation separated
- Cell division destroys nucleus
- Pores control all ins and outs

Mitochondria

- Respiration machines, make ATP
- Mitochondrial DNA

Taking mitochondria: symbiogenesis

- Mitochondria were separate organisms
- Eukaryotic cell is a "second-level" cell, cell from cells

Internal membrane system

- Vesicles: vacuoles, lysosomes etc.
- ER: canals
- AG: membrane stacks
  Both ER and AG control transportation of proteins and carbohydrates

Ribosomes

- Bigger then prokaryotic
- Associated with ER

Eukaryotic cell: pluses and minuses

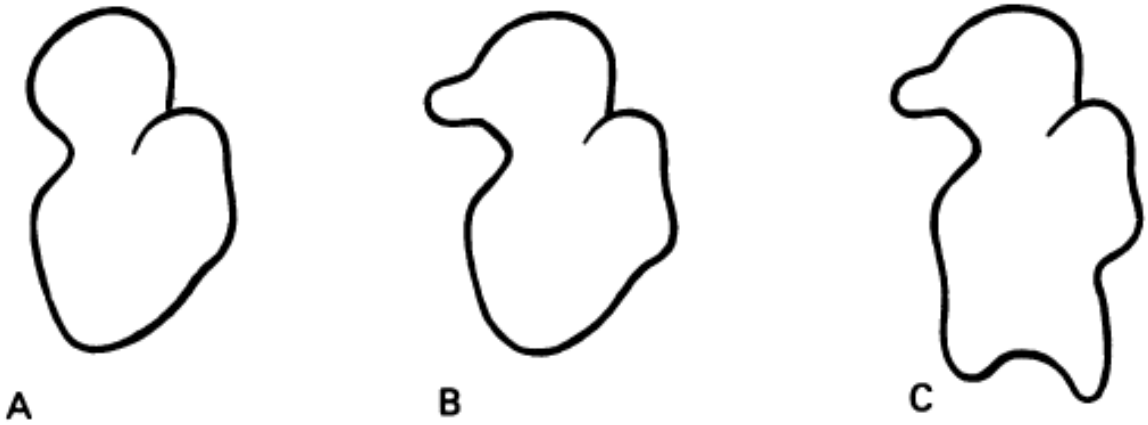
- Flexible, but bigger and no cell wall
- Nucleus, but so many DNA poses a problem
- Mitochondria are very effective, but less controlled

18.2 Evolutionary steps towards the eukaryote

Antibiotic resistance and actin

- Archebacteria were probably first prokaryotes who changed their biosynthetic pathways in order to become resistant to majority of antibiotics
- They also invented actin, the main protein of cytoskeleton

Ribosomes of core bacteria (A), archebacteria (B) and eukaryotes (C)



18.3 Cell division

Cell cycle

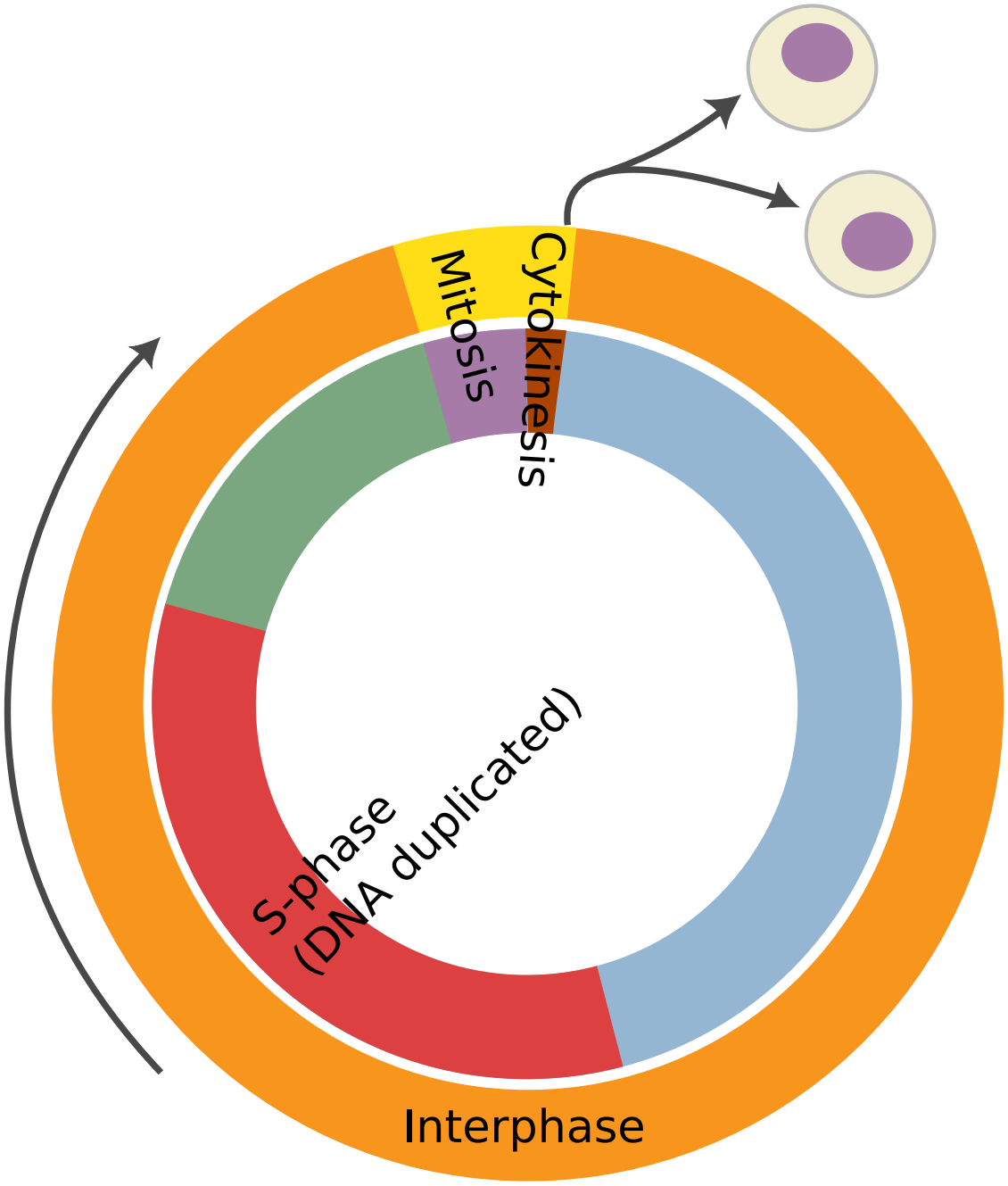
- To multiple, cell should first store energy for DNA duplication
- Then duplicate DNA during S-phase, synthetic phase (period)
- And only then to divide DNA (mitosis) and then rest of cell (cytokinesis)

This is the **cell cycle**

Mitosis

- Mitosis is an equal division of nucleus where daughter cells will receive the same DNA information as mother cell
- **The goal of mitosis** is the equal distribution of pre-duplicated DNA
- Time between two cell divisions is called **interphase** so cell cycle = interphase + mitosis + cytokinesis

Cell cycle

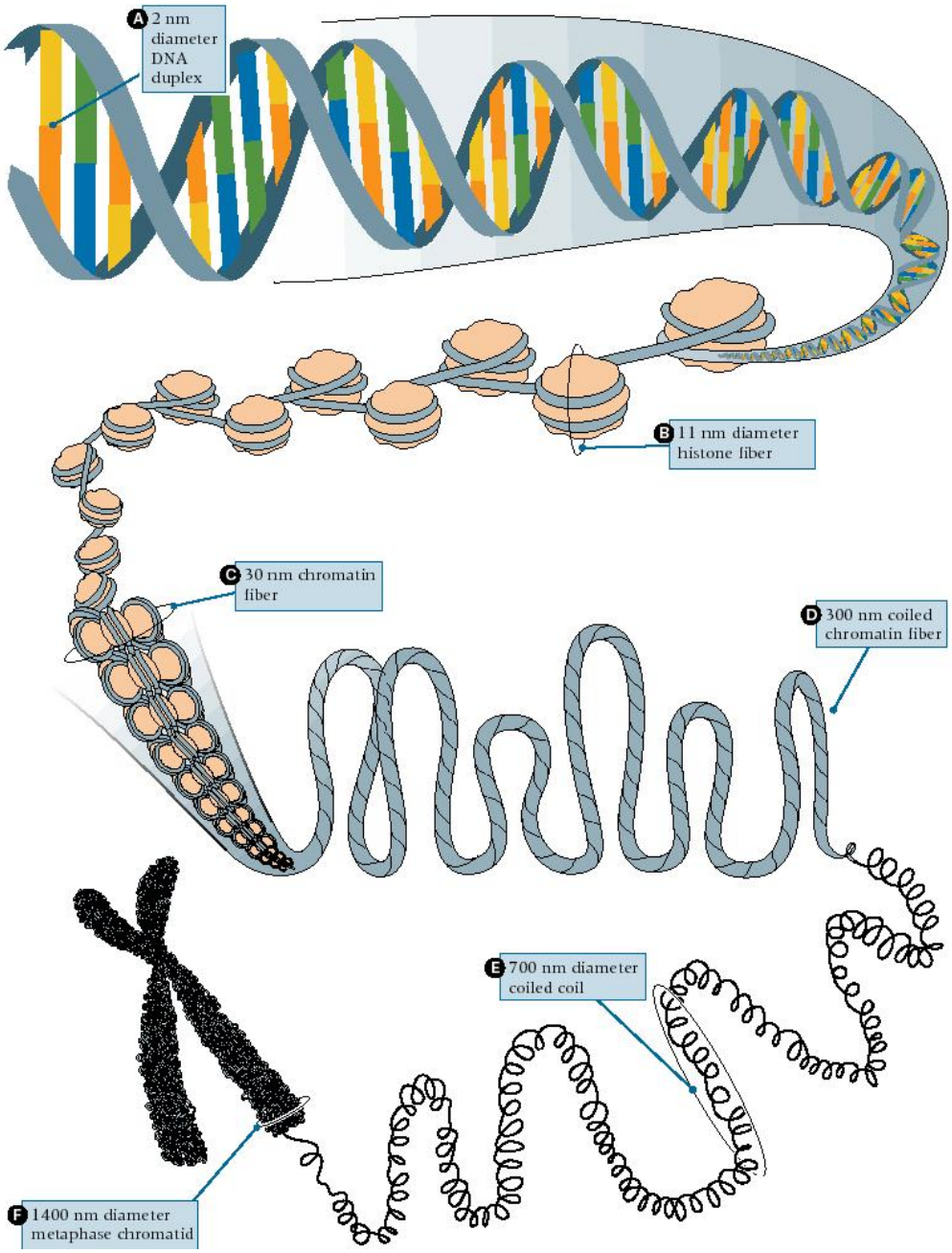


18.4 Mitosis

Stages of mitosis

- Prophase
- Metaphase
- Anaphase
- Telophase

Super-coiling of DNA into chromosome



Stages of mitosis

Summary

- Eukaryotic cell is a "second-level", enhanced cell
- Symbiogenesis is one of evolutionary steps towards eukaryote
- Mitosis is an equal division of nucleus

For Further Reading

References

[1] Eukaryote. http://en.wikipedia.org/wiki/Eukaryote

[2] Symbiogenesis. http://en.wikipedia.org/wiki/Endosymbiotic_theory

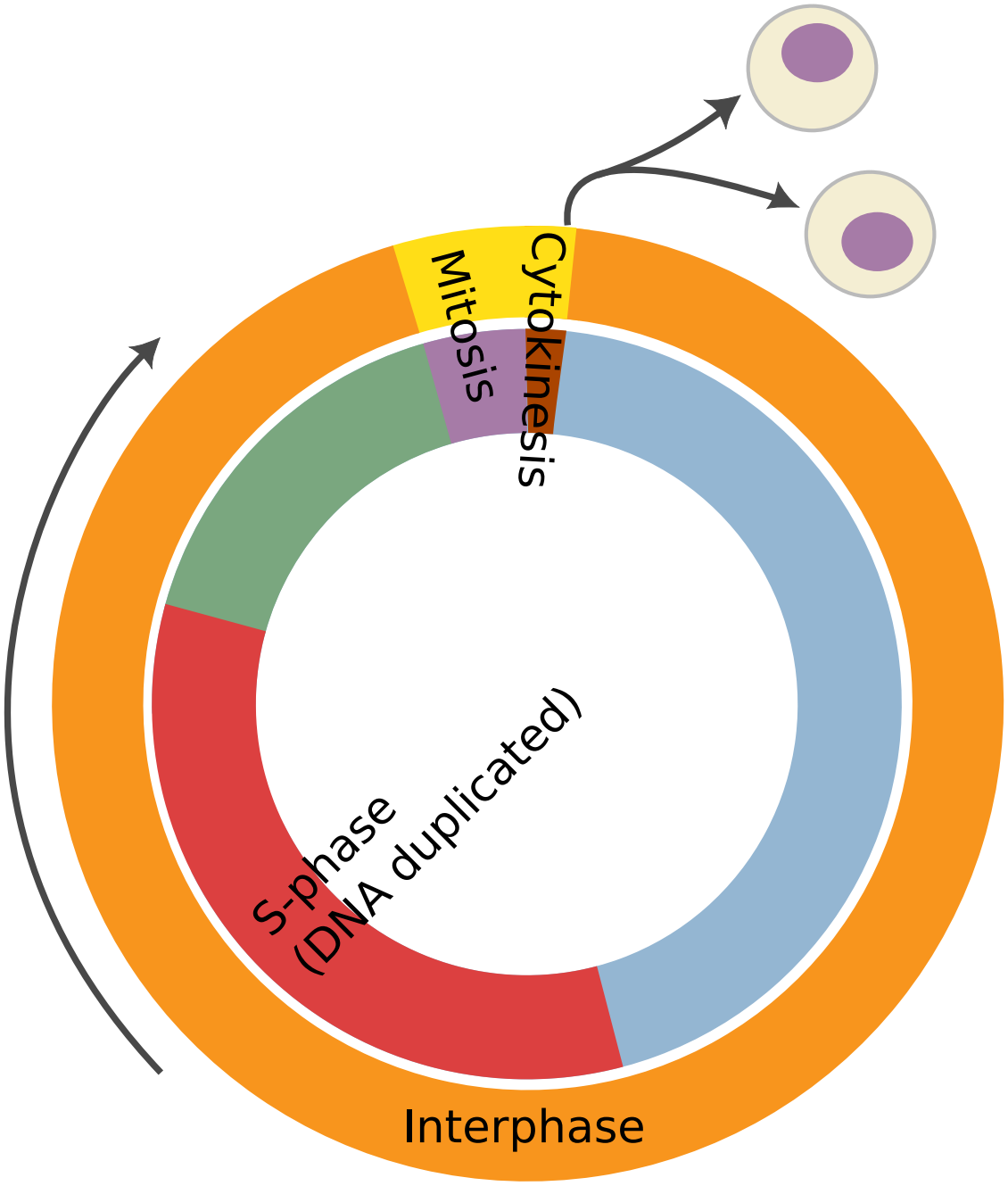
[3] Mitosis. http://en.wikipedia.org/wiki/Mitosis

Outline

19 Where we are?

19.1 Cell cycle

Cell cycle



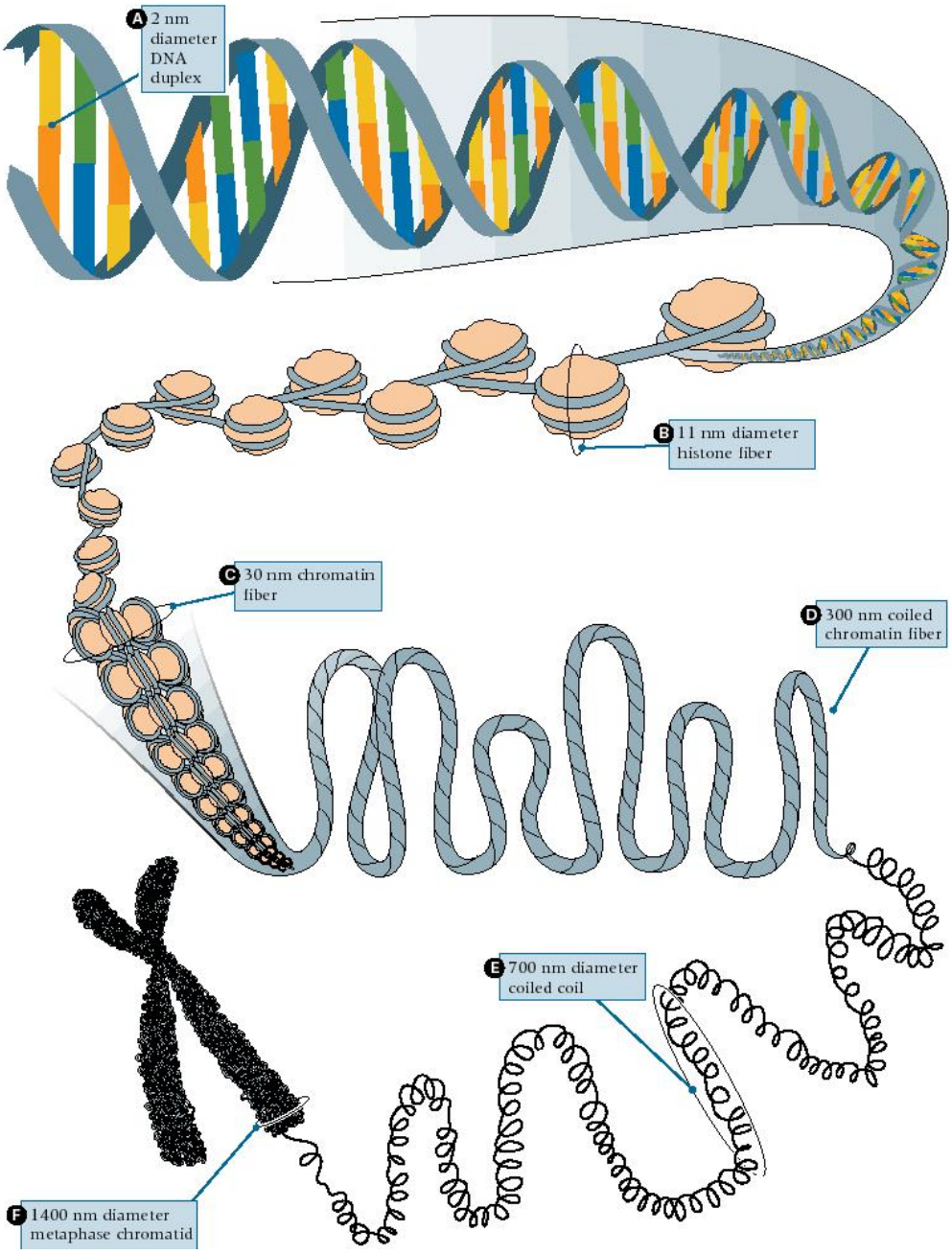
20 Cell division

20.1 Mitosis

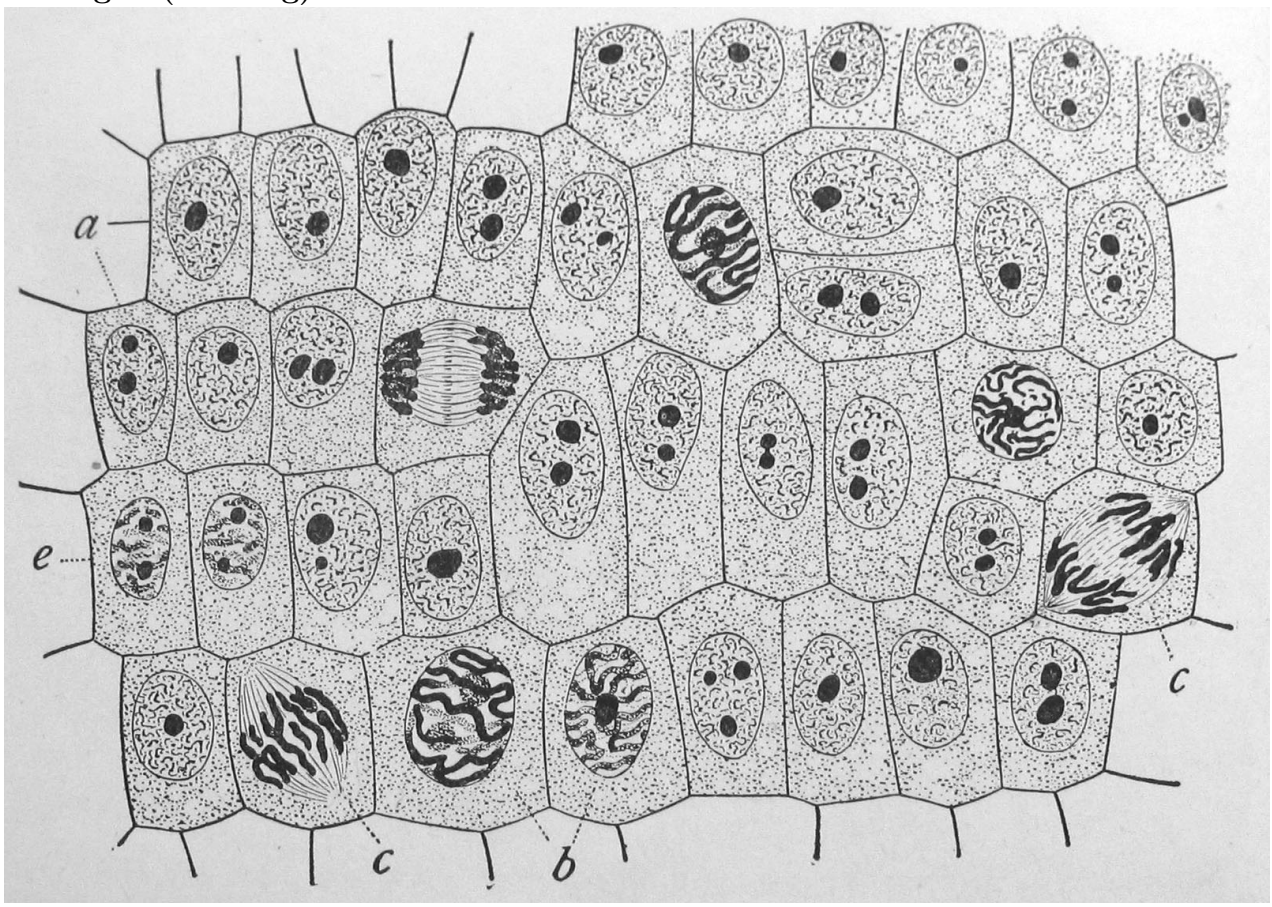
Stages of mitosis

- Prophase
- Metaphase
- Anaphase
- Telophase

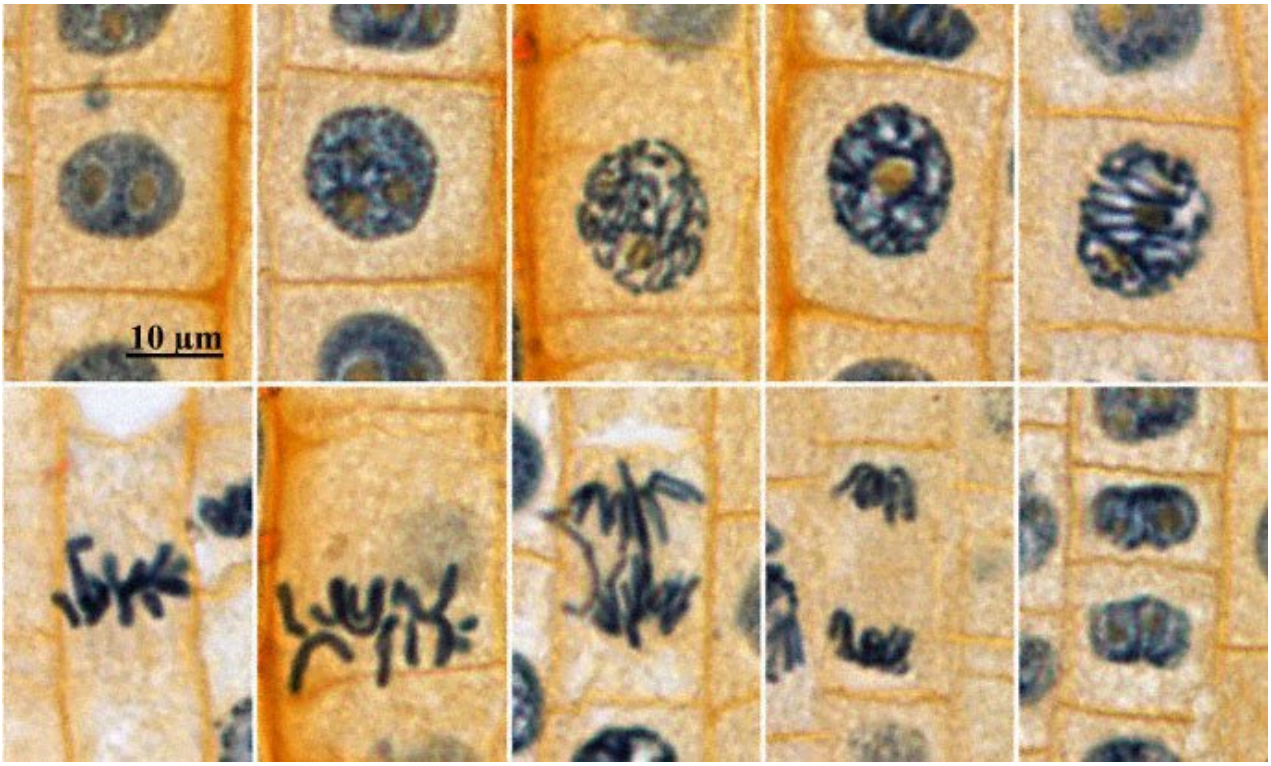
Super-coiling of DNA into chromosome



Which stage? (drawing)



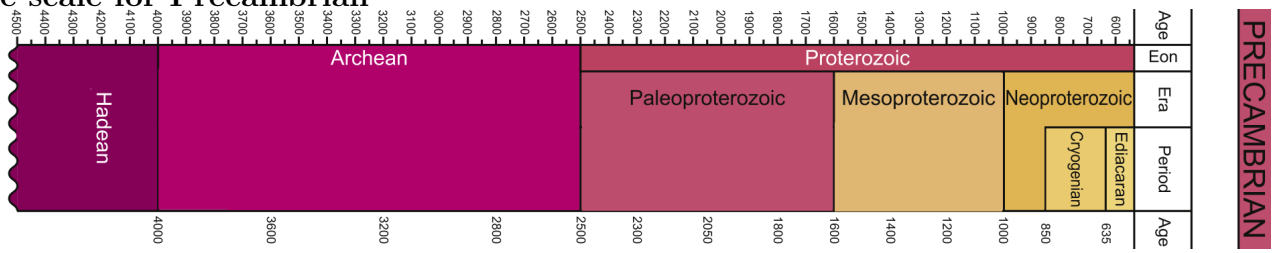
Which stage? (photo)



21 Life in late Precambrian

21.1 Cryogenian period and Snowball Earth

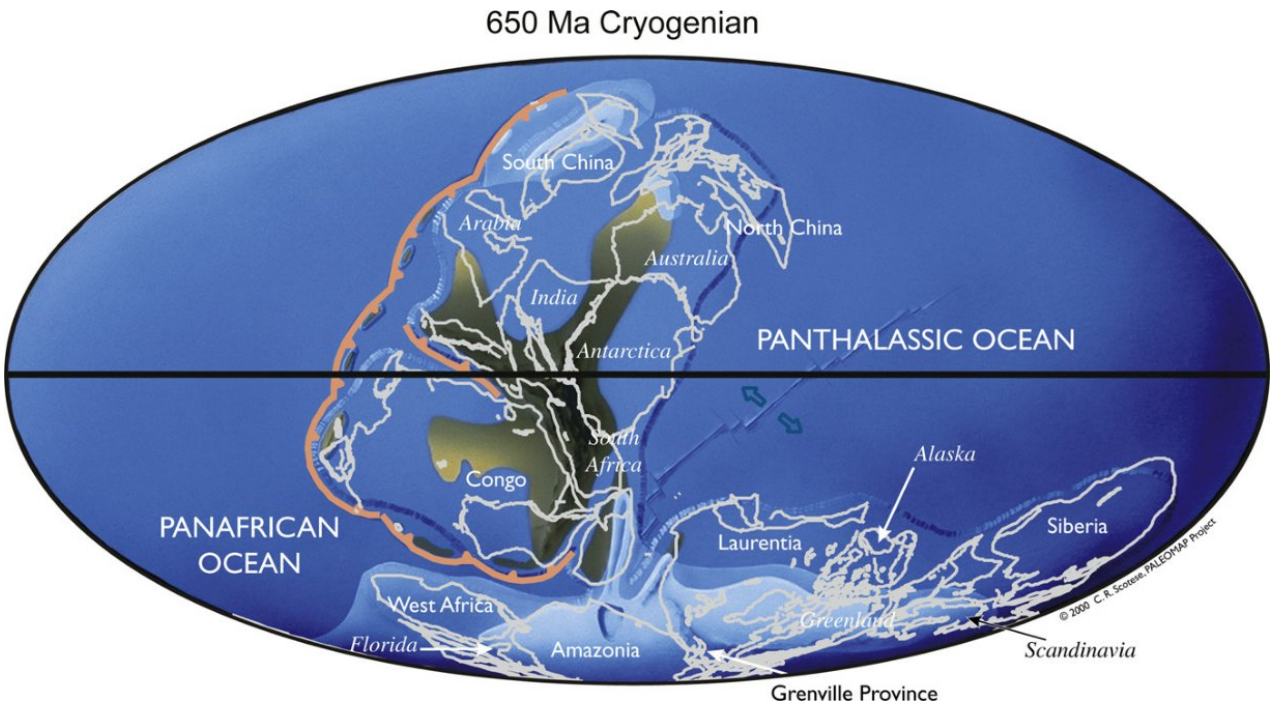
Time scale for Precambrian



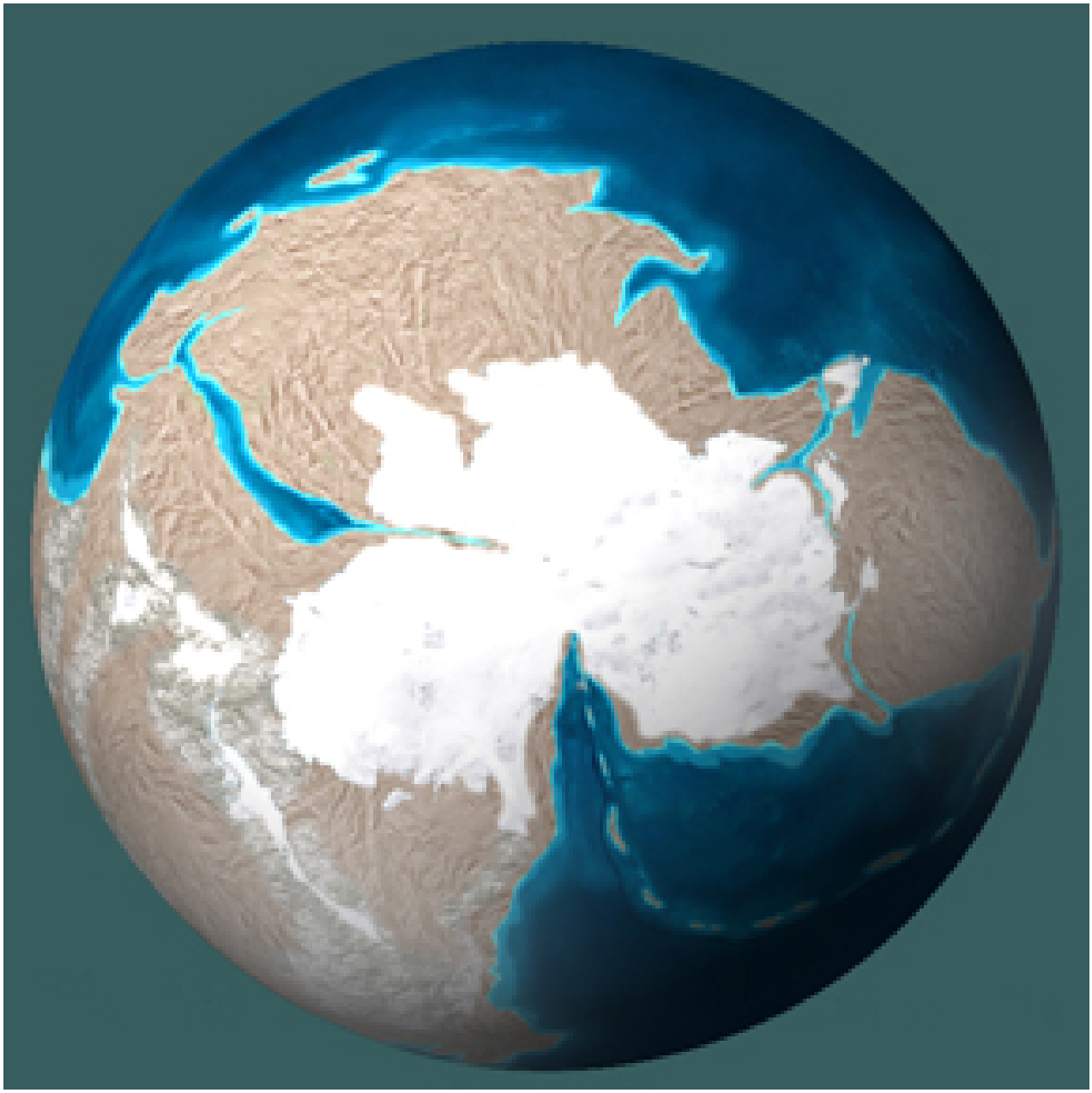
Rodinia—the super-continent

- Tectonic plates formed (and will form) one continent several times
- 650 Mya this continent—Rodinia was formed right over the South Pole

Cryogenian continents which formed Rodinia



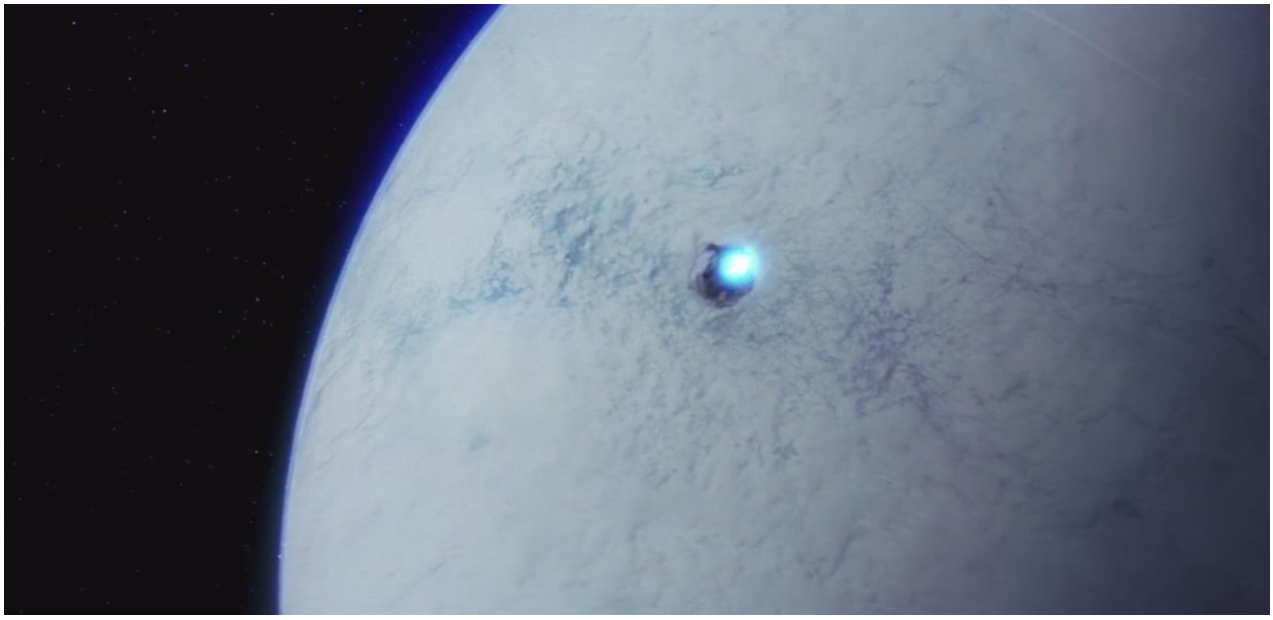
Rodinia: view from South Pole



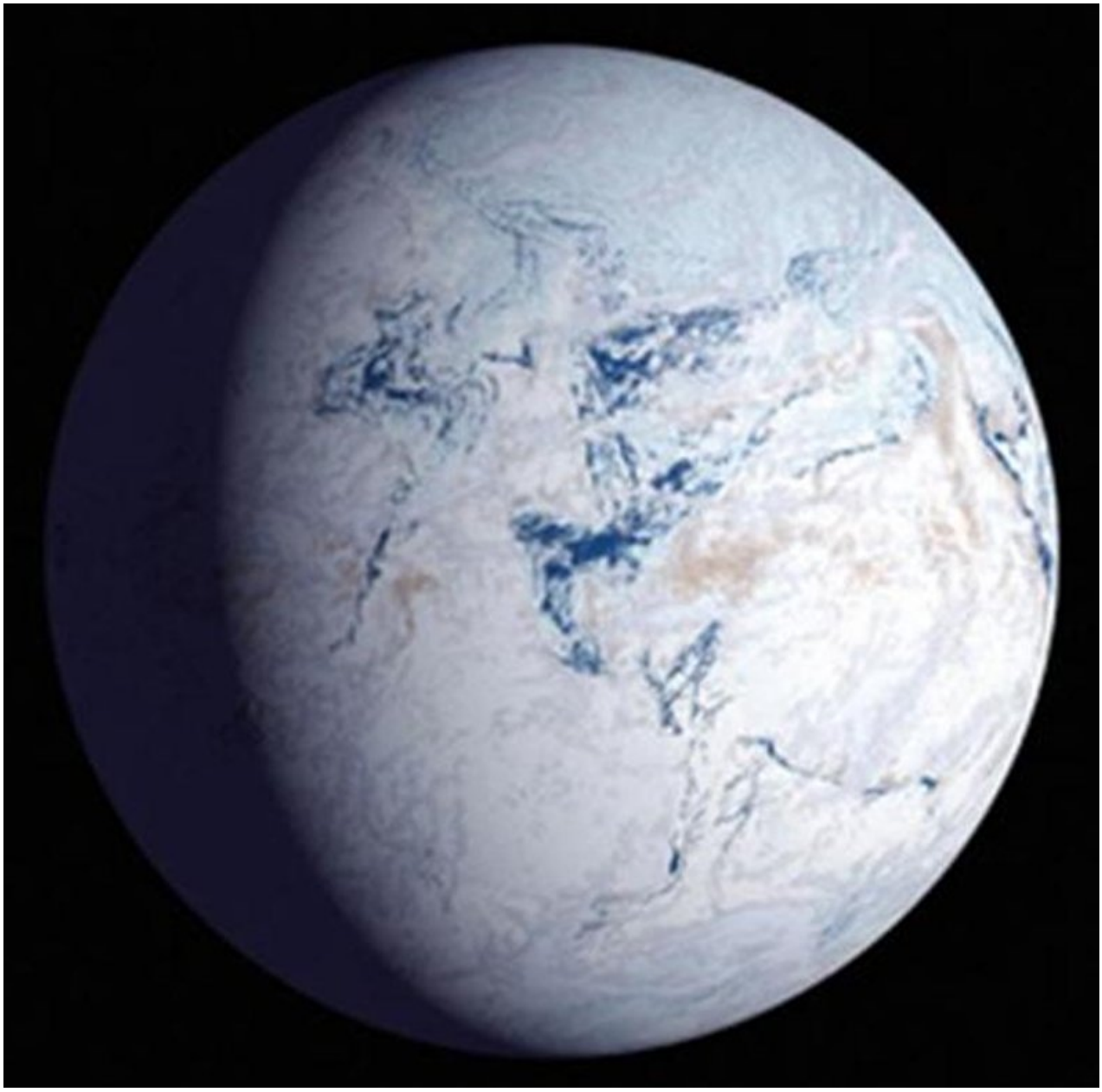
Marionan glaciation: Snowball Earth

- First global glaciation was started because ice started to concentrate over the pole and increase Earth albedo (this is the positive feedback)
- And because the configuration of continents blocked the equatorial warm current
- And because concentration of oxygen was high but greenhouse gases (like CO_2)—small
- As a result, from time to time Earth was completely covered with ice sheet 1 km tall!

"Star Wars" Hoth, the ice planet

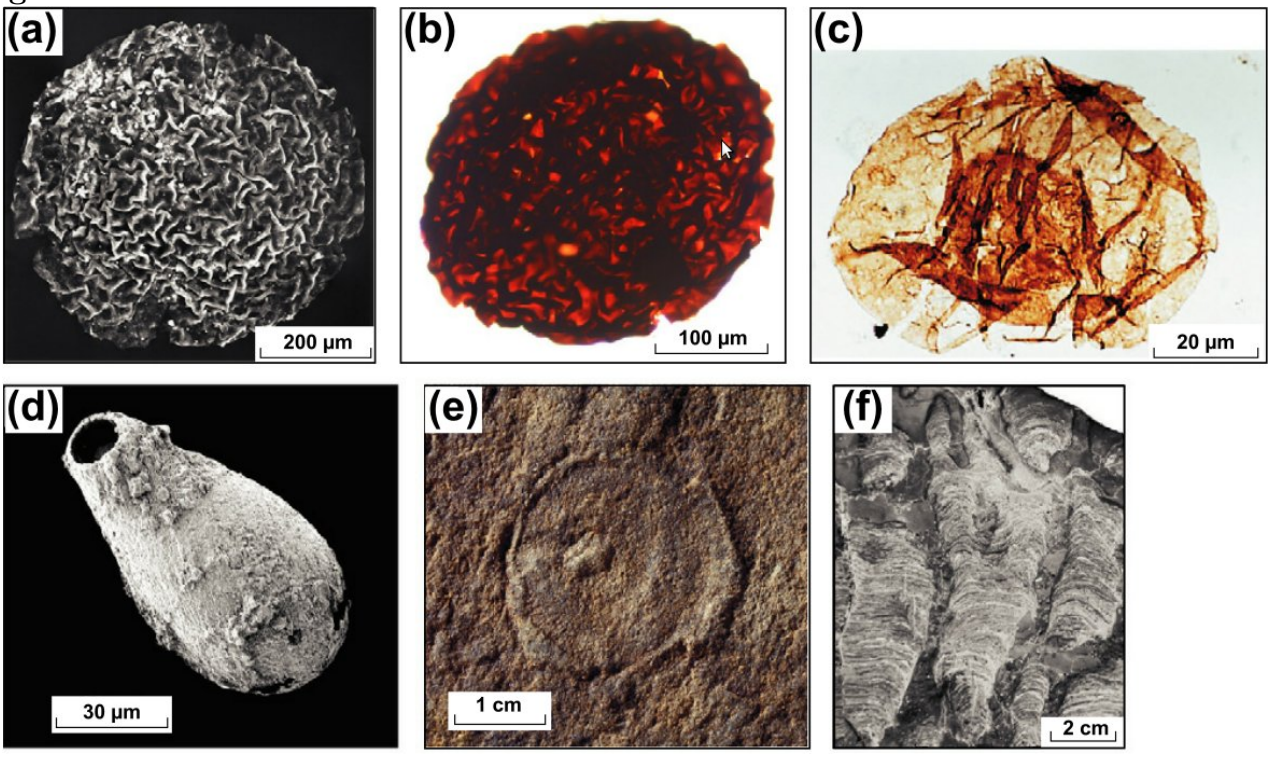


Snowball Earth



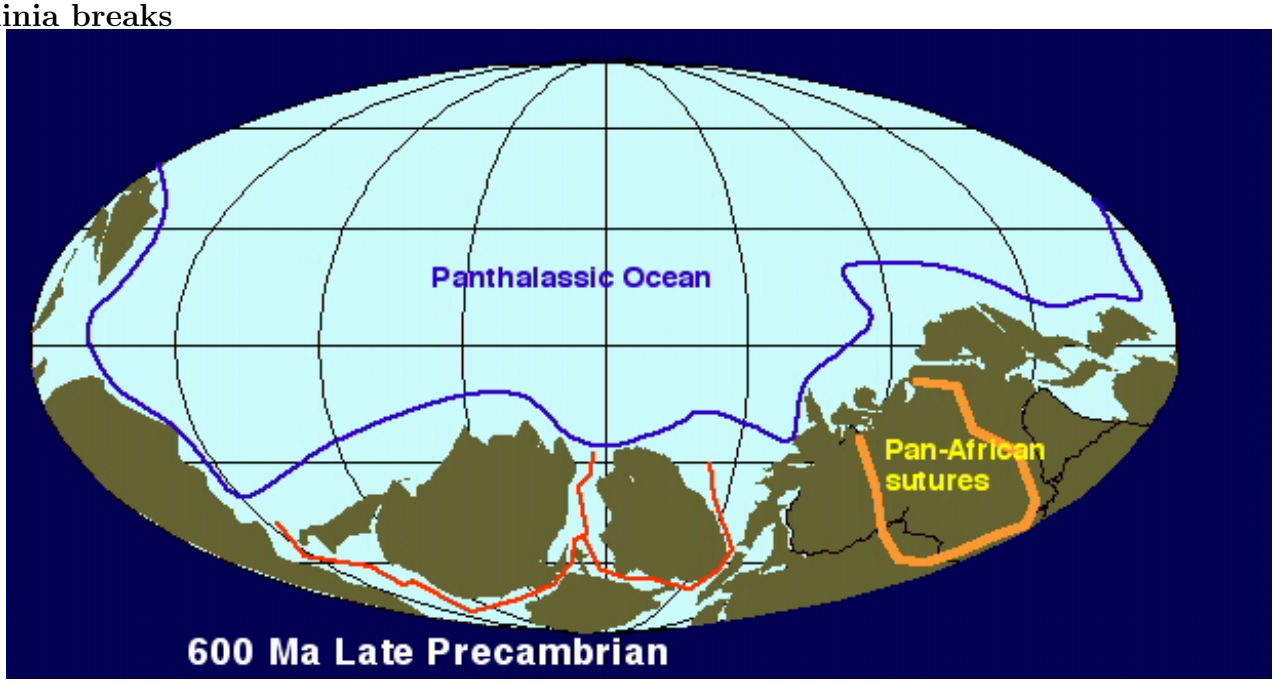
The evidence of Marinoan glaciation: diamicrite layers everywhere on Earth

Cryogenian fossils

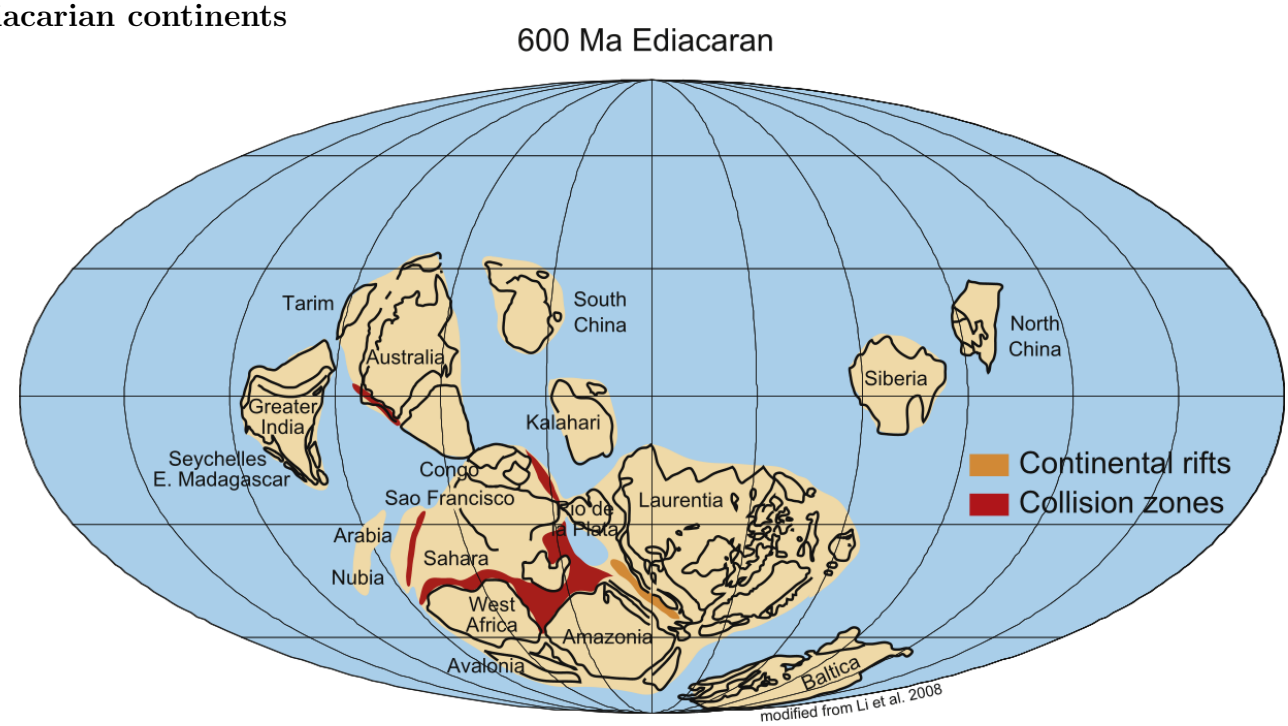


21.2 Ediacarian period and multicellularity

Rodinia breaks



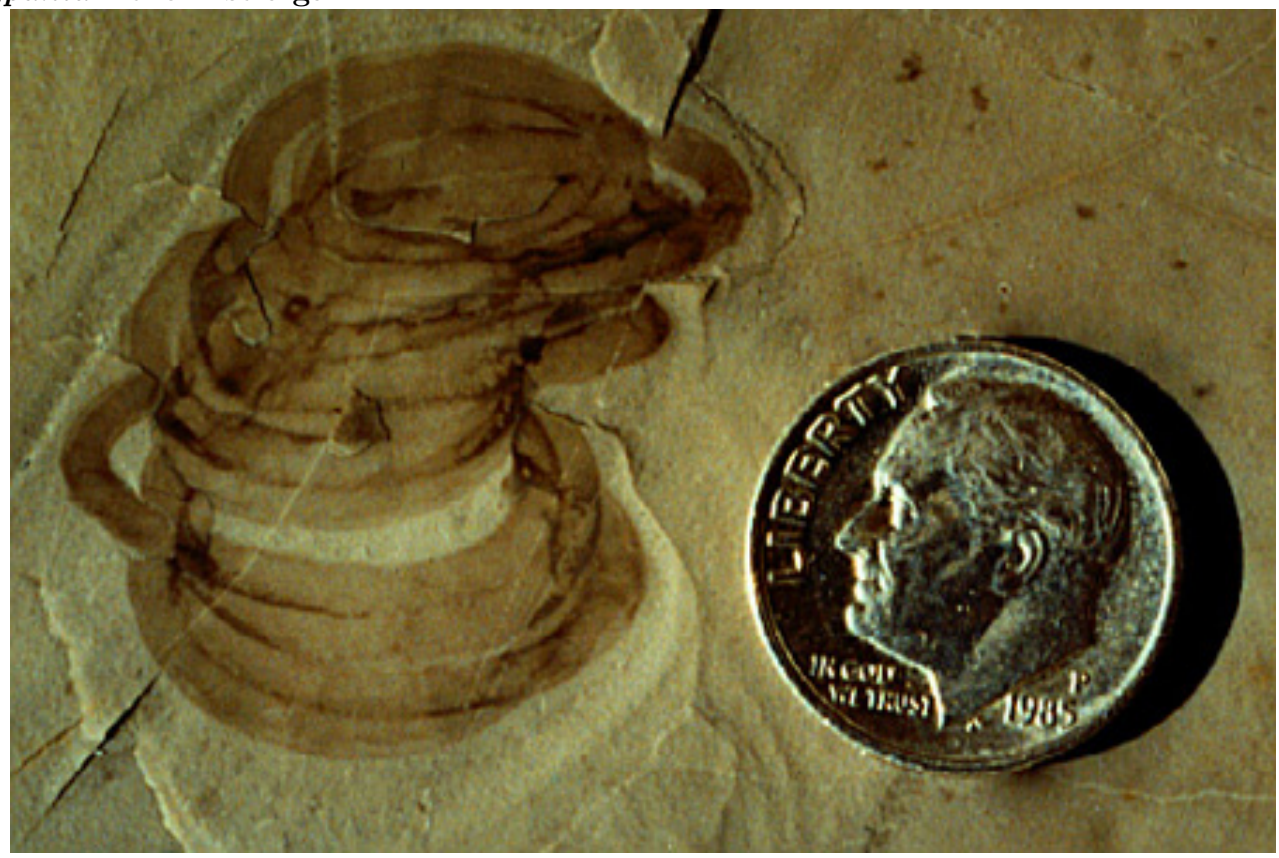
Ediacarian continents



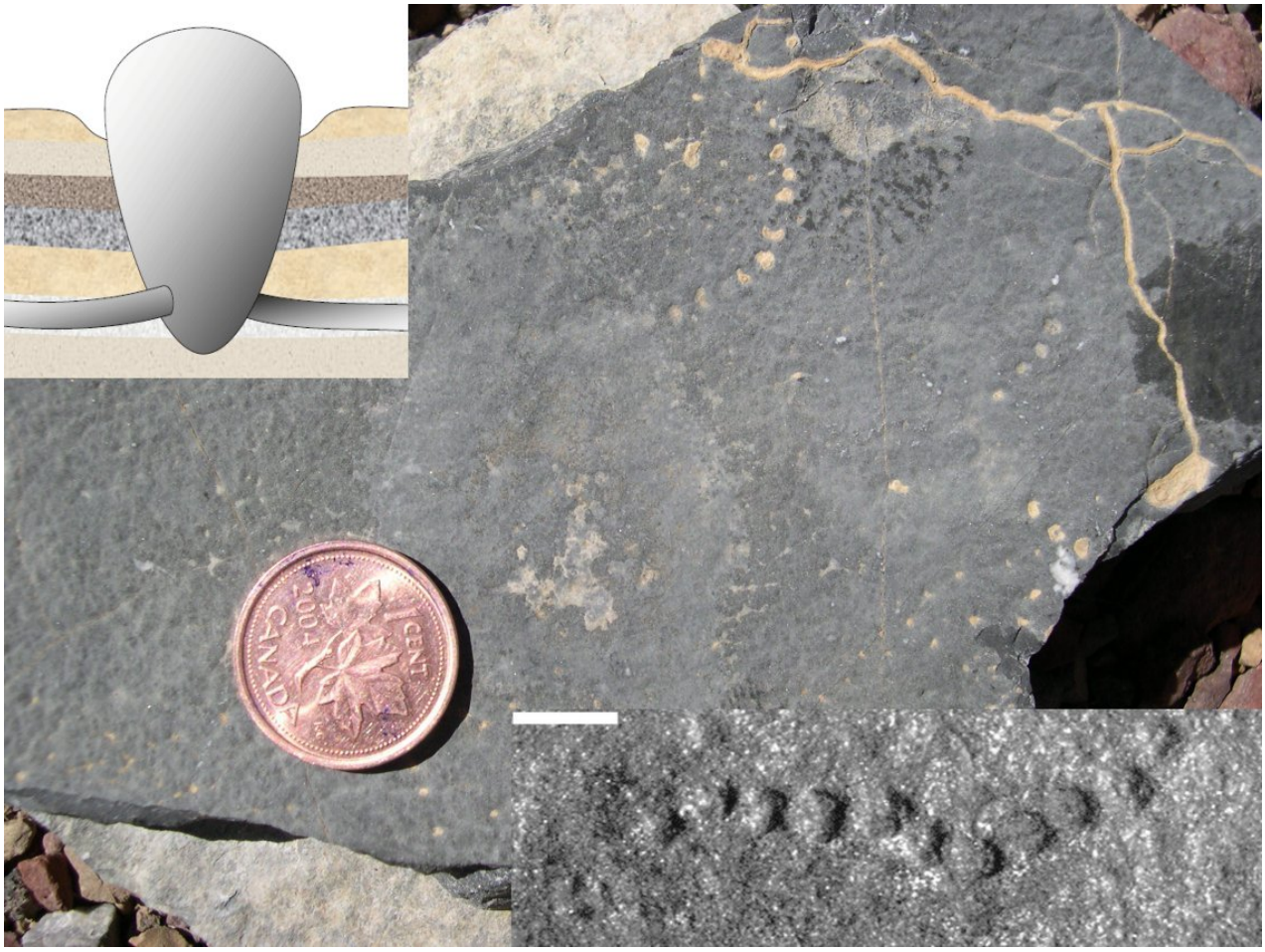
First multicellular life

- Apart from some enigmatic forms (like *Grypania* and *Horodyskia*), multicellular eukaryotes were not known before Ediacarian
- From the beginning of Ediacarian, multicellular Lantian **algae** were known, then—**rangeomorphs** from Mistaken Point and then—fabulous "**Ediacara garden**", the fauna of animals without skeleton

***Grypania*—the first alga?**



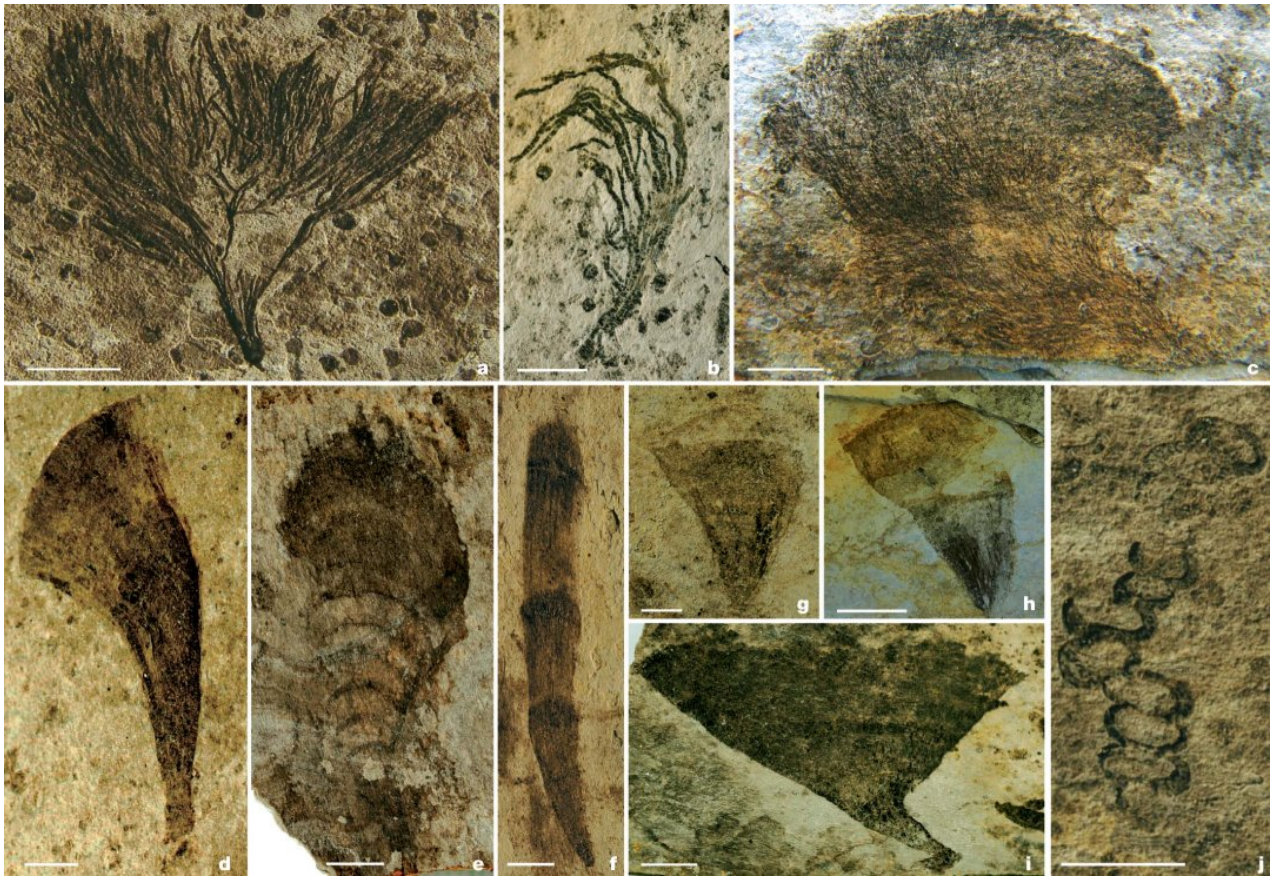
***Horodyskia* and its interpretations**



Multicellularity and origin of death

- Ediacarian fossils (and maybe some Cryogenian) were most likely **multicellular**
- Multicellular assemblages were probably originated from incompletely divided cells
- Initially, those assemblages were only benefit from their size, this is the example or race of arms between predator and prey
- Then, they started to use a division of labor: differentiated into somatic and germ cells
- Wheres germ cells are specialized for multiplication and will continue to "live" in next generations, somatic bodies have to die
- Unicellular living organisms are still potentially immortal

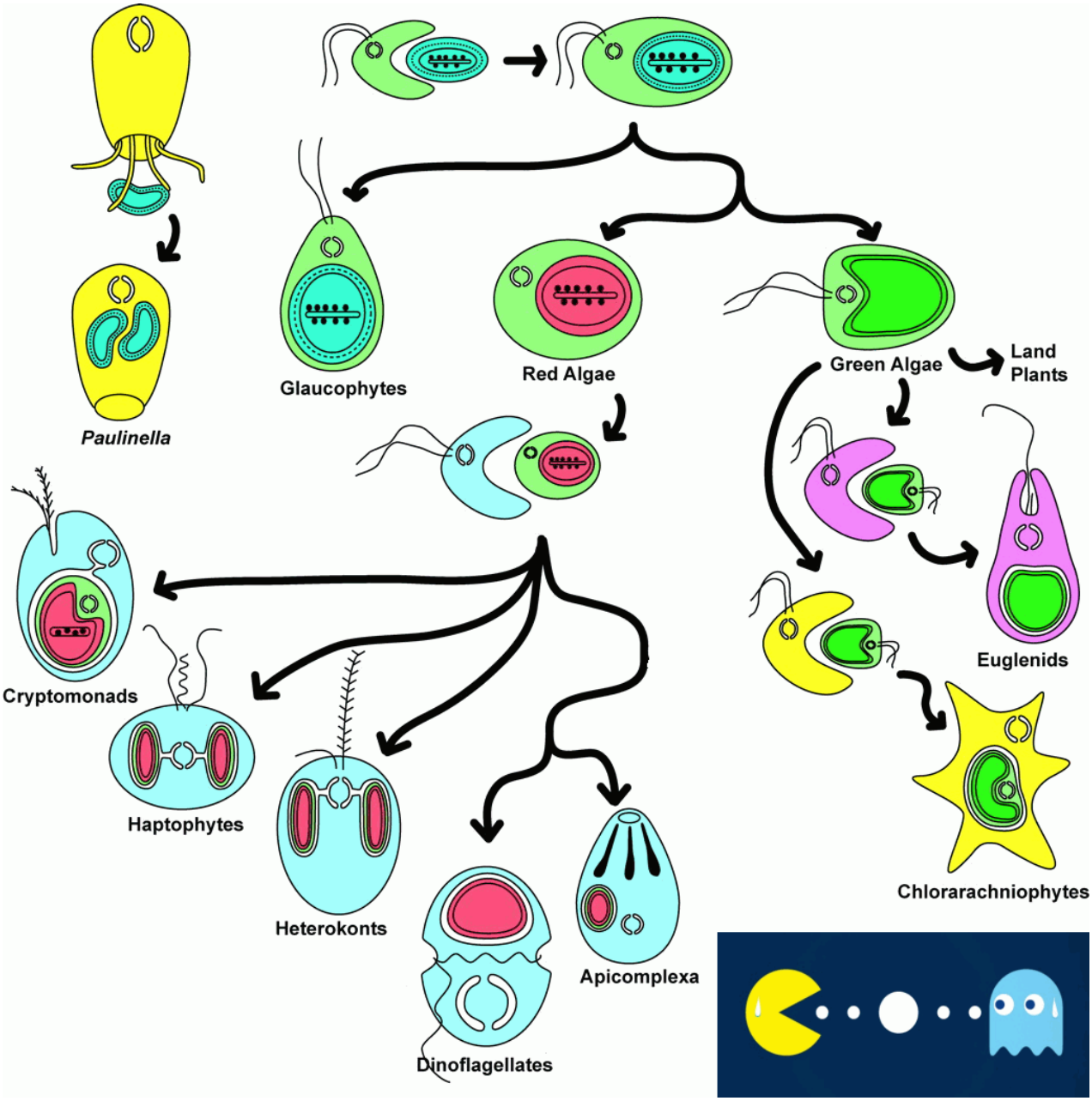
Lantian (China) macroscopic algae



What are algae?

- Eukaryotes which are capable for photosynthesis with chloroplasts
- All chloroplasts were symbiotic (cyanobacteria in the past), and some even secondary symbiotic (other alga in the past)

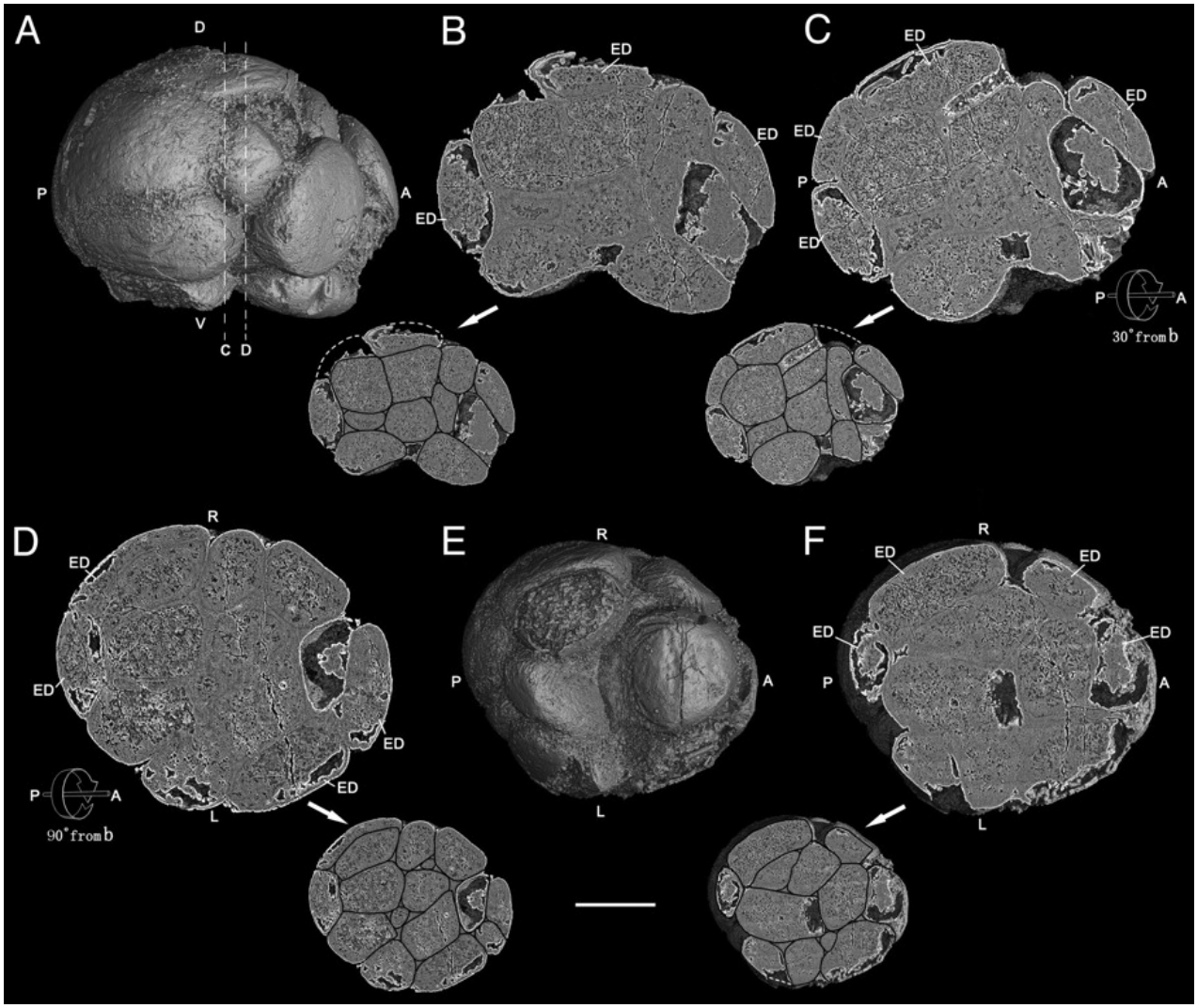
"Pacman game" of algae origin



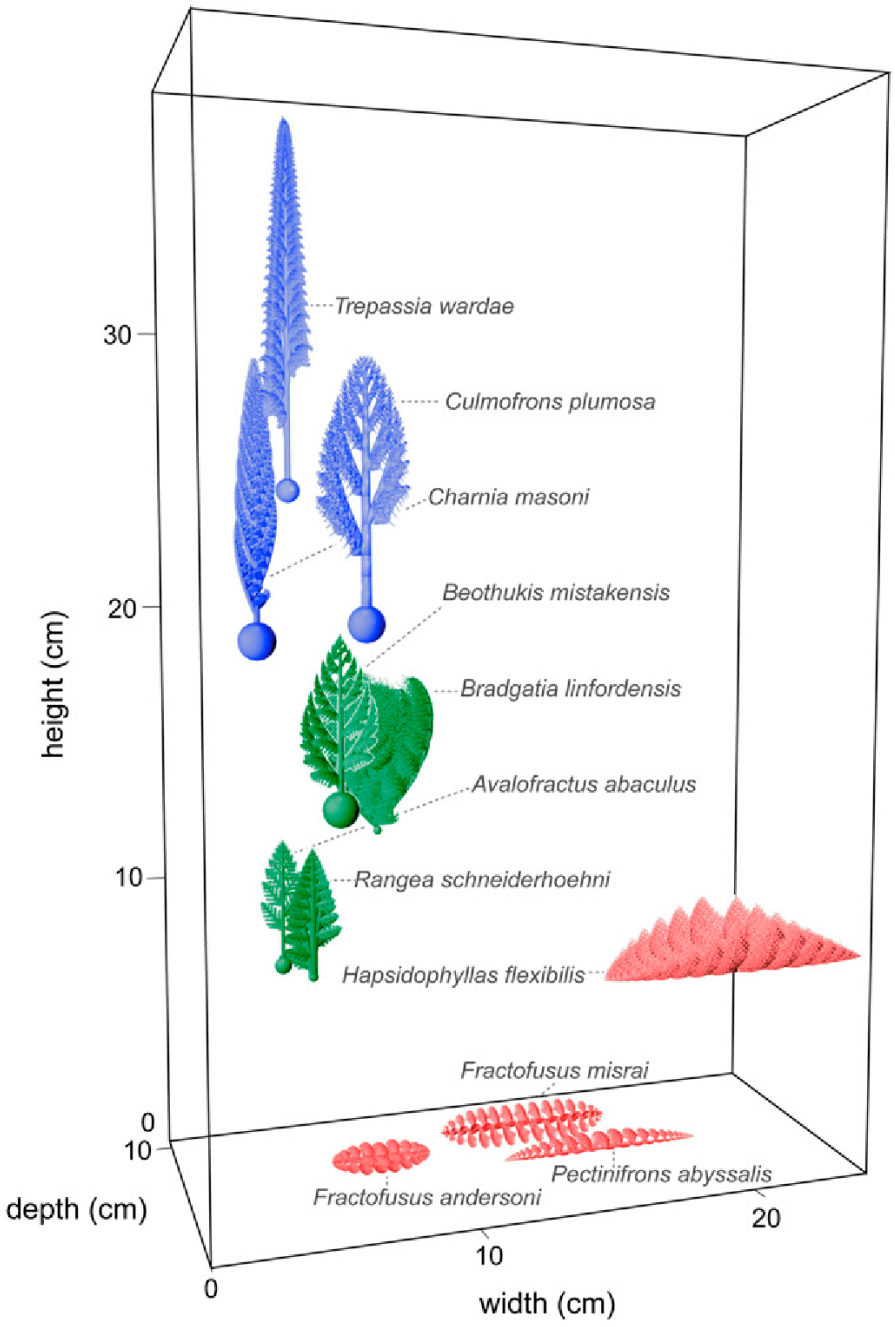
Lantian algae: probably, life without animals

21.3 First animals

Doushantuo (China) "embryos"—first animals?

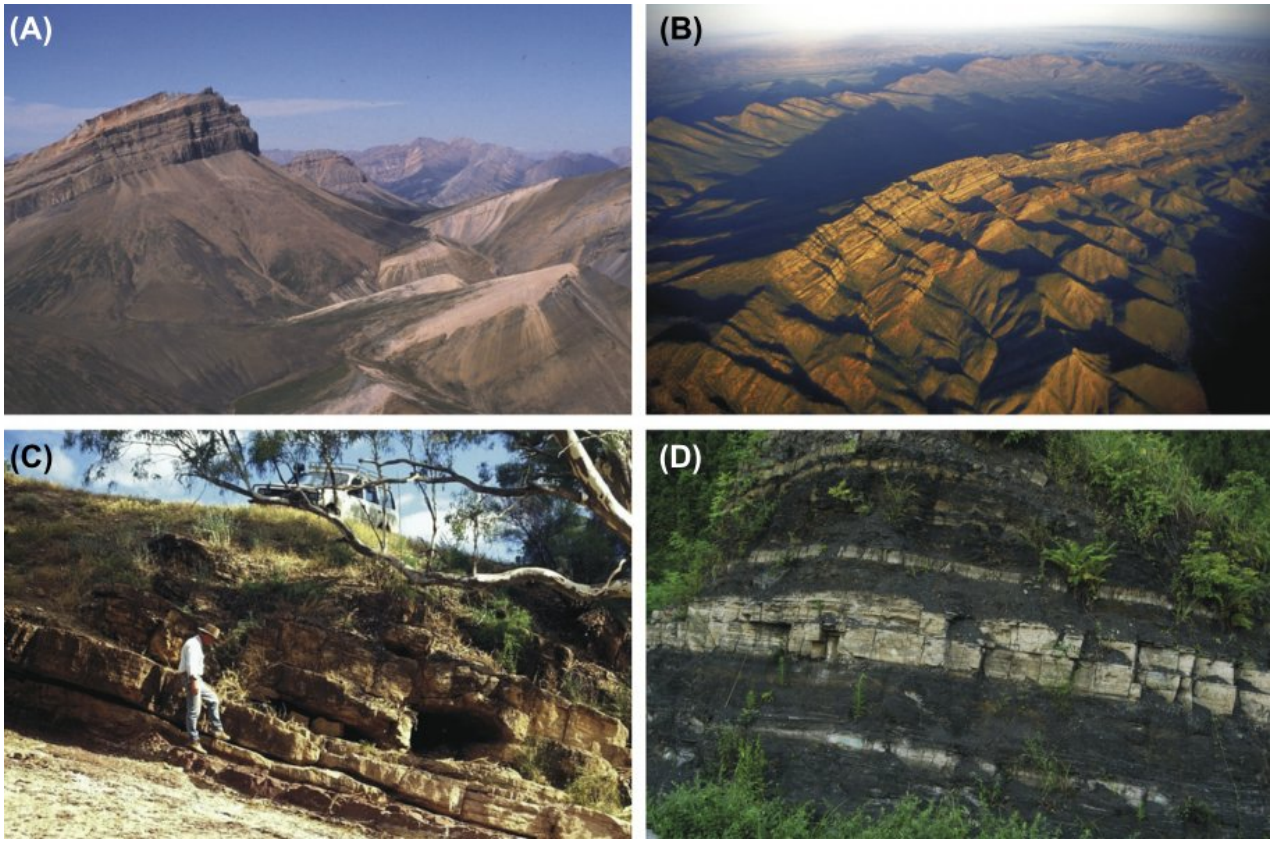


Mistaken Point (Canada) fauna: rangeomorphs

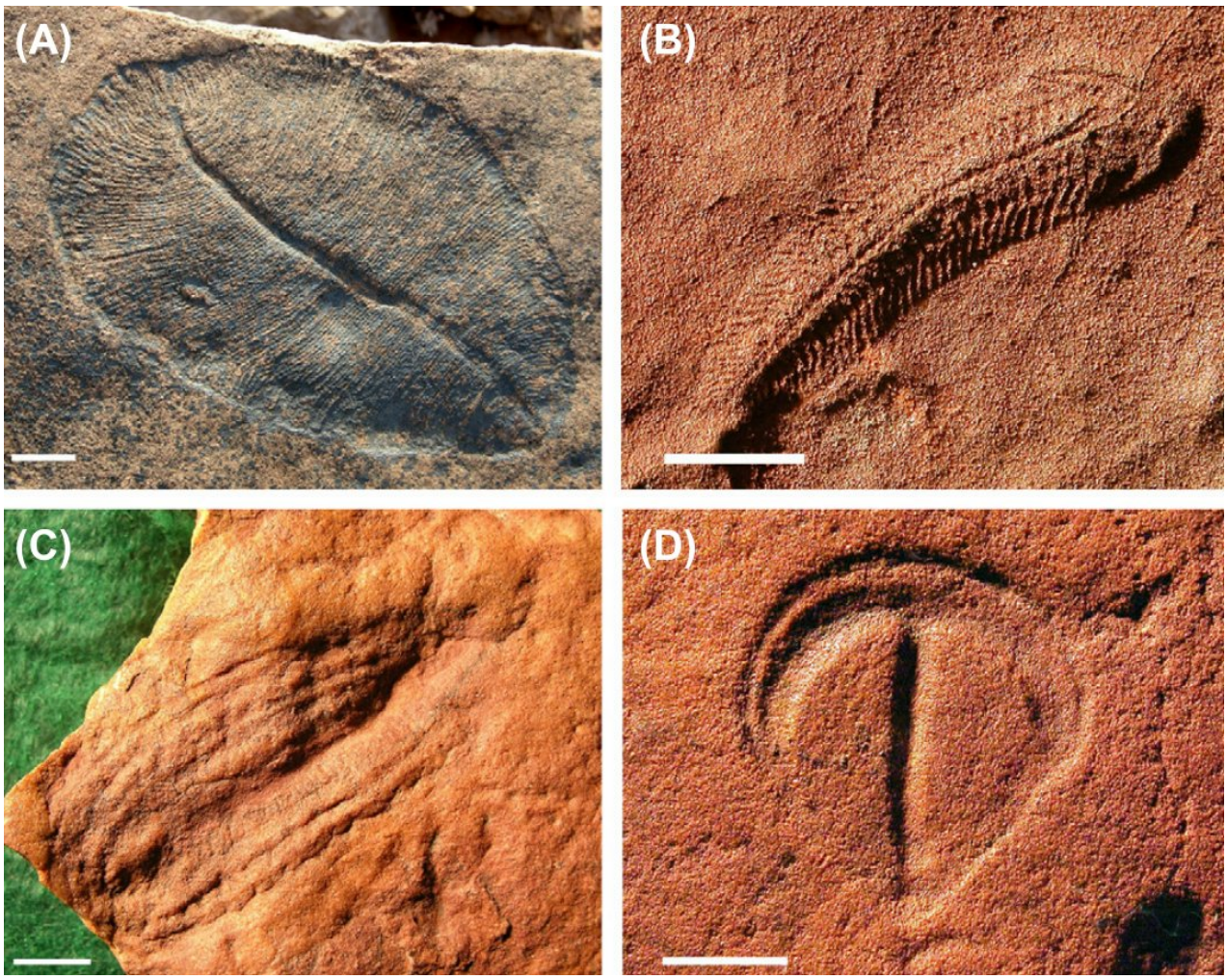


Extant sea pen (Pennatulacea soft corals)

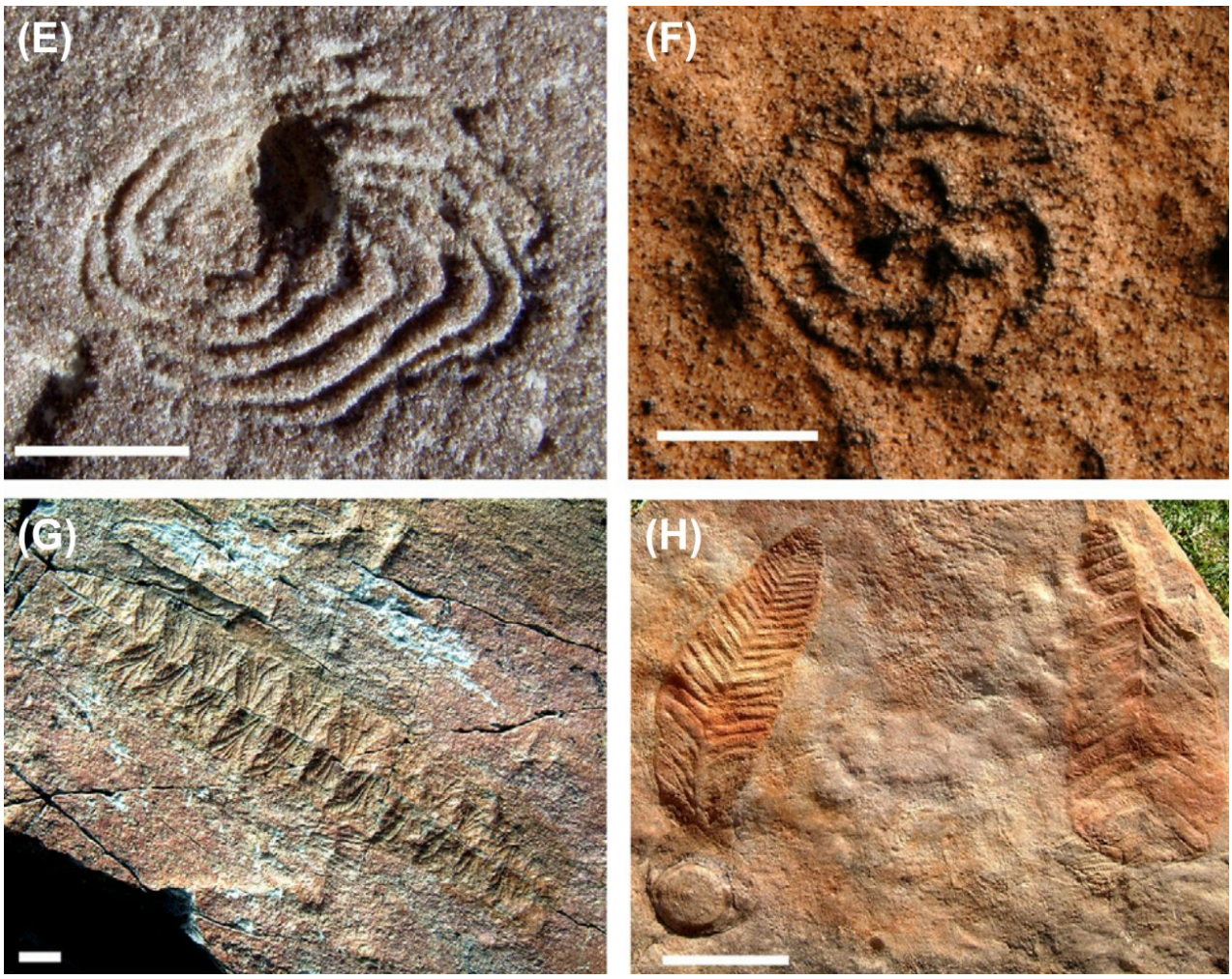
Finding Ediacara biota



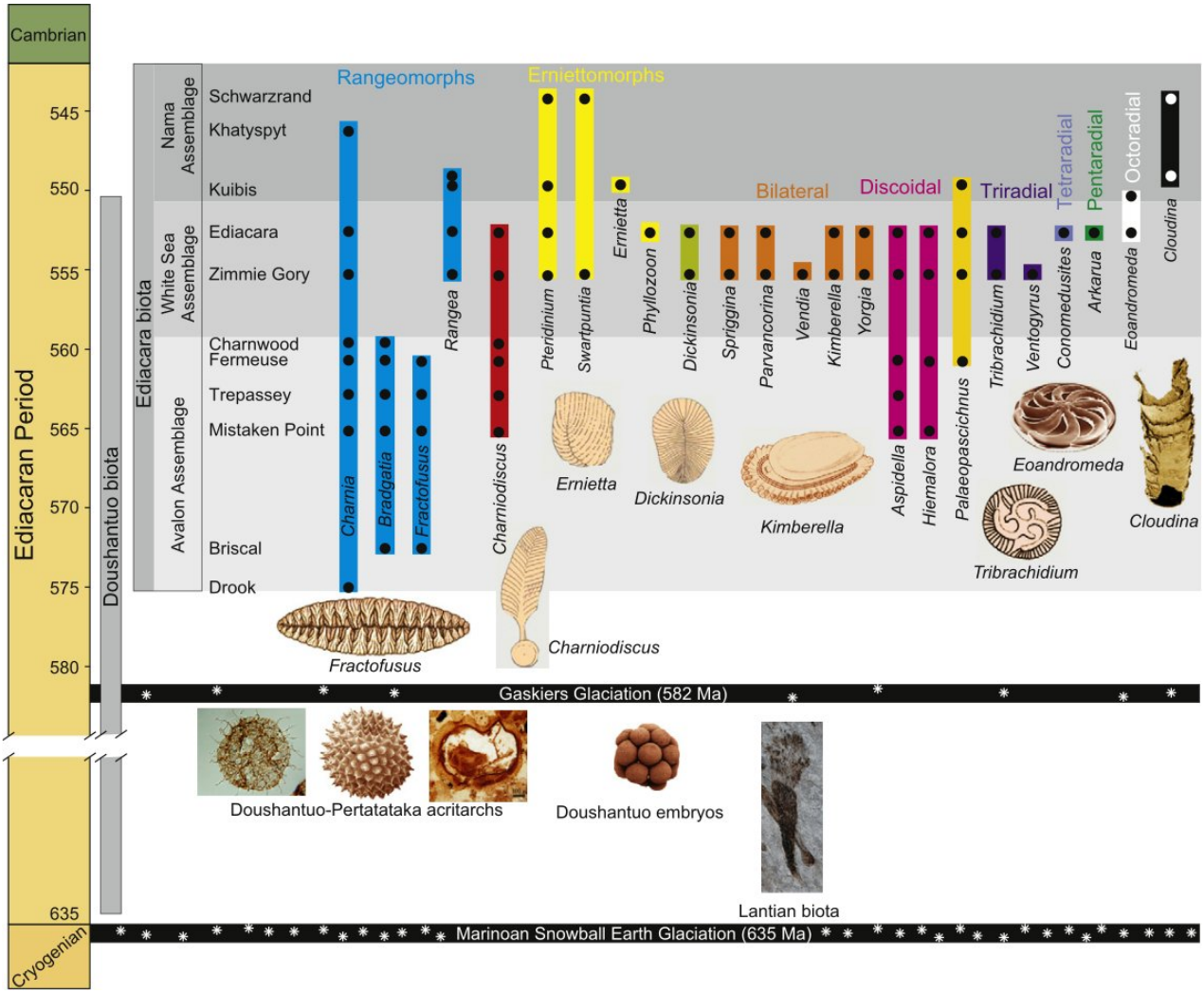
Ediacara Garden: *Dickinsonia*, *Spriggina* etc.



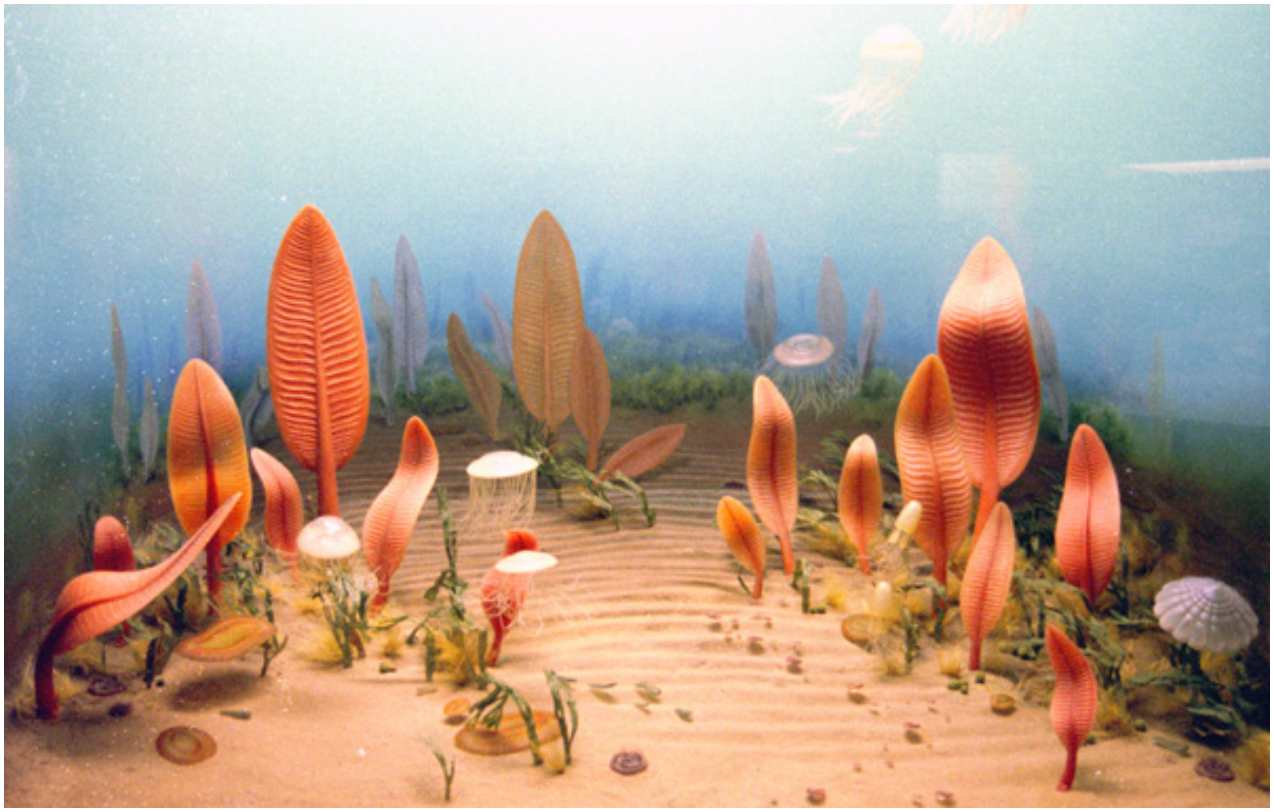
Ediacara Garden: *Eoandromeda*, *Charniodiscus* etc.



Life in Ediacarian



Ediacara "garden"—no predators *of macroscopic size*, nobody had skeleton



Origin of tissues—the most important event in late Precambrian

- **Tissues** are assemblages of similar cells doing the similar job
- Tissues are one level more over the eukaryotic cells
- Multicellular animals also have multiple tissues whereas multicellular algae and cyanobacteria are still on pre-tissues level of complexity
- **Multi-tissued** body is a great achievement, except for cancer...

Summary

- Mitosis is an equal division of nucleus
- In Cryogenian, Marinoan glaciation covered the whole Earth
- In Edicarian, multi-tissued eukaryotes appeared

For Further Reading

References

[1] Mitosis. `http://en.wikipedia.org/wiki/Mitosis`

[2] Ediacara biota. `http://en.wikipedia.org/wiki/Ediacara_biota`

22 Movies

- BBC: First Live, `https://en.wikipedia.org/wiki/First_Life_(TV_series)`. Episode 1. Arrival. 00:00:00–00:46:00 (*Spriggina*).
- BBC: First Live, `https://en.wikipedia.org/wiki/First_Life_(TV_series)`. Episode 2. Conquest. 00:00:00–00:45:00 (velvet worm)