6

The Origin and Evolution of Life on Earth

The Origin and Evolution of Life on Earth

LEARNING GOALS

6.1 SEARCHING FOR LIFE'S ORIGINS
- When did life begin?
- What did early life look like?
- Where did life begin?

6.2 THE ORIGIN OF LIFE
- How did life begin?
- Could life have migrated to Earth?

6.3 THE EVOLUTION OF LIFE
- What major events have marked evolutionary history?
- Why was the rise of oxygen so important to evolution?

6.4 IMPACTS AND EXTINCTIONS
- Did an impact kill the dinosaurs?
- Did impacts cause other mass extinctions?
- Is there a continuing impact threat?

6.5 HUMAN EVOLUTION
- How did we evolve?
- Are we still evolving?

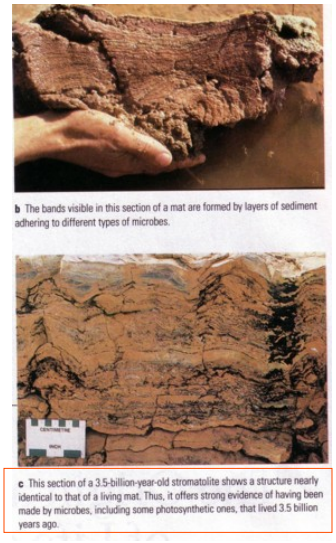
THE PROCESS OF SCIENCE IN ACTION

6.6 ARTIFICIAL LIFE
- How can we create artificial life?
- Should we create artificial life?

Three Lines of Evidence for Early Life on Earth

1
- **Living stromatolites** contain layers of sediment intermixed with different microbe types
- Look identical to **ancient stromatolites** that date back to 3.5 billion years ago (3.5 Gya)
- Indirect evidence for photosynthesis at 3.5 Gya

a These large mats at Shark Bay, Western Australia, are colonies of microbes known as "living stromatolites."



b The bands visible in this section of a mat are formed by layers of sediment adhering to different types of microbes.

c This section of a 3.5-billion-year-old stromatolite shows a structure nearly identical to that of a living mat. Thus, it offers strong evidence of having been made by microbes, including some photosynthetic ones, that lived 3.5 billion years ago.

Early Life on Earth: 2 & 3

2
- **Individual fossilized cells** in ancient rock dating 3.2-2.5 Gya
- Results are *not unambiguous* and are under debate
- There are a total of three examples found in 3.2-3.5 Gy old rock samples

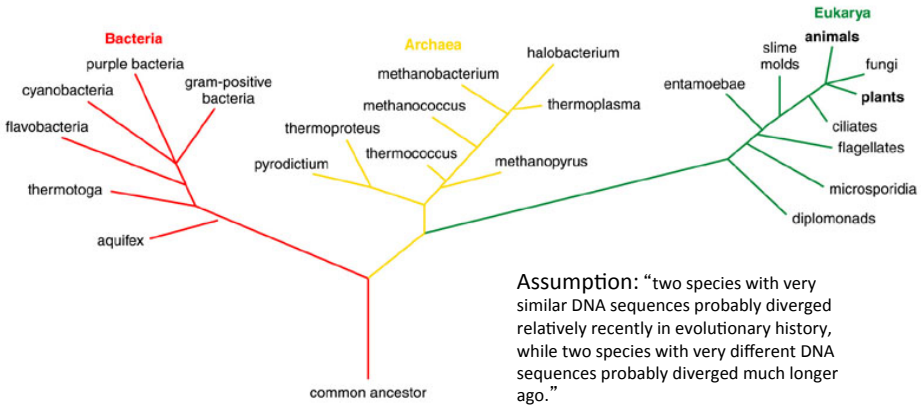
3
- **Carbon dating** using ratio of ^{13}C to ^{12}C isotopes in ancient *metamorphic* rock dating back to 3.8 Gya!
- Living organisms and fossils have smaller ratio of ^{13}C to ^{12}C than does inorganic matter, like rocks
- Rock ages not dated, but based upon the metamorphic rock in this case laying below sedimentary rock that is 3.85 Gy old.

Very indirect evidence and non-biological reasons not ruled out

Evolution via Comparative DNA

Tree of Life does not tell us "when" a species diverged… only relative relationships

The three **domains** are well established, but the ordering of branches with domains is "quite uncertain".

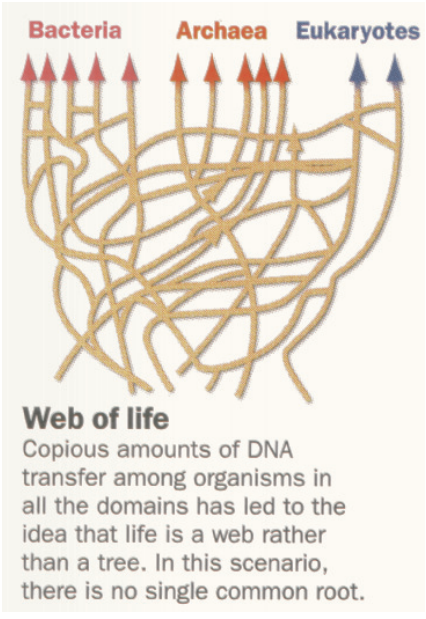


Assumption: "two species with very similar DNA sequences probably diverged relatively recently in evolutionary history, while two species with very different DNA sequences probably diverged much longer ago."

Common Ancestor?

Evolution via Comparative DNA

An alternate view?



How did Life Begin?

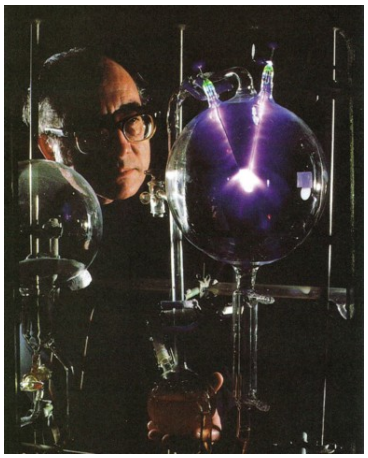
Miller-Urey Experiment based upon hypothesis that ingredients for life could be produced under normal early-Earth conditions.

Flask 1 : liquid water (ocean)
gases water vapor, methane, ammonia, and hydrogen (atmosphere)

Flask 2 : energy in the form of electrical discharge (lightning)

Flask 3 : Cooling and condensation for flow back into flask 1

Created host of organic molecules and amino acids used by life!



Where did Live Originate?

The idea of small ponds energized by electrical discharge, etc. has been replaced with the idea of thermal vents, *probably deep sea and possibly hot springs-* lots of chemical energy available and very stable environment from sterilizing impacts, etc.

Miller-Urey and Others

Short comings of original M-U experiment:

- methane and ammonia not as abundant in Earth's early atmosphere.
- carbon dioxide believed to be most abundant; re-run of experiment yields far fewer organic molecules

Several Variations of M-U experiment have been performed now…

They have varied variable from the energy source (UV light to mimic the sun, as opposed to discharges to mimic lightning), to the atmospheric chemistry

Between all of these experiments, ALL of the amino acids used by life have been produced including *all five bases used in DNA and RNA*. They have also produced several complex *sugar molecules and lipids*!

Extraterrestrial/Terrestrial Sources of Organic Molecules?

- brought to Earth via impacts
- non-atmospheric terrestrial source is deep-sea vents

How do you make the Transition from Chemistry to Biology?

Starting with an "organic soup" in the Earth's oceans, and an energy source to drive chemistry, it is possible that the organic molecules A, G, C, and U began bonding chemically according to their bonding rules. Using hydrogen bonds, a given molecular strand could be "produce" its sister strand, which then could "reproduce" the original strand.

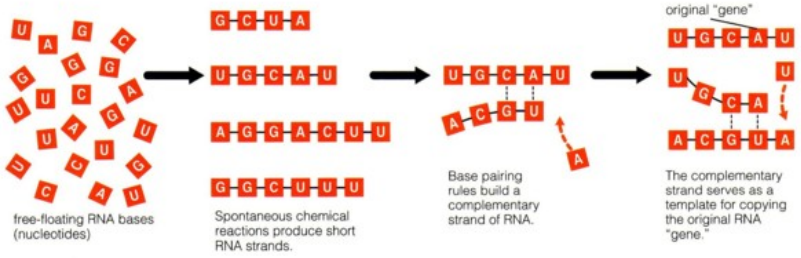


FIGURE 5.6 Because RNA can catalyze its own replication, many biologists envision a primitive "RNA world" in which life first arose. Short strands of RNA may have self-assembled from components available in the environment, perhaps with the aid of clay or other minerals. Some strands may have been capable of catalyzing their own replication. Self-replicating RNA molecules may then have competed with one another and evolved through a sort of molecular natural selection. A, G, C, and U represent the four RNA bases.

Natural Selection of RNA World?

DNA is too complex too start out, and it depends upon RNA for reproduction…
RNA is a good candidate – single strand, backbone simpler, contains hereditary information

DID LIFE START OUT AS AN "RNA WORLD"?

RNA WORLD and Clay

"**Chicken and Egg Problem**" RNA duplication today requires enzymes (proteins) as a catalyst, but protein enzymes are produced by RNA!

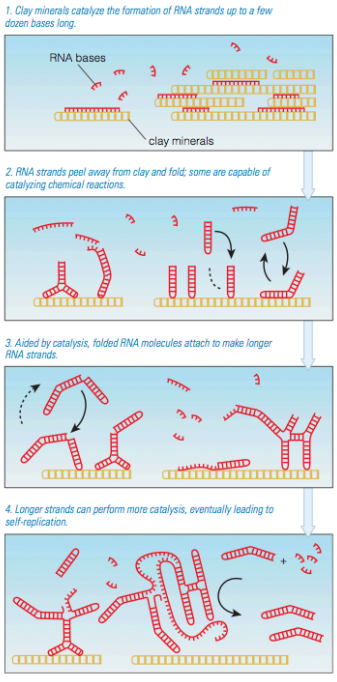
RNA would need a catalyzing agent

Role of Clay:

Clay could solve need for enzyme proteins to jump start the process.

Clay is a good site for concentrating organic molecules, a condition required for reactions to proceed.

Clay may have been central to RNA World. Organic molecules adhere to minerals in clay; in laboratory experiments, RNA with up to 100 base pairs have been produced!



Developing The Cell

Pre-cells may have been common (seen easily in laboratory experiments)

1. Amino Acids in cooling water form enclosed spherical structures
2. Lipids in water form closed "membranes"

Diversity of Amino Acid Shells

The amino acid shells can

- grow and shrink in size by adding or subtracting additional amino acids
- split into two daughter shells
- selectively allow some types of molecules to pass through and block others in/out
- store electrical energy on surface-discharge could aid chemical reactions inside

Examples of Pre-Cells

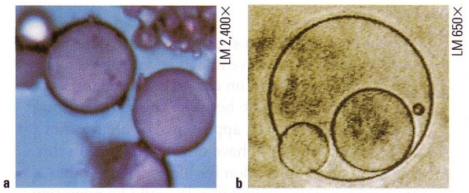


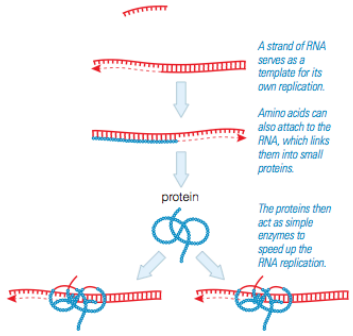
FIGURE 5.8 Laboratory versions of pre-cells. (**a**) These microscopic spheres were made by cooling a warm-water solution of amino acids. Although they are not alive, they exhibit many lifelike properties. (**b**) These microscopic membranes are made from lipids that when mixed with water spontaneously form enclosed droplets.

Transition from Chemistry to Biology

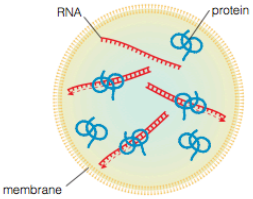
Competitive RNA survival…

In the RNA World, those RNA/protein molecules that may be concentrated in some form of "bubble", or "pre-cell" would benefit over others not in a protective shell.

Water (transport medium) can pass through the the amino acid "bubble". Additional organic material can pass into the bubble, and then it is available to the enclosed RNA without competition from other RNA molecules in the RNA organic soup. Thus, enclosed RNA wold have Unequal Reproductive Success compared to free-floating RNA.



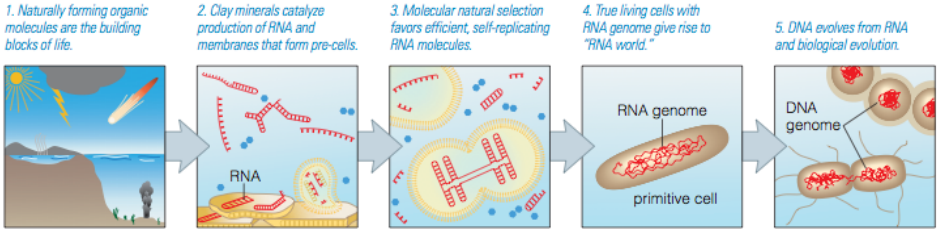
a This diagram shows a self-replicating RNA molecule that has evolved the capability to produce a primitive enzyme that helps its own replication.



b If the RNA and the enzyme are isolated from the outside environment inside a pre-cell, then only the molecules in this particular pre-cell will benefit from the new enzyme, a fact that can speed up the molecular evolution.

Putting it Altogether

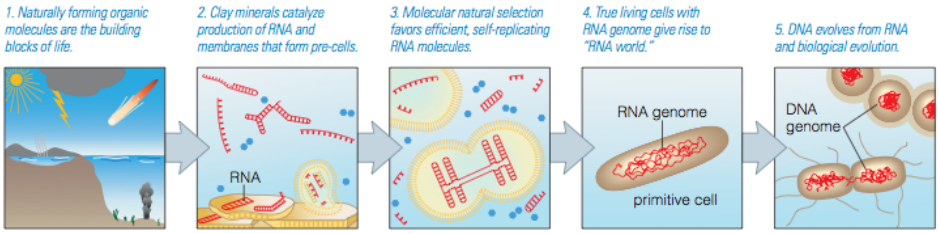
1. Through some combination of atmospheric chemistry, chemistry near deep sea vents, and impacts of asteroids and comets, the early Earth developed at least localized areas in which amino acids, building blocks of nucleic acids, and other organic molecules were dissolved in a dilute "organic soup".



2. More complex molecules, including short strands of RNA, grew from the building blocks in the organic soup, perhaps with the aid of reactions using clay or other mineral surfaces as templates for their assembly. Some of the RNA molecules were capable of two-stepped reproduction (original -> sister -> copy of original, i.e., self-replication).

Putting it Altogether

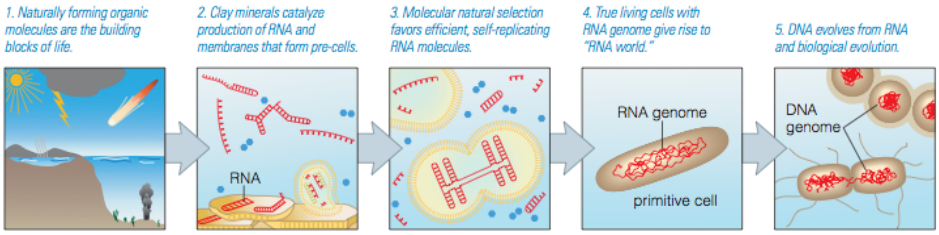
3. Membranes that formed spontaneously in the organic soup enclosed some of these complex molecules, making "pre-cells" that facilitate the development of cooperative molecular interactions in an environment free of competition from other reproducing molecules.



4. Natural selection among the RNA molecules in pre-cells gradually led to an increase in complexity, until eventually some of these structures became true reproducing "living" organisms

Putting it Altogether

5. Natural selection then rapidly improved and diversified life. The RNA duplication randomly diversifies, stumbling upon a double helix configuration that is very robust, and therefore has unequal reproductive success. DNA became the favored hereditary molecule, and life continued to evolve ever since.



None of this is well understood and is primarily in the realm of speculation.

Transition from Chemistry to Biology

"…unless laboratory experiments someday show that such minerals can take simple organic molecules all the way to something resembling a true living organism, we won't know if such a scenario is really possible."
- The authors of the book

We still need to ask ourselves…

So, perhaps RNA naturally duplicated itself in an RNA WORLD… but:

- *Why would this process develop into something driven to be self sustaining?*
- *Why would it continue to diversify and become more complex and specialized?*
- *All this eventually led to intelligence?*
- *Why did it not just continue on at the low level of "reproductive curiosity chemistry"?*

Could Life Have Migrated to Earth?
The Story of ALH84001

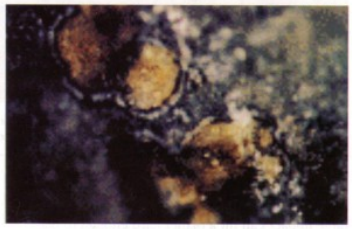
(Allen Hills region, 1984, first one found)

Volcanic rock that formed 3.9 billion years ago
Spent 16 million years wandering solar system
Lands on Earth 13,000 years ago

Sat in a lab for 10 years before being studied!

Was once infiltrated by liquid water

a The martian meteorite ALH84001, before it was cut open for detailed study. The small block shown for scale to the lower right is 1 cubic centimeter, about the size of a typical sugar cube.



b A microscopic view of a thin slice of ALH84001 shows orange carbonate globules, indicating that the rock was once infiltrated by liquid water. The grains are about 0.1–0.2 millimeter across. The globules formed about 3.9 billion years ago.

Table 7.3 The History of Meteorite ALH84001

Time	Event
4.5 billion years ago	Solidifies from molten rock in the southern highlands of Mars
4.0–4.5 billion years ago	Affected by nearby impacts, but not launched into space
3.9 billion years ago	Infiltrated by water, leading to the formation of carbonate grains within the rock
16 million years ago	Blasted into space by an impact on Mars
13,000 years ago	Falls to Earth in Antarctica
December 27, 1984	Found by scientists
October 1993	Recognized as a martian meteorite
August 1996	Announcement that ALH84001 contains possible evidence of martian life

In 1997, it was announced that fossilized Martian life existed in ALH84001. If life formed on Mars, it may migrated to Earth. Results is now not accepted. If such migrations occurred, they would be limited within solar systems.

Could Life Have Migrated to Earth?
The Story of ALH84001

In iron rich layers, crystals of magnetite are found similar in size and shape to those made by bacteria on Earth

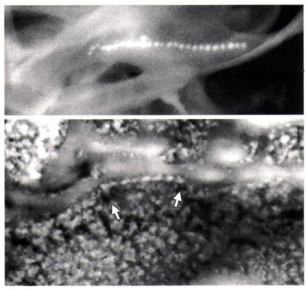
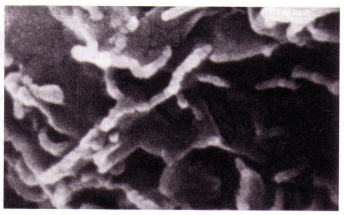


FIGURE 7.31 Top: Microscopic chains of magnetite crystals produced by bacteria on Earth. Bottom: Similar chains of magnetite crystals found in the carbonate globules of ALH84001. The similarity to the terrestrial chains has been cited as evidence of life on Mars.

Rod-shaped structure with segments were found in images of the rock

Look like ordinary Earth bacteria but 100 times smaller

Could be "nanobacteria" or "nanobes" as recently discovered on Earth (but these new "organisms" are not known to be living, though appear to contain DNA)



b This photo shows terrestrial "nanobacteria" in a sample of volcanic rock from Sicily. They are close in size to the structures seen in ALH84001. The scale bar at the bottom is 1 micrometer, or 1,000 nanometers.

Carbonate globules have alternating layers of magnesium, iron, and calcium-rich carbonates.

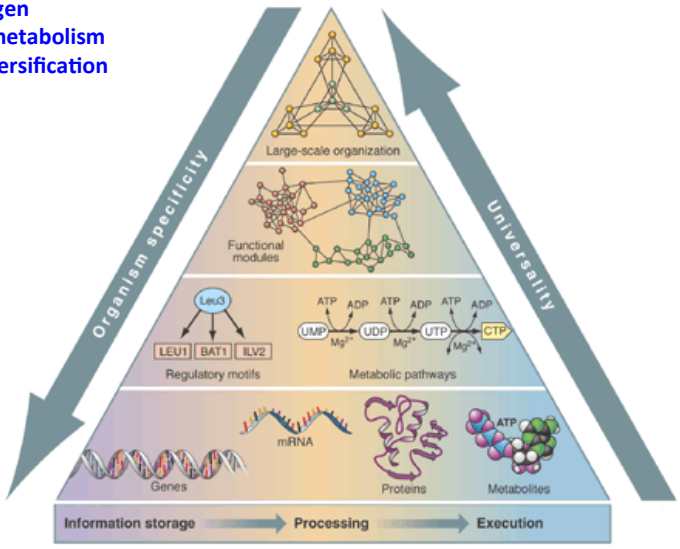
This is found on Earth due to biological activity

These contain polycyclic aromatic hydrocarbons – but can have biological and non-biological origins

a This photo shows rod-shaped structures found in the carbonate globules of ALH84001. They measure about 100 nanometers in length and are as small as 10–20 nanometers in width.

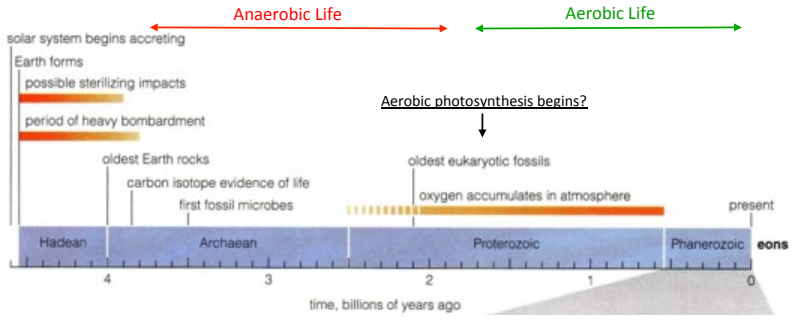
Steps to Complex Life on Earth?

- **Rise of oxygen**
- **Increased metabolism**
- **Genetic diversification**



Early Evolution and the Rise of an Oxygen Rich Atmosphere

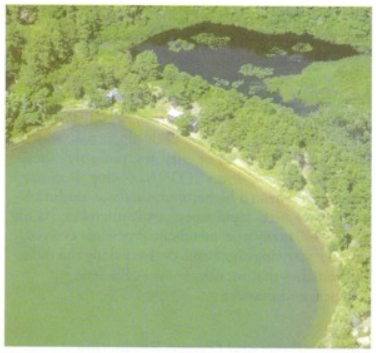
- First fossils of cells found 1-2 billion years after origin of life (about 2.2 Gya)
- Metabolism before this time must have been **anaerobic** (non molecular-oxygen based)
- It is believed that **aerobic photosynthesis** (oxygen based) in surface-water bacteria developed some 3.5 Gya from anaerobic bacteria (for example, even today, purple and green sulfur bacteria used H_2S rather than H_2O in photosynthesis)
- The rise of oxygen would be slow… without a constant source it would take only a few million years for all the oxygen to be react out of the atmosphere via **oxidation reactions** (i.e., fire, rust, fruit discoloration, etc.). Today, living organisms remove the most oxygen.



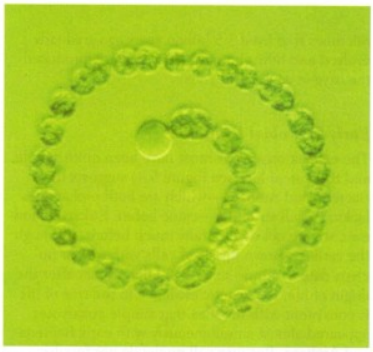
Early Evolution and the Rise of an Oxygen Rich Atmosphere

Cyanobacteria are a good candidate for the first aerobic photosynthesizers.

Earliest fossil cells resemble modern cyanobacteria. The release of oxygen as a by-product of their metabolism may be the primary source for creating our oxygen rich atmosphere.



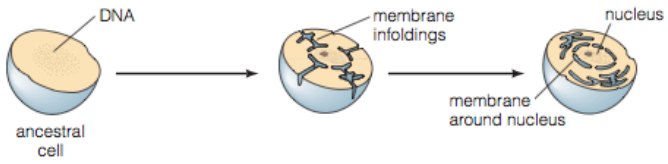
a The blue-green color of this lake (in Cape Cod, Massachusetts) is the result of a population explosion, or "bloom," of cyanobacteria.



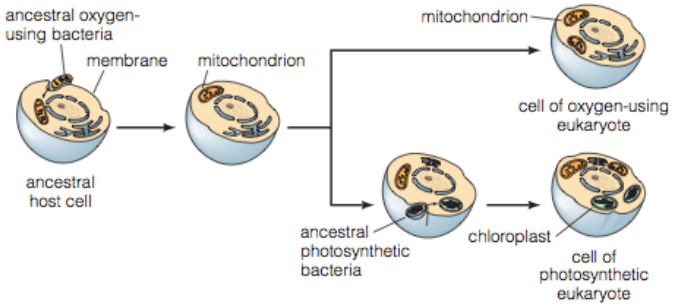
b This micrograph shows individual cyanobacteria from the lake.

FIGURE 5.10 A bloom of cyanobacteria. Cyanobacteria split water and release oxygen in photosynthesis and are thought to have been responsible for the rise of oxygen in the Earth's atmosphere.

Hypothesis for the Development of Eukaryotic Cells



a Early eukarya probably lacked a cell nucleus, but some large cells may have developed membrane infoldings that compartmentalized certain cell functions, ultimately leading to the creation of a cell nucleus.



b Mitochondria and chloroplasts may have evolved as small bacteria invaded a larger host cell, forming a symbiotic relationship.

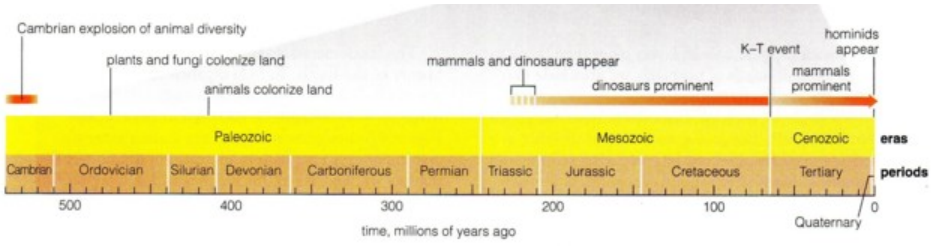
Cambrian Explosion of Diversity

Phyla – "body plans" (chordata, anthropoda, etc)

Modern animals appear to comprise ~30 different phyla (body plans)

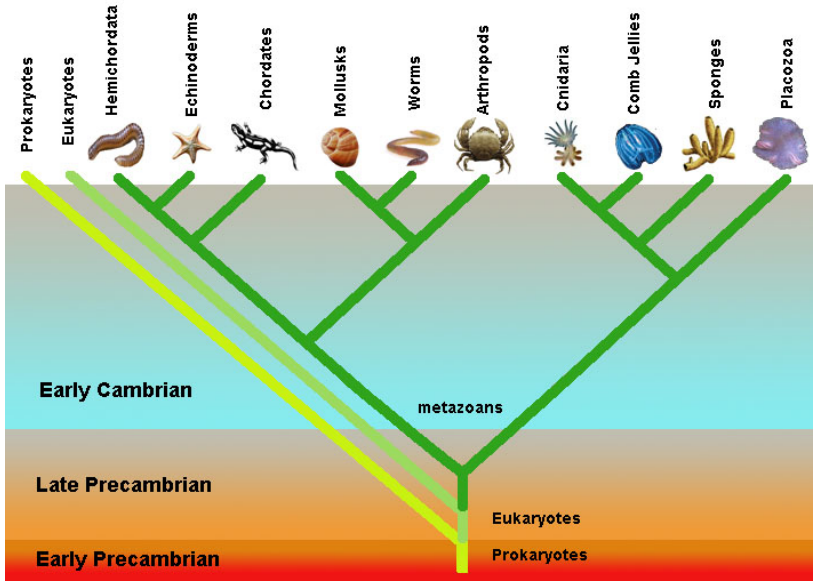
Nearly all the living and extinct phyla made their appearance at the Cambrian Era, this is called the **Cambrian Explosion** of diversity, which occurred a few eons after the rise of Eukaryotes. There has been no "second" explosion of diversity.

1. **Why did the Cambrian explosion occur so suddenly yet so long after the development of Eukaryote?**
2. **Why hasn't any similar large-scale diversification happened since?**



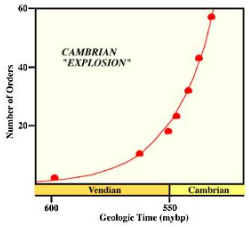
The "Cambrian Explosion"

Evidence in the fossil record shows that all major phylla were established in the transition from Late Precambrian to Early Cambrian time



Cambrian Explosion of Diversity

Why then, why once?

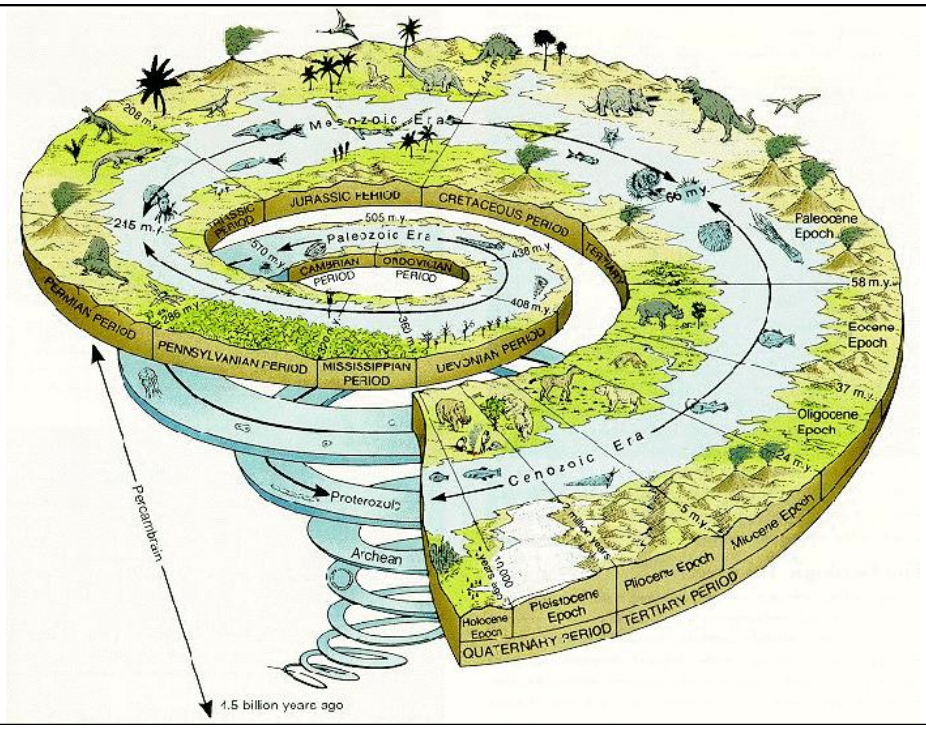


1. **Why then:** The ***oxygen level*** may have remained well below the present level until about the time of the Cambrian era. Oxygen may have been necessary for the development and survival of larger and more energy-intensive (aerobic) life forms.

2. **Why then:** Genetic complexity would be necessary for an explosion of diversity. It may have taken a couple billion years for eukaryotes to develop to the point of ***genetic complexity*** required for the Cambrian explosion. Some believe this it the most important factor regulating the occurrence of explosion.

3. **Why then:** Until ~550 Million years ago, the climate of the Earth varied greatly, including episodic Snow-ball Earths. The ***climate stabilized*** at the onset of the Cambrian era, providing a major shift in the pressures for survival on populations.

4. **Why only once:** (i) Ecological niches were wide open (unfilled). (ii) There was an absence of dominant predators in the niches. Thus, the Cambrian explosion may have been a singular ***window of opportunity*** for Nature to openly experiment with new phyla (body-types) and fill ecological niches.



Impacts and Extinctions

The boundary between the Cretaceous and the Tertiary Periods, ~**65 Mya**, marks a mass extinction. Dinosaur fossils exist below this boundary but not above it.

The KT Boundary

Somewhat uniformly distributed about the globe.

Rich in Iridium, which is rare on Earth, must have been introduced by extraterrestrial object

Probably a 10-15 km sized comet/asteroid.

K-T layer (black), also contains soot (from fires), spherical rock droplets and shocked quarts (commonly formed in impacts) and comprises high abundances of iridium, gold, osmium, and platinum (more common to meteorites than to Earth).

Meteor Crator: created 50,000 ya by 50 meter (~150 ft) asteroid
1 kilometer across (~0.62 mi) and 200 meters (~600 ft) deep.

The KT Impactor?
(Chicxulub Crater)

Discovered in 1991

Matches 65 million year age

Crater is 200 miles across

Off of Yucatan Peninsula

Impactor was 10 km across

Force of 100 million hydrogen bombs

The "smoke from the gun" that exterminated the dinosaurs?

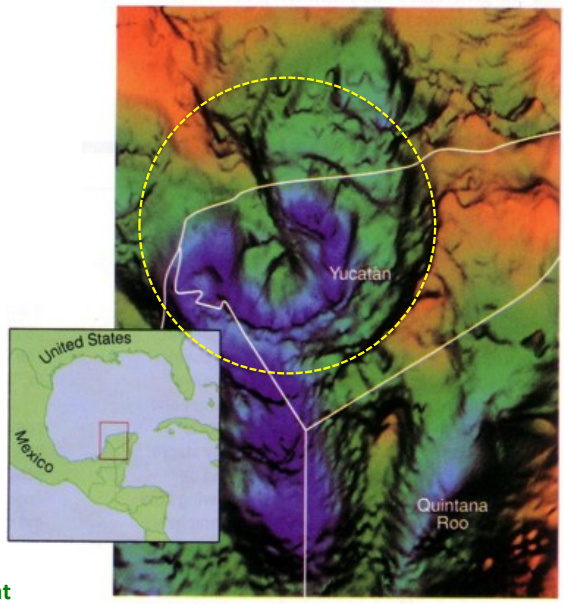
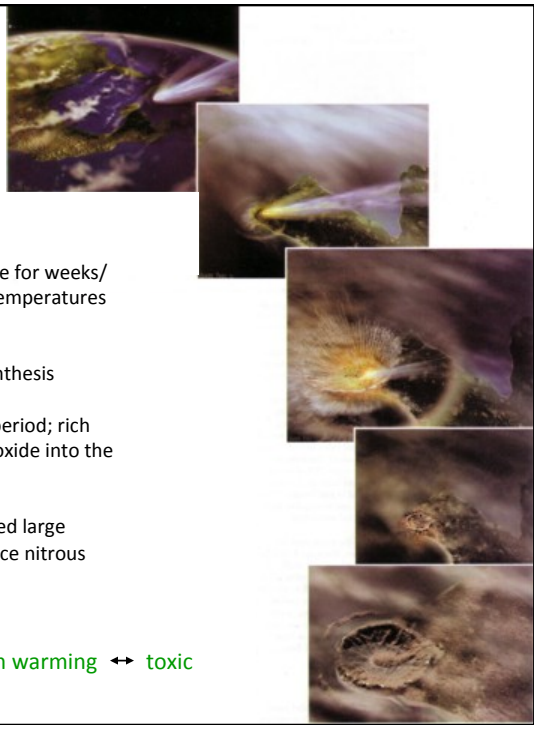


FIGURE 5.15 This false-color image, made with the aid of precision measurements of the local strength of gravity, shows an impact crater with its center near the northwest corner of the Yucatán. The white lines on the image correspond to the coastline and borders of Mexican states.

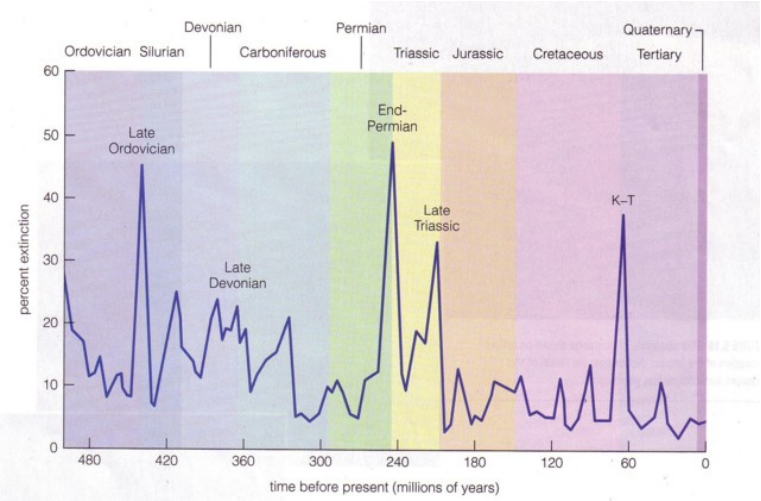
Artist's Conception of The K-T Impactor



- dust and smoke remained in atmosphere for weeks/ months, blocking sunlight and causing temperatures to fall
- reduced light would stop most photosynthesis
- cold period followed by unusual warm period; rich carbonate compound release carbon dioxide into the atmosphere (greenhouse gas)
- driven chemistry in atmosphere produced large quantities of toxic compound, for instance nitrous oxides

Immediate cooling ⟶ Long term warming ↔ toxic

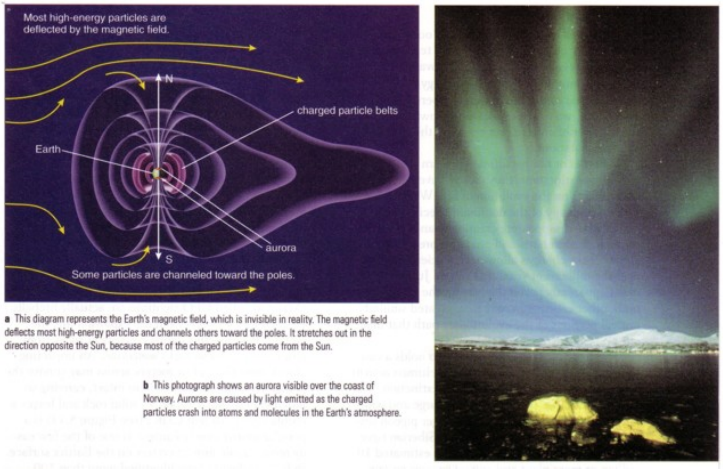
Percent Extinctions with time…



Mass Extinctions occurred at least three times. KT may have killed 99% of all living organisms, while causing extinction in up 75% of species and 40% of all genera.

Other Dangers: Magnetic Field Failure, Supernovae

Extinction can happen through rapid bad mutations (cancer), caused by radiation from the solar wind, or supernova explosions in our neighborhood of the galaxy. Alternatively, the ozone layer could have decreased dramatically at times, or the Earth's magnetic field could "switch off" at times…



a This diagram represents the Earth's magnetic field, which is invisible in reality. The magnetic field deflects most high-energy particles and channels others toward the poles. It stretches out in the direction opposite the Sun, because most of the charged particles come from the Sun.

b This photograph shows an aurora visible over the coast of Norway. Auroras are caused by light emitted as the charged particles crash into atoms and molecules in the Earth's atmosphere.

Other Dangers: Continuing Impact Threat

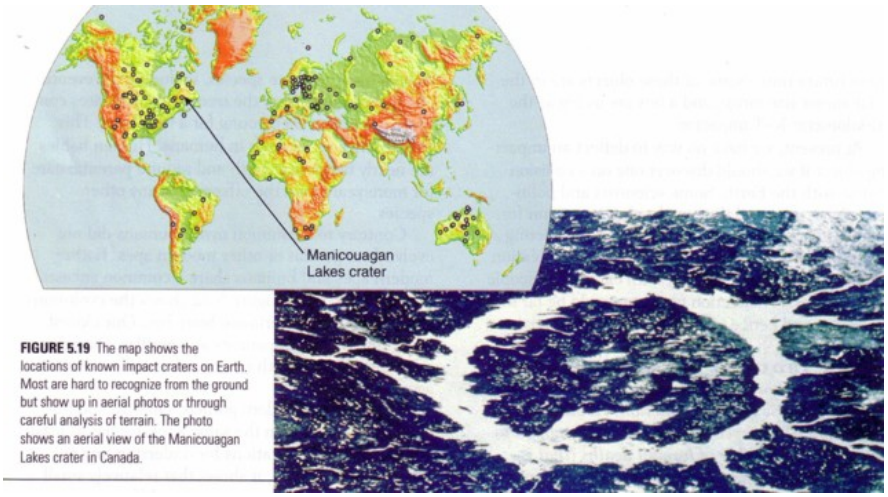


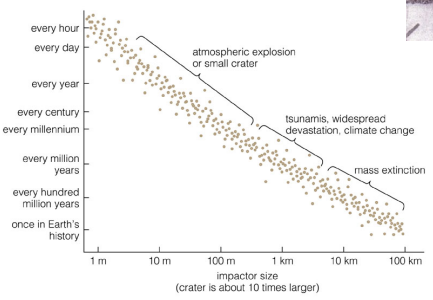
FIGURE 5.19 The map shows the locations of known impact craters on Earth. Most are hard to recognize from the ground but show up in aerial photos or through careful analysis of terrain. The photo shows an aerial view of the Manicouagan Lakes crater in Canada.

Other Dangers: Impacts

The 1908 Tunguska Event

Equivalent to several atomic bombs

Comet or asteroid 30 meters across (~100 ft).



No impact crater, exploded in air

Forests flattened and set on fire

Knocked over people and things 200 km away!

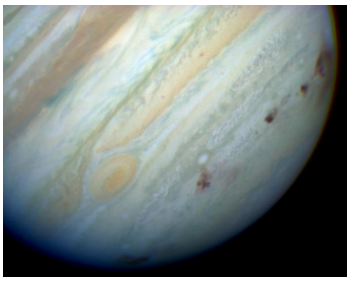
Future? Not if. When.

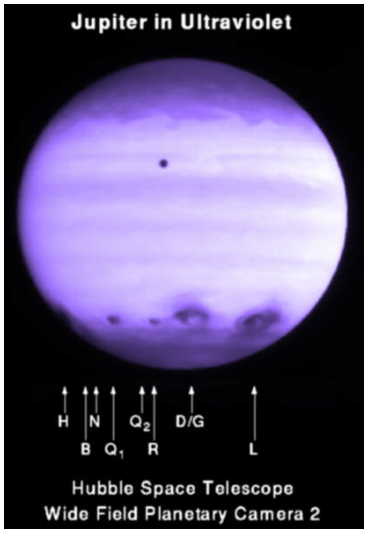
http://cosmiclog.nbcnews.com/_news/2013/02/15/16969092-nuclear-like-in-its-intensity-russian-meteor-blast-is-the-largest-since-1908
NBC Video of Russian Meteor Feb 14, 2013 2:51

Other Dangers: Impacts

Jupiter Shoemaker-Levy Impact

Over 6 days, 21 distinct impacts were observed, with the largest coming on July 18 at 07:33 UTC when fragment G struck Jupiter. This impact created a giant dark spot over 12,000 km across, and was estimated to have released an energy equivalent to 6,000,000 megatons of TNT (600 times the world's nuclear arsenal).

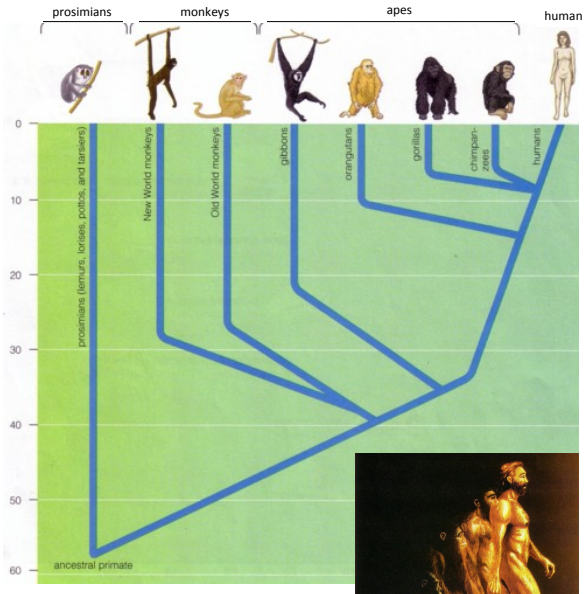




http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=11263 (Images/Movie) Jupiter Shoemaker-Levy Impacts 0:25

Human Evolution

- closest relatives are gorillas and chimpanzees
- we shared same ancestor about 6-7 mya
- 98% of our DNA sequences are identical (2% causes all of the difference!)

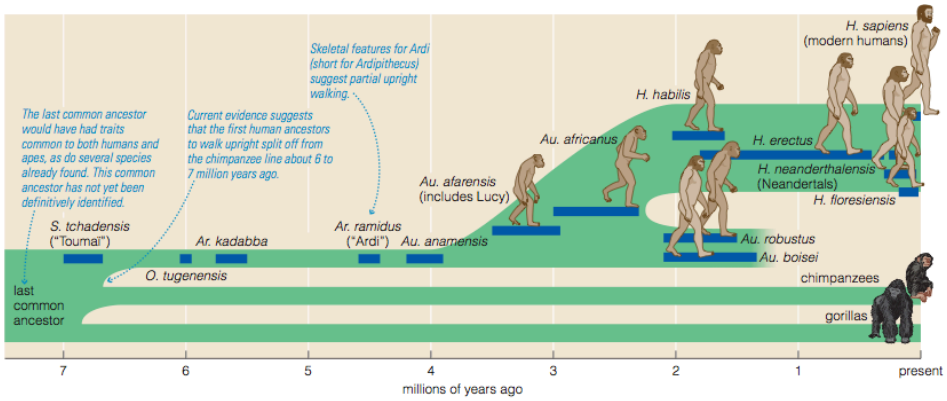


Major Misconception…

- Humans did not follow a direct path way from stooping apes to erect walkers (as shown in the artists concept- lower right)

(wrong)

Human Evolution



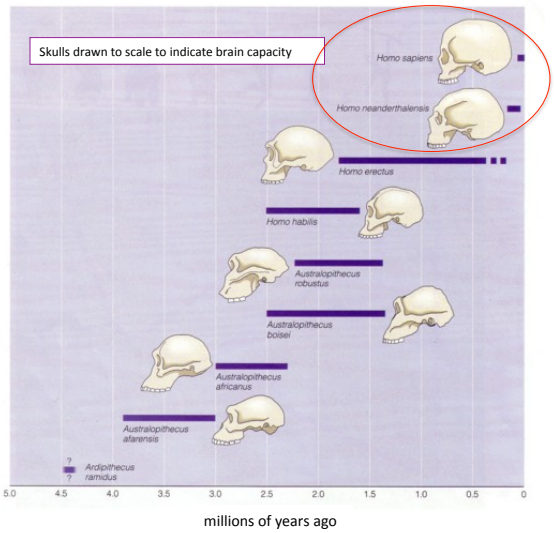
Only Homo Sapiens (us) have survived the split from the chimpazee line some 6-7 million years ago.

Why? Because we beat our contemporary competitors to death with clubs, though modern evidence suggests that 10-20% of our DNA is common to Neanderthals, indicating some interbreeding within the last 200 thousand years.

Human Evolution

Some inter breeding- though Neanderthals are now extinct

Note that sometimes two or more hominid species co-existed on the Earth several times!



Other Misconceptions…

- there is no longer a "missing link"; fossil record and genome comparison suggest a path back to earliest microbes!
- all humans are the same species; genetic differences between races are smaller than genetic variations between individuals in a given race.

Beyond Darwin: Advanced Civilization Evolution

There are now three types of evolution occurring that are unique to humans on Earth:

1. cultural evolution

   Transmission of knowledge accumulated over generations. Requires language, speaking and writing. It accelerates with time as knowledge accumulates (biological Darwinian evolution is on natural and random time scales)

2. technological evolution

   Increased computer power helps us understand science and technology faster, and this in turn helps us build more powerful computers… feedback loop. Again, tt accelerates with time as knowledge accumulates.

3. genetic engineering (evolution!?)

   We already sustain life that would otherwise die via medical knowledge. That blows out the Darwinian curve already…. But genetic engineering constitutes a new level of manipulating organisms within environments… it is outside Darwinian evolution altogether.

Good or bad… advanced civilizations can alter the course of evolution through their choosing, rather than remain subject to random process of natural selection.