

Chapter 6 The Archean Eon of Precambrian Time

I. Introduction -

A. Hadean and Archean together represent about 90% of Earth's history (Fig 6-1).

1. **Hadean** represents first 500 to 600 myr of Earth's history. This is an interval for which we have no rock record on Earth. However, we understand from the moon rocks and meteorite ages that Earth was formed.
2. **Archean** - The time represented by oldest rocks (~4 Ga) until 2.5 Ga which is the beginning of the Proterozoic.
 - a. Archean rocks differ fundamentally from those of the Proterozoic.
 - b. No biostratigraphy to differentiate. A chronologic date of 2.5 Ga is arbitrarily chosen as boundary. This is in contrast to all other subdivisions in the Geologic time scale.
 - c. 2.5 Ga represents the age when the rock record shows evidence for modern Plate tectonic style of sedimentation .
 - d. Development of **felsic** crust and start of small continents. Form the **cratons**.
2. All of the remainder of geologic time up to the present day is designated the **Phanerozoic Eon**.

II. Ages of the Planets and Universe

A. Age Constraints

1. Rocks on Earth: **3.96 billion years old**; Canada and Greenland rocks; detrital zircon from Australia – 4.4 to 4.2 billion years old
 - a. Plate Tectonics and erosion the reason for this for lack of record older than 3.96 Ga.
 - i. Plate tectonics recycles the crust into the mantle. Until there was felsic or "light" continental crust, almost all of the early crust was subducted eventually. Also, the first 500 to 600 myr of Earth's history was subjected to meteorite bombardment. Latent heat released when energy of impact is converted into heat. This tended to perpetuate "**magma**" oceans of the Hadean.
 - ii. Erosion: Evidence for water existing as a liquid early in Earth's history means that erosion has been constantly attacking the exposed rocks.
2. **Meteorites**: 4.6 billion years old - extraterrestrial objects captured by Earth's orbit.
 - a. stoney meteorites consist of rocky material (Fig. 6-8 to 6-9)
 - b. iron meteorites or metallic meteorites - High abundance of Fe. Nickel is the second most abundant element
 - c. come in all sizes - important for atmosphere and ocean development (See below)
 - d. Radiometric age dating (Rb-Sr; K-Ar; U-Th) cluster at 4.6 Ga
3. Rocks from the **moon**: 4.6 billion years old

III. Age and Origin of the Universe

A. Age of Universe must consider the **Red Shift (p.199)**

1. light, on passing through a glass prism, is separated into a spectrum
2. the spectra of stars reveal not only the star's composition, but whether it is moving toward or away from the Earth, and at what speed
3. as light from distant galaxies approaches Earth it is shifted towards the longer wave lengths (Reds) in the visible light spectrum
 - a. consider the sound of an approach train or car horn. It has a higher pitch/frequency as it approaches and drops to a lower pitch/frequency upon passing. While approaching the sound waves are compressed (speed of sound plus car) so that they have a higher pitch/frequency. Upon passing the sound abruptly drops to a lower pitch/frequency (speed of sound - velocity of car). This is referred to as the Doppler effect wrt sound. W.r.t. the light spectra, it is an important observation concerning the age of the universe.
4. the greater the distance (and hence velocity) of separation, the wider the observed red shift
5. the red shift indicates the universe is expanding

B. **Big Bang (p.199)**

1. 1914 W.M. Slipher noted that 12 galaxies had red shift
2. 1929 Edwin Hubble noted that red shift increased with distance from Earth - moving away
3. occurred between **15-18 billion years ago**
4. marked the instantaneous creation of the universe

5. only radiant energy, very light particles called **neutrinos**, and electrons existed
6. **fusion** reactions produced simple atomic nuclei
7. by about a billion yrs after Big Bang, matter had been collected into galaxies and stars had probably begun to form

C. **Oscillating universe** cosmology

1. for every big bang there is a big crunch
2. after expansion gravitational forces begin to prevail and cause matter to be drawn back to its place of origin
3. in the last stages of contraction, matter would be returning at enormous speed resulting in compression
4. from the ultra-dense body would come the next big bang and the initiation of another episode of expansion and contraction
5. one estimate would put the time required for a complete cycle at 100 billion years

IV. Birth of the Solar System

A. Grouping of planets and asteroids around the Sun constitutes our solar system

B. Our solar system is located in the **Milky Way galaxy** - spiral type (Fig. 6-3)

1. Sun is located 2/3 of the distance outward from the center
2. completes one rotation every 240 million years

C. **Solar Nebula Hypothesis (Fig. 6-7)**

1. Our solar system was born about 4.6 Ga from a rotating cloud of hot gases following a **Supernova (Fig. 6-7)**
 - a. solar system began as a cold, rarefied cloud of dust particles and gases
 - b. cloud gradually contracted and flattened, took on a counterclockwise rotation, turbulence began to affect the cloud system
 - c. eddies served as collecting sites for matter
 - d. permitted condensation of the concentrated knots of matter
2. **Accretion** - process of accumulation of bits of matter around an initial mass
3. **Proto-planets**
 - a. Large globules formed from swarms of accreting bodies, dust, and gases
 - b. formation required an estimated 10 million years

D. The Sun -The most important member of our solar system.

1. Material that had been pulled into the central region of the nebula condensed, shrank, and was heated to several million degrees by gravitational compression
 - a. the Sun was born when pressures and temperatures within the core became sufficiently high, thermonuclear reactions began
 - b. **Solar radiation**
 - i. stream of radiation from the Sun
 - ii. drove enormous quantities of the lighter elements and frozen gases outward into space
 - iii. planets nearest the Sun lost enormous quantities of lighter matter
 - iv. caused differentiation of the planets
2. Modest star
 - a. composed of 70% hydrogen and 27% helium
 - b. remaining 3% consists of heavier elements that exist as gases
3. Maintenance of Earth's temperature - (-50 to 60°C).
 - a. rotation - one hemisphere at a time sees the sun
 - b. incoming radiation is reflected off the atmosphere and clouds and directed back into space
 - c. the intercepted radiation is absorbed by the atmosphere and radiated back into space
4. The energy that maintains the Sun -**Fusion** - $^2\text{H} + ^2\text{H} \rightarrow ^3\text{He} + \text{n} + \text{Energy}$ (fig. 6-4)
 - a. ultimate force behind the many geologic processes that sculpture the Earth's surface - Hydrologic cycle
 - b. results in winds and ocean currents
 - c. in company with the moon, helps move the tides

E. The Planets

1. 9 planets that revolve around the Sun. in order of increasing distance from the Sun (Fig. 6-2; 6-10)
 - a. Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto

- b. Pluto considered by some to be a large satellite that escaped from Neptune
 - c. The direction taken by the planets as they revolve around the Sun is counterclockwise
2. **Composition**- Planets differ in composition
- a. Mercury, Venus, Earth, Mars have mean densities of 5.4, 5.2, 5.5, and 3.9 respectively
 - i. constitute the inner or **terrestrial planets**
 - ii. small, dense, rocky, and rich in metals
 - b. Jupiter, Saturn, Uranus, and Neptune have mean densities of 1.3, 0.7, 1.3, and 1.6 respectively
 - i. termed the outer or **Jovian planets**
 - ii. compositions of Jupiter and Saturn are dominated by hydrogen and helium

V. Origin of Earth and Moon

A. Differentiation of the Earth

1. Hot Accretion Model
 - a. Earth and neighboring inner planets accumulated material that was very hot
 - b. Earth and neighboring inner planets were not initially homogeneous solid bodies that later differentiated
 - i. the internal zonation of planets developed **during** not after accretionary accumulation
 - c. **Hot heterogeneous accretion**
 - i. begins with a hot solar nebula
 - ii. as it began to cool, heavy, iron-rich compounds condensed, precipitated, and accumulated in masses
 - iii. eventually became the iron-rich cores of the terrestrial planets
 - iv. lower density silicate minerals began to condense and were swept up by the denser masses formed earlier
 - v. eventually became the mantle
 - d. Chemical differentiation was able to proceed throughout the period of accumulation
 - e. Later heating by meteoric bombardment and radioactive decay could have further propelled the differentiation already established
2. **Cold Accretion Model (Fig 6-22)**
 - a. Earth consisted initially of an unsorted, **homogeneous** conglomeration of metals and silicates from its center to its surface.
 - i. experienced differentiation, a process whereby a planet becomes internally zoned or layered
 - ii. planet must have been heated and become at least partially melted
 - iii. iron and nickel in the planet would percolate downward to form the dense core
 - iv. remaining iron and other metals would combine with silicon and oxygen to form the less dense mantle
 - v. still lighter components would separate out of the mantle to form an uppermost crustal layer
 - b. **Heat** needed for differentiation
 - i. **accretionary heat** derived from bombardment by particles and meteoric materials
 - ii. weight of overburden on underlying zones provide heat by **gravitational compression** - also served to reduce the Earth's size
 - iii. **decay of radioactive isotopes** more heat derived from radioactivity in the early days of the Earth than today - many short-lived isotopes
 - c. About 1 billion years after the solid Earth formed there would have been sufficient heat from all sources to melt iron at depths of 400-800 km
 - i. mantle began to form and differentiate
 - ii. lead to the development of the **magma ocean** at the surface

B. Catastrophic Birth of the Moon vs. Asteroid vs Chunk of the Earth

1. Asteroid is more favored at this time for several reasons. (Figs. 11-10, 12)
2. A body 1/10 the mass of Earth (=Mars) hit the Earth with a glancing blow during the early stages following Earth initial accretion
 - a. abundance of Fe and Mg in lunar rocks differ from that in the mantle rocks on Earth
 - b. Absence of water on Moon - expelled during the formation of moon
 - c. small metallic core- absorbed by Earth during collision
 - d. Feldspar rich out layer - heat during moons formation - magma ocean - chemical differentiation.
3. Glancing blow explains two observations about Earth's orbit

- a. it is spinning faster than it should for its position and size
- b. it is tilted at 23.5°

VI. Evolution of the Atmosphere and Hydrosphere

A. The Primitive Atmosphere - the gravitational field of coalescing asteroids was too weak to hold any of the primitive gases. Evidence includes: **Inert gases** are about a million times less abundant in our present atmosphere than in the Sun and other stars; indicates that our atmosphere is not a residue of gases left over from the solar nebula. Therefore, emanated from the Earth.

1. Volatiles

- a. substances easily driven off by heating
- b. scattered uniformly throughout the accreting planet by the process of homogeneous accretion
- c. contained mostly in the impacting bodies that arrived during the late stages of erosion
- d. especially abundant in **carbonaceous chondrites** meteorites content of organic compounds
chondrites: spherical bodies
- e. water and gaseous elements readily released by heat associated with accretion or by subsequent melting and volcanism accompanying differentiation

2. Outgassing

- a. the process by which water vapor and other gases are released from the rocks that held them and then vented to the surface
- b. most outgassing of water occurred within the first 1 billion years of Earth history
- c. evidence of the presence of an early ocean 4.2 billion years ago
- d. Produced a primitive atmosphere rich in carbon dioxide and water vapor, with lesser amounts of carbon monoxide, hydrogen, and hydrogen chloride
- e. volatiles released by modern volcanoes provide an approximation of the composition of the early atmosphere differ because they are released from relatively young rocks that have been recirculated near the Earth's surface by plate tectonic processes

3. An Oxygen-rich Atmosphere

- a. Early atmosphere of the Earth was reducing and nonoxygenic in character
- b. **Photochemical dissociation**
 - i. dissociation of water molecules into hydrogen and oxygen: $2\text{H}_2\text{O} + \text{uv radiation} \rightarrow 2\text{H}_2 + \text{O}_2$
 - ii. occurs in the upper atmosphere
 - iii. water molecules are split by high-energy beams of ultraviolet light from the Sun
 - iv. does not produce free oxygen at a rate sufficient to balance loss of the gas by dissipation into space
- c. **Photosynthesis**
- separating carbon dioxide into carbon and free oxygen

4. Geologic Clues to the Nature of the Early Atmosphere

- a. Rocks provide evidence that the changes in the atmosphere occurred about 3.5 billion years ago
 - i. originally water-laid sediments
 - ii. mineral grains were formed or modified by weathering - requires an atmosphere
 - iii. occurrence of pyrite Fe_2S would decompose in O_2
 - iv. absence of oxidized iron
 - v. occurrence of chert - carbonic acid would dissolve CaCO_3
- b. The advent of an oxygen-rich atmosphere is reflected by the state of oxidation of iron in the rocks - 3 billion years old evidence of periodic abundance oxygen
- c. **Banded iron formations** (Fig 6-24)
 - i. alternation of rusty-red and gray bands caused by a fluctuating supply of oxygen
 - ii. red due to ferric iron oxide (Fe_2O_3) - indicate abundant free oxygen in the environment
 - iii. gray layers contain oxygen deficient iron compounds and suggest a lesser availability of oxygen
 - iv. extensive outcrops of dolomite and limestone

B. The Ocean

1. **Traditional View** - Water derived from volcanic emissions to the atmosphere after it had cooled sufficiently to condense and allow rain to fall
 - a. vast amounts of water were locked within hydrous minerals
 - b. "sweated" from the interior and precipitated onto the uplands

2. Been recycling since outgassing
 - i.* evaporation and precipitation powered by the Sun and gravity
 - ii.* temporarily lost by being incorporated into hydrous clay minerals that settle to the ocean floors, but returned water to the surface in the course of volcanic eruptions

VI. When the World was Young - The Hadean

The Hadean marks an interval of time when the Earth was constantly bombarded by large bodies. The tilt is evidence of the. Uranus is tilted at 90° and its rotational axis points nearly at the sun. Must have been a significant blow. Venus, in contrast, has only a slight tilt and retrograde motion (slight hit). Accretion of bolides has led to the declining rate in impacts (65 Ma is an exception)

A. Craters of the moon.

1. Maria (Latin for Seas) have long been observed (Galileo). (Fig. 6-5)
 - a. Maria are dark basaltic lava flows created by heat of impact.
 - b. Lunar highlands surround them are composed of rock fragments from pulverization.
 - c. Age span 4.0 to 4.6 Ga. Impact were 1000 times more frequency then as now.
 - d. Conclusion: Earth must have been bombarded by bolides as well.
 - e. Jupiter's gravitational field is a deflector.

B. Hotter Earth and Smaller Plates.

1. **decay of radioactive isotopes** more heat derived from radioactivity in the early days of the Earth than today - many short-lived isotopes
2. Faster Plate Tectonics engine-

C. Origin of the Oceanic Crust - Earth's original crust

1. **mafic** - dominated by iron and magnesium silicates
2. derived from an even more mafic (**ultramafic**) underlying mantle
3. Komatiites are ultramafic rocks formed at temperatures >1100°C - reflect the higher temperature gradients that prevailed during the Hadean
4. Extensive partial melting produced sufficient quantities of magma to form an early crust
 - a. tendency for slabs of primordial komatiitic oceanic crust to sink as they were being conveyed laterally by underlying convection currents
 - b. komatiitic additions to the surface may have been replaced by mafic magmas
 - c. added to the expanding oceanic crust at spreading centers

D. Origin of the Continents

1. **Felsic** crust continental crust that is rich in feldspars, quartz, and muscovite
 - a. oldest known patches of felsic crust are 3.96 billion years old
 - b. formed by metamorphism of **tonalite** a variety of the igneous rock diorite that contain at least 10% quartz the Earth has acquired patches of continental crust 4.0-4.3 billion years ago
 - i.* detrital zircon from Australia – 4.4 to 4.2 billion years old (fig 6-30)
 - c. originated at:
 - i.* mid-ocean ridges through partial melting (Table 6-3). Mineral assemblages that compose the felsic rocks have lower melting temperatures. Therefore, as magma cools, the mafic minerals crystallize out first. This leaves the melt rich in the felsic minerals. This process is referred to as **fractionational distillation**. This continues to recycled and partially melt to form additions to continental crust.
 - ii.* subduction zones where slabs of mantle were partially melted, releasing felsic components
2. Early Archean segments of continental crust were small, <500 km in diameter.
 - a. **Protocontinents** is the term for these floating tonalitic crust
 - b. rapid engine of plate tectonics accounts for this.
 - c. Any suturing would have been followed by rifting.
 - d. Only after PT engine slowed did the coalescing of protocontinent into large plates occur.

VI. The Archean Rocks

A. Sedimentary Rocks

1. Most are of deepwater origin - no broad continental shelves to accumulate sediments.
 - a. earliest patches of Archean continental crust
 - b. graywackes and dark shales were deposited in deep water environments adjacent to protocontinents

- c. absence of blankets of well-sorted, ripple-marked, cross-bedded sandstones suggest that Archean protocontinents were steep-sided, relatively small, narrow land masses with rugged shorelines
2. **Granulites and Greenstones** - Archean rocks of cratons are grouped into 2 major rock associations (Fig. 6-32)
- a. **greenstone** associations usually occur in roughly trough-like or synclinal belts prominent features of Archean terranes of all continents lavas of greenstone belts exhibit pillow structures indicate they were extruded under water (Fig. 6-32 6-33)
 - i. Most intriguing characteristic - roughly sequential transition of rock types from highly mafic near the bottom (komatiites) to felsic near the top
 - ii. Typical greenstone succession: felsic volcanics above mafic rocks; overlain by shales, graywackes, conglomerates, and by banded iron formations
 - iii. entire sequence is often surrounded by granitic intrusive rocks
 - b. **granulite** association: composed largely of gneisses derived from strongly heated and deformed tonalites, granodiorites, and granites, as well as layered intrusive gabbroic rocks called *anorthosites* few clues about the nature of parent materials can be found severely