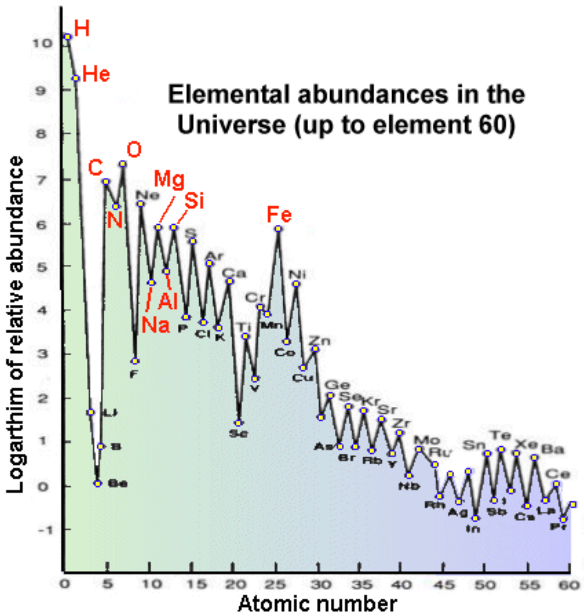
Geology 111 – Discovering Planet Earth

A1) Early History of the Earth

The earth and the rest of the solar system were formed about 4.57 billion years ago from an enormous cloud of fragments of both icy and rocky material which was produced from the explosions (**super novae**) of one or more large stars - [see page 11][1]. It is likely that the proportions of elements in this material were generally similar to those shown in the diagram below. Although most of the cloud was made of hydrogen and helium, the material that accumulated to form the earth also included a significant amount of the heavier elements, especially elements like carbon, oxygen, iron, aluminum, magnesium and silicon[2].



As the cloud started to contract, most of the mass accumulated towards the centre to become the sun. Once a critical mass had been reached the sun started to heat up through nuclear fusion of hydrogen into helium. In the region relatively close to the sun - within the orbit of what is now Mars - the heat was sufficient for most of the lighter elements to evaporate, and these were driven outward by the solar wind to the area of the orbits of Jupiter and the other gaseous planets.

As a result, the four inner planets - Mercury, Venus, Earth and Mars are "rocky" in their composition, while the four major outer planets, Jupiter, Saturn, Neptune and Uranus are "gaseous".

As the ball of fragments and dust that was to eventually become the earth grew, it began to heat up - firstly from the heat of colliding particles - but more importantly from the heat generated by radioactive decay (fission) of uranium, thorium, and potassium (figure below). Within a few hundred million years the temperature probably rose to several thousand degrees, hot enough to melt most things. This allowed the materials to be sorted out so that the heavier substances sank towards the centre, and the lighter substances floated towards the surface.

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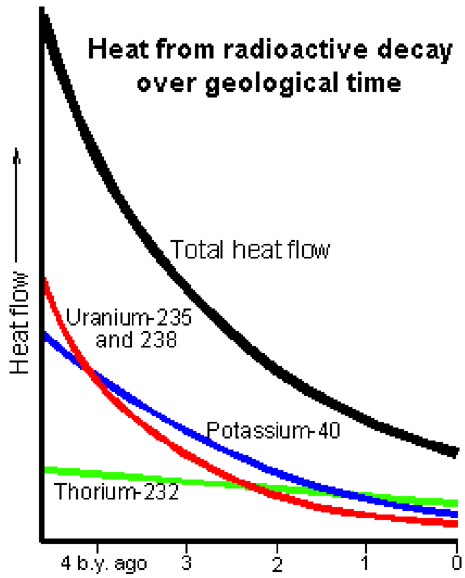
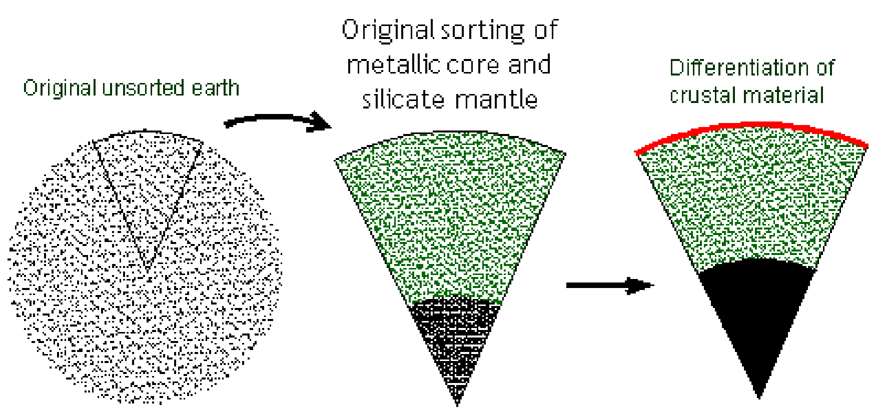
[1] In these notes all references to page numbers, figure numbers and chapters in ***An Introduction to Physical Geology (Tarbuck et al.)*** are enclosed in [square brackets].

[2] Hydrogen (H) makes up approximately 90% of the universe and helium (He) 9%. All of the rest of the elements combined account for less than 1% of the content of the universe.



To begin with, much of the iron and magnesium would have combined with silicon and oxygen to form heavy silicate minerals such as **olivine**: $(Mg,Fe)_2SiO_4$ and **pyroxene** $(Mg,Fe)SiO_3$. Most of the remaining iron (along with some nickel and sulphur) would have migrated towards the centre - forming a very heavy metallic **core**. Meanwhile, much of the aluminum, sodium and potassium would have combined with oxygen and silicon to form minerals such as **quartz** (SiO_2) and **feldspar** ($NaAlSi_3O_8$) that would have floated towards the surface to form the **crust** (see figure below). We will look more closely at the characteristics of the core, mantle and crust later on.

The original material that formed the earth included some hydrogen, oxygen, carbon and nitrogen, and these would have been brought to the surface during volcanic eruptions as molecules such as water, carbon dioxide, methane and nitrogen gas. By around 4 billion years (b.y.) ago it is likely that the earth had an atmosphere rich in carbon dioxide and nitrogen along with lots of water vapour. Initially the earth's surface and atmosphere were probably too hot for the water to come down as rain, but as the crust cooled and hardened it kept most of the earth's internal heat inside, and eventually the atmosphere cooled enough for rain to fall and create bodies of water on the surface.



The early atmosphere was largely composed of carbon dioxide, nitrogen, hydrogen-sulphide, and probably some ammonia and methane. The elements in these substances - particularly the carbon, hydrogen, oxygen and nitrogen (**CHON**) are fundamental to the formation of the molecules that were the precursors of life and those found in all living organisms. There are numerous ways in which these **amino acids** and other similar molecules could have been formed. For example, in 1953 it was shown by Stanley Millar that amino acids could have formed as a result of the interaction between an electrical current - such as lightning - and ammonia and water - as long as there was no oxygen. The early atmosphere had no free oxygen. We know that because the minerals in very old rocks show no signs of being oxidized (i.e., formed in the presence of oxygen, which commonly results in a reddish colouration due to the oxidation of iron).

Sometime in the period between about 4 billion and 3.5 billion years ago primitive life evolved on the earth. No one knows exactly when, how or in what type of environment. The earliest life forms were very simple uni-cellular blobs, very similar to what we call blue-green algae - which aren't algae at all but are blue-green bacteria or **cyano-bacteria**. They fall into the class of life known as **prokaryotes** - cells that lack nuclei. Like other bacteria, these organisms thrived in an oxygen-free environment. They flourished in their billions and trillions and they produced oxygen and consumed carbon dioxide. At first, almost all of the oxygen that they produced was used up in chemical reactions - the oxidation of dissolved substances such as iron, and of dead organic matter. Eventually, however, around 2.5 billion years ago, the substances that were available to be oxidized started to get used up, and the oxygen level of the atmosphere began to increase. We can see evidence of this oxygenation in the composition and appearance of the rocks that formed starting about 2.2 billion years ago and continuing to the present day.

The concept that the earth's environment has been controlled by life (rather than life being controlled by the environment) - is known as the **Gaia Hypothesis** – an idea which was first proposed by James Lovelock in the 1970s. The traditional way to look at our planet's environment is that it is largely controlled by the laws of physics and chemistry, and that we and the rest of the life forms here are very lucky to have found such a nice place to live. The Gaia hypothesis, which is a comprehensive theory of the interaction between life and the environment, suggests that life itself has contributed to the creation and maintenance of the environment that supports us today[3]. The following table shows the compositions of the atmospheres of our neighbouring planets and what the earth would be like without life - contrasted with the actual composition of our atmosphere.

Compositions of the atmospheres of Venus, Earth and Mars (after Lovelock)

Gas	Venus	Earth without life	Mars	Earth with life
Carbon dioxide	96.5%	98%	95%	**0.03%**
Nitrogen	3.5%	1.9%	2.7%	**79%**
Oxygen	trace	0	0	**21%**
Methane	0	0	0	**1.7 ppm**
Average T (°C)	459	290	-53	**13**
Pressure (bars)	90	60	.00064	**1.00**

Some aspects of the Gaia hypothesis include an explanation of the original generation of an oxygenated atmosphere, the storage and safe keeping of billions of tonnes of excess carbon in biologically produced limestone rocks and coal and petroleum bearing rocks, and the gradual

[3] If you are interested, further information on the Gaia hypothesis can be found in ***The Ages of Gaia*** by James Lovelock (QH 331 L688), and in chapters 4 and 5 of ***Gaia - a way of knowing*** edited by W.I. Thompson (QH 331 G22). These books are in the library. There is also lots of Gaia information on the web. Just do a search for “Gaia hypothesis”.

reduction of the level of green house gases (such as CO_2 and methane) in the atmosphere - so that a comfortable temperature has been maintained in spite of the steady and continuous warming of the sun.

At some time around 2 b.y. ago (following the initial oxygenation of the atmosphere) new and more complex life forms started to appear in the oceans of planet earth. These are known as **eukaryotes**. They were multi-cellular, (including several different types of cells) they had an outer membrane, most needed oxygen to live and they reproduced sexually. The evolution of eukaryotic organisms was a crucial step in the history of life on earth.

A2) Geological Time

Geology is a science, and like other sciences, such as chemistry, physics and biology, we can use scientific reasoning to find out how things work. This includes careful field observation and the use of both field and laboratory experiments to model natural processes and test hypotheses. In geology, however, time is a critical factor. Most geological processes are very slow, and many geological events take place over thousands or millions of years. Many such processes simply cannot be duplicated in a laboratory.

As an example of a slow geological process, imagine the formation of the Atlantic Ocean. The continents of Africa and South America and Europe and North America started to split apart around 180 million years and they continue to spread apart. The Atlantic Ocean was formed by a process that continues at a rate of around 2.5 cm per year! Such a process would result in a 2-metre wide crack over a person's lifetime, but over 180 million years produced an ocean that is up to 4500 km wide. It is necessary to have an appreciation of the immensity of geological time to accept that this is a realistic concept.

The earth is approximately 4.57 billion years (b.y.) old - that is 4,570,000,000 years. This is such an incredibly long time that it is virtually impossible to comprehend. One way to help one understand this amount of time would be to imagine that we could compress those 4.57 b.y. into one year—as is described in the text [page 10]. Each month would then be equivalent to 383 million years (m.y.), each day would be 12.5 m.y., each hour would be 500,000 years, and each minute would be 8760 years.

> On this compressed time scale, oceans and continents first appeared in early February, the first very primitive life forms probably evolved by late February, the oldest rocks of British Columbia were deposited in early summer, the oldest rocks of Vancouver Island were deposited in early December, the uplift of the Rocky Mountains was completed by Christmas, the dinosaurs died off on Boxing Day, and the Pleistocene ice age began in the

early evening of December, 31st. The most recent glacial ice melted back from this part of British Columbia around 11:58 PM, and the first people arrived in this area around 11:59 PM. The first Europeans arrived on this coast about 250 years ago, which is equivalent to approximately 2 seconds before midnight on this time scale.

Geologists have divided up time into four eons, namely: **Hadean** (Pre-Archean), **Archean**, **Proterozoic**, and **Phanerozoic** [see p. 9]. Most of the rocks exposed at surface are of Phanerozoic age. There are exposed rocks of Proterozoic and Archean age and just a few of Hadean age (see below).

Up until recently the oldest known rock in the world - ~ 4.0 billion years (b.y.) old – was the Acasta Gneiss, situated at the eastern edge of Great Slave Lake. In 2008 some even older rocks were discovered at a place called Nuvvuaglittuq on the eastern shore of Hudson Bay. Pictured above, these rocks are estimated to be ~4.28 b.y. old making them Hadean in age. (O'Neill et al., 2008, Science, V. 321, p. 1828.)

The Phanerozoic eon has been divided into three eras, namely **Palaeozoic**, **Mesozoic** and **Cenozoic**. The eras have been divided into various periods. For example, the Paleozoic includes the **Cambrian**, **Ordovician**, **Silurian**, **Devonian**, **Carboniferous** (**Mississippian** and **Pennsylvanian**), and **Permian**. The Cambrian started at about 570 m.y. ago (around mid-November if all of time was compressed into one year) and the Permian ended at about 250 m.y. (Approx. Dec. 11). The Mesozoic includes the **Triassic**, **Jurassic**, and **Cretaceous** periods. The Cretaceous period ended about 66 m.y. ago (December 25th), which is about the time that the sandstone, shale and coal exposed around Nanaimo were deposited. The Cenozoic includes the **Tertiary** and **Quaternary** periods. The Quaternary period, which has lasted for 2 m.y., is distinguished by the repeated advance and retreat of ice sheets in the temperate regions on the earth[4].

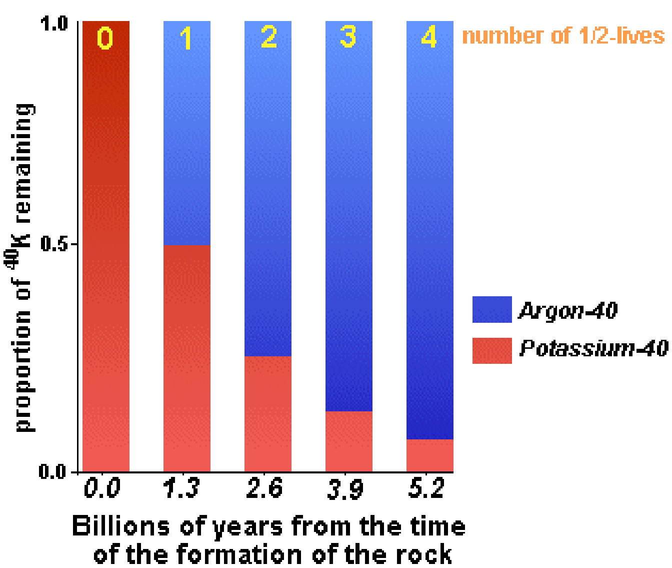
[4] Relax! You are **NOT** expected to know the names or the dates of the eons, eras, periods and so on.

The initial division of time was based largely on evidence from fossils, and as such there was no absolute time scale. As recently as a hundred years ago geologists had a reasonable concept of the relative ages of the rocks that they studied, but they did not have a clear idea of their actual ages in years. Chapter 8 of the text book [p. 217-219] includes a discussion of how fossils are used to provide relative dates of rock units. Of course rocks without fossils (such as igneous rocks) cannot be dated in this way.

Another way of determining the relative age of rocks is to study their spatial relationships. The **principle of original horizontality** states that sedimentary rocks were laid down essentially horizontally. The **principle of superposition** holds that younger sedimentary beds lie on top of older sedimentary beds. Unless the sequence of sedimentary rocks has been turned completely overturned (which does happen), we can assume that the upper layers are younger than the lower layers. Various types of rocks can be intruded by younger igneous rocks, and if we can clearly understand the cross-cutting relationships between the rock types we can make assumptions about their relative ages. This is known as the **principle of cross-cutting relationships**.

Another important geological principle is the **principle of uniformitarianism**, which holds that geological processes which are currently happening – such as formation of mountains, erosion, deposition of sediments, and volcanism – are essentially similar to those which happened in the past, and which led to the formation of the old rocks that we can observe. In other words: "the present is the key to the past." These principles are described in more detail in the text book [page 6 for uniformitarianism and p. 211 for the others].

During the last 50 years techniques have been developed to determine the *absolute* age of rocks on the basis of radioactive decay of elements such as uranium, potassium, strontium, carbon, and several others.



For example, the rare isotope of potassium **^{40}K** decays into the isotope of argon **^{40}Ar**. We know that this decay takes place at a steady rate, a rate which has not changed over geological time, and is the same throughout the solar system. The decay of ^{40}K has a **half-life** of 1.3 b.y., which means that in a rock which is 1.3 b.y. old, half of the original ^{40}K will have decayed into ^{40}Ar (see figure to the left). By accurately measuring the proportions of these isotopes it is possible to estimate the age of a rock. [For more on isotope dating see pages 219 to 223.]

Generally speaking isotopic dating can only be applied to igneous rocks (rocks formed from magma) because they have been heated sufficiently to separate parent isotopes from daughter isotopes. In the case of ^{40}K-^{40}Ar, for example, an igneous rock will have no ^{40}Ar at the time of its formation, and hence any ^{40}Ar found in it can be assumed to be derived from the decay of ^{40}K.

By combining isotopic age information with paleontological information and geological relationship information it has been possible to attach absolute numbers to the geological time scale, and also to determine the absolute ages of most rocks.

Review questions

1. What was the original source of the material from which the solar-system is derived?
2. Why are the four inner planets "rocky" while the four outer ones are "gaseous"?
3. What was the main factor responsible for the heating up of the earth's interior?
4. From what source were the water and the gases of our atmosphere derived?
5. What gas was the main component of the earth's early atmosphere?
6. What gas would have inhibited the initial evolution of life on earth?
7. When and why did the oxygen content of the atmosphere begin to increase?
8. According to Gaia theory, how would our atmosphere be different if there was no life on earth, and how has the presence of life on earth contributed to regulation of the surface temperature?
9. Prior to the development of isotope dating why did fossils only indicate the relative ages of geological formations?
10. Why is the Archaean, which lasted for 1.3 b.y., not divided into as many subdivisions as the Phanerozoic, which lasted for only 0.6 b.y.?
11. A sedimentary rock has three different types of fossils in it, one that lived from 13 to 16 m.y., one that lived from 15 to 19 m.y. and one that lived from 12 to 14 m.y. What can we say about the age of this rock?
12. What is the approximate age of a mineral in which three-quarters of the K^{40} has decayed to Ar^{40}?
13. If you're interested in going a bit further with radiometric ages, try using the graphical method or the formula described on the following web-page: http://records.viu.ca/~earles/geol111/isotopic-dating.htm

    Calculate the age of a mineral in which the proportion of remaining ^{40}K is 0.312.