Just as a political revolution changes the way we think about a country or the world (e.g. Industrial revolution (1790), or the American (1775) and French (1789) revolutions), a scientific revolution changes the way we think about science, the world, the universe and even ourselves.
Examples of Scientific Revolutions

- The Copernican theory of the solar system
- Newton’s gravitational theory
- Geological time
- Darwin’s theory of evolution
- The theory of the structure of the atom
- Einstein’s theory of relativity
- The theory of plate tectonics

Note that two of these are geological
Geological Time

Early western ideas on the age of the earth were based on a reconstruction of biblical history:- Bishop Usher (1701) calculated that the earth was formed at 9:00 a.m. on October 29th in 4004 B.C.

In other words the earth is only about 6,000 years old!

James Hutton (18th century) was the first “real” geologist. He recognized that the earth had to be much older – probably millions of years old. He proposed his principle of uniformitarianism.

Simply stated - geological processes that we see operating today, are the same processes that operated in the past.

“THE PRESENT IS THE KEY TO THE PAST”
What was the geological evidence that convinced Hutton that the earth was many millions of years old?

James Hutton
1726 - 1797
Consider a layered sequence of sedimentary rocks (clay, silt, sand)

- Sediments form by particles (clay, silt, sand, shells) that slowly sink to the bottom of oceans and lakes.
- The lowest layers must be older than the upper layers.

**Hutton’s law of superposition**

- Accumulation rates are typically less than a few millimeters each year.
- Therefore, layers of sediments, such as this, over 8 meters thick must have taken around 8,000 years to form. **WHY?**
Clearly we have a problem!

The problem gets worse when we consider something like the Grand Canyon.

- The canyon is over a mile deep (about 2 kilometers).
- If sedimentation takes about 1 mm/year.
- Then the rocks at the bottom must be **at least 2 million years old!**

\[
2,000 \text{ m} \times 1000 = 2,000,000 
\]

In actual fact, the rocks at the bottom are close to 500 million years old!
The dilemma gets worse!

Consider these folded sedimentary rocks

- Folded layers of sediments in mountain ranges must once have formed slowly in horizontal layers at the bottom of oceans.
- They must then have been pushed into their present position by huge forces acting near the earth's surface.
- **ALL OF THIS TAKES TIME!**
- This is then followed by **erosion** to create valleys and mountains.
- **WHICH TAKES EVEN MORE TIME!**
and even worse!!

CONCLUSION: An unconformity must represent the passage of a great deal of time, and the earth must be many millions of years old.
Here’s how unconformities are produced

- Sediments are slowly deposited on the ocean floor.
- Subsequently they are folded and uplifted to form mountains.
- The mountains are gradually eroded away, producing hills and valleys, and eventually a flat plain.
- The plain sinks below the sea, and new sediments are deposited.

See page 36 - 43 in textbook
It was these geological examples that persuaded Hutton that the earth had to be very old, and that there was:

“no vestige of a beginning, no sign of an end”

This, of course, profoundly influenced how people thought about the earth, and paved the way for Darwin’s theory of evolution.
There are two kinds of information about time:-

- **RELATIVE AGE** - determined by the relationship of one rock layer to another.

- **ABSOLUTE AGE** – obtained from fossil information or radiometric ages.
Example of relative age:-

(Your book goes into this in great detail on pages 36 to 41)
Sequence of horizontal sediments deposited on the ocean floor. Oldest = Lutgrad Formation. Youngest = Leet Junction Formation.

Sequence of sediments intruded at some later date by molten granite body.
Subsequently, these rocks are folded to form a mountain range, and then gradually eroded down to form a flat plain.

The flat plain sinks below the ocean and sediments of the Larsonton Formation are deposited producing an UNCONFORMITY. Then a molten volcanic dike cuts through everything. Part of the dike and Larsonton Formation are then removed by further erosion.
Everything sinks below the ocean once again and we have deposition of sediments of the Foster City Formation.

Continued sinking leads to sediments of the Hamlinville Formation and Skinner Gulch Limestone being deposited. This is followed by another period of uplift above sea level and the beginning of further erosion.
Radiometric dating of the granite and the dike add further information

What do we know?
FINDING THE AGES OF ROCKS

There are basically two methods:-

- **USE OF FOSSILS**
- **RADIOMETRIC DATING**

**Use of Fossils**

Certain organisms are unique to a particular period of geological time. Hence their presence as fossils in a rock indicates that time period. For example on a very broad scale:-

- **DINOSAURS** – 280 to 66 million years
- **TRILOBITE** – 570 to 245 million years
- **AMMONITES** – 280 to 66 million years
- **SHARKS** – 500 million years to the present!

The process is refined and made more accurate by using single species and overlapping fossil assemblages.
Some examples of fossils:

Ammonites

Brachiopods

Trilobites
Here is an example of how index fossils are used to identify the major geological time periods.

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>FOSSIL</th>
<th>AGE (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary Period</td>
<td>Pecten gibbus</td>
<td>1.0</td>
</tr>
<tr>
<td>Tertiary Period</td>
<td>Calyptophrors velatus</td>
<td>66.4</td>
</tr>
<tr>
<td>Cretaceous Period</td>
<td>Scaphites hippocrepis</td>
<td>144</td>
</tr>
<tr>
<td>Jurassic Period</td>
<td>Perisphinctes tiziani</td>
<td>208</td>
</tr>
<tr>
<td>Triassic Period</td>
<td>Trophites subbullatus</td>
<td>245</td>
</tr>
<tr>
<td>Permian Period</td>
<td>Leptodus americanus</td>
<td>286</td>
</tr>
<tr>
<td>Pennsylvanian Period</td>
<td>Dictyoclostus americanus</td>
<td>320</td>
</tr>
<tr>
<td>Mississippian Period</td>
<td>Cactocrinus multibrachiatus</td>
<td>360</td>
</tr>
<tr>
<td>Devonian Period</td>
<td>Mucrospirifer mucronatus</td>
<td>408</td>
</tr>
<tr>
<td>Silurian Period</td>
<td>Cystiphyllum niagarense</td>
<td>436</td>
</tr>
<tr>
<td>Ordovician Period</td>
<td>Bathyurus extans</td>
<td>408</td>
</tr>
<tr>
<td>Cambrian Period</td>
<td>Paradoxides pinus</td>
<td>505</td>
</tr>
<tr>
<td>PRECAMBRIAN</td>
<td></td>
<td>545</td>
</tr>
</tbody>
</table>
An association of fossils helps to narrow the estimate of the time interval.
More on fossils

Some fossils develop particular morphological features (such as ridges, spines and crenulations) that only persist for a few million years. This enables us to narrow down the time in which the rock containing the fossil was formed.

This bronze-age man (~ 4,000 BC) emerged perfectly preserved from a glacier in the Austrian Alps in 1991. Imagine what might emerge from a glacier in the future!
**GEOCHRONOLOGY** – an absolute method (about 1% accuracy for measuring the ages of rocks, based on the radioactive decay of an unstable parent isotope to a stable daughter isotope)

<table>
<thead>
<tr>
<th>Radioactive Parent Isotope</th>
<th>Stable Daughter Isotope</th>
<th>Half-Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>$^{40}$Ar</td>
<td>$1.31 \times 10^9$</td>
</tr>
<tr>
<td>$^{87}$Rb</td>
<td>$^{87}$Sr</td>
<td>$4.88 \times 10^9$</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>$^{207}$Pb</td>
<td>$4.51 \times 10^9$</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>$^{14}$N</td>
<td>5,730</td>
</tr>
</tbody>
</table>

(Half-life is the time in years for a radioactive isotope to decay to half its initial amount)

Precise measurements (Mass Spectrometer) of the abundances of the parent and daughter isotopes give the age at which a rock formed.
The two basic equations for radioactive decay are:-

\[ N = N_0 e^{-\lambda t} \]
\[ D = N(e^{\lambda t} - 1) \]

Where:-
- \( N_0 \) = initial amount of parent isotope
- \( N \) = amount remaining of parent isotope
- \( D \) = amount of daughter isotope
- \( \lambda \) = decay constant = 0.693/half-life
- \( t \) = elapsed time since rock formed

[Note - the sum of the parent and daughter isotopes is always the same]

\[ N_0 = N + D \]
Consider the $^{14}$C dating method:-

$$\text{Age}(t) = \ln\left(\frac{N_0}{N}\right) \times \text{half-life}/0.693$$

Half-life = 5,730 years
$N_0 = ^{14}\text{C} = 13.56$ (a constant because it is the activity of $^{14}$C in the atmosphere)
Therefore to determine the age of charcoal all we need to measure is the amount of $^{14}$C remaining in the charcoal.

If the activity of the remaining $^{14}$C is 3.1, then:-

$$\text{Age}(t) = \ln\left(\frac{13.56}{3.1}\right) \times \frac{5730}{0.693}$$
$$\text{Age}(t) = 12,200 \text{ years}$$
### A simpler (back of the envelope) approach

<table>
<thead>
<tr>
<th>Number of half-lives</th>
<th>Amount of $^{14}$C</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>13.56</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>6.78</td>
<td>5,730</td>
</tr>
<tr>
<td>2</td>
<td>3.39</td>
<td>11,460</td>
</tr>
<tr>
<td>3</td>
<td>1.69</td>
<td>17,190</td>
</tr>
<tr>
<td>4</td>
<td>0.85</td>
<td>22,920</td>
</tr>
</tbody>
</table>

Our example with a $^{14}$C activity of 3.1 and an age of 12,200 years is obviously slightly older than two half-lives, but much younger than three half-lives.
Another example:-

The radioactive isotope $^{235}$U decays to the stable daughter isotope $^{207}$Pb with a half-life of 713 million years. If you analyze a rock in the laboratory and find it contains 50 parts $^{235}$U and 750 parts $^{207}$Pb, What is the age of the rock? Note - you are assuming that there was no $^{207}$Pb initially present in the rock, and that neither isotope has been lost from the rock over time.

\[
\text{Age}(t) = \ln\left(\frac{N_0}{N}\right) \times \text{half-life} / 0.693 \\
\text{Age}(t) = \ln\left(\frac{800}{50}\right) \times 713 \times 10^6 / 0.693 \\
\text{Age}(t) = \ln(16) \times 1,028,860,029 \\
\text{Age}(t) = 2.77259 \times 1,028,860,029 \\
\text{Age}(t) = 2,852,617,316 \\
\text{Age}(t) = 2,853 \text{ million years}
\]

(Note: $N_0 = N + D$ or $50 + 750 = 800$)
Back of the envelope approach:-

<table>
<thead>
<tr>
<th>Number of Half-lives</th>
<th>Amount of $^{235}\text{U}$</th>
<th>Amount of $^{207}\text{Pb}$</th>
<th>Total</th>
<th>Time in Millions years</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>800</td>
<td>0</td>
<td>800</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>400</td>
<td>400</td>
<td>800</td>
<td>713</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>600</td>
<td>800</td>
<td>1,426</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>700</td>
<td>800</td>
<td>2,139</td>
</tr>
<tr>
<td><strong>4</strong></td>
<td><strong>50</strong></td>
<td><strong>750</strong></td>
<td><strong>800</strong></td>
<td><strong>2,852</strong></td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>775</td>
<td>800</td>
<td>3,655</td>
</tr>
</tbody>
</table>

In the previous method we got 2,853 million years
### Some Interesting Ages

<table>
<thead>
<tr>
<th>Item</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age of the earth</td>
<td>$\sim 4.5 \times 10^9$ years</td>
</tr>
<tr>
<td>Meteorites</td>
<td>$4.57 \times 10^9$ years</td>
</tr>
<tr>
<td>Oldest moon rock</td>
<td>$4.1 \times 10^9$ years</td>
</tr>
<tr>
<td>Oldest earth rock</td>
<td>$3.9 \times 10^9$ years</td>
</tr>
<tr>
<td>Oldest rock on the sea-floor</td>
<td>$190 \times 10^6$ years</td>
</tr>
</tbody>
</table>

Why are the oceans so young compared to continents?