Lecture notes 14: The formation of the Earth and the genesis of life

The Earth accreted in some manner out of the protoplanetary disk growing in stages via grains, rocks, planetisimals (size $\approx$ 1 km), and protoplanets (size $\approx$ 100 km) over a period estimated at some 10^8 yr.

Melting of the solid Earth

At some point late in the accretion process we may begin to speak about the planet Earth, though the accretion process continues for several gigayears and the Hadean Earth is continually bombarded by large asteroids. Calculations show that the heat arising from this infall will not raise the temperature to higher than 1500 K, and that only in the upper planetary layers, and that is not enough to melt the Earth. (The Earth has a large moon which presumably was formed by the giant impact of a Mars-sized body with the Earth. Luna?s composition resembles that of the Earth?s mantle, and varoius lines of evidence give and age to the Moon of roughly 4.4 Gyr.)

On the other hand the radioactivity bound up in uranium, potassioum and thorium will heat the terran rocks and this heat has continually greater difficulty escaping as the Earth grows. Radioactivity can raise the temperature to some 2000 ? 2500 K which *is* hot enough to melt iron. The melted iron has a great density and falls toward the center of the Earth releasing great amounts of potential gravitational energy in the process. This heating mechanism is high enough to raise the temperature to some 4500 K and thus to melt the Earth entirely.

The Earth differentiates with high density material collecting in the core and lighter elements towards the surface. In this manner the structure of the Earth is a Fe, Ni **core**, an inner solid core extending some 1200 km, an outer liquid core extending out to 3400 km, a Si, O **mantle** which continues up to the **crust** on which we reside. The mantle is semi-fluid but the outer 100 km is hard and is called the **lithosphere**.

The oldest meteorites have ages on the order 4.55 Gyr, which is presuably the age of the Solar System. Comparisons of the relative abundance of various lead istopes in these meteorites and on the Earth leads towards the conclusion that differentiation took place some 100 Myr after the meteroites were formed.

The rocks we find in the Earth?s crust may be sorted into three types

? Igneous ? molten rock that cools and solidifies. Dense basalt, and the less dense granite are examples. Others include andesite and rhyolite. In general basalts form the ocean floors, granites the continental crust.

? Sedimentary ? formed by the gradual compression of sediments, such as sand and silt at the bottom of oceans and swamps.

? Metamorphic ? is rock that has been structurally transformed by high pressure or high temperatures but not high enough to melt the rock.

These rocks can consist of several different types of crystals or minerals, independent of how it was formed. Fossils can be formed in sedimentary rock and the different strata that are built up can then be classified by the type of fossils they contain, allowing the relative aging of layers.

The oldest rocks one finds on the Earth are 3.8 Gyr old while indivdual grains of zirconium silicate (so called zircons) have been radioactivelly dated to 4.3 ? 4.4 Gyr. Fossil life may be as old as 3.5 Gyr, though some claim to have found evidence for life that is even older.

Outgassing and the Hadean Earth

The protoplanetary disk in the vicinity of the Earth was too hot to allow for the condensation of ices of water, CO_2, and methane. But planetismals from further out in the solar system presumably collided with the proto-Earth and these ices became locked up in the interior of the forming planet. When differentiation occured these materials also melted and percolated to the surface. Volcanic activity (and still is) an important source of volatile elements. Atmospheric gas was therefore released early and it is thought that the oceans were already present already some 200 Myr after the Earths formation. The early atmosphere then consisted of much the same volatile elements we find ejected in todays volcanoes: H_2O, $C0_2$, N_2, H_2S, SO_2. The ejected water condensed and fell in massive rains to form the oceans. There was almost no O_2 in the early atmosphere, rather it was mainly $C0_2$ as compared to todays 78% N_2 and 21% O_2.

From studies of cratering rates on the moon it is clear that the impact rate of asteroids was quite high for the first several 100 Myr of solar system history. The rate first falls off around 3.8 Gyr ago as is evidenced by the relatively ?crater clean? Lunar maria.

Before this time life may have arisen many times in the early oceans. However the many collisions with asteroids with diameters on the order of 350 ? 400 km would ensure that the surface semi-regularly was heated to temperatures on the order of 2000 K, hot enough to cause multiple impact sterilzations. The last of these complete impacts was on the order of 3.9 ? 4.2 Gyr ago.

Origin of the continents and Earth?s ongoing geology

The seafloor crust is a 5 ? 10 km thick basalt layer that is 200 Myr old. This layer is being continually replenished and destroyed by tectonic processes. The continental crust is thicker and is composed of a lower density granite, an older rock that is 20 ? 70 km thick. Continental crust is the result of continually recycled crust which has undergone differentiation as it is re-melted and expelled through volcano action.

Convection transports heat from the Earth?s interior towards its surface through a number of convective cells in the Earth?s mantle. The time scale of this convection is roughly 100 Gyr which corresponds nicely with the timescale of seafloor renewal. The lithosphere (and the crustal rocks it supports) is rigid

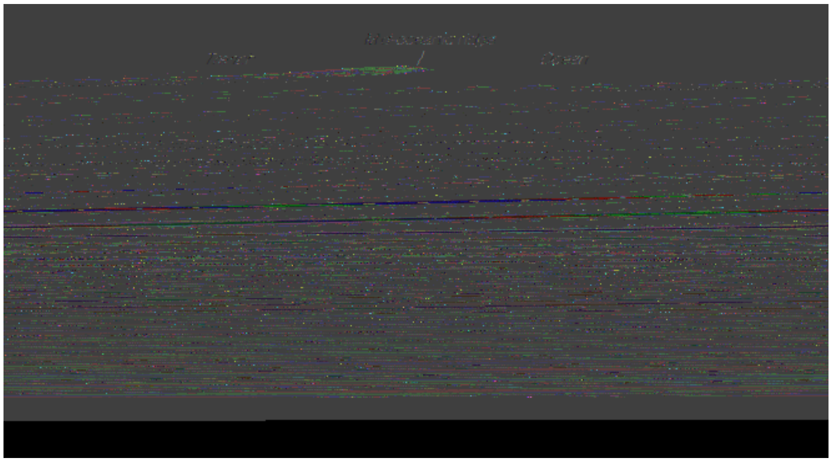

Figure 1: A schematic illustration mantle convection and continental drift in the Earth. Figure borrowed from Götz Bokelmann: `http://www.dstu.univ-montp2.fr/PERSO/bokelmann/research.html`

rock that floats on the mantle material. Plate tectonics, continental drift, is a theory that was first proposed by Alfred Wegener in 1912 but was not taken seriously until one understood that the low density continents float on the denser lithosperic rock and are transported with these. Current theory claims there are 12 continental plates and that continental drift can be followed back in time to a time some 750Myr ago.

The basic mechanism for continental drift is as shown in figure 1: Upwelling regions cause expansion of the oceans and creation of new seafloor material. The older seafloor is pushed aside as is pushed underneath the lower density continental crust. At the edges of continents above subduction regions, hot subducted material may force itself up through weak regions in the continental lithospere and be expelled in volcanoes, this partly differentiated material is thereby added to the constantly growing continental crust.

Climate regulation and change: the CO_2 cycle

The Earth's climate has been stable since Hadean times in the sense that liquid water has been possible throughout. Today the greenhouse effects adds roughly 30 K to the average temperature of 15 C. This greenhouse warming is mainly caused by CO_2, H_2O, and CH_4. In earlier times the CO_2 fraction was higher and with it the average temperature of the Earth which was 85 C. The lower temperature today is due the fact that much of the Earth's CO_2 is bound up in the oceans, which contain 60? what is found in the atmosphere, and in carbonate rocks such as limestone, which contain 170 000? that found in the atmosphere. The balance of CO_2 on the Earth is determined by the CO_2 cycle.

The CO_2 cycle

1. Atmospheric CO_2 is taken up the oceans.
2. At the same time rocks containing Si are eroded by rain and wind and carried to the oceans by rain and by rivers.
3. The Si reacts with the CO_2 in the oceans and form **carbonate** minerals. In the present eon this reaction is done by biological processes, but in the earliest epons inorganic processes were responsible.
4. The caronates fall to the seafloor where they are compressed, form sediments and are carried by plate tectonics into subduction zones and finally the mantle.
5. The CO_2 bound up in carbonates is re-released into the atmosphere by volcanic processes.

The CO_2 level in the Earth acts as a thermostat by the following mechanism: The rate at which carbonates form is senstive the the (ocean) temperature. If the Earth heats up, CO_2 is removed from the atmosphere more efficiently. Thus, eventually there is less greenhouse gases and the Earth cools. Conversly is the Earth cools carbonates form more slowly, the CO_2 abundance in the atmosphere increases and the greenhouse effect becomes more efficient. The time lapse for this process is on the order of 400 000 yr.

Long term climate change The Earth is techically in (the interglacial part of) an ice-age and has been for the last 35 Myr. Exactly what drives such ice-ages is not known but a gradual change in the inclination or tilt of the polar axis driven by gravitational tugs from Jupiter in the range 22^o to 25^o is a possible culprit. A greater tilt makes seasons more extreme with warmer summers and colder winters. Changes in the tilt, along with other rotational and orbital changes correlate well with cycles of ice ages during recent geological history.

There is mounting geological evidence that the Earth has been through a period of massive cooling: a so called **snowball Earth** period 580? 750 Myr ago. During this time glaciers appear to have reached the equator and presumably the oceans have begun to freeze. This could have started a feedback mechanism which would have cooled the Earth even further, since snow and ice reflect sunlight better than water. Snow reflects some 90%, while water only reflects 5% of sunlight received. With less sunlight received the Earth would cool even more producing yet more snow and ice and receiving yet less heat from sunlight. The average temperature could have become as low as ? 50 C during this time. The cycle would only be broken when the CO_2 content in the atmosphere, released from volcanoes, became sufficient to strengthen the greenhouse effect beyond a certain level; such that ice began to melt. The CO_2 level may have risen 1000-fold and the Earth could have melted very quickly, perhaps within a few centuries. It is also likely that the average temperatures could have increased to above 50 C at the end of this period due the high CO_2 content of the atmosphere.

The geological ages of Earth

There are four eons. The following description of these is in part stolen from `http://palaeos.com/Timescale/default.htm`.

- **Hadean.** Formation of the Earth to 4.0 Gyr ago. A ?hellish? time of possible sterilizing impacts and certainly heavy bombardment by left-over planetessimals and debris. At one point, early in this era the moon was formed when a Mars-sized body struck the original Earth, pulverizing both. The first primitive life emerged perhaps several times. Characterized by extensive volcanism and formation of first continents. This outgassing gave the Earth had an atmosphere and oceans.

- **Archean** 4.0 Gyr ago to 2.5 Gyr ago. Diverse microbial life flourished in the primordial oceans, and the continental shields developed from volcanic activity. The first carbon isotope evidence for life date 3.8 Gyr ago, while the first fossil microbes date 3.5 Gyr ago. The reducing (anaerobic) atmosphere enabled Archea (anaerobic microbes) to develop, and plate tectonics followed a regime of continental drift different to that of the Proterozoic and later. During this era, one type of organism, the Cyanobacteria (blue-green algae) produced oxygen as a metabolic by-product; the eventual build-up of this highly reactive gas was to eventually prove fatal to many life-forms. Oxygen build up in the atmosphere took a long time as oxygen needed to saturate with iron and other elements on the Earths surface first.

- **Proterozoic** 2.5 Gyr ago to 550 Myr ago. The Proterozoic, saw the atmosphere changes from reducing to oxygenated, driving the original anaerobic inhabitants of the Earth into a few restricted anoxic refuges and enabling the rise of aerobic life (both prokaryote and the more complex eukaryotic cell). Stromatolites (colonial cyanobacteria), which had appeared during the Archean, were common. The modern regime of continental drift began, and saw the formation of supercontinent of Rodinia, and several extensive ice ages. Late in the Proterozoic a runaway icehouse effect meant that the preceding warm conditions were replaced by a Snowball Earth with ice several kilometers deep covering the globe. Warming conditions saw the short-lived Edicarian biota and finally the appearance of first metazoa.

- **Phanerozoic** 550 Myr ago until present. Is divided into three eras. The **paleozoic** 550 Myr to 250 Myr ago, **mesozoic** 250 Myr to 63 Myr ago, and **cenozoic** 63 Myr ago to present. Early in the 300 million year history of the Paleozoic, atmospheric oxygen reached its present levels, generating the ozone shield that screens out ultraviolet radiation and allows complex life to live in the shallows and finally on land. This era witnessed the age of invertebrates, of fish, of tetrapods, and (during the Permian) reptiles. From the Silurian on, life emerged from the sea to colonize the land, and in the later Paleozoic pteridophyte and later gymnospermous plants flourished. The generally mild to tropical conditions with their warm shallow seas were interspersed with Ordovician and Permo-Carboniferous ice ages. Towards the end of the Paleozoic the continents clustered into the supercontinent of Pangea, and increasingly aridity meant the end of the great Carboniferous swamps and their unique flora and fauna. The Paleozoic was brought to an end by the end Permian mass-extinction, perhaps the most severe extinction the planet has seen. The mesozoic was a spectacular time; The generalized archosaurian reptiles of the Triassic gave way to the dinosaurs, a terrestrial megafauna the like of which the Earth has not seen before or since. Climatic conditions remained warm and tropical worldwide. The supercontinent of Pangea broke up into Laurasia and Gondwana, with different dinosaurian faunas evolving on each. At the end of the Cretaceous period the dinosaurs and many other animals abruptly died out, quite likely the result of an asteroid impact and associated extensive volcanism (tidal waves, extensive fires, acid rain, global winter and subsequent global warming). With the extinction of the dinosaurs and the end of the mesozoic, the mammals swiftly inherit the Earth in the cenozoic. Archaic mammals co-existed with birds and modern reptiles and invertebrates. The current continents emerged, and the initial tropical conditions were replaced by a colder drier climate, possibly caused by the Himalayan uplift. The appearance of grass meant the rise of grazing mammals, and the cooler drier world allowed modern mammalian groups to evolve, along with other lineages now extinct and a few archaic hold-overs.

The molecular components of life

All the major components of cells are made from complex organic molecules.

- **Carbohydrates** serve as sources of energy (sugars and starches) and as structural elements of cells (for example cellulose).

- **Lipids** can also store energy (fats). Perhaps an equally important role is that of cell membranes. Can spontaneously form membranes in water.

- **Proteins** serve a wide variety of roles; as structural elements, as enzymes they serve as catalysts for chemical reactions inside cells such as in aiding the copying of DNA. Proteins are built up of amino acids, which when used in living cells number approximately 20 (out of 70 known in nature), and these are only ?right handed?, while otherwise in nature both types of handedness occur equally often.

- **Nucleic Acids** deoxyribonnucleic acid or DNA is the herditary material of all life on Earth. Ribonucleic acid or RNA helps carry out the instructions encoded in DNA.

Basic cell types

There are two basic cell types; **prokaryotic** and **eukaryotic**. Prokaryotic cells are generally much simpler and do not have a cell nucleus. Examples are *salmonella* and *e-coli*. these organisms are single celled. Eukaryotic organisms, eukaryotes, may either be single celled or multi-celled. Single celled examples are *amoebas*, multi-celled eukaryotes are all plants and animals.

Life is divided into three main domains: **Bacteria**, **Archea**, and **Eukarya**. Detailed DNA-studies imply that archea and eukarya are most closely related.

The importance of H_2O

1. Metabolism requires that organic molecules be readily available for reactions. Liquid water makes this possible by allowing organic chemicals to float within the cell.
2. Metabolism requires a means of transporting chemicals to and carrying waste away from the cells
3. Water plays an important role in many of the metabolic reactions within cells.

DNA and RNA

The herditary molecule DNA is built up in the form of a double helix as shown in figure 2. The zipper between the helixes is built up of four bases **adenine** or A, **guanine** or G, **thymine** or T, **cytosine** or C. T can only pair up with A, while C can only pair up with G. Information is encoded by the order these base pairs are ordered along the helix. **DNA replication** is carried out starting with a complete double helix. The two strands seperate, ?unzipping? the links between pairs. Each strand then serves as template for making a new strand, the end result of which is two indentical copies of the original DNA molecule. There are some dozen enzymes that help in this process, unwinding the helix, making sure the correct bases pair up, checking for errors, and finally rewinding the helix.

The human genome contains some $3 ? 10^9$ DNA bases spread over 46 chromosones, containing a total of 30 ? 120 000 genes. There is a set of rules for how this information is ?read?: The sequence is broken into ?words? consisting of three bases in a row. For the purposes of protein building each word codes either a particular amino acid, a ?start reading? or ?stop reading? instruction. Three bases which can consist of four ?letters? (A, C, G, T) give a total of 4^3 words. This is significantly more than the 20 or so amino acids life is built of. Thus the genetic coding allows for a fair amount of redundancy.

The actual implementation of the instructions coded into the DNA molecule is carried out by various enzymes and the RNA molecule. The latter is similar in structure to DNA but contains only one strand made of a slightly different backbone and uses different set of bases (only one of which is different from

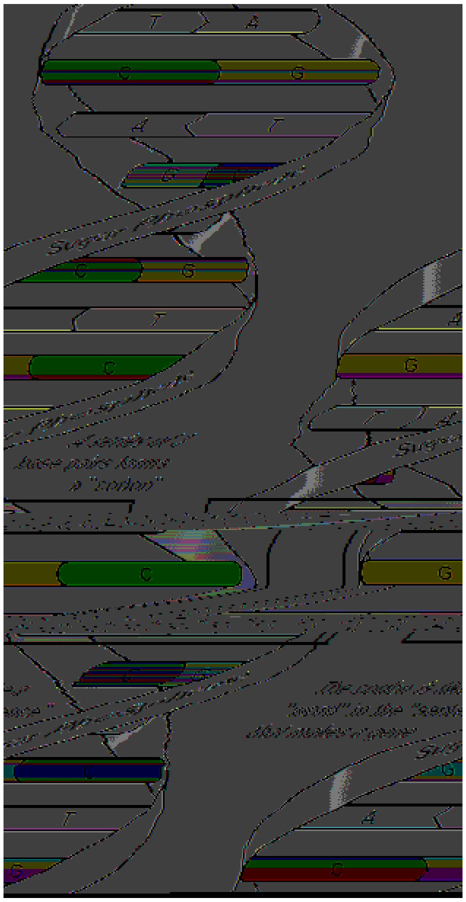

Figure 2: The DNA molecule. Source `http://genetics.gsk.com`

the DNA bases). RNA participates in reading DNA, *transcription* and in the conversion of the instructions into an actual protein, *translation*.

The origin of life

Life seems to have arisen very quickly on the Earth, some 100 ? 500 Myr after the formation of the planet. The study of the evolution of DNA molecules can serve as a clock showing that many organisms on branches of the tree of life (bacteria, archea, eukaryota) close to the root are **extremophiles** such as those living close to deep-sea volcanic vents or in hot springs. These organisms are adapted to life in hot water (*hyperthermophiles* and use chemical energy rather than photosynthesis; they are *chemoautotrophs*. It therefore seems likely that life ?rst arose in the vicinity of such an environment where there is plenty of chemical energy to fuel the chemical reactions that lead to life.

How did life begin? One needs a source of organic molecules such as

1. Chemical reactions in the atmosphere. (Miller-Urey experiment in the 1950?s.)
2. Impacts of asteroids or comets which are known to contain many comples organic molecules.
3. Chemical reactions in the vicinity of deep sea vents or hot springs.

The transition from chemistry to biology requires som sort of self replicating molecule. DNA is probably too complex to be a credible ??rst try?. RNA is the obvious ?rst candidate, it consists of only one strand and short RNA-strands could conceivable have arisen spontaneously in the right environment. A large caveat is that RNA seems to need the assiatance enzymes in order to self-replicate and enzymes need RNA in order to be produced. However, Tomas Cech and colleagues at the University of Colorado in Boulder, showed that some RNA can catalyze biochemical reactions in much the same way enzymes do for which he shared the Nobel Prize in 1989. These RNA molecules are called *ribozymes*. So a plausible scenario is is that RNA or an RNA-like molecule might catalyze their own replication. This has been accomplished in part in laboratory work where RNA-catalyzed reactions have been able top partially replicate.

Thus, short, self replicating strands of RNA could by mutation have evolved leading eventually to DNA. The assembly of complex organic molecules was probably helped if it occured on a substrate of hot sand, clay or rock where strands of RNA up to 100 bases long could form ? as has been accomplished in the laboratory. One possible such mineral is pyrite, FeS_2. Early cell like structures, pre-cells, could have formed spontaneously in the same environment from lipids. Those RNA-strands lucky enough to pass within these membranes would have had an enormous advantage in development as they could shield their replication and any helping enzymes from the outside environment.

We can summarize the origin of life in ?ve steps:

1. On early Earth localized areas with amino acids, building blocks of nucleic acids, were dissolved in a dilute ?organic soup?.
2. Complex molecules including short strands of RNA grew from these building blocks, perhaps as reactions on a clay or other mineral surface. These strands eventually become self replicating.
3. Membranes form spontaneously in the organic soup and enclose complex molecules, the ?rst pre-cells.
4. Natural selection among the RNA strands leads to increasing complexity and eventually something we may label life.

5. RNA molecules are ?nally replaced by DNA as the favored heredeitary molecule.

On a ?nal note: it has been discovered that organic molecules and microbes can survive in space for a certain time. This opens the possibility that life can have been passed between planets, for example from early Mars to the Earth or vice versa.

Early evolution and the rise of oxygen

The ?rst microbes were anaerobic and chemoautotrophs, *i.e.* they gathered energy from chemical reactions in inorganic molecules. We can safely assume that the mutation rate was high in early times. Photosynthesis was an important development ? this process ?rst used hydrogen sulphide, H_2S, releasing sulphur. Later H_2O was used in which oxygen is released as a byproduct. Around 3.5 Gyr ago cyanobacteria (blue-green algea) arose producing vast quanteties of O as a result of their metabolism.

Oxygen is highly reactive and must be continually be resupplied in order to remain in the atmosphere on timescales of greater than 1 Myr. Today most of teh reaction that remove oxygen from the atmosphere are life-based, In early times most of the oxygen released was removed by the process of rust where the iron in the Earth?s crust was the main sink in non-biological oxidation. It took on the order of 1 Gyr before the cyonobacteria could release enough oxygen to saturate the iron minerals in the crust and build up oxygen in the atmosphere. The oxygen content in the atmosphere started increasing 2 Gyr ago and reached its present value about 550 Myr ago, at about the same time as the Cambrian explosion. The fossil record of 200 Myr ago shows charcoal indicating that ?res (needing oygen to burn) were possible in the early forests of the carboniferous.

The ?rst known eurkaryotic cells date back to 2.1 Gyr ago, by which time oxygen was beginning to accumulate in the atmosphere. But DNA comparisons lead one to believe that prokaryotes and eurkaryotes split much earlier. Eukaryotes probably arose as a result of a symbiotic relationship between a large and small prokaryote that could form a nucleus and outer cell pair. Other symbiotic reltationships were formed between early eukaryotes and **mitochondria** the cellular organs by which oxygens helps produce energy and **chloroplasts**, structures in plant cells that produce energy by photosynthesis. Mitochrodria and chloroplasts have their own DNA and reproduce themselves within their eukaryotic hosts. DNA analysis group these within the bacteria rather than the eukarya, they were once once individual bacteria.

The rise of oxygen ignited an explosion of eukaryotic diversi?cation that culminated with the Cambrian explosion 550 Myr ago. In this period of 40 Myr all the basic body plans used by life since were developed. Why did was this evolution so compressed in time? There are four possible answers:

1. The rising oxygen levels allowed both better energy utilization and at the same time an extreme evolutionary stress as oxygen was a potent poison to most species.

2. The genetic complexity of DNA may have reached a certain level that allowed the development of more complex organisms.
3. Climate change, in particular the snowball Earth, may have put extreme evolutionary pressure on organisms.
4. The abscence of efficient predators may have opened a ?window of oppurtunity? for organisms to try out various survival strategies.

The colinzation of land, first by plants, followed quickly, aprroximately 475 Myr ago, followed by insects and amphibians roughly 75 Myr later. By 360 Myr ago, during the carbinoferous period the Earth was covered by vast forests, the remains of which now constitute the basis of our fossil fuels.

Impacts and Extinctions

The K-T event 63 Myr ago. Wiped out the dinasaurs. Chicxulub crater on the coast of Yucatan. Iridium rich sediments.

There have been 5 large extinctions since the Cambrian explosion, or roughly one every 100 Myr.

Other than asteroid impacts, one can imagine vulcanism, an increaed mutation rate due changes in the Earth?s magnetic field and thus increased cosmic radiation, nearby supernova explosions with resultant cosmic radiation, to result in extinctions.

Tunguksa impact in 1908, energy equivalent of several atom bombs.