Earth 50: Planets and the Layered Earth 9-22-06

Formation of Elements
- light elements (up to Fe)
- heavier elements

The Solar Nebula
- inner versus outer planets
- origin of compositional variations
- dominance of Fe,O,Si,Mg in Earth

Age of the Earth

Elements are not evenly distributed in the Earth
- partial melting, gravitational settling

Layered Structure of the Earth:
- compositional layers
- physical properties layering

Early Earth Surface Evolution

Varieties of Surface rocks
- Igneous (Plutonic/Intrusive versus Volcanic/Extrusive)
- Sedimentary (Clastic, Carbonate, Evaporite)
- Metamorphic

The Rock Cycle

Earth 50: The Solar Nebula and Planetary Geology 9-22-06

Business stuff: introductions, class structure, field trips, labs and books

Definitions: Geology

From *Geo* = "Earth" and *Logia* = "science" or "study of" a highly interdisciplinary field merging chemistry, physics, biology, economics, social sciences and more….

Why study geology?

hazards (earthquakes, volcanoes, landslides ...)
resources (minerals, oil, water)
climate change

<u>Formation of the Elements</u>

Stars the size of our sun are capable of creating light elements by combining fusing hydrogen to form helium, fusing helium to form carbon. These heavy elements accumulate in the sun's core by gravitational settling. Most of the relatively light elements are thought to have formed early in the universe, shortly after the Big Bang (~15 Ga).

4H ---> He
6.696×10^{-24}g
-6.648×10^{-24}g
0.048×10^{-24}g $E=mc^2$ yields 1×10^{-12} calories

1g H ---> He yields 1.5×10^{11} calories (enough to boil 2 million liters water)
requires T ~ 60 million K, very high pressures to overcome charge repulsion
balance of gravitational collapse and pressure from heat escape

when hydrogen depleted He ignites (T ~200 million K)
this process can make elements up to Fe

Large elements require higher temperatures (a more massive star than our sun) which also tend to burn out faster (~several million years for a sun 25 times as massive as our sun versus 10 billion for our sun). Hence most heavy elements require large stars which are thought to have been abundant in the first 100 million to 1 billion years of the Universe.

Iron is highly stable and fusion of iron with other elements absorbs energy rather than releasing it. Hence, to form heavier elements there needs to be a massive addition of energy (since mass of products exceeds that of reactants, energy is required) which takes place during super novae when the massive gravitational collapse of a white dwarf star and fragmentation of iron nuclei creates conditions suitable for formation of heavy elements.

super novae - gravitational collapse provides extra energy

Most iron is thought to have formed in the first 3 billion years of the Universe based upon analyses of the composition of old stars

The solar nebula - the raw materials for planets

The idea of planetary formation from a solar nebula dates back about 250 years to Immanuel Kant's "nebular hypothesis". For a good synopsis of current ideas on planetary formation see Schilling (Science, v 286, 66-68) and Kerr (Science, v 286, 68-69).

Timescales of planetary formation:

- few m.y. - original gas rich disk; gas redistributed to either the star or ejected from system via jets along rotation axis of star
- by 10 m.y. - relatively clean system of dust particles (silicates, ice)
- few 100,000 yr - dust particles coalesce to form pebble size fragments
- few m.y. - these coalesce to form km-size planetesimals
- few 100 m.y. - formation of planets from planetesimals. In this clean up phase, particles are either ejected or captured by planets or the stars. These late stage large collisions result in "heavy bombardment" phase that is evident on Moon. Note: one of the defining features of a planet is that it is significantly larger than all other bodies in same orbit - this is one reason why Pluto was demoted.

As the solar nebula cooled, rocky planets formed close to the sun and gas giants formed farther away. This pattern is due to different condensation temperatures and the force of the solar wind—material ejected off the sun—that removed the atmospheres of the early inner planets.

Composition:

Bulk Earth:	Crust:
Fe (35%)	Oxygen (46%)
Oxygen (30%)	Silicon (28%)
Silicon (15%)	Aluminum (8%)
Mg (13%)	Iron (6%)
Ni,S,Ca,Al	Mg (4%),Ca(2.4%),K(2.3%),Na(2.1%)

These elements constitute 90% of the planet and the first two make up ~65% of the planet.

Why the dominance of these elements?

1 H	gas (H_2,CH_4,H_2O)
2 He	only gas
3-5 Li,Be,B	low abundance
6,7 C,N	because lots of H (gas CH_4, NH_3)
8 O	strong affinity for metals (20% with metals, rest H_2O)
9,10 F,Ne	gas
11-15 Na,Mg,Al,Si,P	all like O

20 Ca all make nonvolatile oxides
19 K
26 Fe

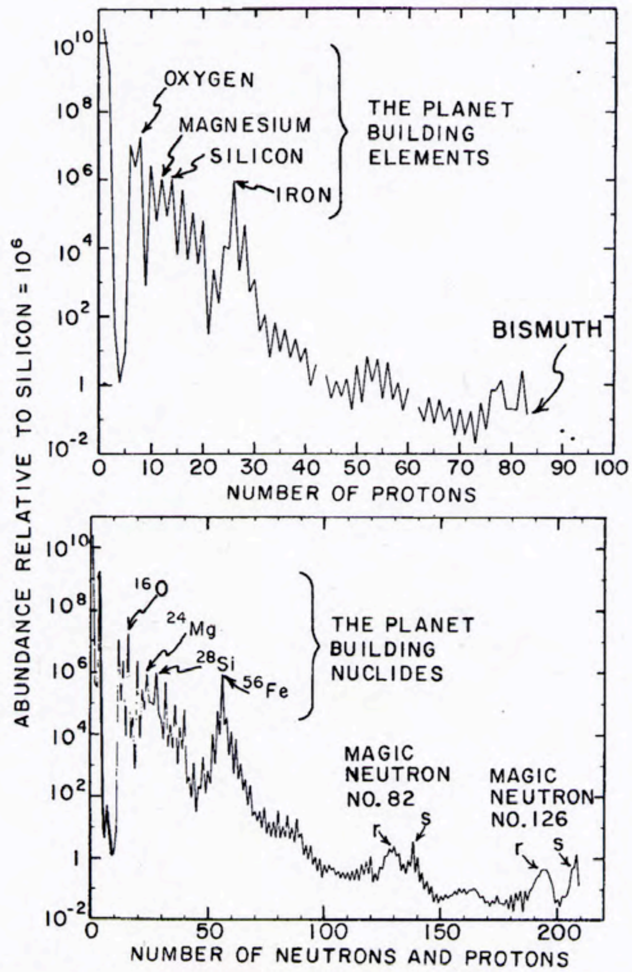

Figure 2-12. The raw material for planet formation: The upper diagram shows the relative abundances of the elements. Up to bismuth there are only two elements not found in nature; technetium (element 43) and promethium (element 61). The lower diagram shows the relative abundance, of the isobars. Only two isobars of nuclear number less than 208 are not represented in nature, those of mass 5 and of mass 8.

The atmosphere of Earth is created almost entirely by later degassing of the planet.

Possible origins of water on earth:

- volcanism (water and CO_2 are largest fraction of emissions) but probably not sufficient for all water on earth
- water-rich planetary embryos (particularly in later large impacts) may exert a strong control

- proximity to sun and gravity also determines where water is preserved (e.g. Venus too hot and Mars is probably too small to recapture volatiles ejected during impacts)

Age of the Earth:

1590: Bishop Ussher's view: a 4000 year old Earth (based upon counting back through generations of prophets listed in the Bible)
1780: Buffon, 100,000 year-old Earth (based upon estimates of cooling of metal spheres from incandescent state)
1900: various dates of ~10,000 ma to 10 billion (from sedimentary processes and astronomical calculations)
Today: ~4.5-4.6 billion years (based upon radioactive dating of meteorites and moon rocks).

But, they are not evenly distributed:

The amount of iron in the Earth is higher than would be expected for a planet it's size by accretion of rocky debris

An answer: Partial melting and gravitational settling.

A current theory is that the early Earth had partly differentiated by gravitational sinking of iron into its core when it was struck by a Mars-sized planetoid that stripped off the outer shell of the Earth. Part of this material blasted free of the Earths surface condensed to form the moon and part returned to the Earth.

Most crustal rocks have a density of ~2.2-2.5 g/cm3. yet measurements of the average density of the Earth suggest a value of ~5.45 g/cm3. Hence the deep interior of the Earth must be much denser than the surface. The core is estimated to have a density of about 13 g/cm3 and to be mostly iron.

Layered structure of the Earth:

Like a hard-boiled egg:

Crust: Oceanic crust is ~7-10 km thick, Continental crust 20-70 km thick (could drive through the crust in ~5 minutes at highway speeds); Rigid and broken into mostly rigid "plates"

Movement of these plates creates Earth surface features and is called "**Plate Tectonics**".

Mantle Lithosphere: 100-150 km thick; is rigid rock and includes the crust but is compositionally richer in Fe and Mg and poorer in Si than the crust.

Mantle Asthenosphere: A weak interval in which mineral grains may be surrounded by films of liquid rock between 100-350 km depth, flow in this layer contributes to movement of the outer brittle crust

Transitional Mantle: ~400-670 km depth ridge rock but with changes in crystal structure that result in denser minerals

Lower Mantle: 670 km to 2900 km Solid rock-- although solid the rock still flows and slowly deforms under great heat and pressure. The mantle is believed to slowly convect or circulate and dense metals or pieces of dense crustal rocks can sink into it, to the depth of the core-mantle boundary

Outer core: 2900-5200 km deep; liquid iron-nickel, flow in which sets up the magnetic field of the Earth

Inner Core 5200-6371 km; solid iron-nickel with a temperature of ~4300°C

<u>Early Earth Surface evolution</u>

Oldest Earth Rocks are about 3.97 billion years (in NW Canada) and most rocks are younger than 3.8 billion. Reflects initial heavy bombardment as seen in ages of craters on the Moon between 3.9-3.8 Billion years. Unlike the moon, the Earth shows little direct evidence of the heavy bombardment because erosion and plate movements have resurfaced the planet many times.

<u>Varieties of Surface rocks</u>

Igneous: formed form molten rock (Magma)

> Intrusive (Plutonic)--cool underground and tend to form large crystals because they cool slowly allowing crystals time to grow
>
> Extrusive (volcanic): formed when magma spills out on the surface and cools rapidly—at least part of the rock is very fine grained or glassy because the rock cools quickly inhibiting crystal formation

Sedimentary: created to eroding other types of rocks or by accumulation of shells (limestone) and precipitates (like salt)

Metamorphic: rocks formed by heat and pressure that change their crystal structure or types of minerals

<u>The Rock Cycle:</u>

(1) Igneous (intrusive/extrusive)
(2) eroded to form sedimentary rocks (boulders to clay) or precipitated as evaporates or as limestones.
(3) buried or intruded to form metamorphic rocks
(4) that melt (eventually) to form magmas