Falling Apple Science Geology Outline

<u>Geography: Mapping the Earth</u>

Introduction: Exploring and measuring

Determining latitude from star positions (review)

Land surveying
- Measuring horizontal and vertical distances with a theodolite
- Example: Cassini's survey of France

Longitude at sea
- Astronomical methods
- Harrison's clock

Sea floor topography
- Automated sonar measurements
- Ridges and trenches

Summary: The world as it is today

We start with geography, because we must know how the Earth *is* before we can investigate how it *was*. In effect, geography serves as the "first-level" for geology. It is not perceptual level; on the contrary, the measurements require some advanced science. The observational base comes in part from astronomy and physics (which have already been discussed at this stage).

This unit should be offered as a separate lesson book (since it is not geology, but a prerequisite). This is a standard subject in every child's education, but our contribution will be original and much needed. Instead of having the students simply memorize the geo-political features of accurate world maps, we will focus on the measurements that led to such maps.

People discovered the present configuration of Earth by measuring positions—both horizontally and vertically, on land and sea, often during courageous trips exploring new territory. An accurate world map is an enormous achievement. We'll start by showing Ptolemy's world map, which was used until the fifteenth century. The students will recognize that this map is very roughly correct in the vicinity of the Mediterranean Sea and hopelessly inaccurate (or sheer fantasy) elsewhere. After a quick review of the European Age of Exploration, we should then show the Ortelius World Atlas (1572). This map is a huge improvement, but it still has major problems (including large distortions of the American continents and Greenland). The students will get the message: Only a few centuries ago, people were ignorant of the world we live on.

The theodolite came into widespread use in the 17th and 18th centuries. It's a tripod with a telescope that can be rotated horizontally and vertically; when properly aligned with a leveling device and a compass, it can measure horizontal and vertical angles very accurately. Using a surveyor's chain to determine a baseline length, triangulation can be used to determine horizontal distances and elevations over ever-larger regions. We should describe some important historical examples, such as the Cassini survey of France and Captain Cook's surveys of Newfoundland, eastern Canada, New Zealand, and Hawaii.

On land, the latitude of a location can be determined easily by measuring the altitude of the noon sun or the north star (or any bright star with known celestial coordinates). On a calm sea, latitude can be determined almost as easily by the same methods.

Determining longitude, however, was more difficult. Because of the Earth's rotation, longitude is equivalent to a time measurement. For example, if you know that an astronomical event occurred at midnight in London, but the same event occurred at 7 pm in Philadelphia, then you know that Philadelphia is 75 degrees west of London (an hour difference implies a 15 degree longitude difference). For example, in a method developed by Galileo, longitude can be determined by observing the times of the eclipses of Jupiter's moons.

But such astronomical observations can be made only on clear nights with a stable telescope; the method doesn't work well on a moving ship. In the early 18th century, longitude navigation at sea was still very inaccurate, with tragic results: Many ships sailed off-course and crashed, and thousands of sailors died. The problem was finally solved by John Harrison, who invented a mechanical clock that kept time very accurately even on a moving ship. (We should discuss Harrison's main innovations—the bimetallic strips to compensate for temperature changes, the frictionless mechanism that did not need lubricant, etc.) This was a great breakthrough in both navigation and mapmaking.

After the continents and islands had been accurately mapped, people were still ignorant about the two-thirds of Earth's crust that is under ocean. This last mapping problem was solved in the mid-20th century when ship surveys made automated sonar measurements of ocean depth. (The measuring devices are complex and we must decide on the appropriate detail of explanation.) The pattern of trenches and ridges eventually led to an understanding of seafloor spreading and to crucial evidence for the theory of plate tectonics.

<u>Stratigraphy: History Written in Stone</u>

- Uniformitarianism
  - Hutton's view of the principle
  - Contrast with "catastrophism" and "gradualism"
- Lithostratigraphy
  - Superposition principle
  - "Way-up" criteria (Loch Tray, Scotland)
  - Cross-cutting relationships (Glen Tilt, Scotland)
  - Unconformities (Siccar Point, Scotland)
- Biostratigraphy
  - Fossils are common in sedimentary rocks
  - Evolution means that fossils can be used as time markers
  - Use of "guide fossils" (trilobites, graptolites, conodonts, ammonites, foraminifera, pollen, brachiopods)
- Event horizons
  - Meteorite impacts
  - Super-Volcano eruptions
  - Earth's switching magnetic field
- Geological eras and periods

Like chemistry, geology was born during the Enlightenment as an off-spring of Newton's scientific method. James Hutton became the father of geology because of his commitment to what is called the "uniformitarian" principle. In essence, this principle states that the world around us was formed primarily by the slow, natural processes that we observe today. Contrary to popular belief at the time, it is not the result of supernatural intervention or cataclysmic events; the world can be understood by reasoning from observation. We need to start with a discussion of Hutton's principle, which does not deny the possibility of major events that occasionally cause some relatively fast changes. But even such events (e.g., unusually large volcanoes, floods, tsunamis or glacier movements) are natural and must be discovered by examining the geological evidence. Typically, the world was formed by slow processes that occur over many millions of years. (We need to distinguish “uniformitarianism” from the “gradualism” advocated by Charles Lyell. Unfortunately, Lyell seemed to misinterpret Hutton’s principle and deny the possibility of any rapid changes.)

Our discussion of Hutton’s method will serve as an introduction to the science of geology, followed by three lengthy chapters on stratigraphy.

The first of these chapters begins with lithostratigraphy, the study of the macroscopic physical properties of rock formations. We begin with the principle of superposition, which simply states that in undisturbed areas the rock layers are deposited horizontally, and the lower ones were formed first and are therefore older than those above. We should show pictures from places in the Grand Canyon where such layered horizontal deposits are easily seen.

In many areas, of course, severe geological activity has caused major deformations in the original rock layers. Here geologists use “way-up criteria” to identify the original orientation of the rock. In some rocks, grain size and gas bubbles give valuable clues (larger grains tend to be near the bottom and gas bubbles tend to be near the top). Also, wind and water erosion leave marks that indicate the original top, even after the rocks have been disturbed.

Some aspects of relative chronology can be determined by what Hutton called “cross-cutting” relationships. At Glen Tilt in Scotland, Hutton saw veins of granite running through the schist and limestone rocks. He realized that the granite penetrated the existing rocks while in a molten state, and therefore the granite was younger than the surrounding rock.

In complex rock formations, Hutton observed what he called “angular unconformities,” that is, formations where the layers of rock are angled quite differently. At Siccar Point, for example, there are layers of dark, hard sandstone that are nearly vertical, with horizontal layers of softer, red sandstone on top. Hutton realized that the original rock had been compressed, uplifted, and eroded, and then the horizontal layers deposited on top. He also realized that such structures require an enormous amount of time to form—there is the deposit of the initial layers, the slow compression and uplift, the erosion, and the deposit of the top layers. It must have taken millions of years, not the thousands that most people believed. (In California alone, there are many dramatic illustrations of angular unconformities, so providing great pictures will be easy.)

By itself, however, lithology cannot identify the rock layers that belong to the same geological period. Rocks of different periods can look similar, and rocks of the same period can look quite different (in different regions). Geologists were able to identify distinct periods of the past only with the help of the fossil record.

The geological study of the fossil record is called biostratigraphy. This is a complex science, but for our course we need an introduction that is stripped down to essentials. This can be done by emphasizing “guide” fossils. Such fossils must be abundant, geographically widespread, well-preserved, and fast-evolving. Not many fossils satisfy these criteria, but there are more than a half dozen that are outstanding. We need guide fossils that span the last 540 million years, from the beginning of the Cambrian period to the present. (I’m giving absolute dates, but we should restrict ourselves to relative dates at this stage. We don’t want to anti-climax the contribution of nuclear physics.)

The best such fossils are often from marine creatures that live in shallow waters and are mobile. In the early period (540 to 250 mya), trilobites (crab-like creatures), graptolites (worms in shells), and condodonts (small eels, usually recognized by their teeth) are excellent guide fossils. In the middle period (250 to 65 mya), ammonites (mollusks with coiled shells) and foraminifera (tiny shell fish) serve very well. In the recent period, pollen and brachiopods (with bi-valve shells) are good. The fact that marine fossils are found in inland areas and even at high elevations is very convenient (and was first noted by Aristotle).

All of these species have gone through many relatively fast evolutionary changes, and therefore the fossils can be used as accurate time markers. For example, a geologist may discover one ammonite fossil in a particular rock, and immediately know that the rock is 210 million years old (give or take a million years or so). The ammonite with that particular shell existed only for about a million years; the shells of earlier and later ammonites are noticeably different.

Major geological events such as meteorite impacts, super-volcano eruptions, and magnetic pole reversals can also be used as time markers.

Small meteorites (up to a few meters diameter) strike Earth fairly often, but they do not have any enduring effect on life forms and the environment. But large meteorites do have such effects, and they create enormous craters and the subsequent fallout causes a distinctive layer in rock deposits over a wide area. It is estimated that meteorites with diameters of at least 5 km impact Earth about every 20 million years. The most famous example is the Chicxulub impact event that occurred 65 mya, when a 10 km meteorite hit off the coast of Yucatan and contributed to the final extinction of the dinosaurs. We should summarize the evidence, including the iridium-enrichment of the rock layer from this time.

Super-volcanoes are defined as eruptions that eject at least a thousand cubic kilometers of material (which is almost a thousand times greater than the Mount St. Helen's eruption). Aside from the enormous lava flows, they leave ash deposits over very wide areas and can cause weather changes and extinctions. On average, they occur once every few hundred thousand years. Example: There was a super-eruption of the Yellowstone Hotspot about 640,000 years ago. The series of super-eruptions in Siberia about 250 mya played a causal role in the greatest mass extinction in history.

Magnetic pole reversals provide a less violent time-marker. The magnetic particles of rocks will align with Earth's magnetic field when the rock is forming (before it hardens). So such rocks provide an historical record of Earth's magnetic field orientation. Evidence clearly shows that Earth's magnetic pole reverses direction about every half million years (the time intervals seem to vary randomly, so this is an average). The last reversal occurred 780,000 years ago.

The combination of evidence from rock strata, the fossil record, and event horizons have enabled geologists to identify geological periods and their order. The transition from one period to another is characterized by major changes in life forms (extinctions or the appearance of new species) and/or major changes in the environment (weather, sea level, the amount of oxygen in the atmosphere and oceans, etc.). In other words, some basic changes occurred that made the world significantly different than it had been.

A great variety of macroscopic life forms have existed on Earth for the past 540 million years. This time span is divided into three eras: the ancient era (Paleozoic, 540 to 250 mya), the middle era (Mesozoic, 250 to 65 mya), and the recent era (Cenozoic, 65 mya to present). The boundaries between eras are marked by major extinction events.

Each era is divided into periods, which are distinguished by the emergence of new life forms and significant changes in the environment. Typically, geologists specify the exact start of a new period as the first appearance of a particular species in the fossil record of a certain region. We should give examples here, but the periods will be discussed later in depth.

<u>Types of Rocks</u>

- Igneous
    - *Granite, basalt, pumice*
        - Granite vs. basalt: granite has more quartz and less metal, and it is lighter in color and less dense
        - Pumice is low density, porous volcanic rock formed when lava foam is rapidly cooled
    - Formation
        - Basalt and pumice were recognized as "magma" rocks very early (by the Greeks and Romans), whereas the magma (or molten) character of granite was identified by Hutton
        - Plutons, intrusions, and eruptions
        - Locations of active and extinct volcanoes
- Sedimentary
    - *Shale, sandstone, limestone, coal*
        - Shale is a fine-grained, gray rock with clay minerals
        - Sandstone is a medium-grained, lighter-colored rock with quartz, feldspar, and mica
        - Limestone is light-colored and made of calcite and dolomite
        - Coal is dark-colored rock made primarily of carbon
    - Formation
        - The idea of sedimentary rock pre-dates Hutton; they are non-crystalline rocks made of compressed, irregular grains

Igneous rocks are broken into particles and then compressed to form shale and sandstone
Fossils and organic material can be compressed to form limestone and coal

Metamorphic

Slate, schist, gneiss, marble

Slate is shale that has been subjected to heat and pressure
Schist derives from sandstone or granite that have been subjected to higher temperatures and pressures; it is grainier than slate and lighter in color
Gneiss is similar to schist, except it has less mica was subjected to even higher temperatures and pressures, which cause it to be coarser-grained and more foliated (i.e., it has wavy bands of different color)
Marble is limestone that has been subjected to high temperature and then re-crystallized

Formation

Marble is the easiest "transformation" rock to understand: if you melt limestone and then let it cool, you get marble—this is evident from igneous intrusions into limestone formations
Slate can be produced from shale in the laboratory
Gabriel Daubree, a French geologist, performed experiments that transformed granite into schist (circa 1860)

Rock cycle

Igneous to sedimentary to metamorphic and back again
Discuss the separation of basalt and granite; in simple terms, explain Bowen's "reaction series" (developed at the Carnegie Institute in Washington D.C. in the early 20th century)

Geographic distribution of rock types

Aside from sedimentary deposits, continents are primarily granite and seafloors are primarily basalt
Metamorphic rocks are found mainly in mountainous regions or near igneous intrusions

The principle of isostasy

Isostasy is buoyancy applied to geology. The Earth's crust floats on a dense, viscous fluid called the asthenosphere. Changes in the elevation of the crust are caused by variations in its thickness and density. In the case of continental mountains, the crust is thicker—it protrudes higher above sea level and lower into the asthenosphere. When continents are contrasted with seafloors, the main issue is density; granite is lighter than basalt, and therefore floats higher. Aside from the geographical distribution of rock types, the evidence for isostasy is based on measurements of gravitational anomalies and seismic wave measurements that reveal deep structure.

At the narrower level of abstraction, the rock types are easily distinguished by their physical properties (e.g., granite, sandstone, gneiss, etc., look and feel quite different). The broader categories (igneous, sedimentary, and metamorphic) can be established by reference to where the rocks occur in formations and by high pressure/ temperature experiments. At this stage, some facts regarding the geographical distribution of rock types must be given without explanation. Later, these facts will be explained by the theory of plate tectonics.

Most courses present the distinction between igneous and metamorphic rocks as if it were on a par with the distinction between granite and slate. In other words, the students are simply told about these broader concepts without the inductive process of arriving at them. We will present the evidence that led to the concepts of igneous, sedimentary, and metamorphic rock. These concepts were developed before the theory of plate tectonics, and then the nature of the rocks and their geographical distribution served as evidence for the theory.

<u>Clocks in Rocks</u>

- Geology set free by nuclear physics
  - The late 19th century conflict between geology and physics
  - The discovery of radioactivity and decay rates
- Radiometric dating
  - The mass spectrometer
  - The uranium/ lead clock
    - U-238 to Pb-206 (4.5 billion years)
    - U-235 to Pb-207 (700 million years)
    - Zircon is often used because U can substitute for Zr but Pb cannot, so there was no lead in the rock initially
  - The potassium/ argon clock
    - K-40 to Ar-40 (1.3 billion years)
    - Potassium feldspar is often used
  - The carbon clock
    - C-14 to C-12 (6,000 years) works well for fossils in sedimentary rock that is less than 50,000 years old
- Measuring the age of Earth (4.5 billion years) from meteorites (lead isotope ratios)

Theory of Plate Tectonics

- Things out of place
  - Coal and fossils of tropical plants found too far north
  - Fossils of warm-weather animals found too far north
  - Evidence of glaciers found in the tropics
- The South America / Africa connection
  - The geographical and geological fit
  - Glacial record in Brazil and Congo
  - Fossil record: mesosaurus, lystrosaurus, glossopteris
  - Wegener proposed that all the continents around the Atlantic Ocean had been joined in a super-continent (Pangea), which had been initially located farther down toward the South Pole
- Sea-floor spreading
  - Volcanic activity along the ridges
  - Age and magnetic orientation of basalt seafloor
  - The Wilson cycle
    - The opening of an ocean (Atlantic), the subduction of an ocean (Pacific), the closing of an ocean (Mediterranean), and continental collision (India / Asia plates)
  - Hot spots and island arcs (Hawaii)
- Mountain ranges
  - Subduction
    - Andes and Cascades (Pacific plates and Americas)
  - Continental collision
    - Alps (Europe and Africa)
    - Himalayas (India and Asia)
    - Appalachians and Atlas (NE America and NW Africa)
    - Caledonides (Greenland and Scotland)
- Magnetic orientation of continental igneous rocks
  - Explanation requires continental drift and magnetic reversals
- Continental drift
  - Plate boundaries
    - World map of volcanoes and earthquakes
  - Measured drift velocities
    - The plate movements today, as measured by GPS, SLR, and very long baseline interferometry (VLBI); it is worth mentioning that movements of one inch per year can be measured today, although the techniques are too complex to describe in detail
  - Physical mechanism of the drift
    - Convection currents in the mantle

This should be told like a detective story. It starts when geologists discover lots of things mysteriously in the wrong place. If oil derives from organic matter, why are there huge deposits of it in desert areas? Why are fossils of dinosaurs that thrived in warm, humid climates found in South Dakota? Why are scratch marks from glaciers found on rocks in Brazil? The list goes on and on.

At the very least, geologists had to concede that Earth has gone through radical changes. Saudi Arabia used to be a rain forest, not a desert; parts of the USA that are now cool and arid used to be warm and wet; parts of Brazil used to be covered in ice; places at relatively high elevation used to be below sea level. These are not exceptions, but the norm. When geologists learned to read the clues, they found that nearly every area had a surprising hidden past.

As soon as there were accurate maps, people noticed the obvious geographical fit between South America and Africa. But the idea that the two continents had been connected wasn't taken seriously until Alfred Wegener noticed similarities in the rock formations, glacial evidence, and fossil records. In 1911, Wegener proposed his "continental drift hypothesis," and suggested that an enormous range of facts could be explained if all the continents had been connected in a super-continent (Pangea) about 250 mya, and Pangea had been located farther south. It then drifted north and broke apart.

The idea still seemed far-fetched, and most geologists regarded such circumstantial evidence as insufficient to support it. There was very little understanding of the seafloor, of mountain-building, or of any underlying causal mechanism for continental drift. At the time of World War II, geology was still in a relatively primitive descriptive stage. But the slow accumulation of evidence over the previous 150 years, in combination with a flood of new data made possible by modern technology, suddenly led to the proof of a grand-scale theory.

The mapping of the seafloor and its magnetic reversals was crucial. It became undeniable that the Atlantic Ocean was growing, the Pacific Ocean was subducting under the American continents, and the Mediterranean Sea was closing. When the plate boundaries were identified, geologists suddenly had a new understanding of mountain-building, earthquakes, and volcanoes. By the

1960s, Arthur Holmes developed a plausible mechanism for the drift in terms of convection currents in the molten mantle. The theory went from far-fetched to proven in a few decades—and the range of facts that it explains is extraordinary.

<u>Paleoclimatology: The History of Weather</u>

- Average temperatures of the past are estimated by oxygen isotope ratios and magnesium / calcium ratios in sediment samples
- Estimation of past atmospheric oxygen and carbon dioxide levels
- The carbon-oxygen cycle and the stability caused by negative feedback mechanisms
- Effects of the distribution of continents
  - Ocean currents and winds
  - Volume of ice sheets

Geologists use oxygen isotope and magnesium / calcium ratios as “paleo-thermometers” to estimate the average temperatures of past ages.

A small percentage of oxygen has an atomic weight of 18 rather than 16. In water molecules, the heavier oxygen evaporates more slowly and condenses more quickly, and the difference in the rates is temperature dependent. When the Earth is colder, it can be shown that there will be higher concentrations of heavy oxygen at low latitudes; when the Earth is warmer, the heavy oxygen will be more evenly distributed. So, for example, if limestone ($CaCO3$) that was formed 300 mya in the tropics is compared to limestone that was formed 280 mya in the tropics, it is found that the older limestone has a higher percentage of heavy oxygen. That means the average global temperature increased significantly during that time interval.

The second paleo-thermometer can also use limestone deposits. Magnesium can substitute for calcium in the molecules, and such substitutions occur more frequently at higher temperatures than they do at lower temperatures. Limestone with unusually low magnesium content may indicate an ice age, whereas limestone with high magnesium content implies a warm period. (Notice that we have two methods that can be compared, and that we need samples from a wide distribution of locations.)

History of the Earth

- Precambrian Age (4,540 to 540 mya)
    - Formation, cooling, structure
    - Bombardment by ice comets
    - Development of prokaryotic bacteria (3,500 mya)
        - Carbon dioxide and water and sunlight converted to carbohydrates and oxygen (changing atmosphere)
    - Development of eukaryotic organisms (2,000 mya)
        - Cell nuclei and sexual reproduction
        - First animal-like nucleated organisms (650 mya)
            - Little jellyfish and worms
    - "Snowball" Earth (750 to 580 mya)

- Paleozoic Age (Ancient life: 540 to 250 mya)
    - Change of conditions
        - Partial break-up of land masses and movement of some land toward tropical regions
        - Global warming and rise in sea levels
    - Age of Trilobites (Cambrian, 540 to 490 mya)
        - Explosion of primitive marine life
            - Seaweed, sponges, mollusks, worms, crustaceans, sea urchins, and trilobites
        - Ends with extinction event probably caused by decrease of oxygen in sea water and global cooling
    - Age of Shell Fish (Ordovician, 490 to 450 mya)
        - Various kinds of shell fish, shrimp, star fish, corals
        - Ends with major extinction caused by drop in sea level, change of currents and global cooling (ice age)
    - Age of Land Life (Silurian, 450 to 420 mya)
        - Melting glaciers and rise in sea level
        - Lots of low lands and shallow seas
        - Coral reefs and first fish with jaws
        - Development of ozone layer (UV protection)
        - First life on land
            - Vascular plants
            - Centipedes, scorpions and spiders
    - Age of Fishes (Devonian, 420 to 360 mya)
        - Warm climate (+6 C above today) and high sea levels
        - Fish
            - Sharks and armored, ray, and lobe-finned fish
        - Forests
            - First plants with leaves, roots and seeds

Major extinction in warm-water marine life
Decrease of oxygen level in oceans
Decrease in coral reefs
End of armored fish and trilobites

Age of Swamps & Coal (Carboniferous, 360 to 300 mya)

Lower sea levels created swamps
Rainforests and trees with very thick bark
Amphibians and gigantic insects (air rich in oxygen)
Formation of supercontinent called Pangea
Rainforest collapse
Cooler, drier weather
Formation of glaciers, drop in sea level

Age of Pangea (Permian, 300 to 250 mya)

Starts with ice age, then becomes warmer and drier
Inland areas
Transition from spore to seed-bearing plants
Land animals
Transition from amphibians to reptiles
Greatest mass extinction
90% of marine species, 70% of land species
Reduced coastal habitat and increased mountain ranges create desert conditions
Severe volcanic activity (mainly Siberia)
Eruptions of basalt increase carbon dioxide, methane, hydrogen sulfide, while decreasing oxygen in the oceans and creating worse desert conditions

Mesozoic Age (Middle Life: 250 to 65 mya)

Age of Recovery (Triassic, 250 to 200 mya)

Marine life
Recovery of ammonites and fish
Development of "lizard flippers"
Large swimming lizards (30 feet long!) with powerful jaws (top of the food chain)
Land animals
Heavily built, plant-eating lizard about the size of a pig (lystrosaurus)
Dominant predator was similar to a crocodile with longer legs (archosaur)
Break-up of Pangea
North America / Eurasia break away from northern South America / Africa

Antartica / Australia start rifting from southeastern Africa
Volcanic activity leads to major extinction

Rise of Dinosaurs (Jurassic, 200 to 140 mya)

Increased coastline and humidity; rainforests come back (high levels of oxygen and carbon dioxide)
Shallow seas increase fish and marine reptiles
Land animals
Enormous plant-eaters (sauropods)
Huge carnivores (theropods)
Flying reptiles (pterosaurs)

New Life and Oceans (Cretaceous, 140 to 65 mya)
North America breaks away Eurasia
South America breaks away from Africa
Growth of the Atlantic Ocean
High sea level, lots of marine life
Limestone characterizes this period
Flowering plants and bees
Ants, termites, grasshoppers, butterflies, and wasps
Rise of mammals and birds
Major extinction
Even higher sea levels cause stagnant epicontinental seas and loss of land habitat
North America collides with Asia, closing the polar sea and causing global cooling
Large meteor impact destroys ozone layer, causes acid rain and more cooling
End of the dinosaurs

Cenozoic Age (Recent life: 65 mya to present)

Age of Mammals (Paleogene, 65 to 23 mya)
Weather recovers (warming, high O_2 and CO_2)
Without predator dinosaurs, mammals and birds diversify and grow larger (marsupials in southern hemisphere and placentals in northern hemisphere)
Key plate movements
India collides with Asia (about 50 mya)
Africa moves toward Europe, closing the Mediterranean sea (about 36 mya)
Atlantic Ocean continues to widen (particularly in the north, where Greenland is pulling way from Scotland and volcanic activity is creating Iceland)
Antarctica moves to South Pole and becomes completely covered in ice
Cooling, decrease in volcanic activity and lower sea levels

- Age of Savannas (Neogene, 23 to 2 mya)
    - Weather similar to present
    - Establishment of widespread grasslands and grazing animals (antelopes, camels, horses, etc.)
    - Development of hominoids (upright-walking apes)
    - Changes in the Mediterranean Sea and the development of the Sahara Desert
    - Uplift of the Rocky Mountains (3 mya)
    - North and South America connect (3 mya)
    - Circumpolar currents replace equatorial currents
    - Permanent ice forms in Arctic (for the first time since the early Permian era almost 300 mya)
- Age of Humans (Quaternary, 2 mya to present)
    - Ice Age
        - Rare and prolonged events (compare to the two previous ice ages, 450 and 300 mya)
        - Self-perpetuating because ice reflects sunlight
    - Homo Erectus (~ 1.5 mya)
        - About our body size with 70% brain size
        - Made sharp-edged flint tools
        - Wore animal-skins for warmth
        - *Used* fire from natural sources (enormous advance)
        - Started in Africa, spread to Europe and Asia
        - Extinct by 200,000 years ago
    - Neanderthals (took over from erectus)
        - Physically strong; brains about the size of ours, but with less front brain and more back brain
        - Made better tools than his predecessor
        - *Created* and controlled fire
        - Extinct by 30,000 years ago
    - Modern Humans (~ 40,000 years ago)
        - Paintings, bows and arrows, oil lamps
        - Animal domestication
        - Agricultural revolution (began 10,000 years ago)
        - Towns and division of labor
        - Bronze and iron
        - Writing and science
    - Milankovitch Cycles
        - Effects on global weather of long-term variations in Earth's orbit and spin axis
    - Advance and retreat of glaciers (creation of Great Lakes)
    - Glacial maximum (18,000 years ago) caused low sea levels and land connections, leading to migrations

Civilization born during a warm interlude in the ice age (during the past 10,000 years)

Concluding Remarks

Glimpse at the Future

Continental drift

Weather

Some Essential References

1. John Noble Wilford, *The Mapmakers*, second edition (New York: Vintage Books, 2000).
2. Jack Repcheck, *The Man Who Found Time* (Cambridge: Perseus Books, 2003).
3. Peter Doyle and Matthew Bennett, *The Key to Earth History*, second edition (Chichester: John Wiley & Sons, 2001).
4. Donald Prothero, *Interpreting the Stratigraphic Record* (New York: W. H. Freeman & Company, 1990).
5. Cherry Lewis, *The Dating Game: One Man's Search for the Age of the Earth* (Cambridge University Press, 2000).
6. Ron Redfern, *Origins: The Evolution of Continents, Oceans, and Life* (University of Oklahoma Press, 2001).
7. *How the Earth Was Made*, pilot and 26 episodes (two seasons), available on Blu-ray from the History Channel.
8. Steven Stanley, *Earth System Theory*.
9. E. Kristen Peters, *The Whole Story of Climate*.