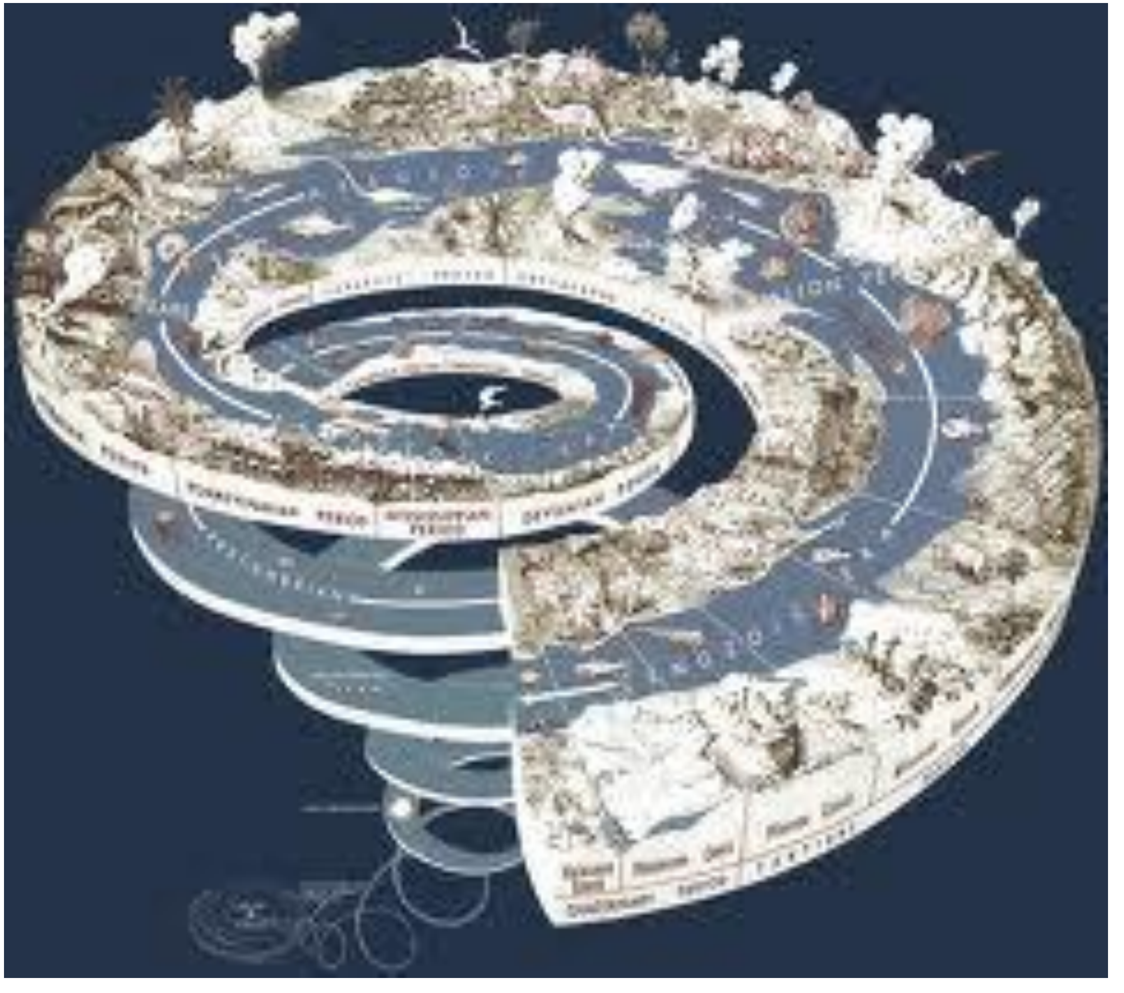
Biogeochemical cycles – Geological, Chemical and Biological Evolution on Earth

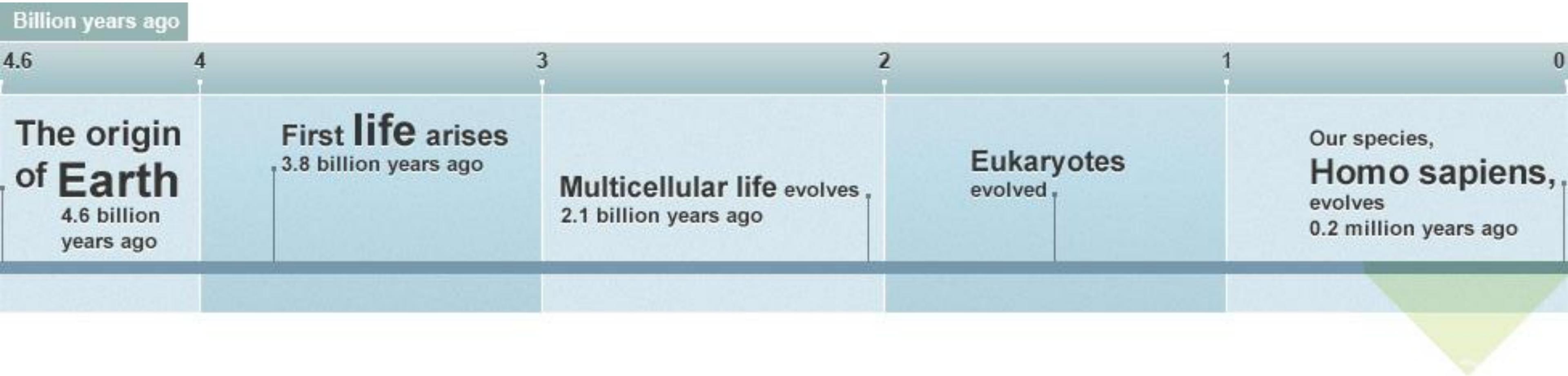


Earth Timeline

The Earth "solidified" about 4.6 billion years ago with the first life probably emerging about 3.8 billion years ago.

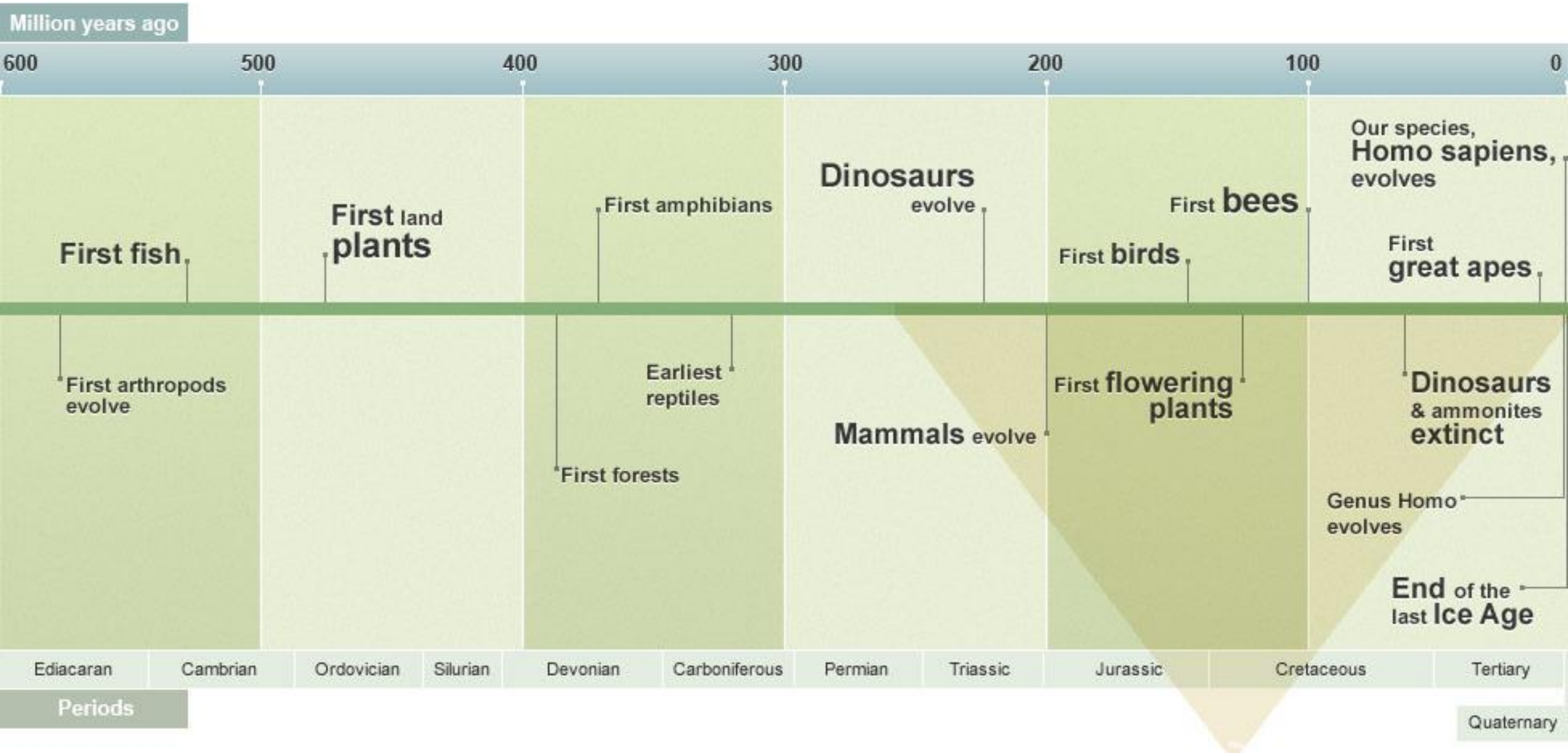
About 1.7 billion years later the first multicellular life forms emerged – after Photosynthesis became a dominant feature on the planet.

Only very recently did the creatures we consider as "part of the fossil record" - i.e. remains to be found in rocks within our geological classification - appear.



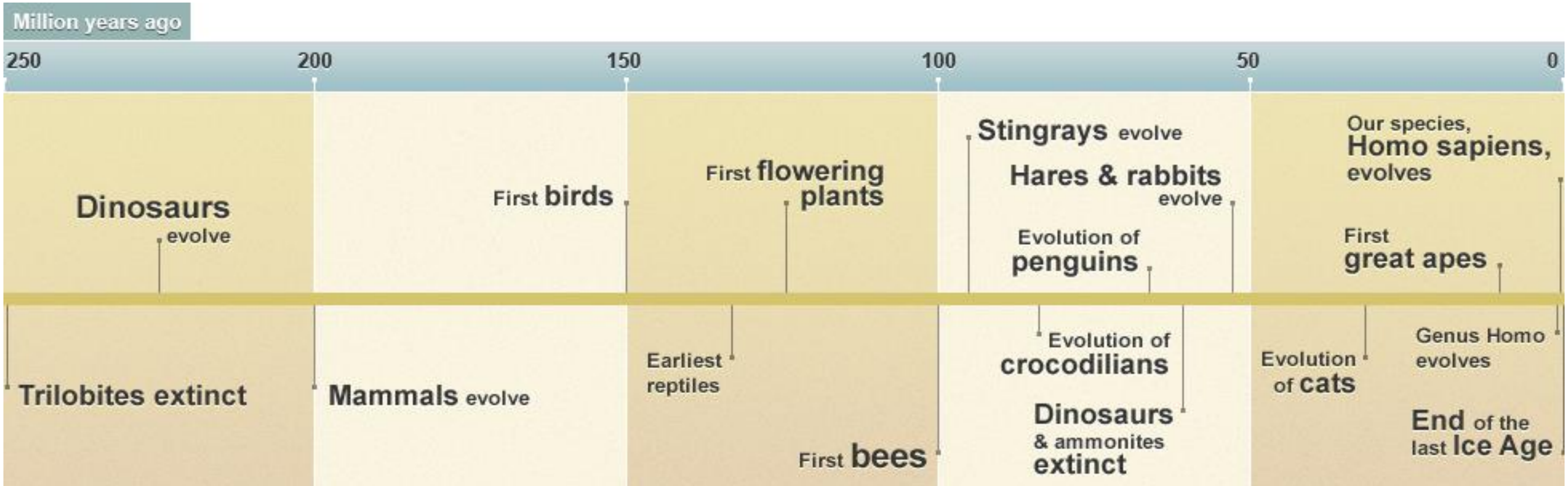
Enlarge this to show Biological Timeline of the fossil record

Timeline of biology in geological context



Enlarge this section to show recent biological timeline

Recent biological timeline



Note that although Homo Sapiens is a very recent addition to the picture, this species has managed to create a very large footprint on the planet.

In the past mass extinctions were caused by naturally occurring catastrophes such as rapid heating (desert Earth) or cooling (snowball Earth) or asteroid hits.

There is a real possibility that Humans will distinguish themselves as the first species to instigate mass extinctions of other species on the planet.

And all the time, this will be monitored, measured and evaluated!

Section though Earth showing the Tectonic Plates floating on the Mantle

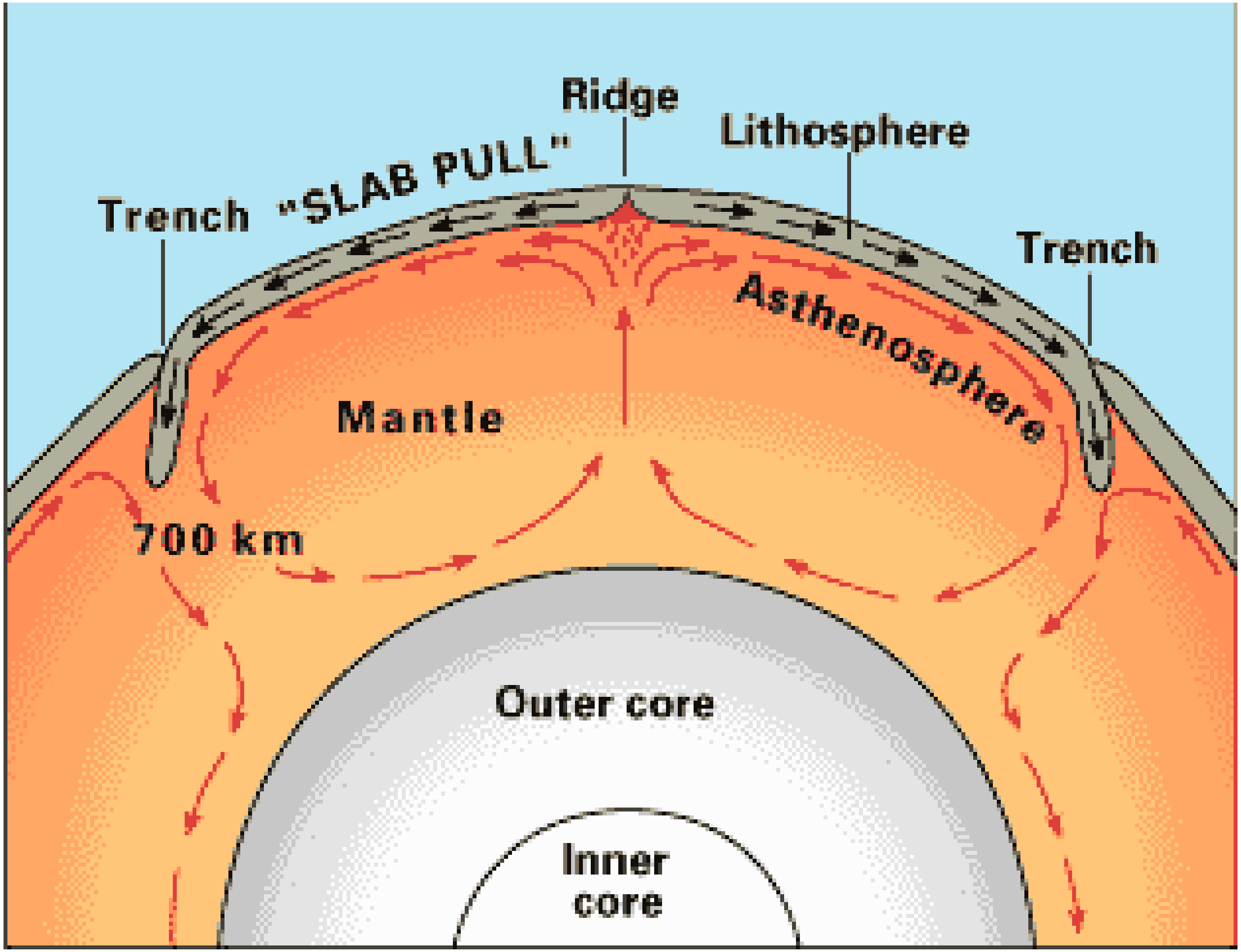
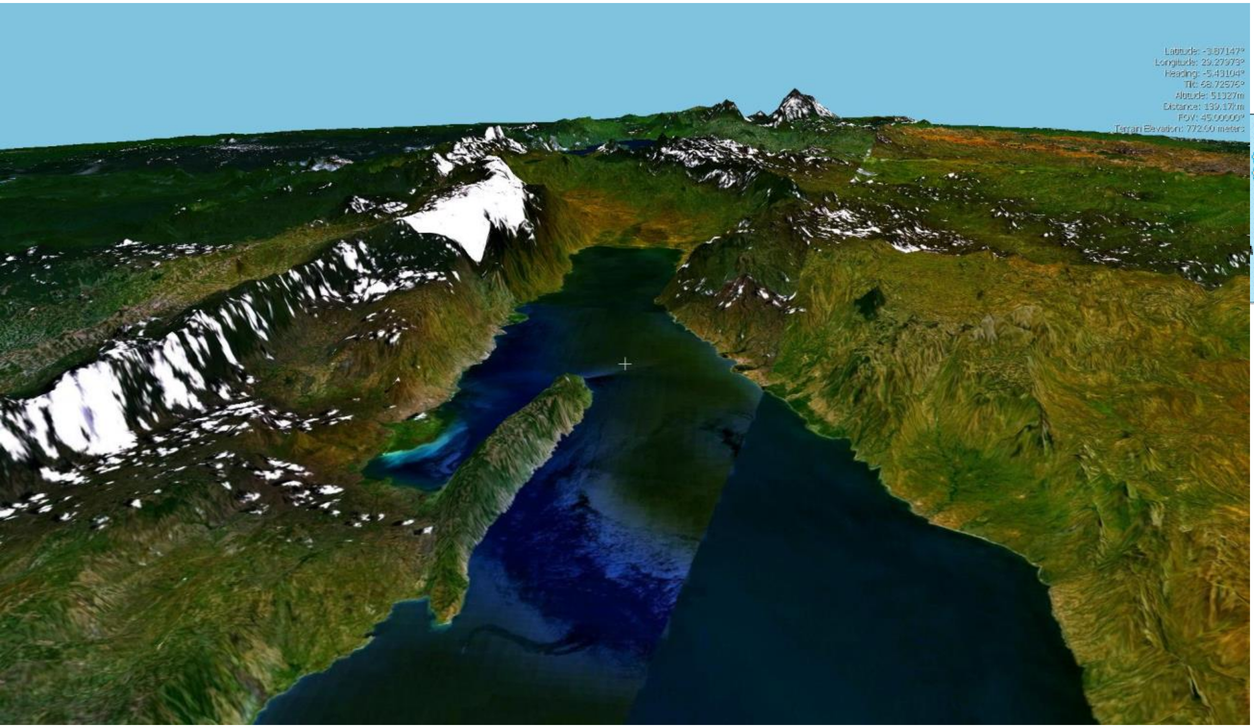


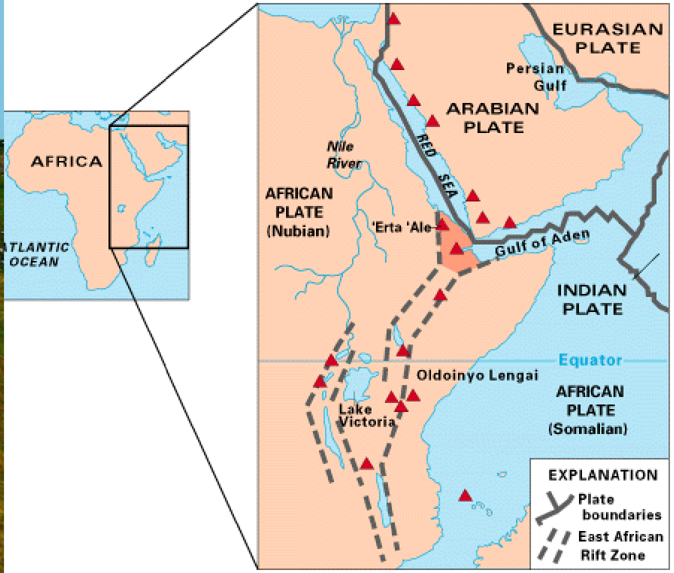
Plate tectonics

- The outermost shell of the Earth - the lithosphere - is tessellated with about twenty giant slabs of rock known as “Tectonic Plates” since they produce the structure on the surface (Greek: *tektonikos* belonging to carpentry, from *tektōn* a builder).
- These plates can move relative to each other at speeds of centimetres per year - approximately the rate at which human fingernails grow.
- The plates slide about on the layer of hotter, softer mantle.
- The mantle is like a supercooled liquid – i.e. a glass.
- Where plates encounter each other, stresses and strains build up manifested in extreme cases by violent earth movements – earthquakes.
- The boundaries of the plates are marked by geological faults although these can occur at some distance from the actual edges just like having a ruck in a carpet which becomes worn.
- Near plate boundaries, molten magma can rise to the surface and erupt to form volcanoes .
- Two types of boundary exist between plates: divergent and convergent.

Divergent boundaries

- The process of adjacent plates moving away from each other is best seen at the oceanic spreading ridges.
- New crust spews out from extensive oceanic ridge systems, like the one seen in the middle of the Atlantic Ocean.
- Smaller scale systems can be seen in rift valleys, such as the African Great Rift Valley (below), Rhine Rift Valley and Scottish Rift Valley.





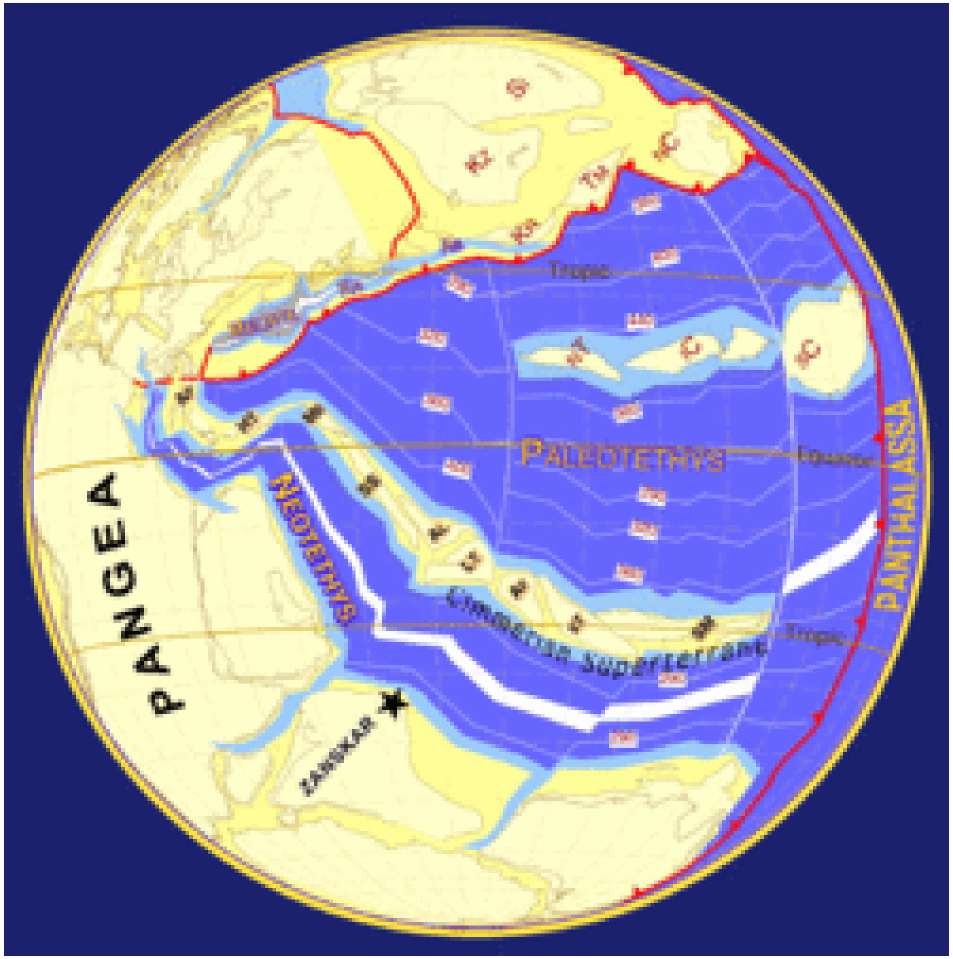
Convergent boundaries

- When two plates meet, a convergent plate boundary forms.
- Usually one plate will slide underneath the other - this will cause some mountain building and lots of volcanic activity - The Andes mountains in Chile are a classic example of this.
- Sometimes plates will collide and one does not flow smoothly under the other giving rise to extensive and rapid mountain building. The Himalayans are an example of this.

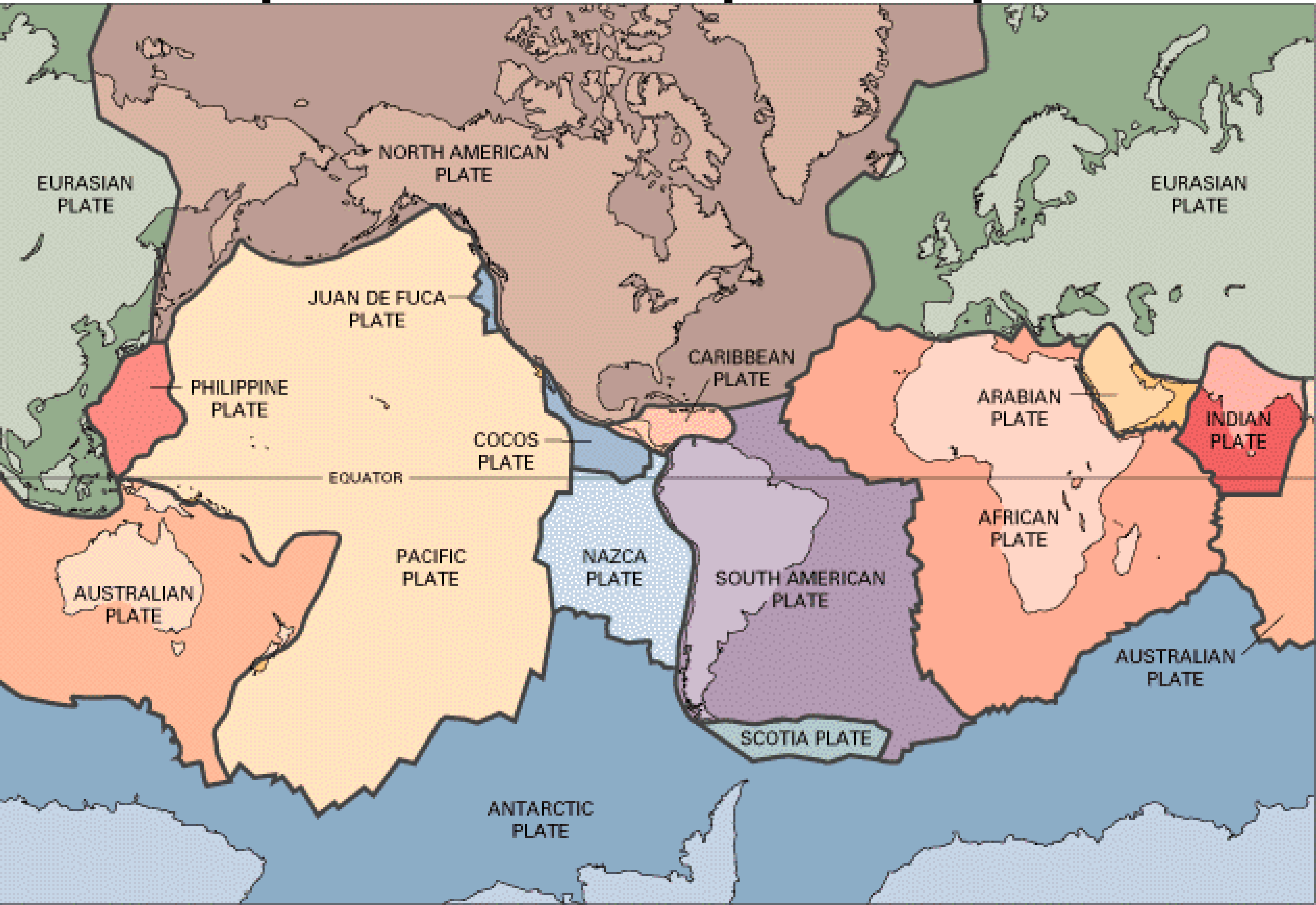
Mount Pinatubo in the Andes showing volcanic activity

The Himalayas

Older mountain building periods and rift valley formation (e.g. Scotland and the Rhine Valley) were in progress when the continental plates started their more recent moves



A map of the tectonic plates at present



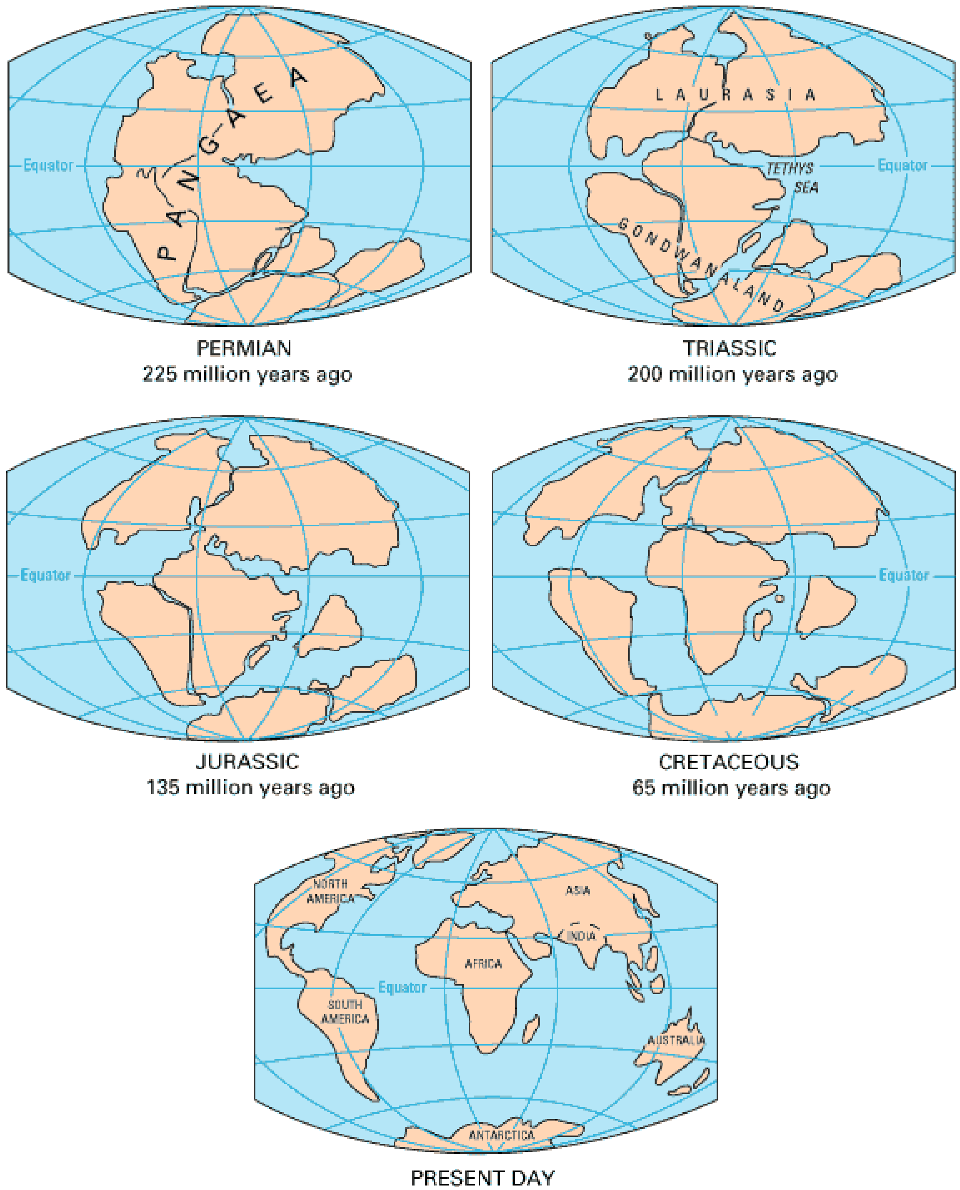
Tectonic plates influence environmental factors

- The plates which form the terrestrial land masses have drifted together and apart many times in the history of life on earth.
- Climate is tied to the position of the plates.
- Plate location determines:
  - ocean currents
  - heat flow
  - salinity
  - oxygen levels
  - glaciation
- Migration is possible if the plates are close together – as for Europe when there was a land-bridge between the British Isles and the European Continent allowing plants, animals and insects to move freely between the two.
- Isolation is possible if the plates are far apart – this is seen in the case of New Zealand which has a unique native Flora and Fauna.

Position of Plates in Recent History

The top four views cover the period when dinosaurs were present – they died out during the Cretaceous period.

It is not known where the plate were before the supercontinent Pangaea existed.



Notice that there is a greater density of plates in the Northern Hemisphere. Recent work predicts that the position of the poles of the Earth's magnetic field might be indicated by plate movement.

Origin of the atmosphere and hydrosphere

- The formation of an atmosphere on a planet is important for the subsequent evolution of chemistry and thus potentially biology.
- Volatile gases were either associated with the Earth during its formation or they arrived through meteorite collisions.
- The volatiles were released during the many incidences of heating and melting of the crust. This process is know as outgassing; most outgassing occurred within the first 1 billion years of the Earth's history, although it still takes place through seismic and volcanic activity.
- The primitive atmosphere was probably rich in CO_2, N_2, with lesser amounts of CO, H_2, HCl and traces of NH_3 and CH_4.
- There was probably no O_2 present in the early atmosphere.
- Any O_2 outgassed would have reacted with the metals of the crust to give stable oxides.
- This lack of O_2 is probably the reason why it was easy to form organic molecules without complicated synthetic procedures we often use today.

The signature of Life

- **What is life?** Difficult to define, but some characteristics are:
- **Order** Living organisms partition resources and nutrients within their systems. This is an energy-requiring process which must be maintained for life to continue.
- **Reproduction** Organisms reproduce their own kind. Life only comes from life.
- **Growth and Development** Heritable characteristics direct the pattern of growth and development producing an organism that clearly belongs to its species.
- **Energy Utilization** Organisms take in energy and transform it to do work. Almost all of life's functions require energy.
- **Homeostasis** Regulatory mechanisms maintain an organism's internal environment within tolerable limits, even though the external environment may fluctuate. This process is known as homeostasis.
- **Evolutionary Adaptation** Life evolves as a result of the interaction between organisms and their environment. As the environment is rarely stable, life must adapt to survive in these new living conditions.

How did life on Earth evolve?

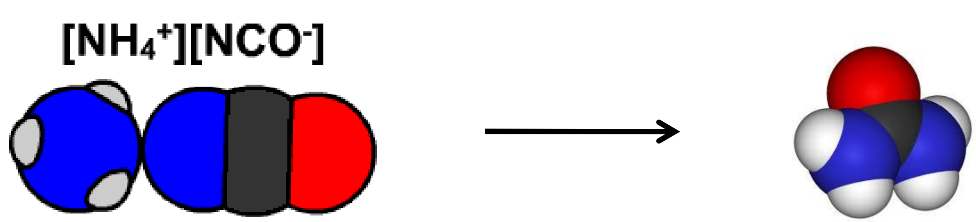
- The big question is how life actually got going on Earth?
- So far, we don’t really know, but chemical experiments show that it is possible to produce the “building blocks for life” (organic molecules).
- Biology takes these building blocks and polymerises them into amazingly complex and precise structures.
- Once a few of these macromolecular scaffolds exist, the Biology can run itself – so the initial formation of the building blocks is like the “firelighter” for any fire – once the fire is going it can be virtually impossible to put out.
- This latter point has been proved over time by the way life still persists in spite of mass extinctions.

Chemical origins of life on Earth

- Experiments concerning the origin of life should take a few important points into consideration.
- How were small organic molecules (amino acids, nucleic acids, lipids) formed in the primitive earth environment?
- How were these small organic molecules joined together to form polymers (long chains of organic molecules)?
- How were abiotically produced molecules segregated to give droplets (protobionts) with chemical compositions different from their surroundings?
- What was the origin of heredity?
    - We will not attempt to answer all of these questions!

History of organic synthesis from inorganic compounds

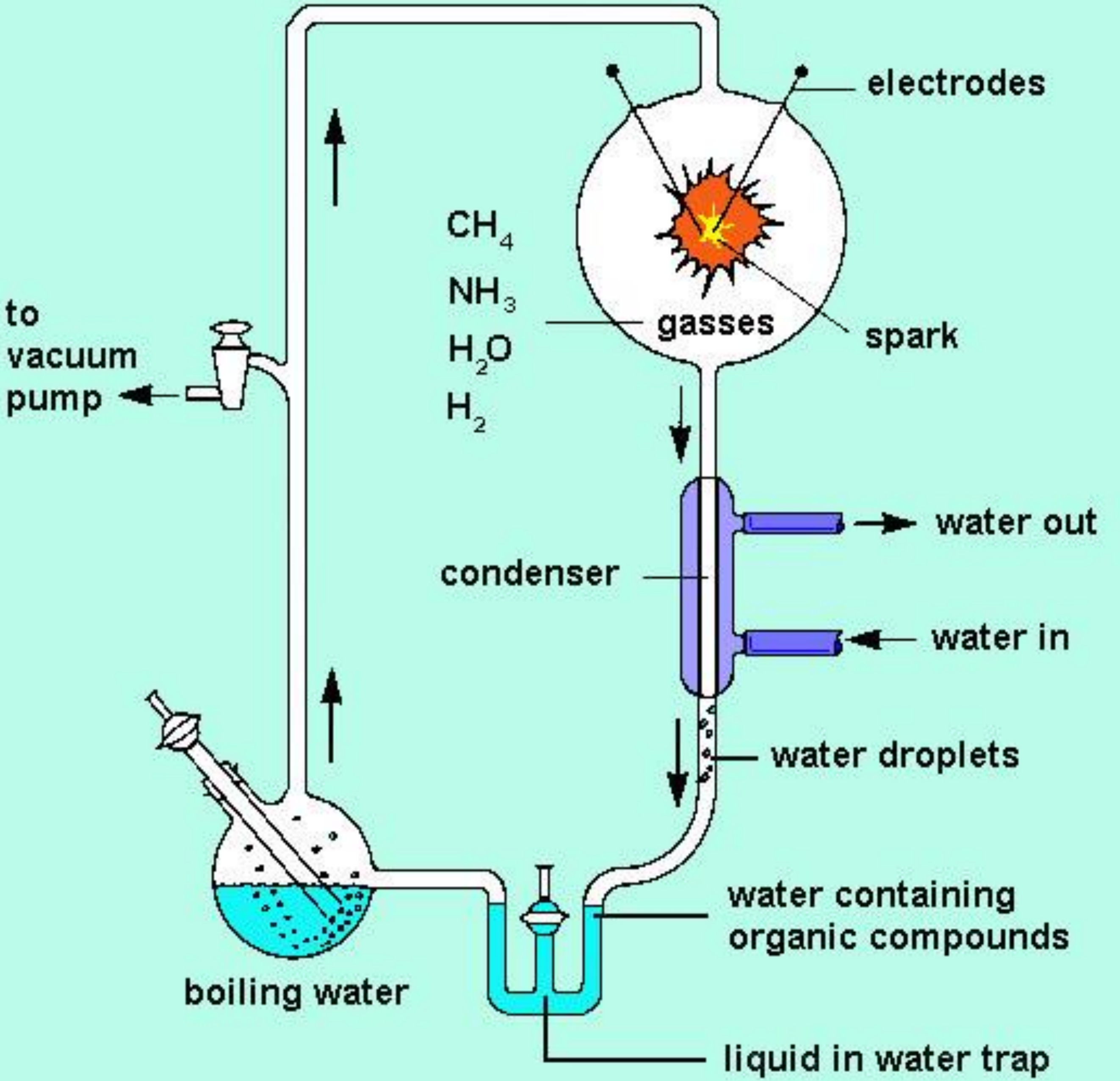
- Famously, in 1828, Fritz Wöhler reported the synthesis of the organic molecule urea starting from a purely inorganic compound.
- The **Wöhler synthesis** is the conversion of ammonuim cyanate into urea.
- This is considered as the starting point of modern organic chemistry, since previously it was believed that organic compounds could only be obtained from living (or ex-living) systems. This view was known as “Vitalism”.
- Urea was discovered in 1799 and previously could only be obtained from biological sources such as urine.
- In the reaction ammonium cyanate first decomposes to ammonia and cyanic acid and these then produce urea via a nucleophilic addition with subsequent tautomerisation.
- Overall reaction is: $NH_4(NCO) \longrightarrow NH_3 + HNCO \longrightarrow (NH_2)_2CO$



A famous experiment with the primordial soup

- In 1953, Stanley Miller and Harold Urey used an apparatus (basically a still) to recreate what is proposed to be the primitive environment of the earth.
- A warmed flask of water simulated the primitive oceans.
- The atmosphere in the Miller-Urey model was composed of H_2O, H_2, CH_4 and NH_3.
- Sparks simulating lightning were discharged into this synthetic atmosphere to mimic lightning.
- A condenser cooled the atmosphere, raining water and any dissolved compounds back into the miniature sea.

The Miller-Urey Experimental Set-Up



Results of Miller-Urey Experiments

- As materials circulated through the apparatus, the solution in the flask changed from clear to murky brown.
- After one week the analysis of the contents of the flask revealed a variety of organic compounds, including amino and nucleic acids thus providing one scenario for the production of organic molecules form simple inorganic precursors.
- The fact that the primitive atmosphere was reducing aided in preventing oxidation of the precursors.
- A reducing environment may also help in the formation of polymeric species.
- The addition of clays into apparatus similar to that used by Miller andUrey can generate polymers.
- The metal ions on the clays probably act as catalysts or templates for the formation of polymers.

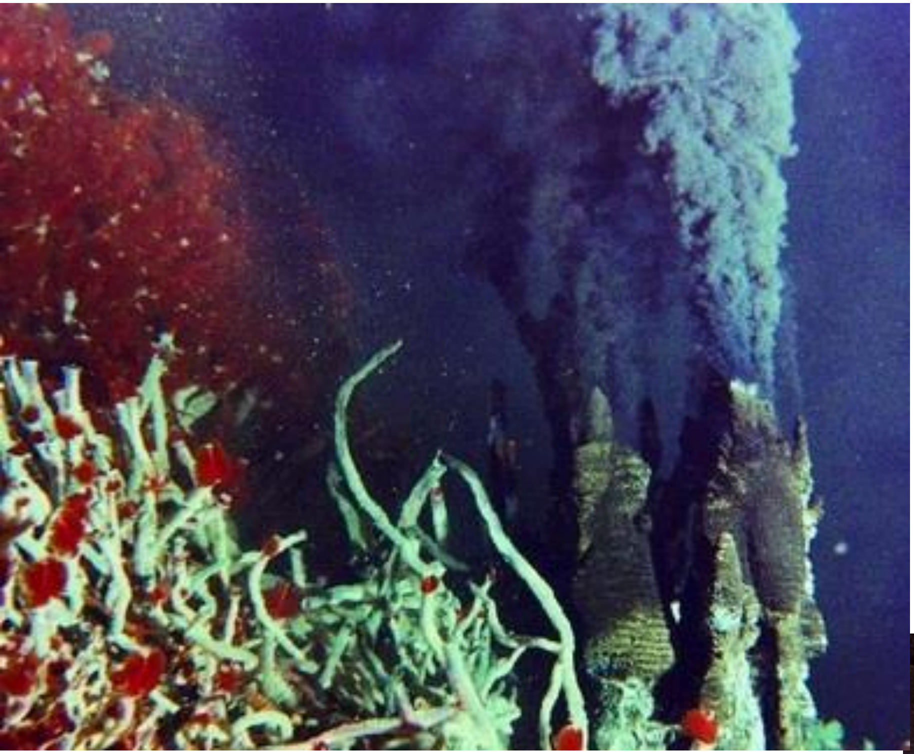
RNA world

- The **RNA world hypothesis** proposes that self-replicating ribonucleic acid (RNA) molecules were precursors to current life which uses deoxyribonulceic acid to replicate proteins and RNA as a messenger.
- RNA is able both to store genetic information, like DNA, and to catalyse chemical reactions as an enzyme (protein) can.
- The suggestion is that it may have played a major step in the evolution of life.
- RNA can be produced in “primordial soup” experiments similar to those of Miller and Urey.

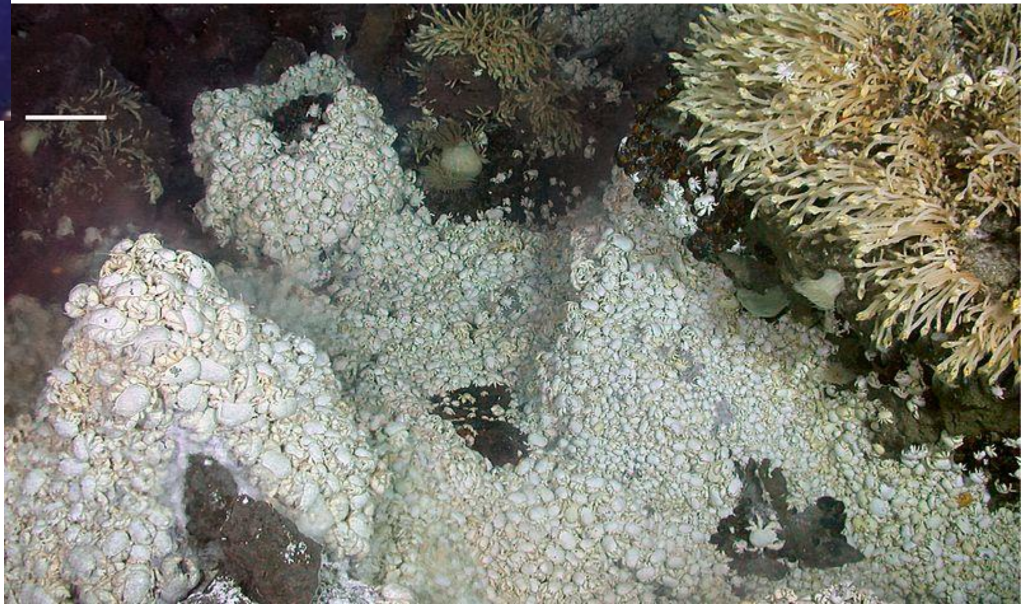
Wächtershauser's theory about the black and white smokers

- This idea links to the suggestion that hydrothermal vents provide a 'reactor' for RNA as explained in the RNA World hypothesis.
- Hydrothermal vents, the black and white smokers, rely on chemical energy from geothermal vents to sustain a complex range of organisms.
- Swarms of bacteria thrive in this environment which acts as an interface between the high temperature vents and cold oxygenated sea water. The bacteria thrive on gases produced by the vents such as methane and use these chemicals to produce simple organic molecules to support the local ecosystem in a similar way to plants using photosynthesis.
- Wächtershauser has proposed that a biochemical cycle grew and assembled the first living cell.
- In this scenario, the chemical coupling of an iron salt and hydrogen sulfide from the hydrothermal vents produced pyrite (FeS_2).
- Simple molecules, such as CO, organic acids and sugars, gather on the surface of the pyrite and are catalysed or templated to produce new molecules. In this way, the system does not use any cellular components and starts from a compound - pyrite - which was abundant in early Earth's oceans.

Black and white smokers as hotbeds for life?



Located 3 kilometers underneath the surface of the Atlantic Ocean, the hottest water ever found on Earth has been found emanating from two black smokers called Two Boats and Sisters Peak. So hot, in fact peaking at temperatures around 450 ^{o}C, that the fluid has moved from being a fluid to being a supercritical fluid

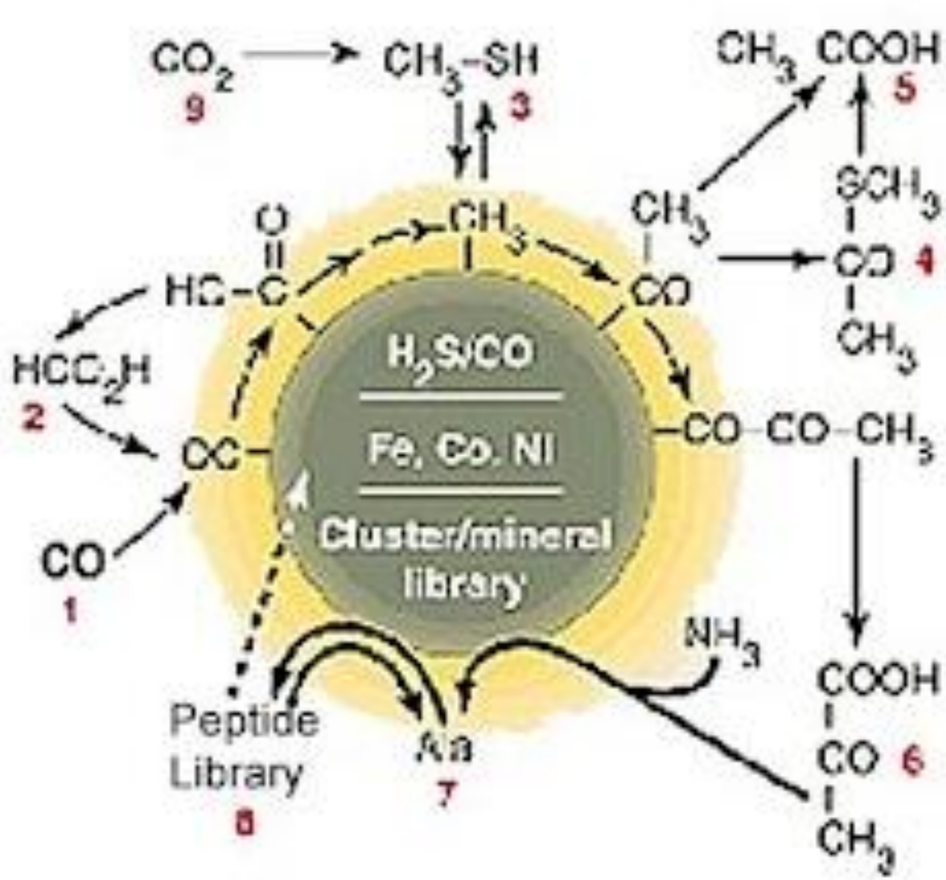


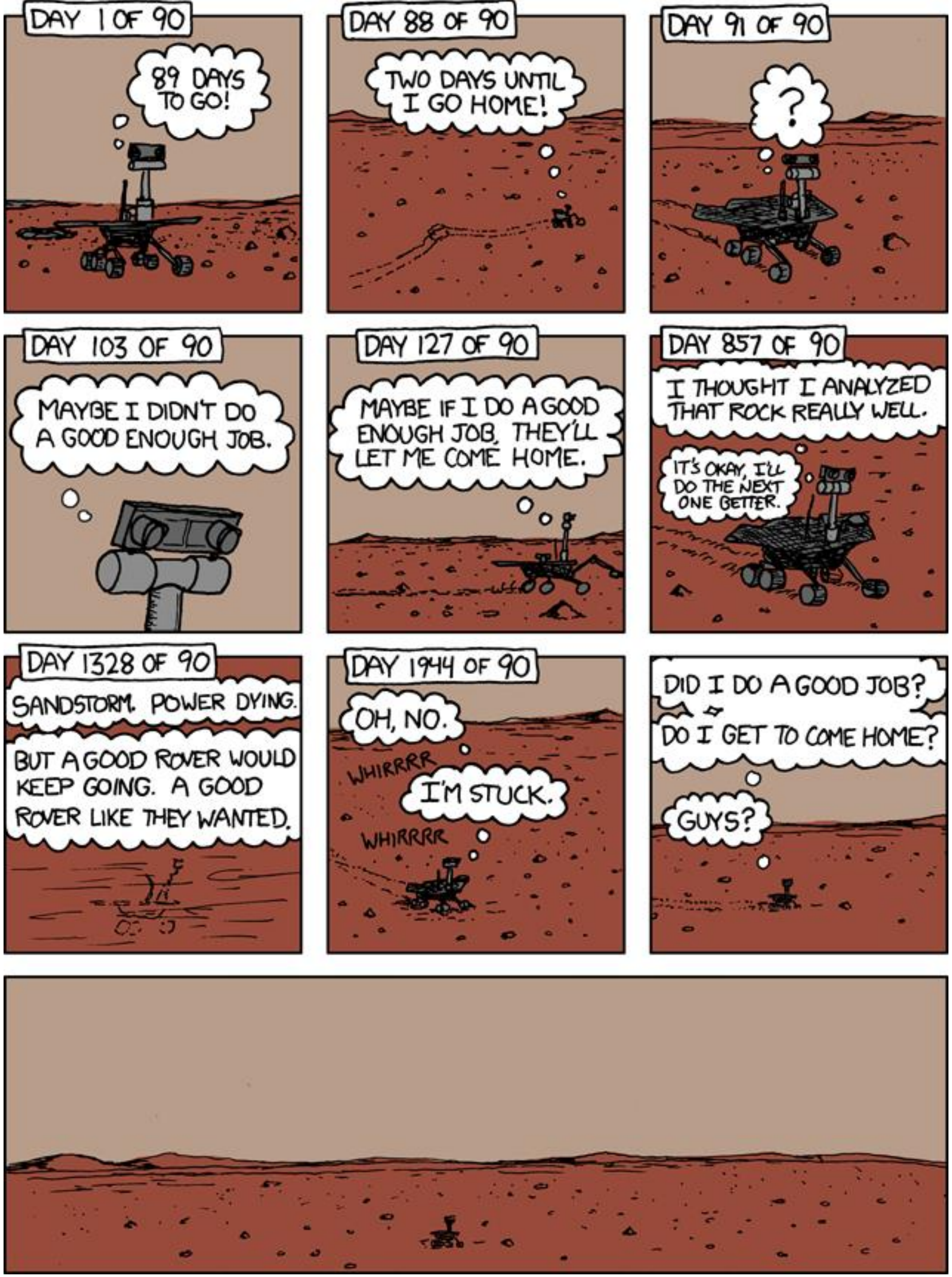
The environment becomes rich in nutrients for other creatures to enjoy a feast (crabs in right picture)

Plus points

- This system could evolve by producing self catalyzing cycles with increasing efficiency which would lead to competing systems.
- Accumulation of lipids on the pyrite could lead to formation of an enclosed membrane leading to the first primitive cell.
- Other experiments have provided evidence, such as the accumulation of amino acids on a pyrite surface, supporting the iron/sulfur world theory.
- Further evidence in support of the theory is the fact that molecular studies of a species' ancestry based on RNA has shown that most ancient organisms were thermophilic and hyperthermophilic (able to survive extreme temperatures) bacteria as well as able to survive on sulphur and methane, the conditions found at hydrothermal vents.
- Such evidence goes against the primordial soup theory of spontaneous generation and RNA world theories.
- In addition, the main metabolic pathway suggested by Wächtershauser in his theory is the reductive citric acid cycle, which has the advantage that it can form new carbon compounds for use in other metabolic pathways enabling the production of most organic molecules important to life.

An iron pyrite particle as a template or catalytic surface for the formation of biologically relevant organic molecules





The fate of the first and very faithful Mars Rover…