History of the Earth

An Integrated and Historical Perspective

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Contents

This photo, taken at Banff National Park, Alberta, shows glacially-fed Moraine Lake. The sky-blue hue you see in the picture is caused by light refraction off of rock flour in the water. This usually occurs during mid to late June of each year, due to increased melting from nearby glaciers.

McMaster University's Integrated Science Class of 2015

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Foreword

This book is the astonishing product of a group of undergraduates at McMaster University in Ontario. The students are 33 members of the Honours Integrated Science Program. They have collectively authored and compiled a book that interconnects history, mythology, religion and anthropology with the earth sciences.

Typically, the narration of a topic begins with the mythology or religious beliefs of ancient cultures, proceeds through the Age of Reason, then into the Industrial Revolution of the 1800s. It then merges into ever more rigorous scientific explanations of natural phenomena. For example, in "The Development of Volcanology" (beginning on p. 24), myths of ancient Greece are briefly described. One myth is that the volcanic eruptions and associated earthquakes were caused by the stirring of Typhon, imprisoned beneath Mt. Etna. (Typhon, according to the Encyclopedia Britannica, is a grisly monster with a hundred heads.) Another ancient Greek myth attributed activity at Etna and other Mediterranean volcanoes to the god of blacksmiths working at his subterranean forge. Later, the Romans had a similar myth, but called the god Vulcan. (The volcano "Vulcan" is off the coast of Italy and is still active.) The narration continues with the goddess of volcanoes in Hawaii, Pele. The author of this section writes about Pele in the past tense, implying that the myths died as Hawaii modernized. I have been to the Big Island of Hawaii numerous times and found that many Hawaiians sincerely believe that the goddess lives today and controls when and where eruptions take place in and around Kilauea, where eruptions have been ongoing for the last three decades. You can see floral and food offerings meant to appease Pele placed alongside recent eruptions.

The author returns to European history following the fall of the Roman Empire. During the Dark Ages and into the Renaissance, religion constrained reasoned investigation of volcanism. Volcanoes were regarded as passages to Hell and various levels of purgatory. In the eighteenth century, the Renaissance gave way to the Age of Enlightenment in which two competing schools of thought prevailed in Europe: Neptunism and Plutonism. Neptunism contended that all (or nearly all) of layered rocks had formed from precipitation from water. Plutonists claimed that the prevailing origin of layered rock was from molten rock flowing from the Earth's interior.

The rest of the nineteenth and twentieth centuries saw an exponential expansion of volcanology that the author, understandably, couldn't begin to cover in the allocated space.

So, who should read this book? Firstly, relatives and friends who should be quite proud of the authors. Then, there would be teachers of earth sciences who would like to convey the relationship of their sciences with the humanities to their students. Most readers of magazines such as Scientific American would enjoy it. One small group of people that could benefit from this book would be geoscience doctoral candidates preparing to take their general exams ("orals"). It was suggested to me that I study an introductory, physical geology textbook to prepare for my orals. Studying a book such as the present one should provide a broader perspective for a general exam.

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A divergent plate boundary in Iceland

History of the Earth

Science is a process – an activity of humanity's sharpest minds – driven by the noble emotion of curiosity. The search to understand nature, fueled by a thirst for knowledge, magnifies itself. Every new discovery has implications that bring new questions to light or offer new technologies which enhance our ability to analyze the world. By the nature of the scientific method, this search will never end. The logic of scientific discovery, grounded in attempts to falsify scientific theories without hope of proofs, necessitates this. Our knowledge of the Earth follows this pattern. There is still an incomplete knowledge of the planet and the development of our understanding continues.

Earth is the vehicle of scientific discovery. Human history is defined by its placement on the planet's surface while the terrestrial environment is shaped by humanity in turn. Within these pages, the progression of scientific knowledge of the Earth's processes and properties will be explored. This journey through the history of the Earth will encompass its most distinguishing feature – life. Living things come in many varieties but no single species has affected the Earth more than mankind. The interaction of terrestrial features with human civilizations is a short but key period which will be covered. Among these interactions will be the development of scientific tools according to intellectual challenges posed by the Earth. The culmination of the histories of the Earth and humanity manifests itself in the modern scientific knowledge of the Earth and is integrated across the sciences.

Figure 1.1: "Earthrise", a picture taken by Apollo 17 astronauts, shows the Earth rising above the horizon of the moon.

Chapter I: Properties of the Earth

Although the Earth's history spans 4.6 billion years, humans have only been present on its surface for a small fraction of that time. It is only in the past few millennia that there have been efforts to quantify and understand the planet Earth and why it alone can support life. Hundreds of influential thinkers, ranging from the time of the ancient civilizations to the present era, have contributed theories and ideas to develop our understanding of this planet into its current state.

Theories regarding fundamental properties of the Earth such as its shape, mass, size, and structure are relatively uncontested and are used in many modern applications. It has taken more than any one single experiment to reach this point. Instead, modern theories and ideas had to be developed and refined over time in order to better understand this extraordinary planet. Modern geologists have the privilege of expanding on the work of early scientists, such as Newton and Lyell, whose efforts form the foundation of modern science.

Knowledge of the Earth and its formation can not only aid in reconstructing the Earth's history, but can also provide insight on processes occurring elsewhere in the universe. In this way, the Earth can be used as a model for information about the formation and structure of distant planets. The topics discussed in this chapter are foundational, and yet still contain many unanswered questions and are the focus of much research today.

Although all of Earth's mysteries may never be uncovered, scientists throughout history have worked toward a complete understanding of the planet. In exploring the development of ideas surrounding Earth's basic properties and formation, this chapter hopes to explain how great minds throughout history have helped form the modern view of planet Earth.

Theories on the Formation of the Earth through Time

Since the rise of *Homo sapiens* the creation of the earth has been hotly debated. Many theories have arisen through the age of humans; from creation myths in ancient times to advanced scientific theories in modern day. The goal of this chapter is to investigate how theories have changed through the ages and the people who contributed to our modern understanding of the earth's formation. The most prominent theories through recorded history will be discussed.

Early Theories (3000BCE-1700AD)

Approximately 3000 years BCE there was a civilization, the Ancient Egyptians, that brought us many advancements in science. They were the first civilization to communicate through written language besides the Sumerians. The Ancient Egyptians had many different gods and many different creation myths, which tended to vary from city to city. Generally, the myths revolved around a god and a pyramid-shaped mound emerging from the **primeval** waters. The first thing to arise from the waters was the mound, which is also when the Egyptians believe the sun god **Ra** emerged (*Figure 1.2*). Ra or Atum-Ra was said to give rise to brother and sister air gods. The air gods then gave birth to the sky and earth gods who created the world, as the Egyptians knew it (Hagin, n.d.). Many other cultures had creation myths involving many different gods as well, including the Ancient Greeks, Romans and Norse all with unique creation myths.

Figure 1.2: The Ancient Egyptian sun God Ra, as can be seen with the Sun perched above his head.

Around 350 BCE **Aristotle** (384 – 322 BCE), a Greek philosopher, suggested that the Earth and the universe have always existed. This theory was quickly dismissed in favour of the views of **Christianity** (Pecorino, 2000).

The next prominent theory of the creation of the Earth involves **Jesus Christ** (c.2BCE-36CE), and the various religions branching from his teachings. Many religions are founded around the Bible and most are fairly similar but differ on some key points due to different interpretations of his teachings. However, the main focus will be on the most prominent religion, Christianity, as it is the most widely believed theist creation theory to date. Judaeo-Christian tradition obtains its creation theory from the Bible, which clearly states that God created the world in seven days.

"And God said, Let the waters under the heaven be gathered together unto one place, and let the dry land appear: and it was so. And God called the dry land Earth; and the gathering together of the waters called he Seas: and God saw that it was good." (The Bible, Genesis. 1:9-10)

According to the Bible this was how the Earth was created, there are many other references in the Bible to the creation of the Earth and an event chronology of the creation. In fact, **James Ussher** (1581-1656CE), a bishop scholar, calculated the date of creation by going back through the chronology of the Bible and found the date of creation to be Sunday October 23, 4004 BCE (Linder, 2004). This is not an exact date for the creation of the earth, due to Ussher having to make interpretations and assumptions for some dates. Scholars note however, that using this method, Ussher was able to determine the dates of non-biblical events with relative accuracy.

Theories of the Enlightenment

From the mid 1500's to the 1700's marked the start of the scientific revolution or age of **Enlightenment** and a change in the way of thinking, moving away from theist views. **Isaac Newton** (1642-1727CE) proposed a new paradigm where the world should be

explained by natural events as opposed to supernatural and that earth may be older than humankind (University of California, n.d.). One of the first people to observe these natural events was **Nicolas Steno** (1638-1686CE)(*Figure 1.3)*, a bishop and scientist like Ussher. He theorized that when any **strata**, a layer or a series of layers of rock in the ground, was being formed, the material on top was fluid-like and therefore nothing above the strata existed during its formation. This observation led to three very important concepts in geology, the law of **superposition**, the principle of original **horizontality** and the principle of **cross-cutting** relationships all dealing with dating the relative age of rocks. These theories also suggested that the Earth must be old for these processes to occur (Waggoner, 2000).

Figure 1.3: A portrait of Nicolas Steno, the bishop and scientist who theorized the laws of superposition, original horizontality and cross-cutting.

Newton's views of the world also aligned with **Charles Lyell**'s (1797-1875CE) theory of **uniformitarianism**, as opposed to catastrophism. **Catastrophism** was a theory supported by **Joseph Fourier** (1768-1830CE) who thought that sudden events rapidly changed the face of the Earth (University of California, 2008). This theory shortened the lifespan of the Earth since it suggests short periods of time could cause major alterations. In 1830, with the help of **James Hutton**'s (1726-1797CE) ideas that the Earth was subject to slow changes that can be seen today, Lyell came up with the theory of uniformitarianism. This theory states that the processes of today were the same processes at work in the past, therefore making the earth very old. The theory proved to be monumental as now much of the Earth sciences is explained by geologically long processes. Hutton and Lyell's theories lead to the concept of the **rock cycle**, as it is known today. Hutton also made many observations about the strata of places he visited in his travels, commenting on **unconformity** and horizontality (University of California, 2008).

In 1862, **William Thomson** (1824-1907CE) tried to recalculate the age of the Earth in accordance with new theories assuming the Earth began as a completely molten planet. He calculated the time it would take for the surface to cool to the present temperature and obtained an approximate age of 20-400 million years old (Rognstad, 2005). These calculations proved to be wrong since they did not take into account convection or radioactive decay, theories that came about after this time. Thomson was given the title "**Lord Kelvin**" for his scientific work and again recalculated the age of the earth in 1892CE after he had done some work with thermodynamics. He used thermal gradients to approximate the age at 100 million years but was still wrong due to the lack of the differentiated Earth model (Rognstad, 2005).

Recent Theories

Planetary **differentiation** was one of the last keys to the puzzle of discovering the Earth's origins. The differentiated Earth model (*Figure 1.4*) showed that the Earth had layers and conformed with uniformitarianism, dealing with geophysics of the Earth. The

Figure 1.4: The differentiated Earth model showing the different layers of the interior of the Earth.

model has high-density materials sinking to the core and lower density materials staying on the surface creating a metallic core and silicate-rich outer crust (Camp, 2006). The pressure difference and densities also allow the planet to have a solid inner core, molten outer core and solid mantle and crust. This helped scientists understand that the earth was much older than originally thought and maybe has a different method of creation.

The final piece to discovering the origin of our planet was the discovery of **radiometric dating**. **Arthur Holmes** (1890-1965CE) was the first to see the significance of the application in geology. It was found that the decay process emitted heat, which most previous calculations used to estimate the age of the earth (Calvert, 2003). The discovery of radioactive decay meant that all previously estimated ages of the Earth were inaccurate since the Earth was creating its own heat rather than just dissipating heat. During the early 1900's Holmes researched the use of radioactive decay to date rocks using their isotopes. Finally in 1927 he published a book where he estimated the age of the Earth to be between 1.6-3 billion years old (Calvert, 2003). The estimate was inaccurate because at the time he was still refining his techniques to measures the isotopic ratios. Later, in the 1950's, scientists would estimate the age at 4.5 billion years overturning his estimate.

Refuter

A Christian geologist named **Steve Austin** (active) still believes in young Earth theories. He highlights possible flaws in present theories including how catastrophism is a more likely cause of Earth's creation compared to uniformitarianism. He believes that many beds and much sediment can be deposited rapidly in a short period of time (Heaton, 1995). One of his major examples is how he thinks that a **slurry** flow created some of the beds in the Grand Canyon (*Figure 1.5*). He also refutes radiometric dating as making too many assumptions for its data.

Figure 1.5: A photograph of the Grand Canyon showing the many different layers of strata, which Austin suggested were laid down in as little as minutes.

Many theories contributed and provided hints to the Earth's origin, including theories about its age and processes that adhere to uniformitarianism. These theories all led to our modern understanding and theory of how the Earth was formed. Although, as can be seen, there is still little opposition to these theories and there is not yet a definitive explanation of the Earth's formation, only theories that can build evidence.

Earth Formation through Astrophysics

Our modern understanding of the age and formation of the Earth has become an intricate and advanced theory that works off established theories from the Enlightenment age as well as theories that have branched from new technology.

Edwin Hubble (1889-1953CE) and **Georges Lemaitre** (1894-1966CE) also contributed to our modern understanding of the formation of the Earth. These two scientists are attributed with the **Big Bang theory**, although it is debated about who came up with the idea first (Gibbs, 1997). Their observations that nebulae and galaxies were moving away from the Earth led them to believe that the universe is expanding (Sloan Digital Sky Survey, n.d.). They then went on to model the universe's expansion and determined that at some point in the past all of the matter in the universe was compacted into a single point in space. This point in space then erupted in some way, which is where the "big bang" term was coined, and the universe was created as the matter spread out from the point, creating galaxies and other celestial bodies. This is the modern understanding of the formation of the Universe and Earth's earliest beginnings. There are many new theories arising, however the majority of astrophysicists still agree with a version of the big bang theory.

The Earth formed as part of the development of the solar system. One of the techniques now used to estimate the Earth's age and origin focuses on the analysis of **chondrites** (*Figure 1.6*). Chondrites are meteorites formed from material that is considered to represent the original material from which the solar system formed. They are made up of calcium-aluminum-rich inclusions (CAIs), silicate spherules and a fine-grained matrix (Scott, 2007). Chondrites can be dated using radiometric dating techniques and provide an important record of what was happening in the early solar system. Using techniques initially developed by Holmes for isotopic dating, scientists calculate the ratio of aluminum 26 to magnesium 26. Aluminum has a **half-life** of about 0.73 million years for which it radioactively decays into magnesium. The data we gather from this is a relative age between the chondrules, molten grains that have cooled, in the chondrites and the CAIs. The decay of the aluminum to magnesium can be used to determine the age of the meterorites and estimate the timing of early solar system events. It is also possible to find an absolute date of formation for these chondrites using other isotopes such as lead-207 and lead-206. Lead-207 decays from uranium-235 with a half-life of 704 million years whereas lead-206 decays from uranium-238 with a half-life of 4.5 billion years (Tatsumoto, 1973).

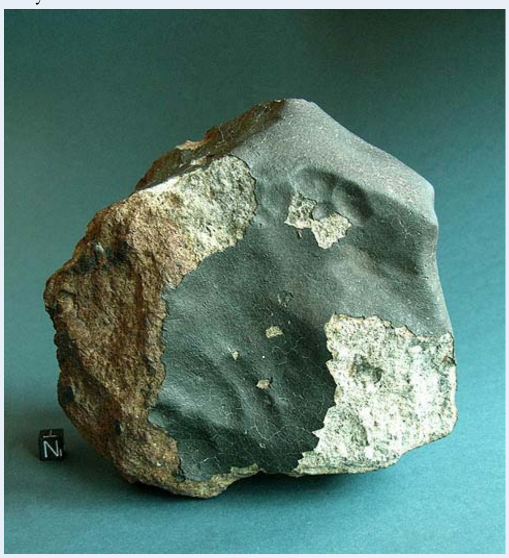


Figure 1.6: A chondrite found in North Africa, which also shows the energy of some of the collisions in the early Solar System evident from the melting on the surface.

Chondrites are generally dated to be 4.6 billion years old, about the age of our solar system. These absolute dating techniques can be combined with the relative dating techniques to compare different chondrites. The composition of the chondrite meteorites tell us that during the early solar system there were large amounts of dust forming into large disks by analyzing key chemicals known to be abundant at that time. This was a key discovery to the formation of our planet as the dust and debris became **planetesimals**, large bodies that could now exert their own gravity (Scott, 2007). The chondrites also helped date the age of the Earth to our current understanding of 4.54 billion years.

The theories of the 20th and 21st century have greatly increased our knowledge of how the Earth formed. These theories have been put together to come up with the protoplanet hypothesis. After star formation there is a gaseous protoplanetary disk surrounding the star. As previously mentioned it is believed that the Earth started off as an **accretion** of dust in the solar system. This dust accumulated due to the rotation and gravity of the sun (Scott, 2007) forming planetesimals from the protoplaentary disk. As the planetesimal grew it collided with more dust and grew larger. This attracted more dust to it, promoting further growth and finally forming a **protoplanet**. Many protoplanets could form fairly close together and inevitably there were collisions heating the forming planet and melting its materials. At this point the differentiated Earth model begins to come into effect as the materials melt and sort by density. Eventually the planetesimal grows to the size of a planet with its own orbit around the sun, which is how it is believed the Earth formed (Scott, 2007).

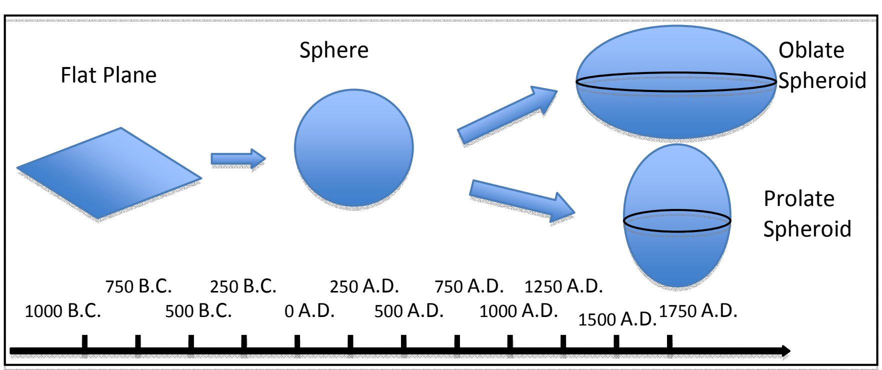
Discovering the Shape of the Earth

In 1996, the spacecraft, **Lunar Orbiter 1** produced the first photograph of the planet Earth from its trajectory around the moon (Dick, 2006). Prior to this accomplishment, scientists were unable to view the Earth as a whole and were forced to rely on mathematical, astronomical, and logical reasoning when theorizing about the Earth's structure and shape. Many scientists have speculated about the shape of the Earth throughout history proposing a variety of different shapes, from planes to cylinders (Figure 1.7) (Robinson, 2011). It was not until the mid 18th century that the figure of a flattened spheroid was confirmed, settling an outstanding debate from the time of the Ancient Greeks (Robinson, 2011). This important discovery has aided in visualizing and quantifying our remarkable planet.

The Flat Earth Theory

The most primitive figure of the Earth was developed by some of the world's oldest civilizations (Robinson, 2011). These civilizations came to the common conclusion that the Earth was a flat plane, suspended in space. On clay tablets, the Sumerians and Babylonians recorded their belief that the Earth was a surface located between sky and the underworld (Garwood, 2007). Similarly, Ancient Egyptians wrote on papyrus of the Earth god, Geb, who stretched out to create a plane on which people could live (Garwood, 2007). Across the Mediterranean Sea, the early Ancient Greeks also shared the belief of a flat earth. However, it was in Ancient Greece that these theories developed and took on a new form (Garwood, 2007).

Figure 1.7: A timeline of the dominant models of the Earth throughout history



The Earth as a Sphere

The philosophers of Ancient Greece proposed several new, innovative shapes of the Earth. This divergence from the flat Earth model represented a step away from the traditional religious beliefs and a step towards a more scientific way of thinking. One of these prominent thinkers included **Thales** (625 – 547 BCE), who adapted the model to a buoyant, circular disk that floated in the universe (Garwood, 2007). This was followed by **Anaximander** (611 – 545 BCE) who claimed the Earth was cylindrical with man-kind inhabiting the top circular face (Garwood, 2007).

It was in this intellectual environment that the idea of a spherical Earth was conceived. Although it is uncertain who should be credited for this novel idea, this notion can be traced to **Pythagoras** (582 – 500 BCE) and his fellow Pythagoreans (Garwood, 2007). Pythagoras is most well known for his contributions to mathematics including his observations of right-angled triangles in Pythagorean theorem. It is unclear why the Pythagoreans believed the Earth to be a sphere. However, it has been hypothesized that this opinion stemmed from their belief that a sphere is the ideal shape (Garwood, 2007).

The spherical model was re-examined by **Plato** (427 – 347 BCE) and his influential pupil, **Aristotle** (384 – 322 BCE). Aristotle sought to prove the accuracy of this model and he discussed his findings in many of his written works (Garwood, 2007). He proposed three reasons to accept the spherical Earth figure. Firstly, Aristotle observed that on the horizon, a ship's hull disappeared before its mast (Garwood, 2007). If the Earth was flat, these two components should vanish simultaneously. The Greeks were avid observers of the moon and stars and Aristotle was no exception. Secondly, Aristotle examined lunar eclipses and rationalized that the circular shadow cast by the Earth onto the moon could only be made by a round object (Garwood, 2007).

Finally, Aristotle noted that at different latitudes the stars varied in position. These findings were published in Aristotle's book *On the Heavens* which was widely distributed to the public (Garwood, 2007). This spherical Earth theory would become dominant in Greece and eventually spread to the rest of the world.

Once the shape of the Earth had been determined, there was a shift in focus from qualitative to quantitative observations (Garwood, 2007). Greek academics began their attempts at measuring the size of the Earth using mathematics and astronomy. **Eratosthenes** (276 – 194 BCE) calculated a value for the circumference of the Earth using geometry (Garwood, 2007). Although his logic was flawed, his results were surprisingly accurate by modern day standards. Philosophers also started broadening their area of study to the universe and the Earth's position within outer space (Garwood, 2007).

Other parts of the world took more time to abandon the flat Earth theory outlined in the Bible and other religious scriptures. Nevertheless, the spherical Earth model became well known throughout Europe and the Middle East and remained uncontested until the **Enlightenment** (Garwood, 2007).

The Many Contributions of Isaac Newton

The spherical Earth theory was commonly accepted by the public and the scientific community until the publication of **Isaac Newton's** (1642 – 1727) *Principia* in 1687 (Figure 1.8) (Hoare, 2005). In the first edition of the *Principia*, Newton hypothesized that the Earth is an imperfect sphere, slightly flattened at the poles. He came to this conclusion after examining the results from experiments conducted by **Jean Richer** (1630 – 1696) in Paris and Cayenne. Richer measured the length of a **seconds pendulum** at these two latitudes and found that the pendulum had a definitively shorter swing by approximately 188 seconds per day in Cayenne (Hoare, 2005; Greenberg, 1995). Newton attributed this effect to a smaller gravitational force per unit mass at the equator compared to northern latitudes.

In the third edition of the *Principia* (1726), Newton further described his thoughts on the Earth's shape. He viewed the Earth as a rotating homogenous fluid with two balanced columns meeting at the center and running along the equatorial and polar axis (Greenberg, 1995). Newton postulated that if the Earth rotated around its polar axis, the equatorial axis would experience a centrifugal force in addition to the force of gravity. In order for the two axes to balance and be in accordance with the universal inverse square law, the equatorial axis must be longer than the polar axis (Greenberg, 1995). From these observations Newton calculated the ellipticity or flattening of the Earth using the formula:

$$\varepsilon = \frac{E - P}{P}$$

Thus, Newton concluded that the Earth was an **oblate spheroid** with an ellipicity of 1/229 (Greenberg, 1995).

Newton's discoveries would spark a debate between the English and French philosophes at the heart of the "Age of Reason" also known as the Enlightenment.

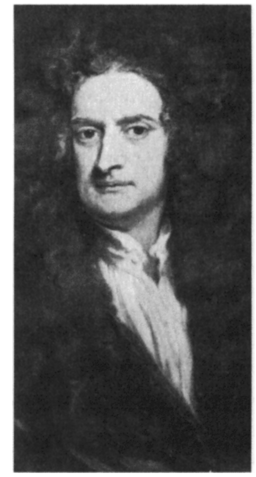


Figure 1.8: A portrait of Isaac Newton, who contributed much to the scientific world including his idea that the Earth was an oblate spheroid.

The "Age of Reason"

During the late 17th century, two prominent groups of intellectuals existed in Western Europe (Robinson, 2011). The **Royal Society** located in London and the **Academie Royale des Sciences** of Paris, were two institutions at the forefront of scientific thought during this time period. After Newton's findings were announced, the societies became locked in a debate over the true figure of the Earth (Robinson, 2011).

Although Newton was a member of the Academie Royale des Sciences, his theories were not as popular in France as they were in London (Hoare, 2005). The French were reluctant to replace Descartes' principles with Newton's new theory of gravity. Concerning the Earth's shape, the French favoured the **prolate spheroid** while the English supported Newton's suggestion of an oblate spheroid (Hoare, 2005). The prolate model reasoned that Richer's observations were caused by uneven distribution of mass in the Earth's interior with more material at the poles than at the equator. This phenomenon was supported by **Jean Picard** (1620 – 1682) who incorrectly found the length of a degree to decrease going North from the Equator

(Hoare, 2005). This controversy lead to the publication of numerous papers in the 1730's on this topic.

For this particular discovery, the French played a more active role than the English (Hoare, 2005). This was, in large, due to one member of the Academie, **Pierre Louis Maupertuis** (1698 – 1759). Maupertuis was a mathematician who, after an inspiring trip to London, was responsible for converting the society to Newtonian principles. In order to determine the Earth's shape, Maupertuis organized two expeditions to compare the measurements of a degree of latitude near the equator and near the Arctic Circle (Robinson, 2011). These two trips were the first scientific expeditions to be conducted on an international scale, paving the way for many more scientific discoveries (Hoare, 2005).

The Peru Expedition

Peru was selected to be the equatorial location for the degree survey. The party departed on May 16th, 1735 and was composed of several esteemed society members including **Louis Godin** (1704 – 1760), **Pierre Bouguer** (1698 – 1758) and **Charles-Marie de La Condamine** (1701 – 1774) (Hoare, 2005). The group would return to Paris eight years later after facing countless complications and struggles in Peru. Overall, the trip was poorly planned, fraught with problems, and progressed at a painfully slow pace (Hoare, 2005). The intent of the voyage was to measure a degree, near the village Quito, using a surveying method called **triangulation**. This was accomplished by setting up a network of triangles between two points located approximately a degree apart (ICSM, n.d.). A baseline was established by carefully measuring the side length of one triangle within the triangle array. Trigonometry could then be used to solve for the remaining side lengths and the distance between the two points using the baseline and measured angles (ICSM, n.d.). This method is necessary because angles could be more accurately measured than large distances (Hoare, 2005). Astronomical sightings were used to determine the position of the relevant points on the Earth's surface and to determine the curvature of the Earth.

From the start of the journey, problems arose with both the group members and the destination. Although all brilliant thinkers, the surveying party lacked leadership and confrontations were common (Hoare, 2005). At several points in the expedition the group split up, leaving individual members to make their own way to complete their objective. A severe miscalculation of funds also hindered the party and delayed its advancement (Hoare, 2005). The party soon realized Peru was a difficult place to complete its work. The terrain was rugged and the inexperienced Frenchmen struggled with the precarious trails and river crossings, as well as the physical fitness required to traverse Peru's mountains and valleys (Hoare, 2005). This made the process of placing pegs to form triangles slow and arduous. Collecting astronomical data proved challenging because of nearly constant fog and cloud cover (Hoare, 2005). The party was often forced to remain at a location for days until the sky cleared. Peru was also a haven for disease and insects which affected many of the party members throughout the journey, taking the life of one (Hoare, 2005). Misfortunes continued when political relations between the Spanish and the French became strained, causing problems for La Condamine and their two Spanish guides. The result of all these factors was a long and gruelling trip for the travellers; however it was not without accomplishment. Despite the many setbacks, the survey was successfully completed yielding a final measurement of 56 753 *toises* (110611.6 m) (Hoare, 2005).

The Lapland Expedition

Shortly after Godin and company embarked for Peru, Maurpertuis gained approval from the king of France to conduct a similar experiment in the North (Hoare, 2005). The Swedish – Finnish border in the Arctic Circle was chosen as a destination and the party departed on April 20th, 1736. This expedition was less eventful than its southern counterpart. Although the team experienced difficulties with the terrain and climate, the survey was conducted precisely and efficiently. A degree was found to be greater at northern latitudes with a length of 57 437 toises (111944.7 m) (Hoare, 2005). The party returned to Paris on August 20th, 1737, at the same time the scientists in Peru began taking their preliminary measurements (Hoare, 2005).

These two expeditions confirmed Newton's theory that the Earth is an oblate spheroid, a figure that remains accepted to this day. This discovery was an important contribution to the understanding of the Earth and has proven useful in many applications of geodesy including mapping, navigation, and surveying. The Peru expedition was the first of its kind, and soon expeditions became a common method in the pursuit of scientific discovery.

Geographic Coordinate Systems

Discovering the shape of the Earth was an important step in the development of modern mapping and navigation systems. Satellite imaging has allowed the shape of the Earth to be further refined to a more precise model. As well, significant improvements to satellite technology have greatly advanced navigation, allowing for the transmission of real time data and positioning. Today, maps are not only used to display locations on the Earth's surface but are also useful in the analysis of geographic data.

Geospatial data are created when an object such as a city or geographical feature is assigned a coordinate, linking it to a position on the Earth's surface (Chang, 2012). This is accomplished using a Geographic Coordinate System(GCS) (ESRI, 2012). A GCS has four main components: a datum, spheroid, prime meridian, and unit of measure (Chang, 2012). Combined, these components allow data to be referenced in a way that provides information about its position relative to other points and the Earth's surface.

A coordinate is defined by angular values of longitude and latitude (ESRI, 2012). These values represent the angle created by a position on the surface of the Earth, the center of the Earth, and a baseline of longitude and latitude. For latitude values this baseline is the equator and for longitude values it is the prime meridian (most commonly running through Greenwich, England) (Chang, 2012). Lines of equal latitude and longitude create a grid called a **graticule**.

A **datum** is used to relate a graticule to a chosen spheroid. It specifically defines the position of the spheroid in relation to the Earth's center (ESRI, 2012). There are several different spheroids that have been developed for mapping of specific areas, all with different axial lengths (Chang, 2012). This is because the Earth is an irregular spheroid with the South Pole located closer to the equator than the North Pole. In order for precise mapping, cartographers orient the graticule in a way that maintains accuracy for the region of interest (Chang, 2012).

Because there are a variety of spheroids and datums, there are also many different GCSs. In Canada, the most common GCS is NAD 1983 (ESRI, 2012). This coordinate system was designed for use in North America and was created using ground and satellite observations. It uses the Earth's center of mass as an origin and the GRS180 spheroid. NAD 1983 is programmed to shift with the North American tectonic plate to prevent it from becoming obsolete with time (ESRI, 2012).

Two common applications of GCS are in **Geographic Information Systems** (GIS) and **Geographic Positioning Systems** (GPS). GPS is a commonly used navigation system that uses satellites to determine geographic position and route to a desired location (Figure 1.9) (Chang, 2012). The GCS used in GPS is WGS84. GIS is an information system that is able to store, analyze, manipulate, and display geospatial data. It is used to solve problems by combining maps and statistical data for analysis (Chang, 2012). GIS is used by governments and businesses for a wide variety of purposes. Geospatial data is incredibly useful and essential to the functioning of modern day society. GCSs are key to referencing data to positions on the Earth's surface (Chang, 2012).

Figure 1.9: GPS devices come in many different forms including handheld devices (top), vehicle devices (middle), and devices in cell phones (bottom).

Measuring the Mass of the Earth

Weighing a planet is hard. This difficulty is increased when those wishing to weigh it are confined to its surface. However, scientists are nothing if not persistent in their goals. It was only after much struggle, long years of tedium, and several prophetic jumps in reasoning that humans came to learn the mass of the planet on which they lived. Even more remarkable than the thought of 18th-century scientists attempting to measure the mass of an entire planet was the fact that they were within 1% of the modern-day value (Figure 1.10).

The Genius of Newton

In 1687, **Sir Isaac Newton** (1642-1727) published the *Philosophia Naturalis Principia Mathematica*, or, as it is more commonly known, the *Principia*. In it, he formulated his **Law of Universal Gravitation**. In plain terms, the Law states that any two given objects will exert an attractive force on one another, that this force increases with their combined masses, and that it decreases with distance between them. In expressing the formula of the Law, it becomes necessary to convert it into modern units and terms. This is particularly true of mass. Mass is measured in kilograms and is different from weight, which is measured in newtons. Mass is the amount of matter an object contains. Weight is a measure of the force that a planetary body, like the Earth, exerts on an object due to gravity (NPL, 2010). This is given by:

$$F = \frac{GM_1M_2}{d^2}$$

wherein F is the force of attraction due to gravity between any two bodies, M_1 and M_2 are the masses of those two bodies, d^2 is the square of the distance between them, and G is the **gravitational constant**. While Newton did not know the value of the constant at the time of writing, or even during his lifetime, he did know it would be a very small number and had a rough idea of its value. He was credited with hypothesizing the Earth had a density somewhere between five and six times that of water (Newton, 1687). This suggests a value of G somewhat near the modern one. The conversion between G and density is possible as, after experiments to measure the size and shape of the Earth (see *Chapter 1*), knowing the planet's density was equivalent to knowing its mass, and vice-versa. Newton also proposed a method by which one, at least in theory, could measure G. As he knew all bodies will attract each other to some extent, if one were to place two objects of known mass a known distance from each other and measure the force they exerted on each

Figure 1.10: The planet Earth, with a mass of 5.9736×10^{24} kg and a density of 5.515 g/cm^3 or 5.515 times that of water.

other, one could solve for G. From here is it a simple rearrangement of variables to solve for the Earth's mass. Newton had given the world a way to weigh the Earth. However, gravity is a very, very weak force. By picking up this textbook, the reader has overcome the combined gravitational exertions of an entire planet. To measure the force of gravity between two weighable objects is an extremely difficult task, and Newton himself was not sure that anyone could achieve such a measurement. Perhaps it is not surprising, then, that the world would have to wait another half-century for anyone to even make an attempt (Poynting and Thomson, 1909).

The first attempt at solving this problem was made by redefining what was considered 'weighable'. The experiment occurred during the same ill-fated Peruvian expedition that measured the length of a degree at the equator amid some of the most inhospitable terrain on Earth (Ferreiro, 2011). Along the way the members stopped at a mountain named Chimborazo, whereupon **Pierre Bouguer** (1696-1758) became the first to make a serious attempt at a measured value of the Earth's mass. He used a version of Newton's original theoretical experiment. The first mass, a plum bob of known weight, was suspended by a string and allowed to hang freely in order to measure its deflection, and thus attraction, towards the second mass: the mountain itself. The distance between the plum bob and mountain was measured and the weight of the mountain was estimated by vague, tenuous means. No result of any precise quantitative value was yielded by the experiments, but two valuable lessons were still learned: that the planet's density was much too great to allow for a hollow or water-filled core (two popular theories of the day), and that the basic idea behind the experiment seemed valid (Poynting, 1894). Bouguer himself saw the experiment as unsatisfactory and did not have any confidence in the result. He (presumably resenting the original choice of location) suggested that the experiment be taken up once more if a more suitable mountain in France or England were found (Danson, 2006).

The Schiehallion Experiment

It was 30 years before anyone got around to the task. The **Reverend Dr. Nevil Maskylene** (1732-1811) was, at the time, England's Astronomer Royal. As such, his duty was to advise the British crown on matters of astronomy. Thus, it was as a highly respected and established scientist he approached Britain's Royal Society in 1775 with a proposition: form a committee and hire an expedition to find a mountain of roughly uniform shape so that a reasonably accurate measurement of its volume might be made (Maskylene, 1775). The expedition was as much in pursuit of glory for the nation as it was in pursuit of scientific ideas. In arguing for the expedition, Maskylene was sure to mention that credit for a discovery as monumental as the Earth's mass would surely be more at home in England than anywhere else (Maskylene, 1775).. Whatever the reason that ultimately swayed his contemporaries, his approach must have worked: explorers were commissioned and set out at once, and it was not long before a suitable mountain was found in Scotland. The mountain was named Schiehallion and by the very next summer instruments had arrived at its base and observatories had been set up (Poynting, 1894). The experiment was carried out in much the same way as it was at Chimborazo, except for a few improvements that had been retrospectively suggested by Bouguer and now implemented by Maskylene. There were more instruments, more readings, and more locations, but ultimately they were still measuring the deflection away from zero that the mountain brought about in a plum bob. More interesting, this time, was the problem of how to measure the mass of the mountain. This, the researchers planned, would be calculated from the average density of stone (2.5 times that of water), and multiplied by the mountain's volume (Poynting, 1913). However, this proved to be an issue. They had no way of knowing that the mountain was made of uniform material throughout, and thus that its overall density was that of average stone. This issue was not addressed, and it was considered to be a necessary contribution to error. In addition, while the mountain was roughly uniform in shape, it was still not a perfect cone. To solve this issue, cartographers divided the mountain into rough sections and aimed to calculate the volume of each segment. To do this, they took many measurements from various points on the mountain's faces. Each of these points was labelled with their corresponding elevations. When famed geologist and expedition member **James Hutton** (1726-1797) got the idea to draw lines between points of equal elevation, he invented contour lines (Danson, 2006). In the end, the expedition's data yielded a result of Earth's density being between 4.56 and 4.87 times that of water. Thirty years later, a more accurate re-measurement of the same mountain's density brought this number up to five. In the end, using plum bobs, an odd mountain, and simple arithmetic, the values of the Earth's density that were suggested by Maskylene's data sets were still within about 20% of the modern measurement of the Earth's density.

The Cavendish Experiment

It would be another 20 years before the world would have any measurement more accurate. The **Reverend John Michell** (1724-1793) proposed and built a device that utilized principles Newton had first suggested 200 years earlier (Figure 1.11). Unfortunately, he died before he could make use of his own invention. It was packed up and sent to **Henry Cavendish** (1731-1810), likely because he was already known and respected worldwide as an eminent physicist and quantitative experimentalist. Cavendish carefully studied the machine and rebuilt it with slight modification (Poynting, 1894). Both Michell's and Cavendish's devices consisted of a long, horizontal rod from which two small lead balls were hung on each end. The rod itself was suspended on a wire, so that it could twist freely. Two larger lead spheres would be placed on opposite sides of the rod near the small lead balls, such that gravitational attraction between the two pairs of balls would cause the rod to twist ever so slightly (Cavendish, 1798). Before the experiment, Cavendish measured the force required to twist the wire by a unit degree. Thus, as the rod's twisting could also be measured in degrees, the genius of the device allows the gravitational attraction between these two balls to be directly measurable (Poynting, 1913). The force involved here was so small that even the slightest factor could throw off Cavendish's experiments by huge margins. He reported that air currents formed by minute temperature differences between ends of the rod would disrupt his results. He ended up locking the device in a completely enclosed room in which he had installed a window. He took measurements through a telescope peering in from several rooms away. He installed scales that allowed him to measure distances of less than 100ths of an inch.

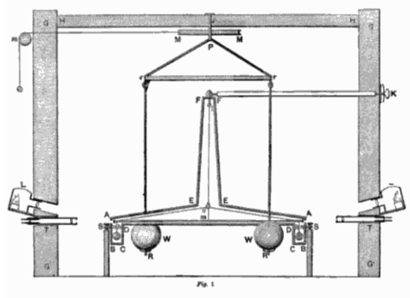


Figure 1.11: The apparatus for weighing the world. Invented by John Michell and recreated by Henry Cavendish.

All of this is a roundabout way of stating that Cavendish was nothing short of meticulous in his methods. It was his dedication to preciseness in his work that would eventually bring him success. In the end, without leaving his house or armchair, Cavendish was able to generate a measurement of the Earth being 5.448 times the density of water (Poynting 1913). This was within 1% of 5.515, the modern value for the density of the Earth (Jungnickel and McCormmach, 1996). Thus ends the story of the 1700s man who weighed the Earth from his armchair in order to confirm, without leaving his house, the predictions Newton had given a hundred years prior.

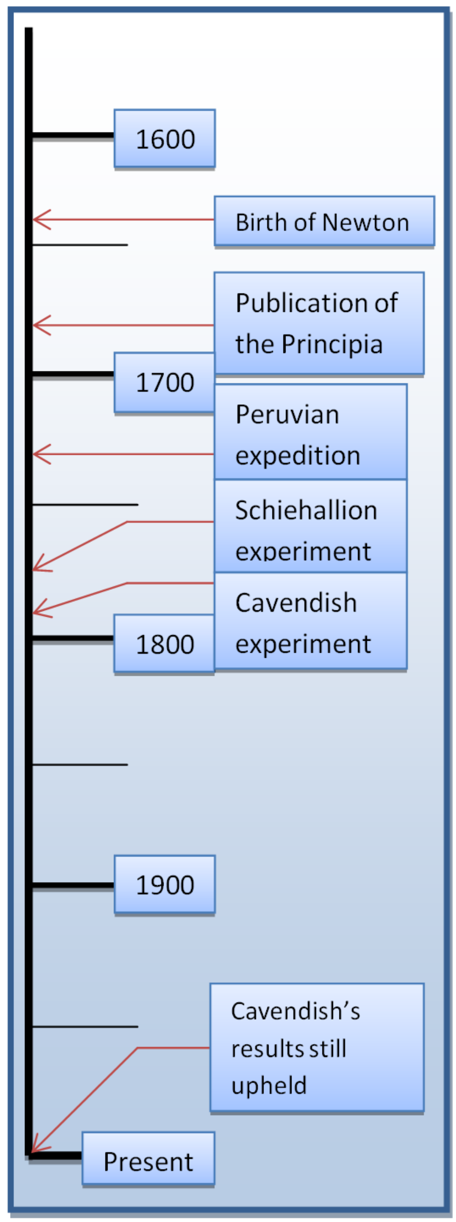


Figure 1.12: A timeline outlining major events spanning from the birth of Newton to the present day.

The Masses of Galaxies

The ability of science to measure mass is not limited to objects found on planet Earth. In fact, the masses of other planets, stars, and even galaxies are all within the scope of scientific knowledge. In order to measure these massive cosmological entities, astronomers are using some very old techniques to establish and validate some very new concepts.

The masses of planets, stars, and galaxies can be approximated using concepts developed in Enlightenment era physics. Newton's law of gravity states that the acceleration of any object as it orbits another is proportional to the mass of the body it is orbiting (Seeds and Backman, 2010). Thus, in the case of a planet's orbit, the heavier the star, the faster the planet will rotate about it. That is, if one imagines two stars identical except for their masses, each with a single planet at the same distance away, the heavier star's planet will orbit faster. This phenomenon scales predictably and thus, if the speed of a planet in orbit about a star is known, the mass of the star can be calculated (Smolin, 2006). This is, in essence**, Johannes Kepler**'s (1571-1630) Third Law.

Figure 1.13: A galaxy. Its mass can be calculated by measuring an outer star's orbiting velocity and distance from the centre of mass.

This approach can also be used to measure the masses of galaxies (Seeds and Backman, 2010). If the diameter of the visible portion of a galaxy is known, the period of the outermost stars can be calculated using the Doppler Effect. This is because the period of a galaxy, often in the hundreds of millions of years, is an impossible length of time to directly observe. This yields a measurement of all of the mass contained within the chosen star's orbit. Selecting an outermost star for measurement will yield the mass within the entire visible portion of the galaxy (Smolin, 2006).

In Practice…

In recent decades, astronomers have measured the mass of a galaxy using the above procedure, known as the **rotation curve method**, and then measured it again by simply counting all of the stars, visible gas clouds, and dust that they can see in the galaxy. These individual objects are then assigned approximate weights. Conventional understanding suggests that these two estimations of mass should be approximately equal. However, they are not and show considerable differences (Smolin, 2006). The errors are not small and can be on the order of a factor of ten, all trending in the same direction. The explanation for these differences in mass estimation may lie in the fact that there is not enough visible matter to account for all of the mass that exists in galaxies. The apparent lack of visible matter in galaxies stimulated the development of the modern concept of a new type of matter, one that does not emit or reflect light. To account for discrepancies in mass estimations, this new type of matter must also make up the majority of matter in many galaxies. Physicists and astronomers have dubbed this novel material **dark matter**, and there seems to be no shortage of it (Smolin, 2006). By its very nature, a material that does not interact with light is difficult to study. However, despite the fact that there exists no modern instrument that can directly observe it, it is interesting to note that its existence was established by the use of physical formulas over 300 years old. What other wonders do the genius minds of learned scientists like Kepler or Newton hold for the modern world?

Structure of the Earth: Early Beliefs to Modern Theories

With roots deep in the mythologies of ancient cultures, a history full of evolving views, and a modern model very different than the ideas preceding, our perceptions of the Earth's structure have wildly changed, and are likely to continue to change.

The Classical World and Medieval Europe

For many ancient civilizations, the interior of the Earth was an underworld for the dead; but contrary to **Judeo-Christian** views, this was not always a place of punishment for the damned.

The **Hades** of the ancient Greeks and Romans, for example, was a massive underground chamber separated by five rivers, with different areas for people based on their deeds during life (Homer, c. 800 BCE).

In ancient cultures, the Earth's interior evolved with the addition of mythology rather than by scientific discovery. The oldest descriptions of Hades can be found in **Homer**'s (c. 800 BCE) epic *Odyssey*. In his work, Homer divides Hades into Elysium, a place where "men lead an easier life than anywhere in the world", and Tartarus, a Christian Hell-analog (Homer, c. 800 BCE). While Homer's underworld was sparse on topographical descriptors and focused more on events occurring within Hades, the generations of poets that ensued added increasing amounts of detail.

By **Virgil**'s time (70 BCE – 19 BCE), the underworld was significantly more detailed. In Virgil's *Aeneid*, Tartarus was described as a massive walled fortress encircled by a river of molten flame, Elysium was equated to a spring meadow, and Asphodel Meadows had been added, which was a limbo where neutral shades resided (Virgil, c. 24 BCE).

In medieval Europe, ideas about the interior of the Earth were well-established in the populace by the Catholic Church. **Zeitgeist** beliefs were conveyed by *Inferno*, the first **cantica** of **Dante Alighieri**'s (1265 - 1321) three part epic the *Divine Comedy* (Conard, 2011).

Dante portrayed Hell as a series of nine concentric circles deep inside the Earth, with inner circles dedicated to the punishments of increasingly severe sins. The innermost circle, situated at the centre of the Earth, held Satan prisoner in a vast frozen lake of his own tears. Dante noted the change in direction of gravity as his protagonist progressed beyond this circle (Alighieri, 1555).

Alighieri's work drew heavy inspiration from *Aenid* from over a thousand years prior and borrowed frequently from Virgil's story elements. For instance, the walled city of **Dis**, containing the inner four circles of Hell (Alighieri, 1555), is heavily based off of Virgil's own description of Tartarus (Virgil, c. 24 BCE). Greek mythological creatures such as **Cerebus** and the **Minotaur** also appear, along with Greek underworld rivers such as the **Styx** and **Phlegethon**. Finally, it is Virgil himself that guides the protagonist, Dante, through the centre of the Earth (Alighieri, 1555). Like the *Aenid* before it, Dante's work would hold cultural impact for centuries to come (Conard, 2011).

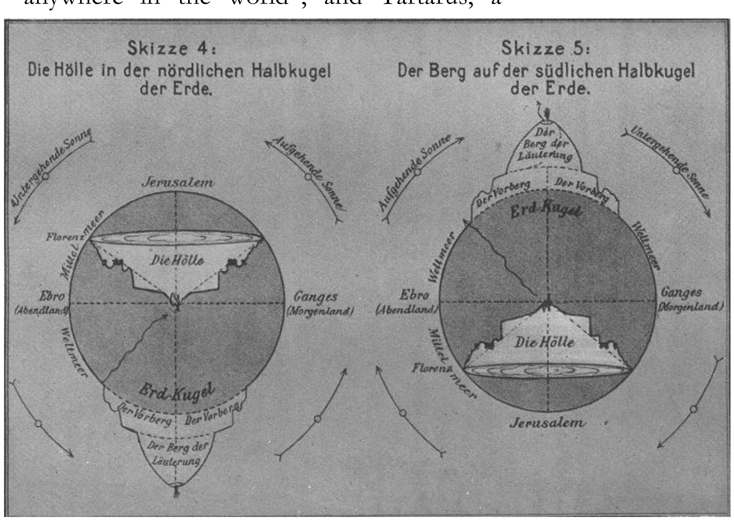


Figure 1.13: The Earth's interior according to Alighieri's Inferno. Here, Hell is shown as a series of concentric circles terminating at the Earth's core. The circles are perpendicular to Jerusalem and have an entrance close to Florence, Italy, where Dante entered the nine circles in the Divine Comedy.

Hollow Earth

As European culture was enamoured with the concept of a subterranean underworld at the time, it seemed only logical that following the **Scientific Revolution**, the first serious scientific models of the Earth suggested it was hollow.

Throughout the late 17th and early 18th centuries, **Edmond Halley** (1656 - 1742) developed and updated an early **concentric sphere model** in his paper, *An account of the cause of the change of the variation of the magnetical needle with an hypothesis of the structure of the internal parts of the Earth*.

Halley argued for his model by citing **Isaac Newton**'s (1642 - 1727) *Principia* (1687), in which Newton erroneously calculated the density ratio of the Moon to the Earth to be nine to five. To this end, Halley rationalized that four-ninths of the globe was cavity (Halley, 1753a). Halley then elaborated upon his model by drawing upon his study of magnetic compass variations at high latitudes and changes in **magnetic declination**, which he accounted for by postulating that the Earth possessed four magnetic poles (Halley, 1753a). Finally, when questioned about the cause of an exceptional aurora borealis display in Northern Europe in 1716, Halley suggested that they were caused by luminous vapour escaping from deeper levels of the Earth through thinner ground at the poles (Halley, 1753b).

Thus, Halley came to the conclusion that the Earth consisted of a series of three concentric shells and a solid core, each with their own luminous atmosphere, magnetic poles, rotational speed, and, to the joy of science fiction writers for centuries to come, possible inhabitants (Halley, 1753a).

While Halley did acknowledge weaknesses in his model (for instance, what would cause the oceans from leaking to a lower level in the event of a catastrophic earthquake?), it proved to be quite popular. Six versions of his paper were published in total, two posthumously (Halley, 1753a).

To the credit of early scientists, Hollow Earth provided a plausible explanation for many unaccountable phenomena at the time. Earthquakes, volcanoes, sinkholes, and springs sufficed to show that the planet was not completely solid. Caverns provided access to strange worlds beneath the surface, and, in the absence of understanding a mechanism for their formation, fossils reasonably suggested that an inner world could harbour undiscovered creatures (Griffin, 2000).

Although Hollow Earth was scientifically rejected by his time, the American **John Cleves Symmes Jr.** (1780 - 1829) created another Hollow Earth model by amalgamating concentric and **central sun models**; the result was an Earth composed of five hollow spheres with access points at the poles (Griffin, 2004). Symmes even proposed an expedition to the high arctic to find such access points. President **John Quincy Adams** (1767 – 1829), a supporter of Symmes's ideas, almost publicly funded Symme's expedition had it not been for the disapproval of congress. Unfortunately for Symmes, and to the relief of American taxpayers, Adams left office before anything could occour, and the succeeding president, **Andrew Jackson** (1767 - 1845), immediately canceled any government support for Symmes (Griffin, 2004).

While Hollow Earth existed in literature long before Symme's time, his efforts in America to promote his ideas inspired an outburst of works from the **subterranean fiction** genre in the 19th century, which, to some degree, continues to this day (Griffin, 2004).

Symme's rich geographical descriptions of his model inspired the imaginations of authors such as **Jules Verne** (1828 - 1905), **H.P. Lovecraft** (1890 - 1937), **Thomas Pynchon** (b. 1937), and many others. Anonymously authored *Symzonia* (1820), a utopian novel which details an adventure in a Symmes-esque Hollow Earth inhabited by humanoids, is one famous example (Fitting, 2004). Although Hollow Earth had no place in science, it had found a permanent spot in the imaginations of authors.

While Hollow Earth was very popular among the general public as a subject of fiction, the expansion of scientific knowledge caused increasing problems to Hollow Earth supporters. Especially concerning were problems described by widely accepted Newtonian physics, which predicted that a hollow body would, over time, collapse to form a solid body; what would stop a Hollow Earth from becoming a solid sphere (Griffin, 2004)?

Figure 1.14: Halley holding a drawing of his concentric Hollow Earth model.

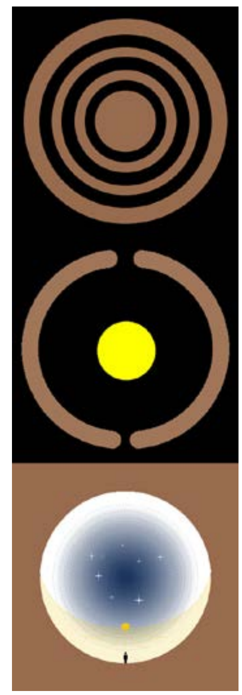


Figure 1.15: Hollow Earth models can be divided into three main groups: concentric spheres, central sun, and concave. Concentric model was the earliest model. Central sun model was popular amongst writers of subterranean fiction. The most recent addition is ***concave model*** *(c. 1960; Griffin, 2000).*

Solid Earth

The idea of Solid Earth developed concurrently with Hollow Earth. Like early Hollow Earth models, the first Solid Earths were based on a mixture of incorrectly interpreted observations and fantasy; for instance, after he was inspired by a trip to Mt. Vesuvius in Italy, **Athanasius Kircher** (c. 1601 - 1680), described the Earth as a solid mass fissured by fire channels, each originating from a chamber at the core and terminating on the surface at volcano (Fitting, 2004).

Multi-phased layered models resembling modern views were not developed until much later than Kircher, when the density and shape of the Earth were known. In the late 18th century, Henry Cavendish (1731 – 1810) indirectly determined the density of the Earth by accurately measuring the **gravitational constant** with a torsion balance (Bolt, 1982). Since the radius of the Earth and gravitational acceleration were known at the time, this allowed the calculation of the Earth's mean density with the formula:

$$M_{earth} = g_{accel}\frac{R_{earth}^2}{G}$$

This gave a value around 5.45 g/cm^3.

By the mid-19th century, it was shown that the Earth was not a sphere, but an ellipsoid flattened bout the equator. Mathematicians

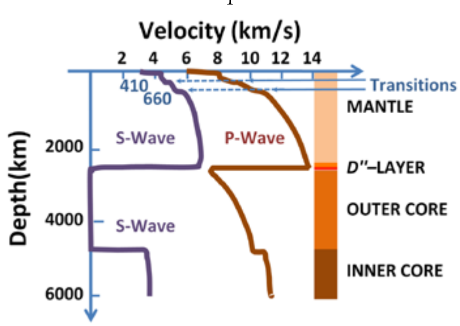


Figure 1.16: A graph depicting earthquake wave velocity in each layer of the Earth. S wave velocity at the inner core is hypothetical; as liquids cannot host transverse waves, S waves cannot breach the liquid outer core to reach the inner core. An S-wave shadow forms on any location more than 104° from the epicenter; S-waves received beyond this are faint and the result of repeated reflections off the outer core boundary.

at the time theorized that this shape was caused by centrifugal forces during a time when the Earth was completely liquid. From here, they made other rational arguments, such as an increase in density of materials towards the center of the Earth, caused by **planetary differentiation** (Bolt, 1982).

A problem faced early geophysicits attempting to model a Solid Earth: in 1870, it was known that temperatures increased with depth at a rate of about 1 C° per 50 metres. At this rate, temperatures at depths of 500 km would have exceeded 10 000 C°, which is hotter than the surface of the sun. To account for this, geophysicists postulated that the Earth cooled from the core and the surface, concentrating heat somewhere in the middle. As a result, most Solid Earth models of the time had a dense solid core, a fluid or **plastic** mantle, and a low density crust (Bolt, 1982).

From here, an impasse was reached. How large are each of the layers, how sharply are they defined, and what are they comprised of? Speculation on possibility was no substitution for hard evidence.

Such questions were finally settled by the invention of **seismology** at the turn of the 19th century, when geologists realized that earthquake waves were affected by the structures they traveled through (Bolt, 1982).

Richard Dixon Oldham (1858 – 1936) was one of such individuals. In his 1906 publication, *The Constitution of the Interior of the Earth, as Revealed by Earthquakes*, Oldham supplied evidence for a distinct central core by observing differences in **S-wave** and **P-wave** arrival times at observatories worldwide. He noted that at locations beyond 130° from the **epicenter**, S-waves begin to arrive drastically later than P-waves. Oldham explained this by suggesting the existence of a central core through which S-waves where significantly slowed while P-waves were relatively unaffected. From this, he estimated the radius of the core to be 0.4 R, a little off from the modern value of 0.55R. While in modern times, we know that the S-waves Oldham observed beyond 130° were reflected S-waves travelling in the mantle, his paper was none the less the first attempt to analyze the Earth's interior using seismology (Bolt,1982).

Using Oldham's technique, another fundamental discovery was made in 1909 when **Andrija Mohorovičić** (1857 - 1936) found the first evidence for a sharp boundary between crust and mantle rocks. By observing a sharp difference in S-wave and P-wave arrival time ratios near 2° for local earthquakes, he hypothesized a change in the physical properties of rock at a depth of 50 km. Although varying in depth, this discontinuity was later shown by to occour worldwide (Bolt, 1982). Today, it is named the Mohorovičić discontinuity in his honor. From these origins, the current model of the Earth was developed: one of a thin crust floating over a viscous mantle, supported by a liquid outer core and a solid inner core. While minor details are ever subject to change, it is unlikely that a paradigm shift such as that from Hollow Earth to Solid Earth would ever occur again.

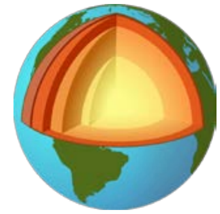


Figure 1.17: The modern "onion" model of the Earth's structure.

Modeling the Interiors of other Planets

Astrogeologists are faced with challenges that Earth-bound geologists are not; they often do not have the privilege of freely taking rock samples, seismographic readings (with the exception of the Moon and Mars; although these tend to be too weak to be of any analytical use), or drilling boreholes. So what can one do to determine the structure of a planet from the confines of a space probe?

Such a task often consists of two components: direct observation and intelligent guesswork (Scharringhausen, 2004).

Many properties of a planet important to its structure may be directly observed: gravitational acceleration, **oblateness**, radius, magnetic field strength, and atmosphere permitting, surface rock composition and topography (Scharringhausen, 2004).

From gravitation acceleration and oblateness, the mass and density of a planet can be determined (Scharringhausen, 2004). From the presence or absence of a magnetic field, deductions about a planet's core structure can be made. A planet's topography may also give hints as to if plate tectonics are or were active on the planet (Schombert, 2012). Surface rock composition may give astrogeologists an idea of how differentiated a planet is (Schombert, 2012). If a lander can be successfully deployed upon a planet surface, further measurements can be made. All inner planets are assumed to have undergone a phase during which they were completely liquid prior to a period of cooling. During this time, differentiation occurs. Because larger planets lose heat more slowly, and thus remain molten longer, they tend to have better differentiation of layers, a thinner crust deficient in heavy elements, and larger heavy metal cores (Schombert, 2012).

The structure of Mars was modelled using such techniques. Being smaller than the Earth, Mars is thought to have cooled more rapidly and to have poor differentiation of elements, resulting in an abundance of heavy iron at its surface, and a thick crust (1% of total radius, opposed to Earth's 0.5%) (Schombert, 2012). Finally, the Martian core is likely solid, and incapable of the **dynamo effect**, as Martian landers and orbiters have only detected a weak magnetic field (Luhmann and Russel, 1997). While these techniques are satisfactory for terrestrial planets, it more is challenging to work on the gas giants, as they lack any visible solid surface features, and conditions in their interiors push the limits of what laboratories can simulate. As such, our understandings of their interiors tend to be based on theoretical predictions rather than actual data based on the behaviour of matter at extreme conditions (Scharringhausen, 2004).

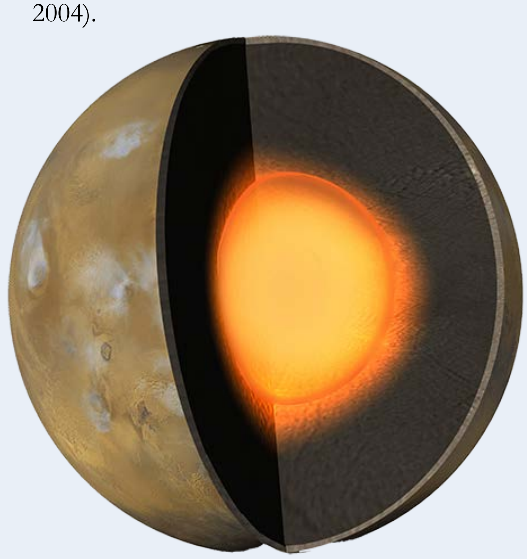


Figure 1.18: An artist's impression of Mars's interior. Note the solid core and thick crust.

Figure 2.1: Interior Earth processes often have dramatic impacts on the Earth's exterior. This is evident in the formation of volcanoes and also in their explosive activity.

Chapter II: Interior Earth Processes

For thousands of years, the processes and phenomena associated with the interior of the Earth have influenced human populations ignorant of the changes occurring beneath their feet. Governed by the structure of the Earth's interior, these processes also determine several of the events that are manifested on the exterior of the Earth. These phenomena include earthquakes and volcanic activity, frightening happenings that became integral parts of many early religions.

The main contributor to interior Earth processes, internal mantle convection, drives plate tectonic movement, which in turn causes volcanoes, earthquakes and ***tsunami***. Volcanoes occur on plate boundaries and above mantle plumes, while *tsunami* are caused by the displacement of large volumes of water. This displacement of water can be caused by meteor impact, landslides, underwater explosions, and most frequently, by tectonic action.

While contributing to many belief systems and confounding human populations, these processes also drove the development of much conceptual knowledge in the field of geology. Understanding of the driving forces behind observable natural phenomena developed gradually over time, leading to a better understanding of the cause of natural disasters, as well as techniques with which they can be analysed and predicted.

Development of the Theory of Continental Drift

The concept of continental drift has been one of the most revolutionary ideas in physical geology to come to acceptance in recent times. Although elements of this theory had been suggested a number of times previously, it was not until the twentieth century that it received much attention (Hallam, 1973). Before this time, most geologists followed the more traditional view that the continents and oceans were stationary, and remained largely unchanged throughout the Earth's history (Caplan, 1987). As a result, the concept was almost universally rejected by the scientific community for many years until new technology brought to light evidence vindicating the idea.

Precursors to the Theory of Continental Drift

Although the concept of continental drift is most often attributed to **Alfred Wegener** (1880-1930), it had been suggested several times previous to his initial publication in 1912 (Hallam, 1973). Indeed, aspects of the theory had been suggested as early as 1620, when **Francis Bacon** (1561-1626) pointed out the "general conformity of outline of continents [of Africa and South America]." Others, including **Alexander von Humboldt** (1769-1859), suggested that the continents had originally been connected by a bridge of land which had since subsided or been otherwise depressed. Neither of these theories had any suggestion of the movement of continents, however, and instead relied on the idea of the vertical movement of the crust to explain how these continents might have previously been connected.

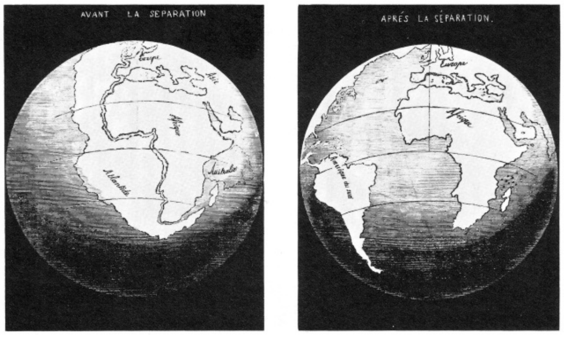


Figure 2.2: Illustrations by Snider-Pellegrini, showing the way he imagined South America and Africa would have fit together during their formation (left) and their gradual separation following a cataclysmic event (right).

One of the first people to suggest that continents could move laterally was **Antonio Snider-Pellegrini** (1802-1885). In his 1858 publication *La Creation et ses mysteres devoiles* (Creation and its Mysteries Unveiled), he suggested that the continents had formed originally as one massive whole, and subsequently had been broken up during some catastrophic event (Figure 2.2). In addition to the fit between Africa and South America, Snider cited the existence of matching plant fossils in Europe and America as evidence for this hypothesis. Although his hypothesis contained many of the same elements as the current understanding of continental drift, it was rejected by many for seeming too far-fetched (Hallam, 1973).

In spite of its unpopularity, this theory did receive support from some individuals. **Osmond Fisher** (1817-1914) proposed that the fragmentation of the original continent may have been caused by a huge collision or impact in what is now the Pacific Ocean (Hallam, 1973). This idea matched well with his own theory that the Moon was a piece of the Earth which had been flung loose by such an impact. Several others at the time echoed this association between the formation of the Moon and the separation of the continents. On the whole, however, the idea of significant movement of the continents continued to be thought of as fantastical.

F. B. Taylor's Proposal

Frank Bursley Taylor (1860-1938) was one of the first to propose the idea of continental drift as it is now understood. Unlike many of his predecessors, Taylor's inspiration was not the similar coastlines of Africa and South America. Instead, he focused on providing an explanation for the arcuate shape of the **alpine orogeny** in Southern Asia and the Mediterranean (Taylor, 1910). He suggested that the crust underlying most of Asia was slowly creeping south towards the equator. In regions such as the Indian peninsula, the exposed shield rocks would hinder this movement, and the resulting slow-down would result in the formation of the mountain belts as the crust 'piled up.' In addition to the Himalayas, Taylor pointed out the similarity between Paleozoic rocks in

Greenland and Northern Canada as evidence that they had once been joined but had at some point broken and drifted apart.

In spite of the evidence for his idea, Taylor was unable to suggest a plausible mechanism which might cause continental drift in his 1910 paper. As a result, his work did not have significant impact on geological paradigms at the time.

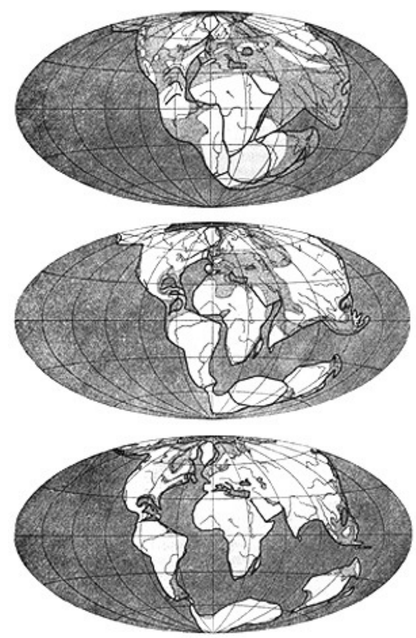
Alfred Wegener's Theory

Although Alfred Wegener is primarily remembered today as the father of the theory of continental drift, he was actually originally trained as a meteorologist (Schwarzbach, 1986). It was not until 1910 that Wegener began to speculate—independently of Taylor—on the idea of the continents moving. Like so many before him, Wegener started with the matching coastlines of Africa and South America. He was reportedly also inspired by a report detailing evidence of a former land bridge connecting Brazil and Africa. This evidence included many matching fossil types on either side of the Atlantic, which he felt solidified the connection between the two continents. Wegener began collecting more evidence to support this idea until January of 1912 when he gave a lecture on the topic in Frankfurt (Hallam, 1973). This lecture formed the basis for his later publication, titled *Die Entstehung der Kontinente und Ozeane* (The origin of continents and oceans), as well as much of his later work on continental drift. In his book, Wegener proposed that sometime during the Mesozoic era, the present-day continents were actually one amalgamated **supercontinent** which he called Pangaea. Over the course of time, this supercontinent broke up into large fragments which slowly drifted apart, until reaching their present positions (Figure 2.3).

Wegener envisioned continental crust forcing its way slowly but inexorably through the ocean crust, driven by some great force (Hallam, 1973). The nature of this force was not known to him at the time, although he tentatively suggested either ***Pohlflucht*** ("flight from the poles") or tidal forces as possibilities. Both were soundly rejected by the scientific community, however, since neither of these forces is strong enough to induce movement on such a large scale (Holmes, 1944). In the end, Wegener remained unable to suggest a satisfactory mechanism which would actually cause continental drift to occur.

For the most part, the reaction to Wegener's proposal was very negative and even outright hostile. Many critics of his theory declared the evidence to be circumstantial at best, and in some cases completely incorrect (Hallam, 1973). Some of these criticisms were valid, as much of Wegener's evidence was culled from the findings of other geologists—in some cases, data were taken out of context, or generalizations made incorrectly (Schwarzbach, 1986). Others accused Wegener himself of stubbornly clinging to his theory despite evidence to the contrary, and called his merit as a scientist into question: "Whatever Wegener's own attitude may have been originally, in his book he is not seeking the truth; he is advocating a cause, and is blind to every fact and argument that tells against it" (Lake, 1922, cited in Le Grand, 1988). Sadly, Alfred Wegener died during an expedition in Greenland in 1930, long before his idea came to popular acceptance.

Figure 2.3: Wegener's reconstruction demonstrating (from top to bottom) a map of the world during the time of Pangaea, during its breakup, and at the present day.



Wegener's Supporters: Holmes and Du Toit

Not everyone at the time disagreed with Wegener's proposal. **Arthur Holmes** (1890-1965), a prominent British geophysicist, was a strong supporter of the theory of continental drift. He remained unconvinced by Wegener's proposed mechanisms, however, and in 1929 he proposed his own theory in his paper *Radioactivity and Earth Movements*. Rather than tides or gravity, Holmes suggested that **convection cells** in the Earth's mantle were responsible for the movement of the Earth's crust. Holmes also included a chapter on continental drift in his book *Principles of Geology,* where he further discussed the possibility of continental drift being caused by convection. This concept would later prove to be one of the founding ideas of **sea-floor spreading.**

Another influential supporter of Wegener's proposal was **Alexander Du Toit** (1878-1948), who eventually became a staunch supporter of the theory of continental drift. Du Toit made many contributions and refinements to Wegener's theory in his book, *Our wandering continents*. Du Toit sought to present more evidence in favour of continental drift, while also correcting mistakes and errors in Wegener's proposal. Du Toit also proposed that Pangaea broke into two supercontinents, the northern Laurasia and southern Gondwana, prior to complete break up. He created an independent timeline of events for each, based on evidence such as marine deposits, various mountains and matching terrestrial fossils across wide regions.

Paleomagnetic research and the theory of sea-floor spreading

Although the theory of continental drift lost some of its stigma with the work done by Holmes and Du Toit, it remained an unpopular idea until the 50s and 60s, when new technology allowed a far greater capacity to investigate the ocean floor (Caplan, 1986). In particular, the advent of **paleomagnetism**, or the study of changes in the Earth's magnetic field as recorded by rocks, helped to provide evidence in support of the slow movement of the Earth's crust. In the mid-1950s, analysis of magnetized rocks on the ocean floor revealed that their position relative to **Magnetic North** had gradually changed (Caplan, 1986). This was attributed by most to either a change in the position of Magnetic North relative to **Geographic North** or a change in the position of the continents relative to Magnetic North.

Another new idea which helped to popularize continental drift was the proposal of sea-floor spreading by **Harry Hess** (1906-1969). Based on the observation that younger ocean crust was found around **mid-ocean ridges**, he proposed that new ocean crust was actually formed at these ridges by magma from the mantle (Figure 2.4). Once cooled, the new ocean crust would be slowly carried away from the ridge by convection currents and eventually subduct back into the mantle to be recycled (Hallam, 1973; Schwarzbach, 1986). This theory was met with much more enthusiasm than any of the previous theories relating to continental drift.

Sea-floor spreading was further established by the success of the Vine-Matthews-Morley hypothesis which postulated that if sea-floor spreading were to occur, there would be symmetrical patterns of magnetized rocks extending outwards on either side of the ridges where ocean crust was formed (Caplan, 1987; Hallam, 1973). Further investigation eventually revealed that this was the case (Figure 2.4).

This proposal resolved the main problem facing continental drift, the inability to describe just what was causing the continents to shift. Convection currents, similar to those described by Holmes, provided a force strong enough and persistent enough to move the Earth's crust (Condie, 1997). This theory also helped to circumvent the argument that continental crust could not move through oceanic crust due to being less dense. Instead of the continents ploughing through oceanic crust, as Wegener suggested, the oceanic crust was sinking below the

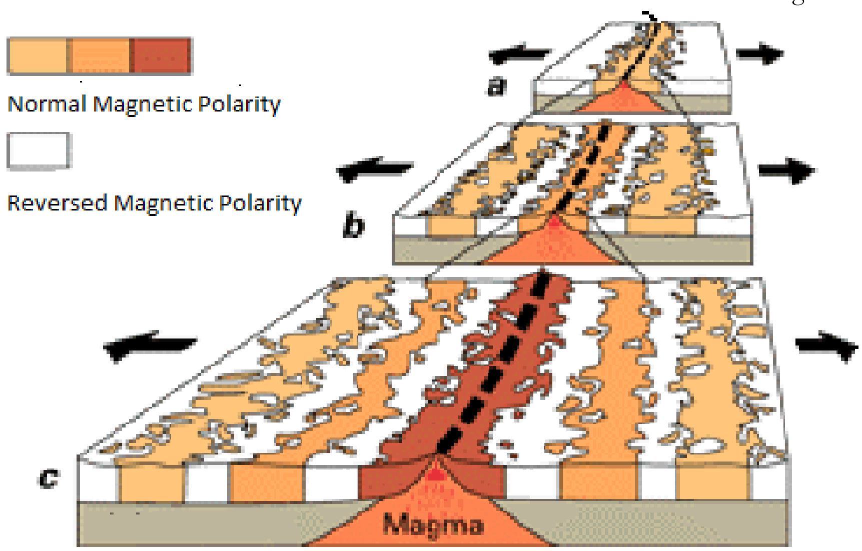


Figure 2.4: This diagram demonstrates the formation of new ocean crust at mid-ocean ridges. As new ocean crust continues to form and spread outwards, a symmetrical pattern of magnetized 'stripes' appears, reflecting the orientation of the Earth's magnetic field at the time of formation.

continents as a result of its greater density (Condie, 1997).

At this point in time, all but the most tenacious opponents of continental drift conceded that the evidence in favour of the theory was convincing. Today, the concept of continental drift has become one of the foundations of modern geology.

Plate Tectonics and Modern Geology

The theory of *Plate Tectonics* postulates that the Earth's lithosphere is composed of a number of large plates (Figure 2.5), which float on top of the mantle. These plates are able to move relative to one another, resulting in the motion of the continents over the course of long periods of time. The mechanism causing this motion is still a topic of ongoing investigation. It is thought to be driven by currents in the mantle, which form as a result of convection cells. Plate movement is also thought to be caused by the effects of gravity on tectonic plates at mid-ocean ridges where the elevation is greater, and at **subduction zones** where plates tend to be colder and denser. This is referred to as the **ridge-push, slab-pull hypothesis** (Tanimoto and Lay, 2000).

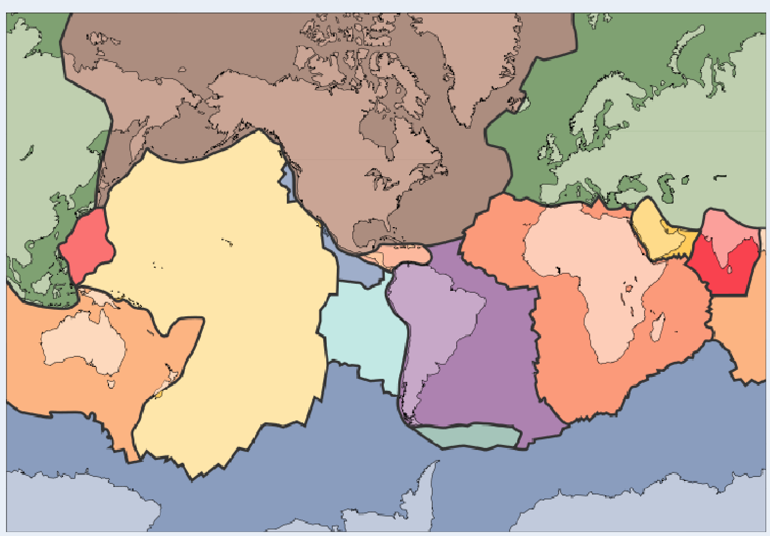
Many important geologic formations are observed at the margins between plates. The types of features depend primarily on two factors: the direction of motion of the plates relative to one another, and the types of plate which are in contact. For example**, convergent plate margins** often result in geographic features such as mountain ranges and volcanoes (Condie, 1997). At **divergent plate margins**, rift valleys and volcanic islands have been known to form as magma rises up through the gap and eventually solidifies to form new ocean crust. The third type of boundary, called a **transform margin**, occurs where plates move in opposing directions and is associated with high levels of seismic activity. In many cases around the world, it is possible to determine the past movements of tectonic plates by analyzing the ages of geologic features caused by plate movement (Condie, 1997). The modern directions of plate movement can be determined using measurements taken by satellites.

Many of the geologic processes associated with tectonic activity, such as earthquakes and volcanic activity, are extremely hazardous to humans. As a result, it is important that we are able to forecast the occurrence of these phenomena. By understanding the mechanism underlying earthquakes and looking at past trends in seismic activity, it is possible to predict which regions are most at risk and what events may be recognized as precursors more destructive quakes. The same logic can be applied to volcanic activity.

Plate tectonics also has implications for fields such as palaeoclimatology, the study of the Earth's past climate. Various types of evidence, such as types sediment deposits or fossils, can be used to infer the climate of a particular region. By correlating information about the past location of a continent and its regional climate during the same time period, a more complete picture of the Earth's climate can be stitched together to form a more comprehensive whole.

The theory of plate tectonics has far-reaching implications for a variety of fields in geology and Earth science. For this reason, it has become a pivotal part of the modern understanding of the Earth.

Figure 2.5: This image shows the subdivision of the Earth's lithosphere into its component plates. There are eight large primary plates, which make up the majority of the surface area of the Earth, and many smaller secondary plates.



The Development of Volcanology

Volcanoes and their eruptions have long fascinated and terrified people all around the world. **Volcanology** has a long history filled with multiple different theories that have attempted to explain where volcanoes came from, how, and why they erupt. In early history, volcanic activity was attributed to supernatural forces such as the gods, but as time progressed and scientific thought began to replace superstition, the field of volcanology emerged as a new branch of science.

Mythology and Early Beliefs

In early history, information concerning volcanic eruptions was handed down between generations as legends and stories. Many cultures have their own sets of volcano legends, several of which include the presence of a god or goddess who rules over a volcano. Two cultures whose mythologies strongly featured volcano gods were the Greeks and the Hawaiians. In ancient Greek mythology, Typhon was a feared Titan who was imprisoned underneath Mount Etna (Figure 2.6) and guarded by the god Hephaestus. They believed volcanic activity and earthquakes near Mt. Etna were due to Typhon rolling and stirring in his prison (Sigurdsson, 1999; Lockwood and Hazlett, 2010). The Greeks also believed that Hephaestus, whom they called the god of smiths, had his forges underneath the volcanoes of the Mediterranean, including Vulcano, Mt. Etna and Santorini. His forges were considered the source of smoke, fire, and earthquakes from these volcanic areas (Sigurdsson, 1999). The Romans later equated Hephaestus with their god Vulcan, the figure whose name became the base of the word volcano (Lockwood and Hazlett, 2010).

Figure 2.6: Eruption from Mt. Etna, as seen from the International Space Station. In ancient Greek culture, this volcano was believed to be the prison of a destructive giant called Typhon.

In Hawaiian mythology, the goddess Pele inhabited the Kilauea volcano. Pele was a vengeful goddess who was constantly at war with the Hawaiian goddess of the sea (Sigurdsson, 1999). Through the story of the war between Pele and the sea goddess, the Hawaiians explained the geological clash occurring between the volcano and the ocean. Interestingly enough, the Hawaiians also understood that the islands within the chain were of varying age, knowledge that would not become scientifically confirmed until the late nineteenth century (Lockwood and Hazlett, 2010).

The Dark Ages and the Renaissance

During the **Dark Ages**, which in Europe lasted from the fall of the Roman Empire until the rise of the **Renaissance** in the 15th century CE, study into the nature of the Earth was restricted by religion (Sigurdsson, 1999). Volcanoes held their place in the religious understanding of nature as the gateways to a fiery Hell. These gateways were thought to lead to the centre of the Earth, where the various layers of Purgatory and Hell could be found (Sigurdsson, 1999). **Alchemists**, who were active in both the Dark Ages and the Renaissance, had a variety of beliefs concerning the nature and origin of volcanoes. One such view was that volcanic eruptions occurred when air was forced though confined spaces, creating friction. Another view was that sulphur, coal, and oil were burning underneath the ground, and volcanic eruptions occurred when the pent up gases from these internal fires were explosively released (Lockwood and Hazlett, 2010). During the Renaissance, science began to gain independence from religion. Throughout this time, the idea that volcanoes were formed from upwards pressure from gases released by internal fires endured.

Conflicting Theories in the Eighteenth Century CE

In the early 18th century the Renaissance was coming to an end, and the **Age of Enlightenment** was beginning. At this time the views of alchemists began to fade, to be replaced with new ideas based on scientific thought. In the field of volcanology, the mid-eighteenth century was a defining period. In this time, the competing geological theories of **Neptunism** and **Plutonism** emerged (Sigurdsson, 1999). Although many geologists subscribed to each school of thought, the main ideas behind each theory were defined by two independent geologists.

Abraham Werner (1749-1819) was a well-known and influential German geology teacher and the figure responsible for the development and spread of the Neptunian Theory of the Earth (Sigurdsson, 1999). In this theory, Werner attributed all rock formation to precipitation from ancient oceans and suggested that volcanic eruptions were an anomaly tied to the combustion of coal (Sigurdsson, 1999; Lockwood and Hazlett, 2010). A large problem for Werner was the existence of **basaltic rocks** in both areas he thought to be sedimentary deposits and in deposits clearly formed around volcanoes. To explain this, he suggested that the basalt being produced by volcanic eruptions was formed from the melting, eruption and reforming of pre-existing basalt (Sigurdsson, 1999). Werner's theory had very little supporting evidence, but conformed to biblical concepts, specifically those of Genesis and the Flood, a correlation that may have been partly responsible for the popularity of the theory (Sigurdsson, 1999).

James Hutton (1726-1797) (Figure 2.7) was responsible for the development of the competing theory of Plutonism. Hutton's theory suggested that beneath Earth's crust lay a perpetually heated area, and that volcanic rocks were formed from cooling of molten rock from the interior (Sigurdsson, 1999; Lockwood and Hazlett, 2010). After many observations of sedimentary rocks with basaltic layers and **cross-cuts**, Hutton concluded that the basaltic layers had been formed when magma melts forced their way up from the heated interior into cool sedimentary rocks. He also believed that volcanoes acted as a pressure release system, allowing excess heat from Earth's interior to be vented onto the exterior of the planet. In 1785, Hutton wrote a paper outlining the evidence for a Plutonic Earth and against Neptunism. This attack against the Neptunist theory was considered by some to be an affront to the church, as Neptunism was supported by the Bible (Sigurdsson, 1999). The revolutionary ideas behind Plutonism were not popular because Hutton's explanation for the presence of heat in the Earth's interior was vague, and Hutton's contemporaries were more interested in the Neptunist combustion theory.

Developments in the Nineteenth and Twentieth Centuries CE

The continuing development of volcanology through the nineteenth century CE was driven by both technology and the eruptions that occurred during that time. Many volcanologists working in this time period travelled to make observations of volcanic eruptions rather than theorize based on the observations of others. Travel to eruption sites was made more convenient with the invention and spread of the telegraph. The use of telegraph technology allowed the immediate transmission of information concerning volcanic eruptions (Lockwood and Hazlett, 2010). This instant form of communication gave volcanologists the opportunity to organize expeditions to erupting volcanoes, allowing them to make field observations instead of relying on second hand descriptions. When Krakatau erupted in 1883, the use of telegraphic communication meant that the eruption was well documented by scientists (Lockwood and Hazlett, 2010). The rise of instant communication led to a rise in the number of scientists conducting field studies, and a focus on the role of field studies in the pursuit of knowledge. One of the first volcanologists to conduct research with a focus on field studies was **George Poulett Scrope** (1797-1876). His observations of the Italian volcanoes Stromboli, Vesuvius, Mt. Etna, and the Phelgraen fields led to his publication of what is now considered to be the first modern volcanology textbook (Lockwood and Hazlett, 2010). In this book, entitled *Volcanoes; The character of their phenomena, their share in the structure and composition of the surface of the globe, and their relation to its internal forces*, Scrope published his ideas on the nature of volcanic eruptions, the minerals that could be found in eruptive materials, and his observations on the role of water as a force behind eruptions. Scrope's focus on the importance of field observations paved the

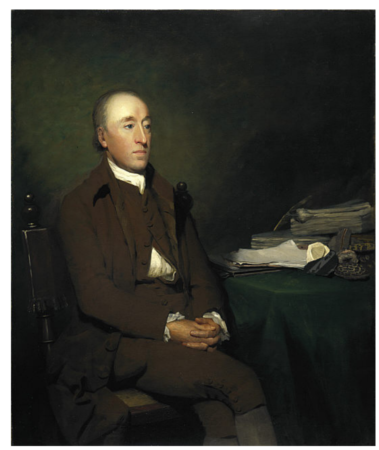


Figure 2.7: James Hutton developed the Plutonic theory of the Earth. His idea that the interior of the Earth was heated was the basis for much controversy in the eighteenth century.

way for major advances in the field of volcanology (Lockwood and Hazlett, 2010).

In the early twentieth century, multiple volcanic eruptions occurred that influenced the direction of the field of volcanology. In 1902, **Mount Pelée** (Figure 2.8) erupted, devastating the nearby city of St. Pierre, Martinique. This event drove the careers of three interacting volcanologists, **Francis Lacroix** (1863-1948), **Frank Perret** (1867-1940), and **Thomas Jagger** (1871-1953) (Lockwood and Hazlett, 2010). Lacroix and Perret were present in Martinique after the eruption, and witnessed the damage, while Jagger encountered them at the eruption of Vesuvius in 1906. Each of these three volcanologists had their own contributions to the field, but they were tied together by their desire to observe volcanic activity over long periods of time. Lacroix founded the *Observatoire Volcanologique de la Montagne Pelée*, the purpose of which was to observe Mt. Pelée and watch for future activity. Perret was also interested in observing Mt. Pelée, and lived on its slope from 1929 until his death (Lockwood and Hazlett, 2010). Jagger was also a strong believer in the observation of volcanoes; however his ideas were more widespread. Jagger wanted geologists to focus on the impact geologic processes have on humans, and to have less concern for the events of the past. This idea, termed humanistic geology, was the reason Jagger wanted permanent observatories to be present on volcanic mountains, in order to learn more about the nature of volcanoes and be able to predict their eruptions (Lockwood and Hazlett, 2010).

The next great name in volcanology was **Alfred Rittman** (1893-1980). His studies of **magmatic evolution** and development of the eruption diagram system were of great value to the field of volcanology. In 1936, he published his standard work, entitled *Volcanoes and their Activity*. In this work he described the use of petrographic, geochemical and geophysical methods of analysis to understand volcanoes as well as their eruptions (Lockwood and Hazlett, 2010). Also in this work, Rittman attempted to explain the mechanism behind volcanic eruptions by suggesting the presence of a layer of basaltic magma under the crust of the entire globe. This idea was consistent with the theory of continental drift and thermal mantle circulation that had previously been put forth by **Alfred Wegener** (1880-1930) and further developed by **Arthur Holmes** (1890-1965). The idea of a liquid mantle driving plate movement and volcanism was not widely accepted until the 1960s, when the theory of sea floor

Figure 2.8: The 1902 eruption of Mount Pelée devastated the city of St. Pierre, Martinique and inspired the development of permanent volcano observatories as well as the idea of humanistic geology.

spreading became popular (Sigurdsson, 1999). Research conducted since the middle of the twentieth century has broadened the horizons of the field of volcanology, and allowed a greater understanding of the processes that drive these great mountains to erupt so fiercely.

Volcanoes on Other Worlds

Until the advent of space exploration, volcanoes were only known to exist on planet Earth. Nothing was known of their existence on other planets, although it was theorized in the seventeenth and eighteenth centuries that the craters covering the surface of the moon were of volcanic origin (Sigurdsson, 1999). The first conclusive evidence suggesting that volcanoes were present on other planets came with the 1971 discovery of the Martian volcano Olympus Mons. As exploring spacecraft travelled further, beyond the asteroid belt and into the outer solar system, they began sending back images and evidence suggesting that volcanic activity was present on other bodies as well, including the moons of Jupiter (Lopes and Carroll, 2008). Studying and describing volcanic structures on other worlds presents a challenge, as volcanologists cannot yet travel to these other planets to carry out field studies. Instead, they rely upon the information and images sent to Earth from rovers and satellites (Lopes and Carroll, 2008). In the case of Mars, all current knowledge concerning volcanoes on the planet's surface comes from satellite images, environmental analysis for methane, and information from several rovers, including Spirit (launched in 2003). Spirit sampled rocks on the Martian landscape to determine their mineral composition, and provided direct evidence for the formation of these rocks in a volcanic environment (Lopes and Carroll, 2008).

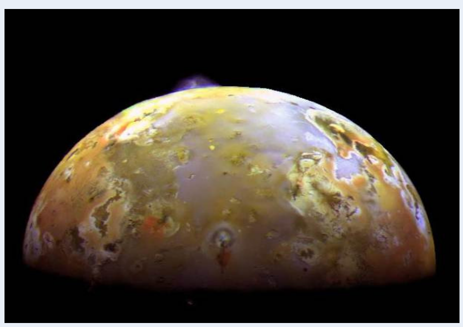


Figure 2.9: Volcanic activity on Io as seen by the Galileo spacecraft. Io is one of the most volcanically active bodies in the solar system.

Io (Figure 2.9) is a Galilean moon of Jupiter, and in terms of volcanic activity, is one of the most interesting bodies in the solar system. Researchers began to notice that Io was very different from its neighbouring moons when modern telescopes came into use. As telescopes became stronger, scientists began to see that Io had a very different colour than its neighbours, and also contained sulphur, silicates, and sodium rather than water. The first clear images of Io appeared when Voyager 1 travelled past in 1979. These images showed umbrella shaped plumes extending from the surface of the moon, the first clue that Io was a volcanically active world (Lopes and Carroll, 2008). Volcanic activity on Io is thought to occur because of the distance of its orbit from Jupiter. Io's orbit sits close enough to Jupiter that the gravity of this massive planet causes the surface of the moon to shift about 46m every day. This rise and fall is thought to heat the interior of the planet, which causes volcanoes to erupt as an energy release mechanism (Lopes and Carroll, 2008). The Voyager 2 and Galileo spacecraft sent back images showing a wide range of volcanic activity on the moon, including large lava flows, volcanic craters filled with lava lakes, and Pillanian eruptions forming huge volcanic plumes.

Although volcanic material on Io is largely sulphurous and siliceous, and its internal heating mechanism is very different from that of Earth, the structures found on Io are analogous to those found on Earth. For example, the Loki crater on Io has characteristics similar to the Kilauea lava lake in Hawaii (Lopes and Carroll, 2008). As humanity moves further and further out into space, the study and understanding of volcanic activity will no doubt become as important on other planets as it is here on Earth.

Determining the Size of Historical Explosive Volcanic Eruptions

Volcanoes are an important part of history and have impacted the conditions of surrounding environments since before human history was experienced and recorded. When an explosive volcano erupts, spewing an **eruption column** into the atmosphere, it is difficult for nearby human populations not to notice. However, if the eruption occurred in the prehistoric past, firsthand observations from volcanologists cannot be used to determine the magnitude and intensity of the eruption; rather, these must be interpreted from the **geologic record** (Figure 2.10), allowing the story of its eruption to be deciphered. The development of techniques used to determine the size of past volcanic eruptions has long been an area of interest to geologists. Various methods were developed and modified over the course of the last century. Today, the size and effects of past eruptions can be interpreted through analysis of ash and **pumice** deposits, lake and marine sediments, peat bogs, sulphuric acid records in glaciers, and **tree frost rings** recording climate change (Oppenheimer, 2011).

Figure 2.10: Layers of volcanic tephra and pyroclastic debris, as in this image from Chimborazo, Ecuador, can be studied to determine properties of an eruption.

Historical Accounts

Prior to the mid-twentieth century CE, a reliable method to determine eruption magnitude did not exist (Chester and Duncan, 2005). Human populations may have been knowledgeable about local volcanoes, but would not have known to compare their size and activity to those in other parts of the world before the development of global communication systems. Thus, any scale recording and relating the size of eruptions globally would have been impractical. Rather, the measurement of eruptions was simply in the form of local accounts of the extraordinary effects caused by their activity. After the 1815 CE eruption of Tambora and that of Krakatau in 1883 CE, historical texts record events such as the shrouding of the sun by volcanic ash with descriptions such as: 'daytime darkness two days later and 500 km distant' from ships logs, journals and letters (Foster 2005, p.282). After the 44 BCE eruption of Mount Etna, records were made of the sun being veiled, 'for during all that year its orb rose pale and without radiance,' (Oppenheimer 2011, p.131). Even in non-literate societies, major volcanic eruptions are recalled as a 'Time of Darkness' or 'Great Darkness' (Foster 2005, p.282). Cataclysmic eruptions, such as Krakatau in 1883 CE, are also recorded as having been heard from great distances (Oppenheimer, 2011). During the eruption of Krakatau, detonations of the volcano were heard 3650 km away in Diego Garcia and 4800 km distant in Rodrigues in the Indian Ocean (Oppenheimer, 2011).

Associated natural disasters were also observed following volcanic activity. After the 1815 CE Tambora eruption, the region of Sanggar, southeast of Tambora, is recorded to have experienced a *tsunami* as 'the sea rose nearly twelve feet higher than it had ever been known to do before [...], sweeping away houses and everything within its reach' (Oppenheimer 2011, p.304). **Pumice rafts**, up to five kilometers in length, were also observed by the captain of the ship *Benares*, who noted 'a complete mass of pumice floating on the sea, with great numbers of large trunks of trees and logs among it that appeared to be burnt and shivered as if blasted by lightning,' (Oppenheimer 2001, p.305). These significant effects of volcanic eruptions could only have occurred as the result of eruptions of high magnitude. However, these historical observations were made on the local effects of an eruption at a particular instance in time, and comparisons to previous volcanic eruptions would have been scientifically impossible at the time.

Hubert H. Lamb's Dust Veil Index

It was not until the 20th century that effective methods of classifying volcanic eruptions by size began to be developed. In 1963, after the eruption of the Mt. Agung volcano in Bali, it was discovered that volcanic eruptions interact with the **stratospheric aerosol layer** (Oppenheimer, 2011). Having observed that large volcanic eruptions often led to colder summers in the northern-hemisphere, climatologist **Hubert H. Lamb (1913-1997)** compiled a historical database of **volcanic aerosol layers** from approximately 250 volcanoes classified using a **Dust Veil Index** (DVI) (Oppenheimer, 2011). DVI values are based on the idea that a decrease in sunlight after an eruption is due to the profusion of volcanic dust in the atmosphere. These values focus on the amount of sunlight transmitted through the atmosphere following volcanic eruptions, and are determined using historical records, optical phenomena, radiation measurements, and eruption volume (Parfitt and Wilson, 2008; Chester and Duncan, 2005). Using this scale, eruptions of greater magnitude are given a higher DVI rating, with a theoretical value of 1000 given to the 1883 CE eruption of Krakatau, Indonesia (Chester and Duncan, 2005). However, only a small number of eruptions can be classified in this manner. Eruptions occurring without much time separation, as well as small volcanic events cannot be easily distinguished, and nonvolcanic events such as dust storms are not easily filtered out (Newhall and Self, 1982). Due to the discovery that the sunlight-obscuring effects of volcanic eruptions are caused not only by the sheer amount of dust released into the atmosphere, but also by the release of sulfurous gases, the DVI is no longer used as the most reliable method of determining past eruption size (Parfitt and Wilson, 2008; Chester and Duncan, 2005).

Analysis of Sunsets in Paintings

A similar method to determine historical eruption size was developed by **Christos Zerefos (b. 1943)** and his colleagues at the National Observatory of Athens in 2007 (Oppenheimer, 2011). The coloration of over 500 canvases displaying sunsets, painted by well-known artists in the period of 1500-1900 CE, was measured through analysis of the angle between the vertical and the sun, as well as the proportion of red to green light seen in the skies (Figure 2.11a,b) (Oppenheimer, 2011). Fifty four paintings created up to three years after a major volcanic eruption were analysed for evidence of volcanic aerosols, while the remaining paintings were used as a reference of the standard sunset coloration at the time (Zerefos, et al., 2007). Interestingly, this analysis rendered results very similar to the DVI measurements for the investigated eruptions (Oppenheimer, 2011; Zerefos, et al., 2007).

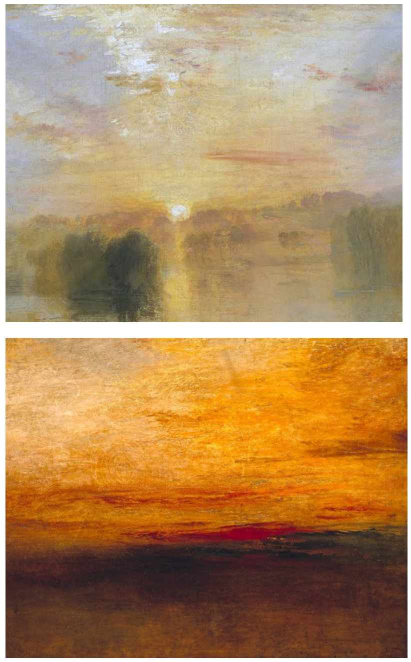


Figure 2.11a,b : The proportion of red to green light in sunset canvases was analysed by Zerefos and his colleagues. Non-volcanic sunsets, such as J.M.W. Turner's 1828 'The Lake, Petworth, Sunset' (top) provided baseline red to green values. The values for sunset canvases painted in the years following a major volcanic eruption, such as J.M.W. Turner's 1833 'Sunset' (bottom), are used to indicate the amount of volcanic aerosols released by an eruption. These two canvases were painted before and after the eruption of Babuyan in 1831 (Zerefos, et al. 2007).

Volcanic Explosivity Index

Developed in 1982 to fill the need for a quantitative way to compare explosive eruptions, the **Volcanic Explosivity Index** (VEI) scales explosive eruptions from 0 to 8, using a range of criteria (Newhall and Self, 1982). Applied to both modern and historical volcanic eruptions, data regarding a volcano's column height, magnitude, intensity, destructiveness, dispersive power, violence, blast duration, and energy release rate are used to classify an eruption as nonexplosive, small, moderate, moderate/large, large, or very large, with descriptors of gentle, effusive, explosive, cataclysmic, paroxysmal, or colossal (Newhall and Self, 1982; Parfitt and Wilson, 2008).

Arguably, the most important resource for determining the size and character of past volcanic eruptions is the geologic record. During an explosive eruption, some **pyroclastic debris** (gases and **tephra**) may be ejected from the volcano and deposited as **airfall volcanic deposits** while more dense pyroclastic debris mixed with hot gases travel along the ground as a **pyroclastic flow**

(Oppenheimer, 2011; Chester and Duncan, 2005). Tephra is composed of fresh pumice, volcanic glass shards, mineral grains and crystals, along with pieces of old lavas, rocks from the **volcanic conduit** or **vent**, from the ground beneath pyroclastic flows, or from the volcano's basement, termed 'lithics' (Oppenheimer, 2011). As volcanic fragments travel in an eruption column then fall to the earth, larger, more dense rock fragments are deposited close to the eruption vent, while a layer of fine ash is deposited furthest from the volcano, leading to a distribution of decreasing grain sizes the further from the volcano (Oppenheimer, 2011; Chester and Duncan, 2005). These volcanic fragments cover the surrounding area, as well as all that is within the area. During the 79 CE eruption of Mt. Vesuvius, an eyewitness account states that, in response to the heavy showers of falling ashes, 'we rose from time to time and shook them off, otherwise we should have been buried and crushed by their weight,' (Smolenaars, 2005). Pyroclastic density flows deposit rock fragments as this hot cloud of ash and magmatic gas flows along the ground away from the volcano at extremely high speed (Parfitt and Wilson, 2008). Both airfall volcanic deposits and debris from pyroclastic flows buried the city of Pompeii during the eruption of Mt. Vesuvius in 79 CE (Marturano and Varone, 2005).

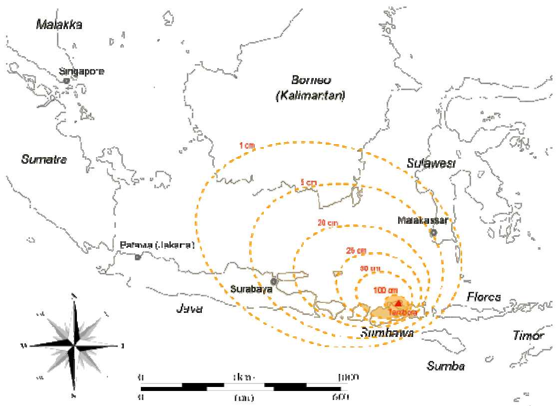


Figure 2.12: An isopach map, as that made for the 1815 CE eruption of Tambora, uses contour lines to connect areas with equal thicknesses of volcanic deposits (Oppenheimer, 2011).

The magnitude of an eruption can be inferred through analysis of the amount of tephra and pyroclasts expelled by the volcano (Oppenheimer, 2011). An **isopach map** (Figure 2.12) can be created by plotting measurements of the thickness of pyroclastic deposits across an area affected by an eruption, then joining areas of equal deposit thickness with contour lines (Oppenheimer, 2011). This method is critical in determining the size of an eruption, as the volume of volcanic deposits can be easily calculated by multiplying the thickness of a deposit by the area that it covers (Oppenheimer, 2011). The presence of fine ash particles with a diameter less than 0.1 mm which erode easily or form sedimentary layers too thin to be observed in field settings must also be accounted for through methods such as mathematical modelling (Oppenheimer, 2011). Using a measure of the maximum deposit thickness, as well as the total volume of material erupted, the magnitude of the eruption can then be calculated, and applied to measurements using the VEI. For example, a measurement of the volume of airfall volcanic deposits (totaling approximately 30 km^3) from the ca. 1525/24 BCE eruption of Thera contributed to the assignment of a VEI value of 6.9 to this eruption (Foster, 2005).

Eruption intensity is evaluated through examination of the pattern of grain size distribution of pyroclastic deposits from which eruption column height, wind velocity and magma discharge rate can be determined (Oppenheimer, 2011). This information is then applied to the VEI.

To account for the incompleteness and poor quality of volcanic data in the past, VEI inventors **Christopher G. Newhall (active in 1982)** and **Stephen Self (active in 1982)** determined the time in each region before which the quality of historical reports significantly decreased (Newhall and Self, 1982). For many regions, this date is 1700 CE, though it may vary by several centuries depending on the exact area. Newhall and Self assumed that reports existing before that time in a specific region detailed more significant eruptions than did the records made once documentation became more frequent. Thus, VEI values of 1 to 4 identified for events occurring before the specified date for a particular region were upgraded by one VEI unit. At the time of its release in 1982, the VEI had already been used to classify over 8000 historical eruptions (Newhall and Self, 1982). Examples of the application of VEI include the eruption of Mt. St. Helens in the United States of America in 1980 which ejected 1.2 km^3 of material, with a column height of 19 km, as well as the 1815 CE eruption of Tambora in Indonesia, which released over 50 km^3 of rock fragments, with a column height of 43 km. Both eruptions are classified as very large, cataclysmic eruptions with VEI values of 5 and 7 respectively

(Parfitt and Wilson, 2008).

As the field of geology continues to develop and technology continues to advance, it is likely that methods of determining historical explosive eruption sizes will also change to more accurately detail the events of the past.

Volcanic Hazard Assessment

While the geologic record can be consulted for information on volcanic eruptions in the past, it is another matter entirely to predict the timing and intensity of future eruptions. Until the 18th century, the memories of local inhabitants were the most dependable method of determining the activity of a given volcano. With the development of systematic geological mapping and an understanding of the types of deposit produced by volcanic eruptions, more accurate predictions can now be made (Parfitt and Wilson, 2008).

The severity and frequency of eruptions of a particular volcano can be measured through analysis of the geologic record. This method is most reliable for volcanoes that erupt frequently, and are surrounded by well-preserved deposits from recent eruptions (Parfitt and Wilson, 2008). Through investigation of past deposits and their ages, geologists are able to identify a range of distances in which human populations would be at risk in the event of another eruption, as well as the approximate date at which an eruption is likely. Determination of the activity and hazard risk of infrequently erupting volcanoes occurs through investigation of volcanic activity in tectonically analogous areas, and probabilistic modelling is used to determine the likelihood of an eruption occurring within a given time period. In areas where future volcanic activity is likely, several geophysical monitoring techniques are employed (Parfitt and Wilson, 2008).

Before an eruption, magma and gasses gather in a **reservoir** beneath a volcano, then ascend through a shallow **volcanic dike** or conduit. This causes the overlying rock to fracture (Parfitt and Wilson, 2008; USGS, 2008). The magma reservoir inflates to accommodate the influx of magma, causing movement along fractures in surrounding rock, as well as the generation of new fractures (Parfitt and Wilson, 2008). This fracturing causes an increase in seismic activity which can be monitored by seismometers installed around the volcano (USGS, 2008; Parfitt and Wilson, 2008).

Deformation of a volcano's surface due to the upwelling of new magma can also be monitored. Several devices are used for this purpose, including Global Positioning Systems, electronic tiltmeters, Electronic Distance Meters, and Interferometric Synthetic Aperture Radar (InSAR). Tiltmeters are one of the oldest instruments used to monitor crustal deformation. An electronic tiltmeter uses the movement of a bubble in a conducting fluid to generate voltage output from an electrode. A change in voltage output corresponds to an alteration of land surface tilt (USGS, 2008). The newest of these methods, InSAR, uses satellite generated radar images to map the ground surface. InSAR is very accurate and provides a multitude of measurements without endangering ground crews (USGS, 2008).

The rate of release of gases such as carbon dioxide and sulfur dioxide can also be used to detect an impending volcanic eruption. The quantity of gas released each day is largely determined by the volume of magma within a volcano's reservoir and hydrothermal system (USGS, s2008). Consequently, a change in gas release rate may imply a change in the amount of magma. The most common manner to analyse gas samples is to collect them directly from **volcanic fumaroles** by hand, then take the samples to the laboratory for analysis (Figure 2.13). While less informative, chemical sensors placed on the volcano provide a much safer way to continuously measure the amount of a specific gas, and can alert volcanologists to any changes in gas concentration (USGS, 2008).

Figure 2.13: For the most accurate measurement of the type and quantity of gases being produced by a volcano, sample collection often must be made by hand. In this image, gas is being collected from Mt. Baker in Washington State, USA.

These detection methods make living in the presence of volcanoes as safe as possible, as they increase the reliability of eruption prediction.

Perspectives on *Tsunami* Through Time

A ***tsunami*** (literally, harbour wave) refers to a large mass of water that has been displaced in a short period of time (Cartwright and Nakamura, 2008). These massive waves can be caused by tectonic activity, or from large amounts of material suddenly entering a large body of water, such as from a landslide or meteorite impact. *Tsunami* are frequently noted for their destructive capabilities, such as the 2004 Indian Ocean *Tsunami* which killed 232 000 people from 55 countries (Figure 2.14) (Bernard et al., 2006). *Tsunami* can be distinguished from other forms of waves by their long wavelengths, which can be hundreds of kilometres long (Cartwright and Nakamura, 2008). The progression of modern understanding of *tsunami* can be tracked through time, from the first recorded reports of the particular features characteristic of *tsunami* waves by the ancient Greeks, all the way to modern computational models that are used to analyse *tsunami* today.

Figure 2.14: 2004 Indian Ocean Tsunami strikes Thailand, catching many unawares.

Early Western Thoughts on *Tsunami*

Tsunami have appeared in records throughout history in many different cultures. Some of the earliest descriptions of *tsunami* appeared in Greek literature, though they were referred to as “flood tides” (Smid, 1970). These accounts of *tsunami* are differentiated from other wave events because they either describe an earthquake that occurred immediately before the event, or they fail to describe a storm event that would account for such large wave activity. Two historical accounts of *tsunami* were recorded from the 5th century BCE. These two accounts differed greatly in their interpretation of the events. The first, made by **Herodoctus** c. (484-425), suggested that the *tsunami* was a result of blasphemy; the people killed had defiled the temple and image of Neptune, the god of the sea. **Thucydides** c. (460-396) wrote the second account which described an earthquake and a *tsunami* as occurring close together in space and time, and also inferred that *tsunami* must be caused by earthquakes. He noted that “at the point where its shock has been the most violent, the sea is driven back and, suddenly recoiling with redoubled force, causes the inundation. Without an earthquake I do not see how such an accident could happen” (Smid, 1970).

After this point however, the very concept of a *tsunami* dropped out of Western thinking and would not reappear for many years (Smid, 1970). Although events that resembled *tsunami* still occurred, they were simply recorded without further analysis.

Tsunami Are Observed in Japan

In Japan, one of the first descriptions of a *tsunami* was made in 684 CE, although the term *tsunami* was not used (Cartwright and Nakamura, 2008). In fact, the first appearance of a “*tsunami*” in text did not occur until 1611 CE, where it was noted that “the people” referred to the event as a *tsunami*. By this time, it was widely recognized that *tsunami* were associated with earthquakes. It is likely that this association coupled with their relatively regular occurrences allowed *tsunami* to be recognized as a distinct phenomenon. That being said, there were quite a few different terms that were used to describe *tsunami*, as a result of their similarity to other phenomena that can cause large waves and flooding.

Despite widespread knowledge that *tsunami* were associated with earthquakes, they were not explained scientifically until after Japan reopened to the west in 1853 (Cartwright and Nakamura, 2008). Common thought at the time was based on the principle of *Yin* and *Yang*; which states that the Earth floats on water and is shaken in accordance with the activities of the other two elements, fire and wind. Buddhism was the predominant religion throughout Japan throughout this time period. There is a Buddhist teaching which encourages the acceptance of disasters without inquiring as to their causes. Many of the references to *tsunami* in the Japanese literature are given in order to teach this lesson. The popular artistic movement of the time, ***ukiyo-e***, provided escapist entertainment with no reference to harsh realities such as *tsunami* devastation.

The Reappearance of Western Thought on *Tsunami*

After the Greek accounts, there is almost no mention of *tsunami* in European literature before the 18th century, although they continued to occur and were noted in historical records (Cartwright and Nakamura, 2008). By 1760 there were some reports of *tsunami*, which led **John Mitchell** (1724-1793) to propose a theory that earthquakes and the *tsunami* that follow them might be caused by "subterraneous fires". He realised that seismic and volcanic activity were a result of geothermal energy, and his work led others to become receptive to the study of *tsunami* and determination of their geological causes.

Generally, western understanding of *tsunami* was impeded by an inability to collect direct measurements of *tsunami* until the 1990s (Synolakis and Bernard, 2006). Without such recordings, there was not an applicable *tsunami* magnitude scale; there were only qualitative intensity scales. Scientists used tide gauges, which could only accurately represent the arrival times and characteristics of the first wave. Initially, it was thought that *tsunami* resembled **bores**, steep fronted waves caused by the meeting of two tides, or by the constriction of a tide rushing up a narrow opening. The fact that bores were notoriously difficult to quantitatively analyze further dissuaded scientists from studying *tsunami* (Synolakis and Bernard, 2006).

The word *tsunami* did not appear in English in any context until 1896 CE (Cartwright and Nakamura, 2008). It is likely that this is the direct result of a policy known as ***sakoku***. From 1633-1853, foreigners could not enter Japan and natives could not leave. Immigrants were punished by death, and any emigrants were exiled.

Prior to the introduction of the word *tsunami*, a "tidal wave" was used instead (Cartwright and Nakamura, 2008). This was abandoned due to the inherent inaccuracy of the phrase. For a time, the phrase "seismic sea wave" was used, but was found to be too limiting, as *tsunami* are not solely caused by seismic activity. The word *tsunami* was first introduced in a *National Geographic* article in 1896, and was first used in scientific literature in 1905. The use of the term then became firmly established during the second half of the 20th century.

Figure 2.15: Alaskan Tsunami Warning Sign.

Tsunami became of particular concern to Americans after an Alaskan generated *tsunami* in 1946 killed 173 people in Hawaii (Bernard et al., 2006). This prompted the American government to form the Pacific Tsunami Warning Center (PTWC), based in Hawaii, intended to warn Americans against distant *tsunami*. A warning center was also established in Alaska after an Alaskan earthquake and *tsunami* killed 120 people in Alaska and the west coast of the United States. In addition to warning Americans about immediate *tsunami* risks, these warning centers were tasked with educating Americans about *tsunami* (Figure 2.15).

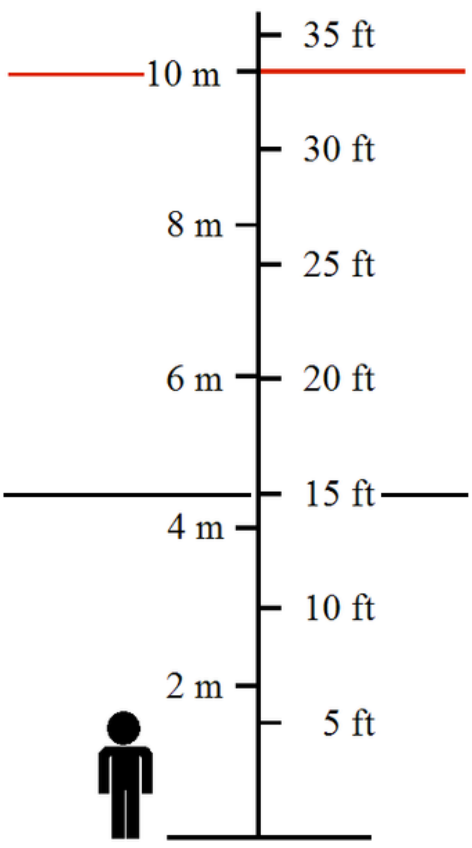
Japanese *Tsunami* Research and Countermeasures

Tsunami science in Japan really began in 1896 CE when the *Meijji Great Sanriku Tsunami* claimed 22 000 lives. This *tsunami* had a height of 38 m and was preceded only by very weak ground shaking (Shuto and Fugima, 2009). As a result, none of the citizens tried to evacuate, leading to the high death toll. This sparked a debate amongst Japanese scholars as to the cause of this *tsunami*; the shaking was so weak that it was concluded that earthquake could not have been the cause. By examining the tide record, it was determined that the *tsunami* was caused by a large **fault motion**. By 1910, it was understood that the fault motions associated with earthquakes are the cause of *tsunami*, as opposed to the earthquakes themselves.

The idea of developing counter-measures was officially introduced in Japan after 1933 (Shuto and Fugima, 2009). These counter-measures included relocating houses to high ground, the construction of coastal dikes, the use of *tsunami* control forests (vegetation can reduce the power of *tsunami*), the construction of seawalls, the planning of evacuation routes and the establishment of *tsunami* memorial events. *Tsunami* forecasting began in 1941 and was accomplished by empirically deriving a forecasting chart. By 1952, this chart encompassed the entire Japanese coast.

In 1960 another major *tsunami* affected Japan (Shuto and Fugima, 2009). This *tsunami* differed from the others that had occurred since 1896, in that its source was a large earthquake off the coast of Chile instead of more locally-occurring seismic activity. Therefore, coastal residents could not feel the ground shaking and no *tsunami* warning was given. This *tsunami* caused damage equal to 2.2% of the national budget, and motivated Japanese scientists to develop an equation to determine if a given source of *tsunami* activity is capable of causing a **far-field *tsunami***. Further research led to a method of determining the initial profile of a *tsunami* from fault parameters in 1971. During the later half of the decade, scientists began to create computational models to provide *tsunami* numerical simulations.

Figure 2.16: Size comparison of approximate 1993 tsunami height, approximate sea-wall height, and average human height. The red line represents the approximate tsunami height, and the black line represents approximate sea-wall height.



A large *tsunami* in 1993, caused the Japanese to reconsider some of their prevention methods (Shuto and Fugima, 2009). Prior to this event, seawalls were one of the major methods of *tsunami* prevention. However, these seawalls were only 4.5 m high, and the *tsunami* that occurred in 1993 was over 11 m high (Figure 2.16). This stimulated the development of a comprehensive *tsunami* disaster prevention program, which had three key components: defensive structures, *tsunami* resistant town development and warning-based evacuations (Shuto and Fugima, 2009). Analysis of the 1993 *tsunami* also revealed that the long-wave prediction models previously employed were incorrect and a 2D/3D hybrid simulation system was adopted instead.

The Establishment of an International *Tsunami* Warning System

The Chilean *tsunami* of 1960 and its resultant lethal consequences (1 000 fatalities in Chile, 61 in Hawaii and 190 in Japan) encouraged the international community to develop distant warning systems. Two commissions were created, one scientific, the other legislative. The scientific commission was entitled the 'Tsunami Commission' and the legislative commission was the 'Intergovernmental Coordinating Group for Tsunami Warnings in the Pacific' (Bernard et al., 2006). The United States offered the Pacific Tsunami Warning Center (PTWC) as an operations center for the entire Pacific Basin and offered to support the creation of the International Tsunami Information Center. During the 60s and 70s local and regional warning centers were established in Japan, the USSR, Tahiti, and Chile, which coordinated with the PTWC (Bernard et al., 2006). A global network of instruments to detect earthquakes was placed throughout the world, which improved the international effort, however the seismological nature of this information caused 75% of the *tsunami* warnings produced from 1949 to 2000 to be unnecessary. During the 90s the technology was developed to create inundation maps at the community level and 73 of these maps were produced in nine countries (Bernard et al., 2006). These new inundation maps allowed for local community planning in case of *tsunami*, such as evacuation procedures. In 1992, the United States decided to address the issues of over-warning and concerns that a large *tsunami*-causing earthquake would occur on the Cascadia subduction zone by forming the National Tsunami Hazard Mitigation Programme (NTHMP). The NTHMP developed the technology to detect *tsunami* in the deep ocean, which paved the way for modern *tsunami* forecasting techniques. The demand for a global *tsunami* warning system was created after the devastating 2004 Indian Ocean *tsunami* killed 232 000 people worldwide.

Modern Methods of Tsunami Detection

Accurate *tsunami* detection is important. If the system lacks sensitivity, then the lack of forewarning could lead to devastation of coastal regions. However, false alarms are not only costly, but can also lead to a tendency to discount future *tsunami* forecasts. Currently, both real-time measurement and modeling technologies are used to detect *tsunami* (Meing et al., 2005).

Currently, the American National Oceanic and Atmospheric Administration use a combination of real-time data collection and mathematical modelling to predict oncoming *tsunami*. The data is collected using a Deep-ocean Assessment and Reporting of Tsunamis (DART) II **tsunameters** (Meing et al., 2005). These have two physical components; the actual tsunameter is located on the bottom of the ocean floor, and is connected to a surface buoy, which acts as a communication relay. This relay allows the tsunameter to both send and receive data using the Internet (Figure 2.17). Regular wind waves cause negligible water movement below half of their wavelength, making the bottom of the ocean an ideal place to detect *tsunami* without interference from wind waves (Meing et al., 2005). When a seismic event occurs, there is some vertical shifting of the sea floor. This shifting of the seafloor compresses the water column above, which presents itself as an increase in pressure. Conversely, if the seafloor falls, the pressure decreases. The tsunameter works by having a computer make pressure readings which are analyzed using a *tsunami* detection algorithm.

Figure 2.17: DART-II tsunameter buoy.

This algorithm estimates the amplitudes of the pressure fluctuations and then tests the measured amplitudes against a threshold value. If the value exceeds the threshold, then "event mode" is triggered. This causes the tsunameter to immediately transmit its data and causes it to give updates every hour. "Event mode" can also be triggered by earthquakes. This is advantageous since earthquake waves travel significantly faster than *tsunami* waves, allowing even greater forewarning. Despite their utility, the effective operation of tsunameters faces several obstacles including vast oceanic distances, the hostile oceanic environment, and logistical/maintenance difficulties.

The "Method of Splitting *Tsunami*s" or MOST model is a computational model which uses the data obtained from tsunameters to create *tsunami* forecasts (Meing et al., 2005). It works in two stages. The first stage involves the exploitation of a pre-computed database of deep ocean model simulations. The real-time tsunameter data is compared to these deep ocean model simulations, and a linear best-fit solution is produced. This stage is completed within a few minutes of data acquisition, and provides estimates of tsunami wave heights at the tsunameter locations. The second stage of the model uses values from tsunameters located just off-shore and non-linear inundation models to specifically determine which communities will experience inundation. This is completed in less than ten minutes.

Global Positioning System (GPS) sensors are another modern tool that has been used to improve methods of *tsunami* detection (Falck et al., 2010). The German Indonesian Tsunami Early Warning System utilises several different types of GPS sensors to improve their systems. They are used to transmit seismological information in real time, improve the reliability of tide gauges and detect *tsunami* as early as possible.

While modern techniques have greatly improved *tsunami* forecasting ability and reliability, the system is still far from perfect, as many of these technologies are still relatively young and have yet to be truly implemented world-wide.

Figure 3.1: Ardeche Gorge, France. An example of external Earth processes operating in a stream environment and characterized by both erosional and deposition events.

Chapter III: External Earth Processes

Exterior Earth processes are governed by observable forces that influence the Earth's surface. These processes affect the distribution of atmospheric compounds, long-term climate, and erosion by wind, water, ice, and other chemicals. They occur in the atmosphere, hydrosphere and biosphere, shaping the external structure of the Earth. The atmosphere provides a domain for the interactions between different surfaces through the exchange of chemical compounds. The biosphere is greatly influenced by biogeochemical cycles, because they provide food webs with ingredients necessary for survival. These cycles are responsible for regulating populations. The hydrosphere has shown its importance throughout Earth history. It has helped to define Earth's surface topography through deposition and erosion, and is essential to sustain planetary life.

These external processes can affect the structure of the Earth through both immediate and subtle changes. These include glaciation, flooding, storms, or changes in the chemical composition of the ocean and atmosphere. Many of these processes have recurred at different magnitudes throughout history and are still occurring today. As science and technology have advanced, it has become easier to trace these events through the geologic record and draw conclusions about past environments.

External Earth processes are examined with the purpose of developing an understanding of past and present events, in order to best anticipate the future. These processes shape the way humans and other organisms interact with the Earth, and are therefore important to understand. This chapter intends to assess how human understanding of these regular and catastrophic surface processes has changed throughout history.

Quantifying the Water Cycle

The evolution of our current understanding of the water cycle was a long process that has been revised throughout history. Notable contributions began with famous scientists such as **Aristotle** (384 - 322 BCE) and **Leonardo Da Vinci** (1452 - 1519).

Aristotle believed there were four earthly elements, air, earth, fire and water, each being accredited with two properties (Biswas, 1970). Water was considered by Aristotle to be cold and humid. There was only a vague distinction between water (cold and humid) and air (hot and humid), however, despite this Aristotle developed an accurate model of the hydrologic cycle (Biswas, 1970). He argued that heat from the sun caused two forms of evaporation: water vapour, as well as a smoky exhalation from the earth (Biswas, 1970). As the water vapour rose, Aristotle claimed it condensed in the upper air and fell back to the earth as rain. The intensity of the rainfall was therefore thought to be dependent upon the condensation of water vapour. The remaining vapour that did not fall as rain was referred to as mist, and became a symbol of good weather (Biswas, 1970).

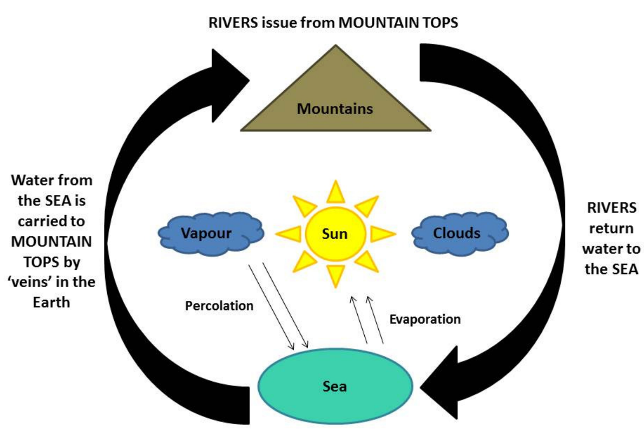


Figure 3.2: The hydrologic cycle as understood by Da Vinci.

Aristotle's ideas contradicted the accepted understanding of water systems at that time (Biswas, 1970). It was believed that all rivers flowed from one reservoir, which supplied enough water to last until the winter rains. Aristotle contradicted this theory, indicating that if a reservoir existed that was big enough to supply water to every river then the reservoir would have to be greater than the earth itself (Biswas, 1970). He instead suggested the formation of new water, referring back to his understanding of precipitation. In addition to the formation of new water above the earth, Aristotle believed that new water was formed within the earth as well (Biswas, 1970). These two processes, as well as the condensation of an unknown vapour source, were Aristotle's three explanations for the origin of rivers.

Da Vinci, like Aristotle, had many important discoveries regarding the movement of water on the Earth. Some of his interesting thoughts compared the Earth to the human body; implying river systems on Earth circulate water like veins circulate blood through the body (Biswas, 1970). Though it seemed unlikely that water could flow upwards to mountains, Da Vinci believed that the cause of blood flow to the top of the head was the same as water flow to mountains (*Figure 3.2*). While his idea of the hydrologic cycle was lacking precipitation, Da Vinci understood much about hydraulics. He stated, "where the channel of the river is more sloping the water has a swifter current; and where the water is swifter it wears the bed of its river more away and deepens it more and causes the same quantity of water to occupy less space" (Biswas, 1970). He also understood through observation that wider channels of water flowed more slowly and as they became narrower, the velocity of the current had to increase, proportional to the decrease of width (Biswas, 1970). Da Vinci had many other notable hydrological ideas on topics including the evaporation of salt water, irrigation, and flood control theories.

After fundamental contributions by Aristotle and Da Vinci, scientists such as **Pierre Perrault** (1608 - 1680), **Edme Mariotte** (1620 - 1684) and **Edmond Halley** (1656 - 1742) began to quantify these ideas and provide evidence for support of hydrologic concepts.

Pierre Perrault

Very little is known about Perrault's personal life. Once a lawyer, he helped himself to the treasury to satisfy creditors and was subsequently caught and fired (Nace, 1974). This was a significant event in Perrault's life as it shifted his focus to the study of hydrology. After his dismissal, little was recorded about Perrault, although the publishing of his book *De l'origine des fontaines* indicated he was far from idle. No one knows what drove him to become a scientist, although it is believed his family played an influential role. Perrault is recognized to have many famous siblings, including Nicolas, a famous theologian, Charles, a critic and author of the Mother Goose fairy tales, and Claude, a physician, scientist and architect of le Louvre (Biswas, 1970; Nace, 1974).

Perrault studied the Seine River in France and the path from its source to Aynay le Duc (*Figure 3.3*). He believed that rain flowed into rivers and replaced all water lost as outflow (Biswas, 1970).

Perrault approximated the surface area of the Seine from its source to Aynay le Duc, as well as the area of the sloped banks on each side of the river. He converted the area into ***toises***, the standard unit of measurement (about 6 ft), and established that the Seine was 31 245 144 *toises* in area (Biswas, 1970). He then measured rainfall over the course of a year and found it to be 19 1/3 inches (Biswas, 1970). With this data he gathered that 224 899 942 ***muids*** of water was added to the Seine in the form of precipitation each year. He also noted that some water would be lost in the form of evaporation or soaked up through root systems of plants (Biswas, 1970; Nace, 1974).

Perrault then proceeded to estimate the **discharge** of the Seine. Using known values of other rivers, Perrault approximated the discharge of the Seine based on width and depth at the river's end, the Aynay le Duc. He concluded that the river carries 36 453 600 muids of water from its source to the Aynay le Duc over the course of a year (Biswas, 1970).

By combining his two findings, Perrault claimed that water in the form of rain and snow was sufficient to cause flow of all rivers on Earth, confirming Aristotle's belief that water was recycled (Biswas, 1970; Nace, 1974).

Figure 3.3: River systems in Northern France. The Seine River, marked in blue, runs through Paris and deposits into the Channel.

Edme Mariotte

Less is known about Mariotte's life than that of Perrault. Even the date of Mariotte's birth is considered questionable (Biswas, 1970). All that is known about Mariotte comes from his writings and, which were prominent for their time.

Likely influenced by Perrault, Mariotte also believed that rainfall was sufficient for the creation of rivers and springs (Biswas, 1970). Unlike Perrault, Mariotte did not measure precipitation and river flow, but instead demonstrated that an increase or decrease in river flow is directly related to the amount of precipitation (Biswas, 1970). Mariotte measured the total amount of precipitation at Dijon, France. Over the course of three years, an average annual rainfall of 15 inches was determined. From this Mariotte concluded the rainfall per square **league** per year was 238 050 000 ft^3 (Biswas, 1970; Mariotte, 1718)

The catchment area of the Seine River near Paris was estimated to have an area of 50 leagues by 60 leagues and therefore a total catchment area of 714 150 000 000 ft^3 (Mariotte, 1718).

Measurements were also taken at the end of the river where the width was 400 ft and the depth was averaged to be 5 ft (Biswas, 1970; Mariotte, 1718). Through the placement of a **float** in the middle of the river, Mariotte could pace alongside the float as it was carried by the river current and determine an estimate of the river's average velocity (Mariotte, 1718). By multiplying the cross-sectional area and the velocity, he calculated the total volume of water passing in the Seine near the point of discharge to be 105 120 000 000 ft^3 and easily replaced by the amount of precipitation in the catchment area (Biswas, 1970; Mariotte, 1718).

Mariotte's findings complimented the theories proposed by Aristotle and Perrault, and further experimentation helped to commend Da Vinci's ideas of current flow.

Though floats had been used by scientists in the past, Mariotte experimented frequently with these devices. He used a ball of wax with a heavy interior so he could submerge it in water and reduce the effect of wind, without having his float completely sink (Biswas, 1970). As the object moved downstream, the speed of the float over a measured distance was determined through the use of a pendulum to measure time (Biswas, 1970).

Mariotte recognized that the velocity of a river varies depending on height. He determined this by using floats of different densities, connected by a string. In general, at the top of the river, velocity is greater than at the bottom. The exception to this rule is when rivers deepen and form cavities (Biswas, 1970).

Edmond Halley

Better known for his astronomical and mathematical discoveries, Halley also contributed to the quantitative analysis of the water cycle. Halley experimented with evaporation, the other half of the water cycle, and added his findings to the ever-growing theory of the origin of springs and rivers (Armitage, 1966).

Halley explained the process of evaporation such that if an atom of water is heated, it expands to become a bubble ten times the original diameter (Biswas, 1970). This bubble is then lighter than air, and can float upwards. As more heat is added, more water molecules expand and float above the air (Biswas, 1970). This can be attributed to the heating of bodies of water by the sun. Halley even hypothesized the effect air temperature would have on the amount of water vapour, indicating that as warm water would hold more salt than cold water, warm air would contain more water vapour than cold air (Armitage, 1966).

The next part of Halley's discovery involved experimentation to determine if evaporation is sufficient to replace the discharged water flowing from rivers. Halley took a pan of water and measured both the depth of water and mass of the water (Armitage, 1966). A thermometer was placed in the dish and it was heated to a realistic summer temperature. After the course of two hours, the mass was taken again and it was found that 0.82286 lbs of water, or 1/53 inch of water had evaporated (Armitage, 1966).

After developing a two hour approximation, Halley estimated that evaporation took place in the summer for 12 hours a day. He used this data, as well as the approximate surface area of the Mediterranean Sea, to determine that each day in the summer; 5 280 000 000 tons of water was evaporated. Halley then calculated the discharge of all nine rivers that flow into the Mediterranean to be 20 300 000 tons and thus replaceable by the total evaporation (Armitage, 1966).

Though his explanation of evaporation was wrong, Halley created an informative model to accurately measure evaporation and apply this technique to various bodies of water (*Figure 3.4*).

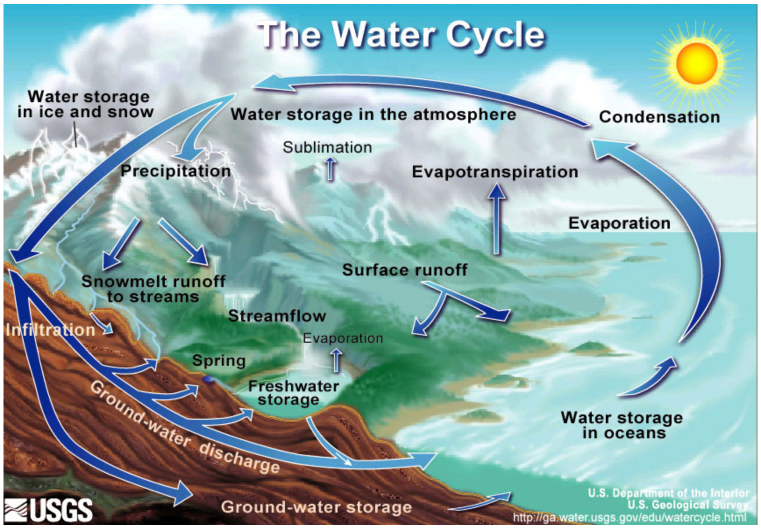


Figure 3.4: The Water Cycle. The work of Perrault, Mariotte, and Halley contributed greatly to our present day understanding of the water cycle. The evaporation of oceans can be seen condensing into clouds. These precipitate down and form runoff and streamflow.

Groundwater Overdraft

The 17th century resulted in many important discoveries relating to the hydrologic cycle; however, one area was completely overlooked. Groundwater is a crucial component of the water cycle, especially due to the fact that 30.3% of the Canadian population rely solely on groundwater for domestic use (Environment Canada, 2011).

Groundwater is water that is found below the earth's surface, in the spaces between sediment grains and rock fractures (*Figure 3.5*). An area of permeable rock or sediment, which can hold and transmit significant amounts of groundwater is called an **aquifer**.

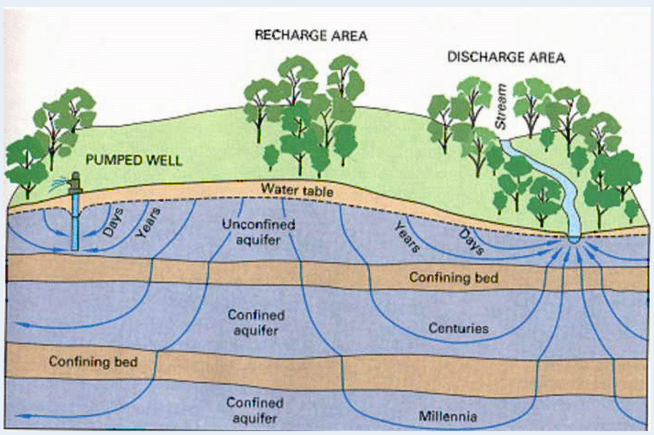


Figure 3.5: Groundwater flow. The hill, or area of recharge, is where water penetrates the ground. The stream, or area of discharge, is where water outflows onto the Earth's surface.

Freshwater is becoming an increasingly valuable global resource. As populations increase, the demand for freshwater to fulfill municipal, industrial, as well as agricultural uses will also increase (Vaux, 2010). That is the reason why the protection and preservation of freshwater is so important today.

Groundwater has the ability to be replenished through a process known as recharge. Recharge occurs when precipitation seeps and percolates into the soil, replenishing water lost from pumping and natural processes. Many groundwater basins are becoming increasingly exploited and **overdrafted**, which poses a threat to the natural balance of the water system. When more water is removed from an aquifer than is readily replaced, the consequences include **land subsidence**, sea water intrusion, reductions in base flow to streams, and reductions in groundwater and surface water quality leading to decreased health of an aquatic habitat (Racz, et al., 2012).

There are artificial techniques being used today to increase groundwater recharge and avoid future overdrafts. The techniques used to increase the flow of water into an aquifer include injection wells, bank filtration in streams and infiltration ponds (Racz, et al., 2012). Artificial recharge produced by infiltration ponds is often referred to as "managed aquifer recharge" (MAR).

Groundwater is difficult to detect and trace, simply because it is hidden below the surface of the Earth. This has caused scientists to experiment with ways to measure infiltration, as well as overcome the issue of overdraft through MAR. Infiltration rates are largely attributed to soil and sediment type as well as changes in saturated hydraulic conductivity (Racz, et al., 2012). This indicates that sediment texture and water table depth both affect infiltration rate and can be used to predict natural recharge of an aquifer.

Another way to prevent overdraft is through societal laws and regulations. From an economic standpoint, it is more beneficial to apply preventative measures than to remediate effects such as overdraft or pollution (Vaux, 2010). Locally developed and managed groundwater programs can be most effective for protecting and managing an aquifer (Vaux, 2010).

Groundwater overdraft is an issue that has global consequences, but scientists and engineers are determining ways to prevent this from happening. Through artificial recharge and management techniques, groundwater can remain plentiful and safe for public use.

The Development of Foundational Techniques for Modern Paleoclimatology

Paleoclimatology is the study of changes in the Earth's climate since its formation. The focus of this field is to decipher past climates by means of compiling data gathered by the application of control and various **proxy** techniques.

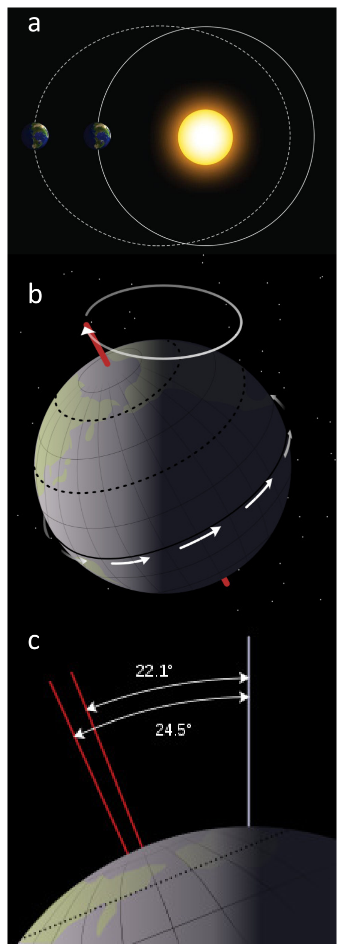


Figure 3.6: The parameters of Milankovitch's model. (a) the eccentricity of the Earth's orbital (b) the precession of the Earth's rotation (c) the obliquity of the Earth ranges between 22.1º and 24.5º. The current obliquity of the Earth is 23.5º.

Sunspots

Human beings, fascinated by the stars began to look to the sun to explain climatic variations on Earth. **Meton of Athens** (active 432 BCE) was recording the position of the sun at the horizon, hoping to find predictable variations in sunrise and moonrise locations. After more than 20 years of data collection he found that when the sun had spots the Earth was both cloudier and rainier (Hoyt and Shatten, 1997). This **sunspot** discovery highlighted the sun as a factor influencing global climate. While some were confident that the sun's variations could explain all weather and climate on Earth, others simply did not (Hoyt and Shatten, 1997). The magnitude of the sun's influence of climate change was poorly understood, meriting further investigations.

Planetary Motion Induced Climate Change

Serbian astronomer and geophysicist, **Milutin Milankovitch** (1879 – 1958), established an innovative new model for the thermal regimes of planets relative to their motion around the Sun (Cronin, 1999). Previous models explained these thermal regimes by relating the Earth's **eccentricity** and **precession**; the deviation of a planet's orbit from a circle and the orientation of a planet around a rotational axis, respectively (Berger et al., 1981) (Figure 3.6a,b). These two parameters had been recognized to oscillate between minimum and maximum values over periods of thousands of years. Milankovitch believed that these models failed to compensate for a necessary parameter. In 1875 he pulled together several known equations, which led him to conclude that the larger the axial tilt of the Earth, the more **insolation** a hemisphere will receive at the time that it is the closest to the sun (Berger et al., 1981; Cronin, 1999). This meant that the seasons would be more extreme with larger axial tilt due to variations in insolation. Milankovitch termed this new parameter **obliquity** (Cronin, 1999) (Figure 1c). His model allowed for variations in insolation over the previous 600 000 years to be calculated with superior accuracy to previous models (Berger et al., 1981).

Dendrochronology

Andrew Ellicott Douglass (1867 – 1962) was an American astronomer, who in the 1920s had been studying the impact of sunspots on climate (Larson, 2011). He was studying trees in the South-western United States, where he observed that tree growth in temperate and colder areas halted in the winter, but resumed in the spring. Douglass found that each ring in the tree's trunk represented a year of growth (Larson, 2011; Libby, 1983). However, not all rings were the same size. Smaller rings were reflective of tougher growing periods, while those with lager bands were indicative of preferable growing conditions. He termed the study of this age-ring relationship in trees

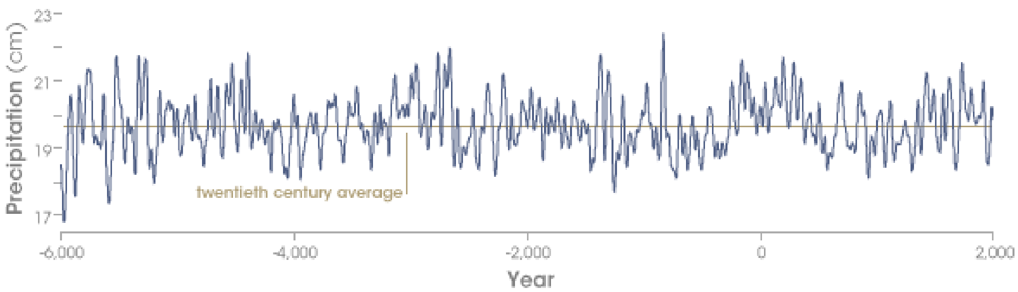


Figure 3.7: Graph of precipitation over the last 6 000 years constructed using dendrochronology along the eastern margin of the Sierra Nevada.

dendrochronology (Libby, 1983). This became one of the first methods of numerically dating ancient objects and events (Larson, 2011).

In the 1950s one of Douglass' former students, **Edmund Schulman** (1908 – 1958) ventured into the White Mountains to measure trees much older than he had studied before (Larson, 2011). He found old trees with much older, dead trees lying on the ground. By analyzing their combined dendrochronology he was capable of deducing the climate record of the previous 9 000 years in the South-western United States (Libby, 1983; Figure 2).

Douglass' tree rings provided information about past precipitation, but they also record individual events such as forest fires (Figure 2a,b).

Figure 3.8: Cross section of tree rings. Each ring represents one year of growth and darker patches are indicative of a forest fire.

Dendrochronology, unfortunately, is limited to wood that has a continuously record, as had in the southwest American states (Larson, 2011). This method can only applied in regions where such preservations are possible; however it provides a valid basis for measurements essential to paleoclimatology.

Isotopes as a Flexible Proxy

In 1912, radio chemist **Frederick Soddy** (1877 – 1956) first suggested the existence of **isotopes**, substances that have two or more different atomic weights for a single element and which are chemically indistinguishable (Fernandez, 2006). One year following, **Sir Joseph John Thomson** (1856 – 1940) sent streams of neon ions through an electromagnetic field (Wolfsberg, Van Hook and Planeth, 2010). The ion deflection was observed by placing a photographic plate in their path (Becker, 2007). Thomson observed two different patches of light on the plate, suggesting that there were two different deflective parabolas (Becker, 2007; Wolfsberg, Van Hook and Planeth, 2010). He concluded that one patch contained heavier neon than the other. This provided the first evidence of stable, nonradioactive isotopes, neon-20 and neon-22 (Fernandez, 2006).

Later, in 1947, following **World War II** (1939 – 1945), American Scientist **Willard Libby** (1908-1980) noted that as plants photosynthesize, they absorb measureable quantities of carbon-14 (Arnold and Libby, 1949). He deduced that when they die they are no longer able to absorb carbon-14 (Arnold and Libby, 1949; Figure 2c). As a result, the sequestered carbon-14 disintegrates at an invariable and known rate, making this a valid method of dating organic matter (Libby, 1961). This technique has also been extended to determining the age of mummies, ancient artefacts and even confirming dendrochronology results (Larson, 2011). Several other elements such as lead and nitrogen, are used to date organic matter such as marine shells and bones, including corals (Larson, 2011).

Radioisotope dating, like dendrochronology is reliant on assumptions, including that the rate of **half-life** decay of the element has remained constant and the sample has not accumulated any more of that element over time (Larson, 2011).

The Rise of Oxygen Isotopes

Harold Clayton Urey (1893 – 1981) began working with the heavier oxygen isotope, oxygen-18. He looked at the ratio of oxygen-18 to oxygen-16 in both carbonate (CO_3^{2-}) and water (H_2O). He calculated that this ratio increased by 1.004 when the temperature changed from 0°C to 25°C (Arnold, Bigeleisen and Hutchison, 1991). This meant that environmental conditions dictate the relative abundances of elemental isotopes. This information was important to the field of paleoclimatology, as it suggested that the ratio of isotopes oxygen-18 to oxygen-16, and other elements would assist with the analysis of paleotemperatures (Arnold Bigeleisen and Hutchison, 1991).

In 1957, **Cesare Emiliani** (1922 – 1995) was analyzing bedrock drilled from the Caribbean (Hay and Zakevich, 1999). He hypothesized that the fluctuations in oxygen isotope ratios were a direct result of water temperature (Emiliani, 1955). This was predicted because the lighter isotope, oxygen-16 appeared to be more easily evaporated, whereas the heavier isotope, oxygen-18 was more easily condensed (Emiliani, 1955). He believed that colder conditions were found to have a greater oxygen-18 to oxygen-16 ratio in ocean water, than warmer conditions (Hay and Zakevich, 1999).

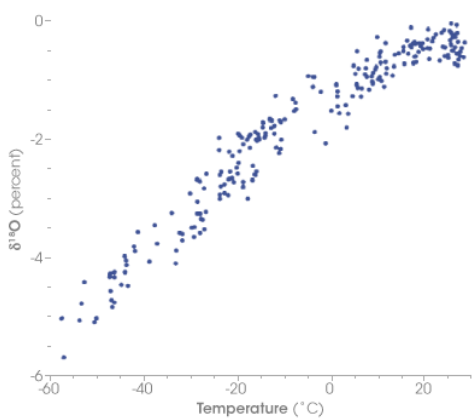


Figure 3.9: Ratio of isotopes oxygen-18 to oxygen-16 against temperature. At lower temperatures there exists a lower oxygen-18 to oxygen-16 ratio, just as Emiliani had suggested

In 1967, **Nicholas Shackleton** (1937 – 2006) discovered that oxygen isotope variations recorded in the calcite-rich shells of foraminifer, tiny marine protists, were controlled by global ice volume changes (Ruddiman, 2006). As ice sheets expand they take up oxygen-16 rather than the heavier isotope, oxygen-18. Shackleton determined that global ice volume rather than temperature, dictate oxygen isotope ratios in marine environments (Shackleton and Opdyke, 1973). This allows past ice-volumes to be determined through the analysis of marine oxygen isotope records (Ruddiman, 2006).

Ice Cores

The end of the 1940s brought with it the cold war and many substantial scientific projects. The **International Geophysical Year** (IGY) program was created through the cooperation of several nations around the world to advance human understanding of the Earth (Korff, 1954). Although the IGY only lasted from July 1957 to December 1958, it ignited the interest of several other agencies to develop unexplored fields. The **Greenland Ice Sheet Program** (GISP) was formed to understand ice sheets, specifically by mapping their thickness and subsurface topology (Grootes et al., 1993). Since ice sheets survive the summer, the temperature in which they are formed can allow them to have well-preserved annual layers. The GISP became one of the first programs to gather data from **ice cores**, vertical cylinders of ice, extracted on site (Bradley, 1999; Figure 4b). They extracted cores 3000m in depth, dating back 100 000 years. Oxygen-18/-16 ratios were measured in the extracted ice cores to determine not only the temperature of their formation, but also global ice volumes at the time ice formation (Bradley, 1999; Grootes et al., 1993).

Fixing the Gap

Milankovitch's theory of orbital climate forcing was either violently opposed or ignored by the scientific community until a group of scientists correlated orbital chronology and paleotemperatures using oxygen isotopes. Collaborating with **Jim Hays** (active 1976) and **John Imbrie** (b. 1925), Shackleton evaluated the Milankovitch model on global ice volumes (Hays, Imbrie, Shackleton, 1976). The team identified three periods where the Earth's orbital changes matched the temperature, isotope and fossil records (Hays, Imbrie, Shackleton, 1976).

During the 1980s, in collaboration with the Spectral Analysis and Mapping Project, Imbrie and Shackleton generated a marine chronology dating back approximately 300 000 years (Martinson et al., 1987).

Paleoclimatology Development

Paleoclimatology provides different tools and techniques for analyzing the past in different environments. Such data can then be arrayed to generate an increasingly more fluid record of the past. It is important to understand the past, in order to develop models, which can predict future changes in climate and their potential influences on the Earth.

The Controversy of a Snowball Earth

In 1964, **Brian Harland** (1917-2003) published a paper where he applied **paleomagnetic** evidence to show ancient glacial tills were deposited in Greenland and Svalbard while they were situated within 10 degrees of the equator (Harland, 1964). He developed the **snowball Earth** hypothesis to explain the presence of glaciers at the equator between 540 and 800 million years ago, during the Neoproterozoic. This fully snowball Earth might have resulted from a reduction in greenhouse gases, predominantly carbon dioxide and methane, in the Earth's atmosphere. (Harland, 1964; Hoffman et al., 1998). This would produce drastic cooling and increase annual accumulation of snow and ice allowing it to become extensively glaciated. The Earth would not retain heat due to the high reflectivity of its surface and absence of the greenhouse trapping of heat in the upper atmosphere (Hoffman et al., 1998). This positive feedback is hypothesized to have continued until the planet was completely covered in ice (Harland, 1964).

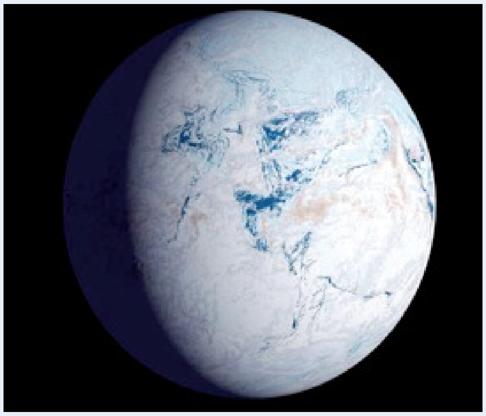


Figure 3.10: Artist's creation of a completely glaciated, snowball Earth.

While the widespread presence of glaciers during the Neoproterozoic at this time is not argued, the idea of the entire planet frozen in ice is controversial. Debates over this astonishing hypothesis have continued for decades.

Harland's original paleomagnetic evidence for low latitude glaciation is questionable because it is dependent on the assumption that the Earth's magnetic field was the same 540-800 million years ago as it is to today, and fails to account for magnetic field reversals every 70 million years or so. it is also possible that the paleomagnetic signatures recorded by Neoproterozoic rocks have been reset by more recent events. (Crowley, Hyde and Peltier, 2001).

The Earth is hypothesizes to have rapidly entered and then recovered from this snowball Earth deepfreeze events through the outgassing volcanoes, which filled the Earth's atmosphere with greenhouse gasses, enabling it retain heat once again. The carbon dioxide levels required to thraw uce covering the entire Earth are estimated to have been 350 times what they currently are, which seems unlikely (Crowley, Hyde and Peltier, 2001).

Scientists such as **Nicholas Eyles** (active in 2004) have been attempting to explain the existence of ice near the equator without committing to complete global glaciation. Eyles found that the breakup of the supercontinent Rodinia, and the later split of Baltica from Laurentia both coincided with glacial periods. His **zipper-rift** hypothesis suggests that tectonic uplift associated with continental break-up created high lands that hosted local glaciers near the equator and that global glaciation is unnecessary (Eyles and Januszczak, 2004).

Paleoclimatic debates, such as that surrounding the snowball Earth hypothesis help to refine the powerful tools and techniques utilized in paleoclimatology.

Religious Stories Initiating Scientific and Rational Theories about a Flood

There are stories of a catastrophic flood recorded by cultures across six continents, often connected to religious or moral lessons (Patten, 1967). The waters in the flood generally originated from a creation story and are sometimes related to a "cleansing" by destroying wicked life (Patten, 1967). Famous legends include the Epic of Gilgamesh, lore of the K'iche', great flood of Hindu people and Noah's ark (Ryan, 1988; Isaak, 1996) In the Bible, the story of Noah involves a global flood with rain for 40 days, covering the tallest mountain with 15 cubits of water, requiring a year for the flood waters to recede (Figure 3.11; The Bible, Genesis, 5-9). While the Bible contains details of the events, the story's purpose may be beyond a simple history lesson (Figure 3.12). The repercussions of a flood of this magnitude require examination of evidence to support its existence beginning with identification of the extent of change required for an event to be global in nature. The opposite approach could also be considered, where evidence in geologic history can be explained by legend. The Biblical flood story can be seen through the layers of the rock and the history of curious, scientific minds.

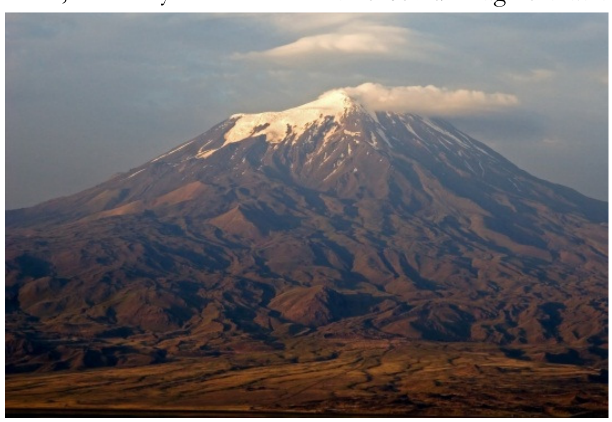


Figure 3.11: Mount Ararat, the location where Noah's Ark is believed to have landed a year after the flood started.

"We need not try to make history out of legend, but we ought to assume that beneath much that is artificial or incredible there lurks something of fact."

Figure 3.12: quote by C. Woolley in 1934

The three main lines of evidence required to validate a global flood occurrence would be a distinct change in the rock layers from before to after the flood occurrence, globally synchronous evidence for these changes, and finally, specific geologic evidence that would indicate flood conditions.

Flood Water Origin

A global flood would require additional water beyond the water found within the current hydrologic cycle. One additional source is water in glaciers and poles, which could have melted in a warmer global climate. The **Intergovernmental Panel on Climate Change** (IPCC) estimated the amount of water from melting glaciers would increase global oceans by only 60 cm (IPCC, 2012). During 1874, **Isaac Vail** (1840-1912) introduced another theory for the source of water using the greenhouse effect called the **antediluvian canopy** (Vail, 1874). A thick atmospheric layer around the earth would contain gaseous water vapour (Patten, 1967). One could imagine that this layer would be similar to continually thick dew, where little evaporation from the land occurred. This layer would then have burst and fallen as the flood (Patten, 1967). The possible changes include a decrease in barometric pressure, a different gas combination within the atmosphere, and particularly, an increase in solar radiation's penetration on the Earth (Whitcomb and Morris, 1970). All these factors seem favourable towards the breaking of an antediluvian canopy (Whitcomb and Morris, 1970). However, the Antediluvian Canopy Theory is discredited because heat would have been trapped to the extent that life could not have survived within the canopy (Rush and Vardiman, 1990). Thus, the question of where the water originated remains inconclusive.

An alternative theory, proposed by **C. Woolley** (1880-1960), suggests that the flood covered the whole earth from the perspective of the author of Genesis. One theory suggests that humanity inhabited the Mesopotamian Valley. This would result in a local flood theory during modern times.

Initial Disaster and Flood Theories

Scientific records show initially the theory proposed was events of great magnitude called **catastrophism** (Patten, 1967). If this theory were true, one would expect to see drastic changes in the crust due to large events such as a global flood. Until the late 19th century, scientists believed both catastrophism and Noah's flood. When uncertainty of a global flood grew in the scientific community, a new theory was needed to describe geologic processes (Patten, 1967). The more recent, opposing theory is **uniformitarism**, which suggests that any changes in the past crust are due to the same processes that occur today (Patten, 1967). The expectation from this theory would result in a more predictable Earth history.

John Whitcomb, Jr. (b. 1924) and **Henry Morris, Ph.D.** (1918-2006) are very controversial figures who contributed to the catastrophic flood theory, and initiated the **Creation Research Society** and the **Institute for Creation Research** (Patten, 1967). While many scientists do not agree with their thoughts and ideas, it is important to understand the direction of the field of flood traditions (Young, 1977).

Evidence gathered in 1961 supporting a worldwide flood includes marine observations, volcanism, tectonics, and fossilization (Whitcomb and Morris, 1970).

Additionally, a great number of mountains today, including the **Appalachian Mountains**, contain fossils of the same time periods, Pliocene and Pleistocene, suggesting that they all formed around the same, recent time period (Patten, 1967). A global flood would result in both a massive death rate of organisms, as well as a good mechanism for preservation over the flood year (Whitcomb and Morris, 1970). However, in the context of the formation of the Appalachians via continent collision, it is unlikely that the range was carved out primarily by water erosion. Instead plate tectonics would have been a greater factor. This results in the possibility of fossils deposited in oceans rising with the plate. However, the method that explains how the fossils remained amazingly intact through the plate tectonics process is unknown (Pollock, 2012).

Alternative Ideas

Davis Young (1995) was awarded the Mary C. Rabbitt Award which commends insight into the history of geology (Newcomb, 2009). He has written *Creation and the Flood: An Alternative to Flood Geology and Theistic Evolution* in which he includes his thoughts and evidence countering the mechanisms proposed by Whitcomb-Morris in their book *Genesis Flood*. The significance in Young's writing is his ability to use modern geology in order to provide new insight into a global flood. The difference of 16 years resulted in advancements in the field of geology and scientific thought that could be used in this context.

Figure 3.13: Anorthosite rock is found across continents, but is only formed in a limited historical time period, suggesting that the land areas were previously one unit.

Overall, Young's objective is to suggest that the flood described in Genesis had the specific purpose to wipe out humanity, but that other catastrophes are quite possible in geologic history (Young, 1977). This opposes "Genesis Flood" theory in which many pieces of geologic history are believed to have been caused by the one flood event.

The evidence provided by Young includes heat flow, radiometric dating, formation of metamorphic rocks, and plate tectonic theory (Young, 1977).

"Genesis Flood" implies that the majority of igneous rock found on earth, from magma flows was formed by volcanic activity during the year of the flood (Whitcomb and Morris, 1970; Young, 1977). The primary issue is the great magnitude of magma released and found in rock layers, which would be required to cool in less than a year. The well-researched **Palisades sill** sample of igneous rock found in New Jersey is a **diabase**. In a lab setting, it was found that a temperature of 1100oC was required for metamorphism. Young estimates that due to the size of the deposit and its estimated temperature, it would take hundreds of years to solidify compared to the proposed single year (Young, 1977).

Detecting Storms: Hurricane Sandy

According to the Bible, the flood was the largest water destructing crisis that the world will ever face in its history (The Bible, Genesis 9:11); however, we still are plagued with wild weather. This is especially true, with **Hurricane Sandy** arriving so late in the 2012 hurricane season (Figure 13.15).

Hurricane Sandy hit the United States shore on October 29 at 19:00. Sandy was one of 3 major hurricanes that **National Oceanic and Atmospheric Administration** (NOAA) originally predicted for the 2012 season; however, its late arrival and collision with a **nor'easter** could not have been predicted at the beginning of the season (Robichaud, 2012).

Sandy was considered an **extra-tropical hurricane** because it formed as a result of temperature differences in air masses. This mode of formation causes a wider, oval shape to the storm drastically expands the impact area. Further, Sandy was unusual in that during the time the storm expanded it maintained hurricane wind power (Voiland, 2012).

The primary factors considered in predicting a hurricane include **El Nino wind patterns**, the ocean temperatures, and atmospheric pressure. Warm water temperatures are able to sustain a hurricane, while the El Nino wind pattern can decrease a hurricane's force (Advameg, n.d.).

The current methods for detecting hurricanes include aircraft and ship detection systems, which directly review current conditions. Alternate methods, which are more indirect, include satellites and Doppler radar systems (BM, 2012).

Hurricane Sandy was primarily identified by radar systems (Voiland, 2012). Radar stands for Radio Detecting and Ranging and is a tool used for locating and evaluating precipitation using the reflection of radio waves. A radar system is composed of four primary parts: a transmitter, switch, antenna and receiver. Radar imaging is available due to the receiver's ability to transform the detected signals into images (BM, 2012).

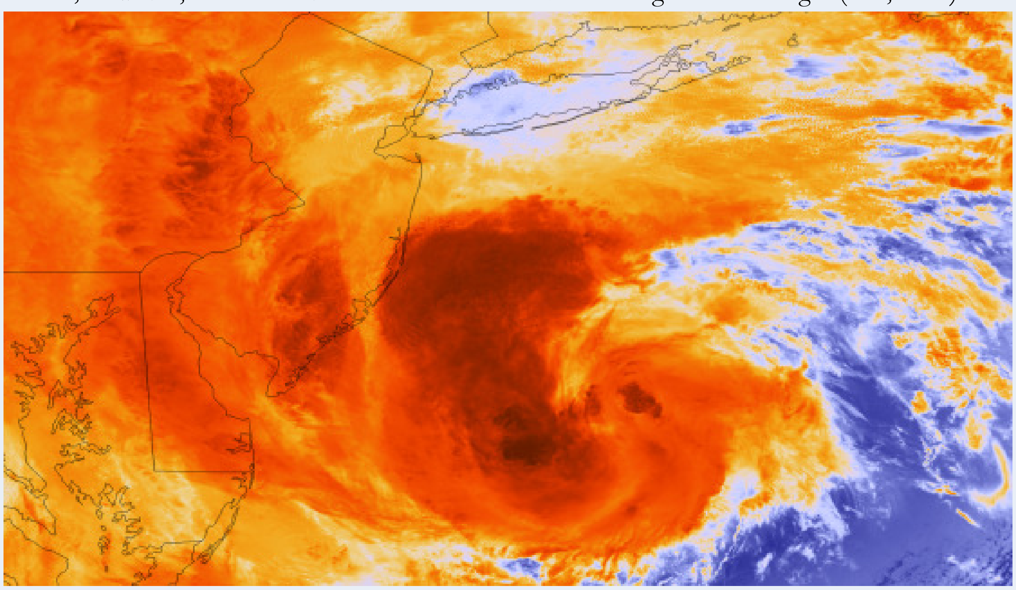


Figure 3.15: Radar Image showing the asymmetrical shape of Hurricane Sandy.

The two main principles required for this technology are **Doppler theory** and knowledge about reflectivity based on **wave theory**. Combining these two ideas, measurements of **reflectivity** and velocity of the storm system can be measured (BM, 2012) This shows the location and form of precipitation.

Hurricane Sandy was also detected further inland by seismometers, due to seismic vibrations created by an increase in wave energy on shore. This occurred six hours before the hurricane hit shore, and before high winds arrived at the area (Oskin, 2012).

The second aspect that Young discusses is the accuracy of radiometric dating. "Genesis Flood" suggests that when the atmospheric Canopy was removed by the rain, an increase in solar radiation caused an increase in the decay rate (Whitcomb and Morris, 1970; Young, 1977). Studies on meteorites demonstrate that solar rays only penetrate a couple of feet deep, and this has been at a fairly constant amount. Further, current radio dating techniques are realistic estimates. Rb^{87} changes to Sr^{87} during the crystallization of igneous rock. This occurs when radioactive strontium (Sr^{87}) replaces calcium in the feldspar plagioclase ($CaAlSi_3O_8$). Most dating requires an estimate of the amount of radiogenic daughter thought to be present in the rock. However, that is not necessary in this case (Young, 1977). The processes of formation and dating of a rock using this method can be found in Figure 3.14.

Step	Process
1	Fact: at the initial formation of the rock Sr^{87} is equal to Sr^{86}
2	Rb^{87} decays to Sr^{87} while Sr^{86} remains constant
3	The ratio of Sr^{87}/Sr^{86} increases as time progresses
4	Fact: The larger the ratio, the more Rb^{87} present in a rock fragment.
5	Geologists compare two rocks to gage relative age.

Figure 3.14 : The steps to understanding radiometric dating using Sr87 (Young, 1977)

The third argument reviews metamorphic processes, which are primarily caused by heat and pressure. Tectonic activity is the primary known mechanism. "Genesis Flood" proposed that metamorphic rocks were almost all formed and exposed during the flood (Whitcomb and Morris, 1970; Young, 1977). However, there are some fossils found in a New England metamorphic sample, suggesting that the "Genesis Flood" theory would believe it was formed within the flood year. It is thought to have required formation conditions of 600°C and five kilobars. This pressure would occur when the New England rock was buried 12 miles. The process of formation and exposure appears too extensive for just one year. Further, Eastern Canada's exposed rock forms consist of two-thirds metamorphic rock, which is even more extensive (Young, 1977).

The final suggestion that Young explored is plate tectonics on a global scale, which include both the theory of continental drift and sea floor spreading. These ideas are most well known to be originated by **Wagner** (1880-1930) and **Hess** (1906-1969) respectively. "Genesis Flood" does not agree with the continental drift aspect of the theory, but cannot explain the Permian age glaciation (Whitcomb and Morris, 1970; Young, 1977). The evidence of continental drift is as follows. Firstly, both the global shorelines and the continental shelves on either side of the Atlantic Ocean correlate well (Pickering, 1907). Secondly, the Precambrian shield, large folds and faults align cross-continentally (Young, 1977). Thirdly, ancient Paleozoic mountains, such as the Appalachians, Scottish Highlands, and Norwegian mountains align and the Andes, Rockies, Alps and Himalayas similarly connect (Young, 1977; Taylor, 1910). The fourth evidence is that large rock deposits are found in areas on different continents that would cover a related area on a supercontinent. More specifically, anorthosite is found in the Adirondack Mountains, in the Americas, and Ghats region, India (Figure 3.13; Young, 1977). Lastly, evidence of a large glacier movement is currently found across continents in the southern hemisphere. The direction of movement of the glacier can be theorised across the supercontinent. If "Genesis Flood's" proposition theory were true, then a supercontinent would need to exist at the beginning of the global flood, and part to approximately the continents' present positions (Young, 1977).

There appear to be two overall perspectives of a flood legend occurring through geologic history. Genesis Flood attempts to find geological evidence for the Biblical flood. Unfortunately, their ideas are limited and often dismiss critical geologic information. Alternatively, Young summarizes many scientists' ideas about rock processes which counter Genesis Flood. Young suggests that the Biblical flood did not create all the possible formations found in present time. These ideas suggest a local, not global, flood. However, theories presented still require more evidence and present more questions. Geologists of future generations have much still to research in understanding the root truth from legends..

Mass Extinction: A Detective Story

The **Permian Triassic (P-T) Mass Extinction,** also known as *The Great Dying,* occurred 250 million years ago, between the last period of the Paleozoic era, the **Permian Period,** and the first of the Mesozoic era, the **Triassic Period** (White, 2002). It is the largest documented mass extinction in history, killing over 96% of marine species, in addition to plants and other terrestrial organisms (White, 2002). It is also the only known **mass extinction** of insects (White, 2002). Much research has been attributed to discovering the cause of an extinction event of this magnitude, and yet to this day the mystery is not completely solved.

In 1841, **Sir Roderick Impy Murchison** (1792-1871) studied the rocks in the Russian Ural Mountains and noticed differences in the rock's composition compared to other older rocks in Britain and younger rocks in central Europe (Erwin, 2006). This was the "discovery" of the Permian Period (Erwin, 2006). Soon after in 1860, **John Phillips** (1800-1874) divided the fossil records into three categories, later known as Eras: Paleozoic, Mesozoic, and Cenozoic (Phillips, 1860). Phillips saw these three Eras as three separate creations of life due to the extreme variance in the fossil record (Phillips, 1860). The mystery was then opened: what caused the disappearance of so many species at the end of the Paleozoic Era?

The Catastrophic vs. Gradual Debate

During the early 1900s, researchers were split between two theories to explain the P-T mass extinction. The **catastrophic theory** was presented by **Otto Schindewolf** (1896-1971), who claimed that an extra-terrestrial agent such as cosmic or solar rays entered the Earth's atmosphere, causing the immediate extinction of a number of species (Newell, 1956). Additionally, the rays accelerated mutation rates within the surviving species, causing rapid differentiation, which would explain the new life forms observed by Phillips (Newell, 1956). The opposition led by **Norman Newell** (1909-2005), presented the **gradual theory** to explain the extinction event. Newell believed the catastrophic hypothesis was unlikely because the extinction was seen most prominently in marine species (Newell, 1956). A catastrophic impact, Newell assumed, would be more likely to wipe out terrestrial organisms. This is because marine organisms living more than 5 m below the ocean surface have water surrounding them, which acts as an effective filter of radiation (Newell, 1956). Additionally, mutations are normally deleterious. Therefore, most mutations would have a negative effect on species as very few mutations would lead to speciation and thus would not lead to a significant increase in biodiversity (Newell, 1956). Newell was of the opinion that the extinction was caused gradually by a decrease in sea level (Newell, 1956).

In the years following to the present day, these two theories have been constantly refined to include more specific mechanisms including volcanism, increased competition, ocean anoxic events, and impact theories (Erwin, 2006).

Era	Period
Cenozoic	Quaternary
	Neogene
	Paleogene
Mesozoic (65-250 million years ago)	Cretaceous
	Jurassic
	Triassic
Paleozoic (250-540 million years ago)	**Permian**
	Pennsylvanian
	Mississippian
	Devonian
	Silurian
	Ordovician
	Cambrian

Figure 3.16: The location of the P-T extinction event, which occurred 250 million years ago, relative to the other time periods.

Volcanism

One major theory is based off of evidence found in Siberia of the most massive set of eruptions in the past 600 million years occurred approximately 250 million years ago (Erwin, 2006). Additionally, there is a layer of volcanic ash in the P-T boundary rocks in Siberia. Evidence for these eruptions is seen in the **Siberian flood basalts** (Erwin, 2006). This extensive feature was created by volcanic fissure eruptions, as viscous magma flowed to fill valleys and lowlands, leaving behind thick layers of igneous rock (Renne and Basu, 1991). Today, after millions of years of erosion, the Siberian basalts still cover 675 000 km² of land (Erwin, 2006). Increased volcanism on this scale could have led to mass extinction as volcanic eruptions release large amounts of sulphur compounds, which in high concentrations would change atmospheric and marine conditions and poisoning of most organisms (Kiehl and Shields, 2005).

Increased Competition

Another theory as to the mechanism of mass extinction was proposed in the 1970s. The theory was that plate tectonic movement, more specifically the formation of Pangaea, was the cause. At the time it Pangaea was considered to have formed in the late Permian era, and it was hypothesized that the collisions of the continents would have modulated biodiversity in two ways (Erwin, 2006). The first is that by decreasing the number of geographically individual biotic provinces, more species would share one habitat thus increasing inter-species competition (Erwin, 2006). The second is that plate tectonic movement affected ocean currents, causing an uneven supply of nutrients to coastline species. This would in turn decrease the number of specialist species due to starvation, and allow generalist species to flourish (Erwin, 2006). However, the refinement of our understanding of the Earth's tectonic movement and the timeline of Pangaea showed that the supercontinent did not form at the appropriate time, undermining this theory (Erwin, 2006). Despite this, the idea of Earth processes involving plate tectonics and inter-species competition as a mechanism of extinction did not disappear.

Newell, as part of his gradual hypothesis proposed the reduction of space and increased competition, as a mechanism for the P-T mass extinction in the 1960s (Erwin, 2006). The cause however was the decrease in sea level, which reduced shallow marine continental shelf environments, which are occupied by many species. Soon after, **Steven Stanley** (b. 1941) proposed continental glaciation as the cause of sea level regression. This is because the formation of ice would reduce global sea levels and could force organisms to congregate around the equator (Erwin, 2006). Stanley's evidence included glacial debris found in Siberia and Eastern Australia, the extinction of tropical reefs, which is common in glaciation, and the scarcity of limestone (Erwin, 2006). This theory was originally well received because glaciation is the accepted cause of the Ordovician Mass Extinction, the second largest extinction event (Erwin, 2006). Despite this, the limited and circumstantial evidence led researchers to question the lowering of sea levels as a cause, leading to the introduction of a series of opposing hypotheses involving ocean anoxia.

Figure 3.17: The formation of Pangea decreased the amount of coastline available, and removed many geographical boundaries between species.

Ocean Anoxic Events

Anthony Hallam (b. 1933) and **Paul Wignall** (active in 1990) in the early 1990s hypothesized that sea level was increasing, not decreasing at the time of the P-T extinction (Hallam and Wignall, 1996). Evidence of this included the presence of *Lingula* and *Claraia* fossils, two species found in low oxygen environments and thin undisturbed beds of limestone during the early Triassic period. The lack of worms and other burrowing organisms also indicates a decrease in oxygen (Erwin, 2006). This led to the development of three major theories explaining how oxygen depletion led to mass extinction.

The first theory by **Yukio Isozaki** (active in 2006) is that the deep oceans had been anoxic for 20 million years prior to the event (Erwin, 2006). This hypothesis is based upon rocks found in British Columbia and Japan that contain slivers of the Pacific Ocean floor during the P-T transition (Erwin, 2006). Before and after the P-T transition, limestone included brick-red chert, an indicator of oxidized iron; however, in the P-T transition rocks, the chert was grey to black suggesting the absence of oxygen (Erwin, 2006). This implies that currents causing ocean mixing between the deep marine and shallow coastal environments were non-existent (Erwin, 2006). This isolated the oxygen-rich surface water from the oxygen-poor deep ocean, and eventually the lack of current mixing prevented nutrients from reaching the coastal environments, causing extinction.

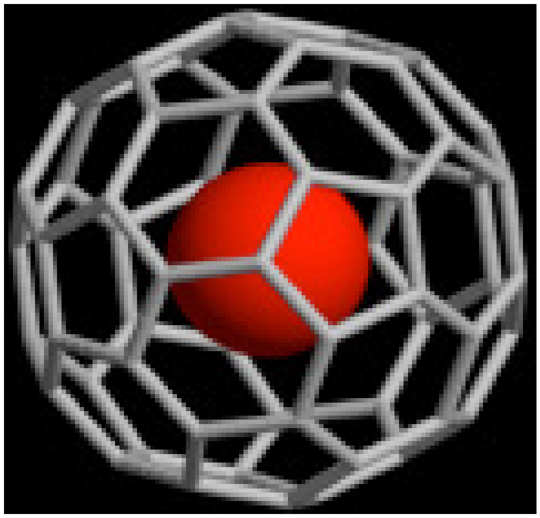


Figure 3.18: An artist's depiction of a Bucky-ball.

The second theory is that the stagnant ocean proposed by Isozaki was unstable and housed a massive amount of carbon dioxide (Erwin, 2006). Subsequent glaciation shifted current patterns in the ocean, releasing carbon dioxide into the shallow coastal environment and the atmosphere, which essentially poisoned all of the organisms (Erwin, 2006).

The third hypothesis proposed by Douglas Erwin (b. 1958) counters the second hypothesis. Since, some bacteria produce methane rather than oxygen, he believed that methane built up 300 – 500 m below sea level as slush (Erwin, 2006). The large methane reserves were stabilized in deep sediments due to high pressure from overlying water; however, once the ice melted the pressure decreased and methane, an important greenhouse gas was released causing the extinction (Erwin, 2006).

Impact Theory

The hypothesis of a meteor hitting the Earth, gained much popularity after a father-son team, **Luis Alvarez** (1911-1988) and **Walter Alvarez** (b. 1940) proposed the theory to explain the Cretaceous-Paleogene extinction event, also known as the dinosaur extinction (Kent, 1981). The theory was widely accepted after high iridium levels were found in the rocks of that time; however, the impact hypothesis was not posited to explain the P-T extinction event until 2000. In 2000, a NASA funded team led by **Luann Becker** (active in 2000) found evidence that a 6 – 12 km diameter asteroid hit the Earth (Becker, 2000). Within the P-T rocks, Becker's team found **fullerenes** containing an unusual amount of ^{3}He and ^{36}Ar, isotopes found most commonly in outer space (Becker, 2000).

Since then, researchers from Tokyo University discovered a layer of "light sulfur" in the P-T boundary rocks (NASA, 2002). This evidence suggests that an asteroid or comet hit the ocean with such force that it reached the mantle. This caused the release of a large amount of sulfur and other mantle materials (NASA, 2002). Current research is being conducted in this area to better develop this theory.

Murder on the Orient Express

Since Phillips differentiated between the fossils of the Permian and Triassic periods, much research to determine the cause has been conducted. The Murder on the Orient Express was a theory put forth by Erwin who suggested that the greatest mass extinction in Earth history was not caused by one individual event, but rather a combination of factors (Erwin, 2006). This was inspired by Agatha Christie's novel *The Murder on the Orient Express* because every passenger in the novel participated in the same murder (Erwin, 2006). This theory, while very difficult to prove, is one possible hypothesis.

Testing each hypothesis can be a daunting task; however, with improving technology, research into extinction events is becoming more feasible. For this reason study in this interesting field will continue to progress in the search of the culprit responsible for the largest mass murder known to mankind.

Modern Dead Zones

Aqueous dead zones, a possible killing mechanism of the P-T extinction, are found in lacustrine or marine environments where there is a lack of life due to the absence of oxygen. The creation of aqueous dead zones can result in mass exterminations on a local or global scale. Dead zones are a problem world wide as they are spreading throughout modern coastal areas at an increasing rate (Jackson, 2008).

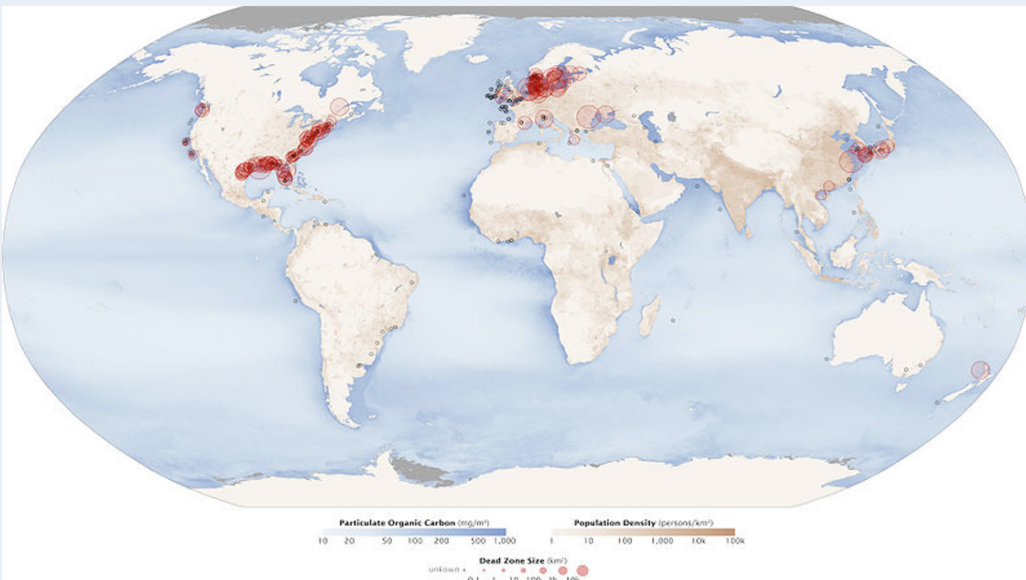


Figure 3.19: Map of the worlds aquatic dead zones, which are coloured red/

Dead zones form by natural process normally occurring in deep ocean basins, but can also occur seasonally in shallow waters (Jackson, 2008). Many dead zones have been significantly enhanced by human impact (Jackson, 2008). **Phytoplankton**, a type of algae, lives at the surface of oceans and lakes in the **euphotic zone** (Diaz, 2008). In this zone they undergo photosynthesis to produce oxygen that is then dissolved into the water, making it available for consumption by other organisms (Diaz, 2008). Increased nutrients such as nitrogen, phosphorus, and sulfur in addition to **water stratification** promote algal growth; however, the large amounts of algae eventually die and sink to the floor where they decompose (Lake Erie LaMP, 1999). Decomposition consumes most of the waters oxygen supply and releases large amounts of CO_2 causing anoxia (Diaz, 2008). Dead zones often occur seasonally, when phytoplankton bloom and die in a short time period.

Lake Erie

In the 1960s Lake Erie was coined the dead lake (Lake Erie LaMP, 1999). It is the shallowest of the Great Lakes and due to current direction, receives inflow from all of the other Great Lakes in addition to rivers and rainfall from Ontario, Michigan, Ohio, Pennsylvania, and New York (Lake Erie LaMP, 1999). Anoxia has occurred every summer in Lake Erie, but due to increased amounts of toxic chemicals flushed into the lake, oxygen depletion rates have been rising over the past 30 years. Another cause of the anoxic environment is the invasive zebra muscle species, which have depleted many of the nutrients in the water and feed on the phytoplankton, thus decreasing the amount of oxygen that can be dissolved into the basin (Lake Erie LaMP, 2011).

To combat this problem, the U.S. and Canadian Federal governments are working together to restore the diversity of organisms in Lake Erie (Lake Erie LaMP, 1999). This combined effort is known as the Lake Erie Lakewide Management Plan. They plan to restore these vital ecosystems through decreasing the amount of toxins poured into this area and managing the dominance of zebra muscles in the ecosystem (Lake Erie LaMP, 2011).

Figure 4.1: Fossilized Velociraptor eggs, found in Dinosaur Valley State Park, Texas. These fossils provide a glimpse into the history of the Earth, and the geological and evolutionary processes through which it is defined.

Chapter IV: Historical Perspectives on the Origin and Evolution of Life

While Earth has a rich and complex geological history, it is the presence of life that makes the planet truly unique. Questions regarding the origin of life and how it has changed over time have always been a focal point of scientific thought. Answering such questions has led to great controversy and disputes since humans first began contemplating life. Through analyzing the fossil record, scientists have continued to refine their understanding of life and its progression from simple, prokaryotic cells to the diverse biota that exist today. By interpreting the depositional environments in which these fossils are found, scientists have formed the building blocks for understanding the interactions between ancient organisms and the Earth. Curiosity about life in the past extends to human origins and the process through which bipedalism, a hallmark of human evolution, came to be.

The development of tools and techniques to perform these analyses has permitted the progression of biological and geological concepts over time. This chapter will chronicle scientific progress throughout history, as the world's greatest thinkers continuously strive to understand the true nature of life on Earth.

A Historical Perspective of the Abiotic Development of Life

Since the beginning of civilization, humans have been fascinated with complex natural phenomena such as the origin and development of life, and have devised speculations and hypotheses to explain them. Perhaps the oldest and most evolved of these ideologies is the **theory of abiogenesis** which, at its most fundamental level, postulates that life initially developed from non-living structures or compounds. Although the most primitive considerations of the abiotic development of life seem absurd to modern audiences, many of these notions persisted throughout the majority of documented history. Indeed, it was only through the development of a rigorous scientific method during the **enlightenment** that natural philosophers began to disprove these ancient ideologies. In the centuries that followed, developments across many scientific disciplines provided insight into the complexity of life, and the conditions under which it might have developed and flourished in the distant past.

Figure 4.2: Fresco of Aristotle. Considered one of the first polymaths and true scientists, Aristotle contributed significantly to the study of living systems in Ancient Greece. Although he lacked experimental procedure and a scientific method, his thorough observations of the world around him lead to the development of many natural philosophies.

Spontaneous Generation: the Origins of Abiogenetic theory

Considering the wealth of knowledge western civilization has inherited from Ancient Greece, it is not altogether surprising that the first principles of abiogenesis had their roots among Greek philosophers. In an attempt to explain the existence and proliferation of animals whose sexual practices and histories were uncertain, early Greek scientists developed the **theory of spontaneous generation** (McCartney, 1920). This ideology postulated that some animals were produced spontaneously from certain non-living substances such as foul water, slime, aged wax, dried perspiration, dampened dust, feces, or decaying organic matter. Since farm animals such as sheep, cows, or poultry had well documented sexual practices, spontaneous generation was generally attributed to insects such as worms, flies, or locusts, as well as less understood animals, including crabs or crocodiles (McCartney, 1920).

Among the most influential of these ancient philosophers was **Aristotle** (384 – 322 BCE; figure 4.1), who suggested that although animals are not created solely from decaying matter, the interaction of the latter with rainwater or other liquids produces new organisms. Indeed, many of the common beliefs concerning spontaneous generation have been attributed to Aristotle, who insisted on many occasions that processes such as aphids arising from dew, flies from putrid matter, and crocodiles from rotting logs, are readily observable truths (Lennox, 2001). Another Aristotelian concept is that of **heterogenesis**. This ideology suggests that organisms are produced from other organisms, in spite of there being no morphological similarities between the two species. A classical example of this belief is Aristotle's assertion that bees are generated from flowers, an idea which most likely stems from observing that the species interact, through what is currently understood as pollination (Lennox, 2001). Aristotle's abiogenetic theories arose from a desire to explain natural phenomena without involving supernatural entities, and can be considered the first form of scientific thought. Although the Greeks made crude observations about the world to which they were exposed and drew somewhat logical inferences, they did not formulate hypotheses or design formal experiments, a shortcoming which was seen until the late medieval age. Indeed, these crude beliefs concerning the origin of life persisted until the beginning of true scientific experimentation during the enlightenment and **scientific revolution** (McCartney, 1920).

Disproving Spontaneous Generation: Abiogenesis during the Enlightenment

As society gradually moved towards the separation of church and state in the 17th and 18th centuries, scientific inquiry and experimentation expanded upon and revised many ideologies that had been accepted as fact during the classical and medieval ages. In this regard, the Aristotelian theory of spontaneous generation was no exception. In 1688, the Italian physician and naturalist **Francesco Redi** (1626-1697) took the first steps towards refuting spontaneous generation. At the time, a prevailing tenet of spontaneous generation proposed that maggots would develop spontaneously on rotting meat (Paustian, 2012). Although it is reasonable that one would arrive at this conclusion, given that rotting meat is often infested with maggots and other small animals, Redi was not convinced that these creatures had appeared *ex nihilo*. Instead, Redi hypothesized that flies laid eggs on the meat, which eventually hatched into maggots, and thus developed the first true scientific experiment to refute the theory of spontaneous generation (Paustian, 2012). This experiment utilized three pieces of raw meat, one of which was exposed to the environment, while the others were covered, respectively, with cheesecloth and paper. The exposed meat quickly became covered in maggots, while fly eggs were deposited on the cheesecloth, and the paper was untouched. Prior to the removal of these covers, neither of the latter two meats was infested with maggots, and it was only when the eggs were moved onto the meat from the cheesecloth that maggots appeared (Paustian, 2012). This experiment provided conclusive proof that life developed from eggs, rather than by spontaneous generation. Unfortunately, Redi's conclusions were refuted in 1745 by **John Needleham** (1713-1781), who performed an experiment which was biased towards spontaneous generation. In spite of similar trials that reinforced the theories proposed by Redi, supporters of spontaneous generation now insisted air was required for organisms to be generated, and it was not until the work of French microbiologist **Louis Pasteur** (1822-1895) in the mid-19th century that spontaneous generation was finally proven incorrect (Levine and Evers, 2009; Taylor, 2001). As part of a contest for the best experiment proving or disproving spontaneous generation, sponsored in 1859 by the French Academy of Sciences, Pasteur devised an experiment which is historically considered to have settled the debate on spontaneous generation (Paustian, 2012). In this experiment (figure 4.2), Pasteur boiled meat broth in a flask, and modified the neck of the flask such that it curved downwards. This modification ensured that air could enter the flask and interact with the broth, but airborne microorganisms could not, since they would settle in the neck by gravity. When the modified neck was replaced with a normal one, microorganisms settled in the meat broth and their growth in the flask was observed. As a result, Pasteur had proved that life had developed in the flask through the presence of airborne microorganisms, rather than through spontaneous generation (Paustian, 2012).

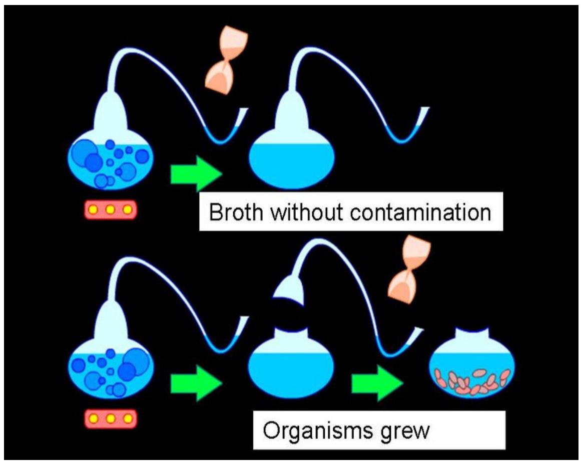


Figure 4.3: Pasteur's experiment to disprove spontaneous generation. In order to refute recent claims that perhaps air was needed to generate organisms, Pasteur used a flask with a curved neck to show that when air alone moved into the flask, no growths developed on the meat broth within. When both air and microorganisms moved into the flask, bacterial colonies began to develop. This disproved the archaic theory of spontaneous generation, while at the same time proving that bacterial cultures grow from microbes.

As a result of recent advances in the fields of chemistry, Earth science, and molecular biology, scientists had begun to search for a modern theory of abiogenesis which was plausible given the environment of the ancestral Earth. Indeed, when **Charles Darwin** (1809-1882) addressed the question in 1871, he was not at all incorrect in his suggestion that life may have originated in a "warm little pond" (Follman and Browson, 2009).

The Primordial Soup

In 1924, Russian biochemist **Alexander Oparin** (1894-1980) took the first step towards the development of a modern theory to explain the origin of life (Taylor, 2001). Based on the well-supported assumption of an electrochemically reducing early terrestrial atmosphere, Oparin suggested that this atmosphere might have

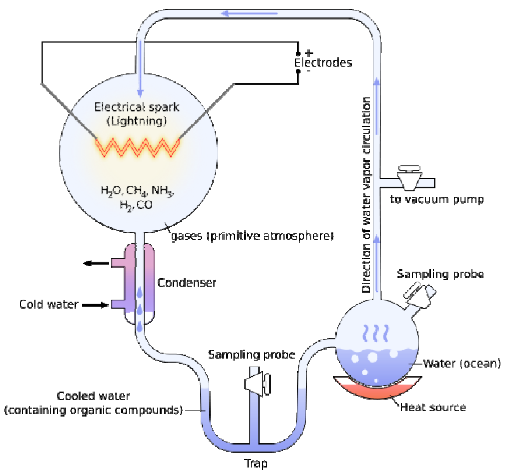


Figure 4.4: The Miller-Urey Experiment. In order to test the modern theory of abiogenesis proposed by Oparin and Haldane, Stanley Miller and Harold Urey attempted to replicate the atmosphere of the early Earth to determine the types of molecules that could be produced. The experimental results showed that in the presence of a highly reducing atmosphere and energetic environment, many compounds deemed necessary for life, such as amino acids and carbohydrates, can eventually form.

consisted of compounds such as water vapour, methane, hydrogen, carbon monoxide, and ammonia (Oparin, 1924). In the hot, gaseous atmosphere of the **Hadean Eon**, these compounds would have reacted to form more complicated molecules such as alcohols, amines, and ketones. As the Earth slowly cooled over millions of years, certain components of the atmosphere condensed and precipitated onto the early Earth to form the first oceans. Within these oceans the compounds continued to combine, eventually forming complex molecules such as carbohydrates, amino acids, and nucleotides (Oparin, 1924). Oparin postulated that although these molecules at first behaved according to the properties of their constituent atoms, new properties would eventually arise due to increasing levels of complexity, and a **colloidal structure** would be produced. It is in this colloidal, foam-like fabric precipitated onto the ocean that Oparin expected life to form (Oparin, 1924). In 1929, British geneticist **J.B.S. Haldane** (1892-1964) proposed the same theory. Haldane suggested that the early oceans, full of reacting organic chemicals, would have formed a **primordial soup** from which the earliest life would develop (Haldane and Dronamraju, 1968). Through the primordial soup model of abiogenesis, Oparin and Haldane proposed that the turbulent terrestrial environment of the past, characterised by frequent electrical storms and volcanic eruptions, provided the energy for the complex reactions which formed life. In addition, the high energy compounds present in the highly reducing atmosphere of the early Earth were necessary for such reactions to occur (Oparin, 1924; Haldane and Dronamraju, 1968). Oparin also reasoned that in this barren environment, the threat of being consumed and metabolized by other organisms was non-existent, which allowed life to slowly develop (Oparin, 1924). Given that the contemporary environment has none of these traits, it is evident that abiogenesis is no longer an active process.

Consequently, abiogenesis is not verifiable outside a laboratory setting. This has inspired a multitude of experiments, intended to determine the accuracy of the predictions put forth by Oparin and Haldane. One of the most important and influential of these experiments is known as the **Miller-Urey experiment** (figure 4.3), performed by **Stanley Miller** (1930-2007) and **Harold Urey** (1893-1981) in 1952 (Taylor, 2001). In this experiment, many of the gaseous compounds hypothesized by Oparin to be present in the early atmosphere were placed into a test tube. Oppositely charged electrodes, designed to simulate lightning storms, generated sparks to provide energy for reaction catalysis. The gaseous mixture was periodically condensed and sampled to analyze composition, thus determining whether complex molecules could form in the early terrestrial environment (Miller, 1953).

At the conclusion of the two-week experiment, it was found that approximately 12% of the originally inserted carbon was part of a **racemic mixture** of organic molecules, and 2% was found in the 11 distinct amino acid types in solution. In addition, various carbohydrates such as **ribose**, a sugar required for the synthesis of nucleotides, were observed in multiple samples (Follman and Browson, 2009). The promising results of the Miller-Urey experiment inspired a number of similar subsequent studies, one of the most notable of which was performed in 1961 by **Joan Oro** (1923-2004). In this experiment, Oro was able to synthesize the nucleobase adenine from simple, prebiotic reactants, effectively demonstrating that nucleotide synthesis on the early Earth is plausible, and might have led to the first self-replicating polymers (Guerrero, 2005).

Although these conclusions provide strong support for the **Oparin-Haldane model** of abiogenesis, recent research has indicated that the early terrestrial environment might have been electrochemically neutral rather than reducing. This suggests that the primordial Earth envisioned by Oparin and Haldane may only have been present in specific settings such as volcanoes and deep sea vents, which are therefore thought to be the most likely locations for the origin of life (Cleaves et al., 2008).

The Origin of Self-Replicating Molecules

Given that life is in part characterised by the ability to reproduce, it is evident that one of the most fundamental questions in abiogenetic theory pertains to the origin of self-replicating molecules. In particular, it is important to understand which biological molecules first developed on the primordial Earth, as well as how these primitive structures evolved into the complex macromolecules seen in modern organisms.

Since the synthesis of proteins requires a sequence provided by nucleic acids, one might at first assume that the latter class of molecules developed first. Unfortunately, the replication and expression of these nucleic acids cannot proceed efficiently without the catalytic action of enzymes, meaning that the independent responsibilities of these macromolecules lead to a **causal dilemma**, similar to the philosophical problem of the chicken and the egg. As a result of the difficulty associated with divorcing the properties of catalysis and information storage in a living system, it seems most plausible that the first self-replicating molecule possessed both of these capabilities (Bernhardt, 2012).

RNA-World Hypothesis

This idea was first proposed by **Leslie Orgel** (1927-2007) and **Francis Crick** (1916-2004), independently, in the early 1960s (Taylor, 2001). Although the possibility that RNA might have played this ancestral role was considered, there was little evidence to support this claim for another twenty years (Bernhardt, 2012). In the early 1980s, independent research teams led by **Thomas Cech** (b.1947) and **Sidney Altman** (b.1939) discovered that in addition to storing genetic information, certain RNA molecules are able to catalyze reactions. These molecules came to be known as **ribozymes**, a discovery that fuelled the **RNA-World hypothesis**, and for which Cech and Altman won the 1989 Nobel Prize in Chemistry (Boston Museum of Science, n.d.; Taylor, 2001).

Since RNA molecules are able to store genetic information and catalyze their own replication, it is likely that these molecules were the first self-replicating life forms. As a result of their relative instability and poor catalytic activity, however, natural selection would eventually have favoured the specification of these properties, thus producing DNA for information storage and proteins for reaction catalysis (Bernhardt, 2012). Further evidence for the RNA-World hypothesis was found in 2001, through the discovery that ribosomes, the cellular organelles responsible for protein synthesis, are in fact ribozymes (Figure 4.4). This discovery suggests that RNA existed prior to proteins, and was the central catalytic structure prior to its replacement by more efficient enzymes (Boston Museum of Science, n.d.).

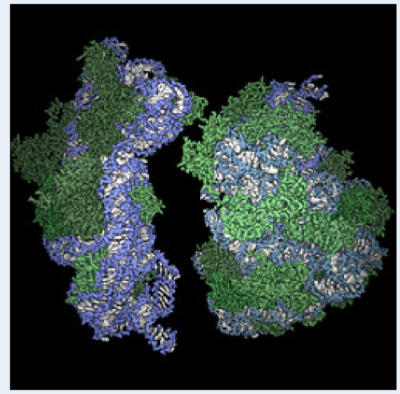


Figure 4.5: Ribosome structure of E. coli. Although ribosomes are composed of both protein (green) and RNA (blue and white), the mechanisms central to translation are catalyzed by the latter component, meaning the organelle is a ribozyme.

Recent research has shown that although RNA can be duplicated without a catalyst, the process is exceedingly slow and is thought to have been quickly replaced, in vivo, through catalysis by ribozymes. Due to small changes in its ribonucleotide sequence, this ribozyme would slowly evolve into **RNA replicase**; a structure specialized for the rapid replication of RNA (Freeman, Harrington, and Sharp, 2008). This was the result of a ground-breaking experiment by Johnston et al. in 2001, in which millions of long RNA fragments, as well as shorter fragments with attached primers, were added to a solution of ribonucleotides. Over the course of several days, the ribozymes which were most effective in their ability to replicate RNA by extending the primer were isolated, mutated in various ways, and placed into similar solutions for subsequent rounds. The culmination of the study yielded a ribozyme with a much higher **fidelity** and replication rate than the original catalyst, and represents humanity's closest approximation to synthetic life (Freeman, Harrington, and Sharp, 2008).

Lamarck, Darwin, and the Geologic Record

The concept of **evolution** has been widely debated throughout history and remains controversial. Of the many conceptions since the 18th century, those of **Jean Baptiste Lamarck** (Figure 4.6) and **Charles Darwin** are the two most studied (University of California Museum of Paleontology, n.d.).

Jean Baptiste Lamarck

Jean Baptiste Pierre Antoine de Monet, Chevalier de Lamarck (1744-1829) was born in the north of France, in the aptly named small village called Bazentin-le-Petit. Lamarck's main studies were medicine and botany, and in 1778 he published a book on France's flora, ***Flore Francaise***, the success of which earned him the position of assistant botanist at the royal botanical gardens (*Jardin des Plantes*). In 1793, the *Jardin des Plantes* was converted into the National Museum of Natural History, where Lamarck became professor of insects and worms (Waggoner, 1996).

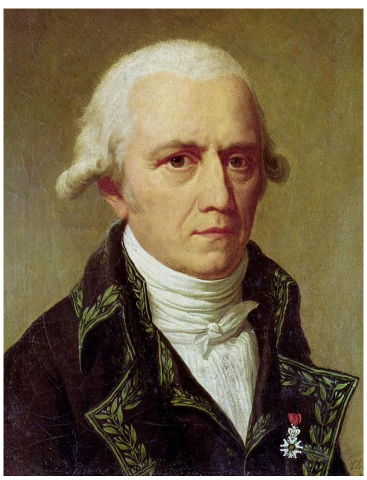


Figure 4.6: Portrait of Jean Baptise Lamarck. Though best known for his incorrect theory of evolution, Lamarck contributed much to the scientific community. In fact, he was the first person to separate the Arachnida, Crustacea and Annelida classes from the class Insecta.

Beginning in 1801, Lamarck started publishing evolutionary theories, mostly outlined in his 1809 text ***Philosophie zoologique***, his best known of which is the "**Theory of Inheritance of Acquired Characteristics**" (Waggoner, 1996). Lamarck's "First Law" or "**the Law of Use and Disuse**" was that the environment an organism lives in affects its behaviour and characteristics. If the environment changes, behaviour will change to fulfill the requirements for success in the new environment. These changes would cause the organism to increase or decrease the use of a certain organ. If the former, the organ would become larger through following generations. If the latter, it would grow smaller or even disappear down the generations. Lamarck's "Second Law" or "the Theory of Inheritance of Acquired Characteristics" postulated that all of these changes were **heritable**. The most famous example of this theory is that giraffes evolved to have longer necks because they needed to stretch higher and higher to reach their food (Campbell, et al., 2007; Waggoner, 1996).

Though Lamarck's theories have been disproved, the basis of his ideas was not completely false. Lamarck compared living forms of certain **species** to their **fossil** forms (Campbell, et al., 2007). He interpreted the fossil record to show different lines of descent, each ranging from older species (most varied from extant species) to those directly prior to present species. The core of Lamarck's arguments is the same as that of Darwin's theory: species are modified through gradual changes influenced by the environments in which they reside (Campbell, et al., 2007; Waggoner, 1996).

Charles Darwin

Charles Darwin (1809-1882) was born and raised in Shrewsbury, west England. His physician father insisted that he go to medical school. However, Darwin quickly realized that he was not interested in becoming a doctor and transferred to Cambridge University with the intention of entering the clergy. A lifelong interest in nature led him to associate with and later become the protégé of a botany professor, **Reverend John Henslow** (1796-1861). Upon graduation, Henslow referred him to **Captain Robert FitzRoy** (1805-1865), who was preparing to travel around the world aboard **HMS *Beagle*** (Campbell, et al., 2007).

Darwin's evolutionary theories mostly developed during the time he spent on the HMS *Beagle*. The main purpose of the expedition was to chart unknown coastlines in South America. Whenever the ship docked for its geographic studies, Darwin would go ashore to observe and collect various plant and animal samples. He found considerable evidence to support his notion that geographic location was a determining factor for the characteristics of species. He noted that species in more temperate regions of South America were more similar to those in tropical regions of the continent than in those found in temperate regions of Europe (Campbell, et al., 2007). In addition to observations of living species, Darwin noted that most of the fossils he found in South America more closely resembled living organisms in South America than those in Europe. In addition to investigating local animal species, Darwin became interested in **geology**. While in Chile, the ship experienced a violent earthquake. Darwin observed that the rocks that were previously found on the coast had been displaced much higher up. This led him to believe that similar geological events could cause fossils of certain species to be found in unexpected areas. His idea was confirmed when he found fossils of marine species on the top of the Andes mountains (Campbell, et al., 2007).

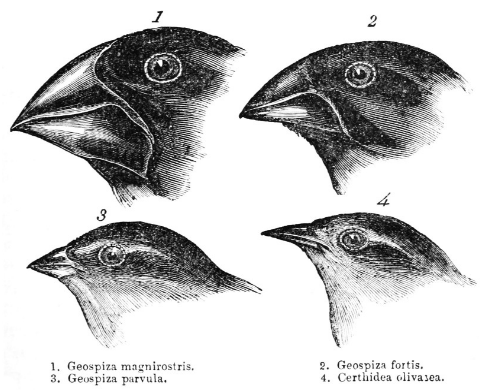


Figure 4.7: Pictorial representations of four different species of the Galapagos finches. Note how each finch has a different head and beak shape, allowing them to most efficiently access food sources in their respective environments.

Probably one of the best known sets of observations from Darwin's trip on the *Beagle* involves adaptive characteristics of the **Galapagos finches** (Figure 4.7). Darwin found that the behaviour and beak morphology of finches differed depending on which of the Galapagos Islands they lived and, correspondingly, on their diet. Each finch had certain **adaptations**, making them better suited for their environment. For example, the cactus ground finch, *Geospiza scandens*, had a long sharp beak that allows it to rip off and eat cactus flowers. On the other hand, the large ground finch, *Gesopiza magnirostris*, had a larger beak, allowing it to crack seeds fallen to the ground from plants. This is one of the breakthrough pieces of evidence that led Darwin to propose his theory of **natural selection** (Campbell, et al., 2007).

On the Origin of Species

In 1859, Darwin published ***On the Origin of Species***, what was to become one of the most influential and controversial books ever written. The book outlined Darwin's observations and theories regarding the evolution of species, the most impactful being his theory of natural selection and adaptation. The theory is outlined by two main inferences that were made from four observations in nature: 1) members within a species have varying characteristics; 2) traits are passed down from parents to offspring; 3) within their environment, species can produce more offspring than the threshold that can be supported; 4) most offspring produced will perish due to environmental pressures such as nutrient deficiency. From these four observations, Darwin drew two major conclusions: 1) those individuals in a population that have traits that are more favourable to the environment, giving them greater chance of survival and reproduction, will produce more offspring than others; 2) the fact that individuals carrying the more favourable trait will produce more offspring will lead to a build-up of advantageous traits in the population throughout the following generations. This represents Darwin's theory of natural selection, or survival of the fittest, the most widely accepted theory of evolution today. It is interesting to note that the basis of Darwin's and Lamarck's theories was the same. They both believed that organisms change over time due to external pressures. It was simply the mechanisms of this change that they postulated that differed (Campbell, et al., 2007).

Darwin further goes on to explain his theory of natural selection in what is now known as his "tree of life" (Figure 4.8). The tree starts at the bottom with different species within the same **genus**. The different branches coming off of each species represent its offspring, each with a variation in its characteristics. The different lengths of the branches represent the fact that all the different variations within the species did not occur at the same time. However, as evident in the diagram, not all of the offspring will survive. Those with the greatest amount of variation, and who are thus better adapted to the environment, will be the only offspring that survive, represented in the figure by variations a^1 and m^1. These variants will in turn undergo variation to produce new offspring that are even better suited to the environment leading to "**descent with modification**" (Darwin, 1958).

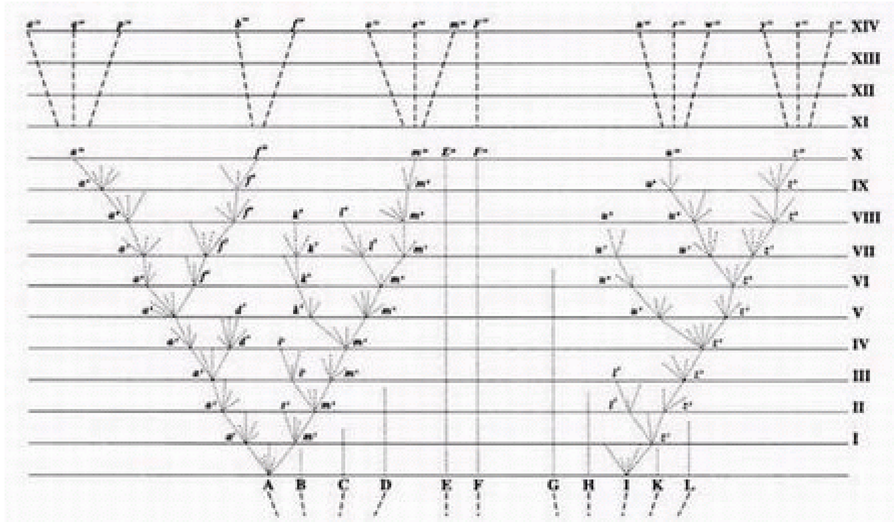


Figure 4.8: Darwin drew out this "tree of life" as an aid for understanding his theory of natural selection. Letters A to L represent different species within the same genus. Each branch represents different offspring of the species with varying characteristics. Only those with favourable characteristics for their environment survive (a^1 and m^1) and produce offspring of their own.

Darwin and the Geologic Record

Darwin used the fossil record as further evidence for his theories, even while fervently stating that the fossil record is imperfect and that its interpretation has limits. He stated that offspring possessing more favourable traits would survive and reproduce more than those lacking the characteristic, leading to the eventual extinction of the latter group. Darwin states that it is important to understand the types of **intermediate** forms of species that should be found in the geologic record. One might expect that, when looking at two species, intermediates should form links directly connecting them. However, this is not always the case when examining the fossil record. The fossil record should contain intermediate links between a species and the common ancestor. All species descending from the ancestral form will thus be modified versions of the **progenitor** (or ancestor). Darwin uses pigeons as an example to support this concept. He states that the rock-pigeon is the common ancestor of both the fantail and the pouter pigeon. If all the intermediate forms of the species were found, there would be a clear lineage between each type of the pigeon and the rock-pigeon. However, there would be no intermediates that directly linked the fantail and pouter pigeons (Darwin, 1958). Darwin's theory suggests there should be many intermediates of a species produced at a relatively rapid rate. Thus, one would expect the fossil record to be littered with these intermediate links (Darwin, 1958). However, this is not what is found in the geological record and this lack of geologic preservation can be attributed to what Darwin refers to as "the imperfection of the geologic record". This may be due to a number of factors: 1) **subsidence**, depression or collapse of land towards sea level, is necessary to produce deposits that are rich in fossils and are strong enough to withstand degradation and **erosion.** The absence of suitable fossil preservation sites may have resulted in large gaps of time between fossil formations; 2) during the periods of subsidence, there was most likely more extinctions, and during times of elevation, there was most likely more variation that was not imprinted into the fossil record; 3) the amount of time needed for the formation of the fossil record is most likely significantly shorter than the amount of time a species remains unvaried; 4) migration of species due to environmental pressures is a key factor as to why seemingly new forms of species arose in different environments; 5) though species do go through transition periods, the length of this transition is short compared to the amount of time that they remain unchanged (Darwin, 1958).

Based on these imperfections, the fossil record should not be expected to preserve all intermediate variations in species types. However, the record would be expected to show after intervals of time, forms of species that are closely allied (also known as representative species). In fact, this is what is found in the geologic record, indicating a gradual change of species throughout time (Darwin, 1958).

Darwin clearly struggled with the saltatory nature of the fossil record, but managed to put it in convincing perspective. In his own words: "I look at the natural geological record, as a history of the world imperfectly kept, and written in a changing dialect; of this history we possess the last volume alone, relating only to two or three countries. Of this volume, only here and there a short chapter has been preserved; and of each page, only here and there a few lines. Each word of the slowly-changing language, more or less different in the successive chapters, may represent the forms of life, which are entombed in our consecutive formations and which falsely appear to have been abruptly introduced. On this view, the difficulties above discussed are greatly diminished, or even disappear" (Darwin 1958, p.12).

Human Impact on Evolution

It is no secret that the world today is very different from what it was millions of years ago. As humans evolved, they took over nearly every part of the Earth, encroaching on other species' **niches**, driving many to extinction. This can be seen throughout all of nature from microscopic organisms all the way to habitat destruction on a macro scale.

The year 2006 marked the 30th anniversary for above-average temperatures throughout the entire world, a phenomenon known as **global warming**. One of the main effects of global warming is the melting of glaciers and polar ice caps (Statistics Canada, 2009). Figure 4.9 shows the change in size of the Arctic sea ice. Not only does the reduction of ice volumes affect species in the arctic region, but the increased melting raises sea levels and leads to flooding of coastal areas (Statistics Canada, 2009; National Resources Defence Council (NRDC), 2005). One example of a large mammal species impacted by humans, is the polar bear. Reduction of ice coverage in their normal habitats has led this species to change its **migration** and feeding patterns (NRDC, 2005). Polar bears are left with two options, either to migrate south or settle on dry land and adapt to new environmental conditions. In other words polar bears may have to evolve to be better suited to their new environment, or face extinction due to habitat loss (British Broadcasting Corporation (BBC), 2012).

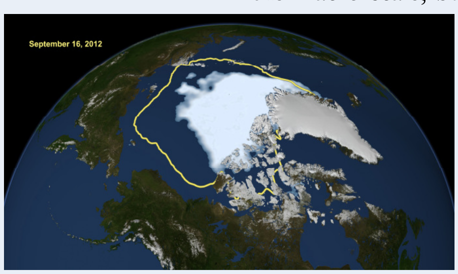


Figure 4.9: Satellite picture of the Arctic ice sheet taken on September 16, 2012 by NASA. The yellow line surrounding the north polar ice represents the boundary of the ice sheet 30 years ago.

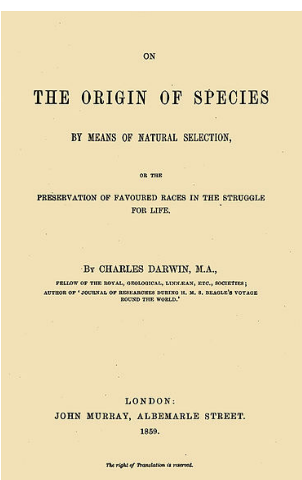
Another example of human impact on the environment is the **forestry industry**. The most ubiquitous form of harvesting trees is **clear-cutting**, where entire acres of trees are felled all at once. In fact, in 1996, of the one million hectares of Canadian forests that were harvested, 86% were harvested through clear-cutting. Of this 86%, less than half were replanted. Not only does this destroy the forest but it also severely affects all species dwelling in this complex habitat. These species must either migrate to other forested areas or adapt to living in less forested environments. The effects of clear-cutting are long lasting, taking decades for the trees to regrow to their previous size, and **biodiversity** is never fully restored (Bernhardt, n.d.).

Humans have not only affected the world at the macro scale, but also at the microscopic level, for example with the use of **antibiotics** in medicine. Antibiotics are administered to patients to counteract microbial infections. These drugs have pressured **microorganisms** to evolve and adapt, setting up an "arms race" between themselves and humans. "**Superbugs**" resistant to all antibiotics have already developed (Voss, 2011). If any of these acquire powerful virulence, they may cause massive human epidemics.

Though many natural processes effect the adaptation and evolution of different species, human impact has taken this to the extreme. From forcing adaptations in microscopic organisms to destroying habitats on a macroscopic scale, humans have altered the evolutionary cadence of this planet.

Punctuated Equilibria: Interpreting Gaps in the Fossil Record

Figure 4.10: Anaximander (c.611-546 BCE) proposed that humans may have originated as sea creatures, one of the first precursors to evolutionary thought.



ON

THE ORIGIN OF SPECIES

BY MEANS OF NATURAL SELECTION,

OR THE

PRESERVATION OF FAVOURED RACES IN THE STRUGGLE FOR LIFE.

BY CHARLES DARWIN, M.A.,

FELLOW OF THE ROYAL, GEOLOGICAL, LINNÆAN, ETC., SOCIETIES; AUTHOR OF 'JOURNAL OF RESEARCHES DURING H. M. S. BEAGLE'S VOYAGE ROUND THE WORLD.'

LONDON:
JOHN MURRAY, ALBEMARLE STREET.
1859.

The right of Translation is reserved.

Figure 4.11: Darwin's 1859 book, On the Origin of Species, remains the most influential work in evolutionary biology.

There are many hypotheses concerning the origin of life on Earth, but the most widely accepted theories suggest that life first arose from the **primordial soup** around 3.9 billion years ago. The most primitive organisms were unicellular prokaryotes possessing the novel ability of self-replication (Lal, 2008). Since then, life on Earth has diversified to include a menagerie of different organisms; a recent estimate is that there are approximately 8.7 million eukaryotic species alone (Mora, et al., 2011). The challenge for paleontologists and evolutionary biologists is to reconstruct the biological history of the past 3.9 billion years to answer the questions: *How has life changed and how does **speciation** occur?* The notion of **evolution** may date as far back as the 6th century BCE when the Greek philosopher **Anaximander** (c.611-546 BCE) hypothesized that humans were descended from fish-like creatures in the sea (Figure 4.10) (Loenen, 1952). Although the groundwork for evolution was already there, it was not until the 1859 publication of *On the Origin of Species* by **Charles Darwin** (1809-1882) that the theory of evolution truly entered the public domain (Figure 4.11).

Darwin, Gradualism, and an Imperfect Fossil Record

The idea that organisms change over time did not originate with Darwin; however, he was the first to propose **natural selection** as the mechanism for evolution (or "descent with modification" as he called it). Analogous to the selective breeding performed by farmers, Darwin described natural selection as the "preservation of favourable variations and the rejection of injurious variations" (Darwin 1859, p.131). According to Darwin, new species appear as the result of a change from one form to another on a population level. In some instances, a single species could split and evolve independently to produce two new species (Darwin, 1859). In either case, Darwin considered the process to be gradual, occurring over a long period of geologic time. This slow and continuous branching of organisms has since been referred to as **phyletic gradualism** (Eldredge, 1985).

If Darwin's view of gradual speciation is correct, then theoretically there should be a continuous series of intermediate evolutionary forms recorded in the **fossil record**. For any extant species there should be an ordered sequence of fossils chronicling its subtle, physiological modifications as it progressed from an ancestral species (Eldredge and Gould, 1972). In practice though, such sequences are seldom, if ever, observed. Anti-Darwinists often use this fact as an argument against evolution by natural selection, and Darwin himself wrote it "is the most obvious and gravest objection which can be urged against my theory" (Eldredge, 1985; Darwin 1859, p.292). Thus began an ongoing quest to bridge the gap between evolutionary theory and geological observations.

In response to the supposed objection to his theory, Darwin posited that the missing links in the fossil record stem from imperfections in the record itself. In making this claim, Darwin identified two major reasons for there to be imperfections in the record: the failed preservation of ancient life and the limited extent of paleontological collections (Darwin, 1859). He argued that the erosion of sedimentary rocks had destroyed many fossils and that a large number of species, including soft-bodied organisms, would decay rather than being preserved. Furthermore, Darwin recognized that geologists had sampled just a small fraction of the Earth's surface, so it was unlikely that the record would be complete (Darwin, 1859). In essence, Darwin chose to solve the discrepancy between the evolutionary theory of speciation and the geological record by looking for imperfections in the latter.

Ernst Mayr and the Theory of Geographic Speciation

Although Darwin's book was titled *On the Origin of Species*, his interpretation of a "species" was not the same as it is today. Building upon the evolutionary genetics research performed in the late 1930s, **Ernst**

Mayr (1904-2005) defined a **biological species** as "groups of interbreeding natural populations that are reproductively isolated from other such groups" (Mayr 1942, p.120). His interpretation of a biological species is still widely used today, and it served as the basis for his proposed mechanism of speciation. In 1942, Mayr published a theory of **geographic speciation**, which states that "a new species develops when a population that is geographically isolated from the other populations […] acquires […] characters that promote or guarantee reproductive isolation after the external barriers break down" (Mayr 1970, p.279). Contrary to previous scientific thought, speciation does not occur on the entire population level, but rather in small, isolated populations. Mayr's geographic speciation hypothesis would later prove instrumental in linking evolutionary theory with geological evidence.

The Research of Niles Eldredge and Stephen Jay Gould

In the 1960s, **Niles Eldredge** (b.1943), a strong advocate of Darwinism, set out to rectify the imperfections of the fossil record. What he needed was a well-preserved, yet easily collected, model organism with which he could investigate gradual physiological adaptations through time (Eldredge, 1985). He decided on *Phacops rana*, a species of **trilobites** that lived around 380 million years ago during the Middle Devonian period. During this period, *P. rana* occupied the shallow, inland sea covering the interior of the North American continent (Eldredge, 1985).

In the months and years that followed, Eldredge collected and studied trilobite fossils from the Appalachians and American Midwest. He tediously measured the features of countless trilobites in search of evidence to show that the organisms had gradually changed throughout **Hamilton time**, an eight million year segment of the Middle Devonian. Unfortunately, Eldredge could not find any indication that the trilobites from the start of the Hamilton sequence were any different than those at the end of the eight million year period (Eldredge, 1985).

Despite his great frustration, Eldredge continued to study these trilobites until he finally noticed an evolutionary change. While examining the compound eyes of his trilobites, Eldredge noticed some slight variation in morphology; trilobites found in the older beds of the Hamilton sequence had 18 columns of lenses in their eyes while those found in the younger beds had 17 (Figure 4.12) (Eldredge, 1985). The trilobites with 18 columns of lenses have since been classified as *Phacops milleri*, and those with 17 columns are known as *Phacops rana*. Eldredge also noted something peculiar about the change in eye morphology; there was a distinct horizon in the rock column representing the sudden shift from *P. milleri* to *P. rana* (Eldredge, 1985).

Figure 4.12: Trilobite specimens have compound eyes, organized in vertical columns of circular lenses. Niles Eldredge found that P. milleri have 18 columns of ocular lenses, while P. rana (above) have 17 columns.

At the same time as Eldredge was examining trilobites, **Stephen Jay Gould** (1941-2002) was conducting similar research with pulmonate snail fossils from Bermuda. Similar to Eldredge's trilobite observations, Gould found that the shell morphology of the snails would remain unchanged throughout subsequent rock beds, before suddenly exhibiting a physiological change (Eldredge and Gould, 1972). Due to the similarity of their observations, Eldredge and Gould began working together to look for a way in which they could explain their respective findings (Eldredge, 1985).

The Emergence of Punctuated Equilibria

Both Eldredge and Gould had originally expected to find intermediate forms in their fossils, indicating the gradual change of one species to another as predicted by Darwin. Instead, they found that a species would remain almost unchanged for millions of years at a time before suddenly producing a new form (Eldredge and Gould, 1972). Just as Darwin found, there seemed to be inconsistencies between the biological theory and the geological record. Darwin circumvented the issue by eliciting that the fossil record was incomplete; however, Gould and Eldredge were dissatisfied with this explanation. Instead, they decided that the inconsistency was due to a flaw in the biological theory, leading them to develop their theory of **punctuated equilibria** (Eldredge, 1985).

According to Eldredge and Gould, geographic speciation does not predict sequences of intermediate forms in the fossil record. Since evolution occurs in small, geographically isolated populations, the fossils of a descendant may not be found in the same rock beds as its ancestral form. Furthermore, the mechanisms of evolution, including natural selection, **genetic drift**, and **mutations**, will occur at an accelerated rate in these smaller populations (Eldredge and Gould, 1972). By adopting Mayr's model of geographic speciation, Eldredge and Gould proposed punctuated equilibria as an alternative theory to phyletic gradualism.

Punctuated equilibria, predicts long periods of "**stasis** punctuated by episodic events of [geographic] speciation" (Eldredge and Gould, 1972). The theory suggests that evolution does not occur gradually as previously thought, but rather a species may remain unchanged for millions of years before rapidly branching off to form a slightly different species (Figure 4.13). Although these events are considered "rapid", Eldredge and Gould proposed that speciation occurs over a period of thousands of years, rapid in terms of geologic time (Eldredge, 1985).

Using the Middle Devonian trilobites as an example, Eldredge and Gould used punctuated equilibria to explain the sudden shift from *P. milleri* to *P. rana* in the fossil record (Eldredge and Gould, 1972). During the Middle Devonian, a segment of the *P. milleri* population became isolated from the whole, undergoing geographic speciation to produce *P. rana*. The two species then entered a period of stasis, co-existing in separated geographic locations for approximately three million years. Midway through Hamilton time, the inland sea began to dry up, resulting in the extinction of *P. milleri* (Eldredge, 1985). Without *P. milleri* as competition, *P. rana* began migrating to the Midwest, occupying the habitat that once belonged to *P. milleri*. Consequently, the fossils of *P. rana* are found directly above those of *P. milleri* in the rock column without a record of intermediate forms (Eldredge, 1985). According to Eldredge and Gould, this pattern of punctuated equilibria and migration is better than phyletic gradualism in reconciling evolutionary theory with geological evidence. They argued that gaps in the fossil record are not merely imperfections, but rather they provide evidence that evolution occurs via punctuated equilibria (Eldredge and Gould, 1972).

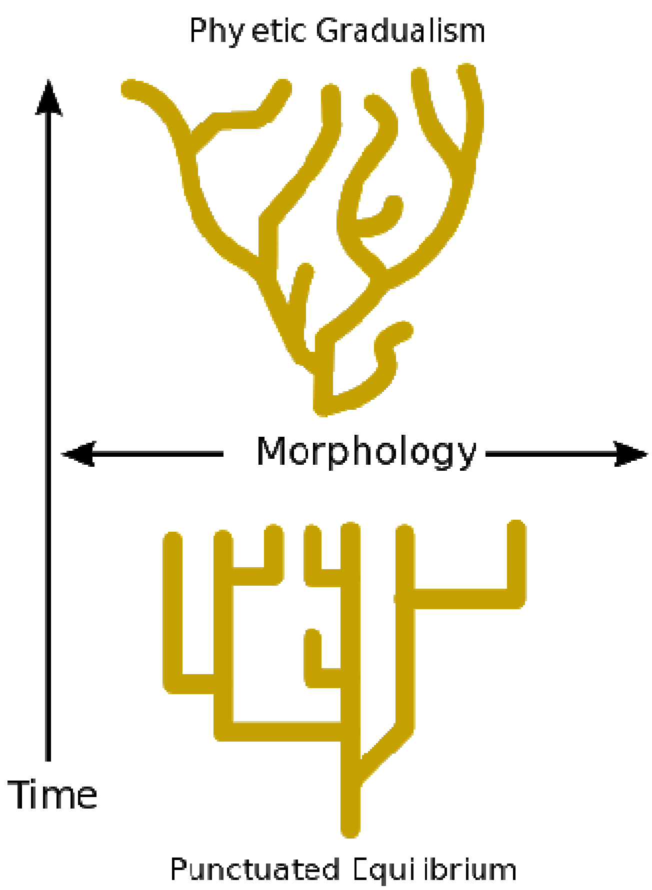


Figure 4.13: A pictorial comparison of phyletic gradualism and punctuated equilibrium. Phyletic gradualism predicts slow and continual changes in morphology over time. Punctuated equilibrium suggests periods of stasis with little morphological change, punctuated by rapid evolutionary events.

The Scientific Reception of Punctuated Equilibria

Since Eldredge and Gould first proposed their theory in 1972, it has become widely accepted in evolutionary biology; however, it does have some critics. Most notably, **Richard Dawkins** (b.1941) has refuted punctuated equilibria, claiming that evolution is likely a gradual process driven by the competition between genes. Dawkins has also been critical of Eldredge and Gould's supposition that punctuated equilibria is contrary to Darwin's scientific thought; instead, Dawkins has suggested that Darwin himself implied some of the ideas inherent in punctuated equilibria (Dawkins, 1986). Regardless of whether Dawkins' criticisms prove to be valid, Eldredge and Gould successfully changed the way in which biologists and paleontologists view evolution. Just as life on Earth has changed over the past 3.9 billion years, the scientific understanding of that change has been adapted, and will continue to be refined in the years to come.

***Archaeopteryx*: A Case Study in Reconstructing Evolutionary Trees**

The theory of punctuated equilibria is useful in explaining the gaps between closely related fossil species in the geologic record. Minor morphological changes in trilobites, such as the transition from *P. milleri* to *P. rana*, occur quickly in the context of geologic time, and thus intermediate forms are seldom preserved in the fossil record (Eldredge and Gould, 1972). However, life on Earth has undergone major morphological changes over the past 3.9 billion years, making it worthwhile to study evolution and the fossil record on a larger scale. On a macroscopic level, significant changes in morphology do not occur suddenly because viable offspring closely resemble their parents (Eldredge, 1985). Consequently, there exist **transitional fossils** which are termed the "missing links" between an extant species and its distant ancestors on the **evolutionary tree** (Heers and Dial, 2012).

The reconstruction of evolutionary trees, showing the relatedness of extant species and their development from ancestral species, is an important research topic in paleontology (Smith and Littlewood, 1994). When placing a new specimen on the evolutionary tree, researchers must compare its anatomical features with the features of potentially related specimens. By examining the anatomy of a fossil, paleontologists can make inferences about the organism's movement and lifestyle, which will ultimately contribute to its placement relative to other ancient species (Heers and Dial, 2012).

Apart from the development of *Homo sapiens* from earlier primates, the evolution of modern birds from bipedal dinosaurs is perhaps the most widely studied of the "missing link" relationships. In 1861, researchers in Germany unearthed a fossilized skeleton of ***Archaeopteryx*** (Figure 4.14). Living approximately 150 million years ago, *Archaeopteryx* has been widely viewed as the connection between **theropods** of the Late Jurassic period and avialans, the earliest birds (Heers and Dial, 2012).

Figure 4.14: The Berlin specimen of Archaeopteryx. Until recently, Archaeopteryx was considered to be the "missing link" in the evolution of birds from dinosaurs.

In 2011, ***Xiaotingia***, a fossil similar to *Archaeopteryx*, was uncovered and studied by Chinese paleontologists (Xu, et al., 2011). In attempting to locate *Xiaotingia* on the evolutionary tree, its anatomical features were compared to *Archaeopteryx*, avialans, and a group of theropods known as deinonychosaurs. With respect to such anatomical features as humerus length, tooth morphology, and the shape of the skull, the researchers found that *Xiaotingia* was more closely related to the deinonychosaurs than it was to the avialans (Xu, et al., 2011). Based on the similarities between *Xiaotingia* and *Archaeopteryx*, they began speculating that *Archaeopteryx* may also belong in the Deinonychosauria class. After further investigation of the skull, shoulder girdle, and vertebrae, the researchers concluded that *Archaeopteryx* should be included in the Deinonychosauria class and removed from the Avialae class. In doing so, they proposed that *Archaeopteryx* should no longer be considered as the "missing link" between dinosaurs and modern birds (Xu, et al., 2011).

This case study of *Archaeopteryx* is one example of the ways in which transitional fossils are being interpreted to reconstruct evolutionary trees. The ultimate goal for paleontological research, now and in the future, is to create a detailed evolutionary tree showing the interconnectedness of all extinct and extant species.

The History of Taxonomy

Classification is at the heart of biology, of science, and of humans and their history. In order to understand the world of organisms, it is necessary to organize the numerous species into a system (Solbrig, 1966). **Taxonomy** began as philosophy, but was quickly applied to biological works. The development of taxonomic works led to the development of nearly all other branches of biology (Solbrig, 1966). Taxonomic works did not explicitly influence other areas of science, but the concept of classifying objects and organisms, especially in the context of attempting to understand them, is universal in scientific studies. Nowadays, taxonomic principles are used in many scientific disciplines, and are prominent in earth science. The most noteworthy collaboration of earth science and taxonomy is the on-going interpretation of the fossil record.

Aristotle

The history of scientific taxonomy starts with **Aristotle** (384-322 BCE) and his **philosophy of essentialism** (Slaughter, 1982). Aristotle first classified his ten basic categories in the form of a branching tree (Slaughter, 1982). The basic principles of taxonomy were laid out both in his works of natural history and logic, as it was fundamental to Aristotle's philosophy of science that nature be sorted into kinds (Slaughter, 1982). There is evidence in Aristotle's writings that his biological studies helped him to develop taxonomical notions as logical concepts. There is also evidence that he found it difficult to apply these ideas of classification of logic to living organisms. Aristotle believed that such a classification would be beneficiary, but his writings showed that he believed it would be impossible to classify all living things (Slaughter, 1982).

In his logical works, Aristotle said that classification involved the determination of the genera, species, and differences of particular things (Slaughter, 1982). Genus and species were relative terms, representing a larger and smaller group, respectively (Slaughter, 1982). The process by which genera are distinguished into species was called **logical division**, in which a number of conditions must be met (Slaughter, 1982). Logical division was the means by which one could form definitions; thus, it played an important role in providing information about the nature of things, their genera, and their species (Slaughter, 1982). For the academic world at the time, this was taxonomy.

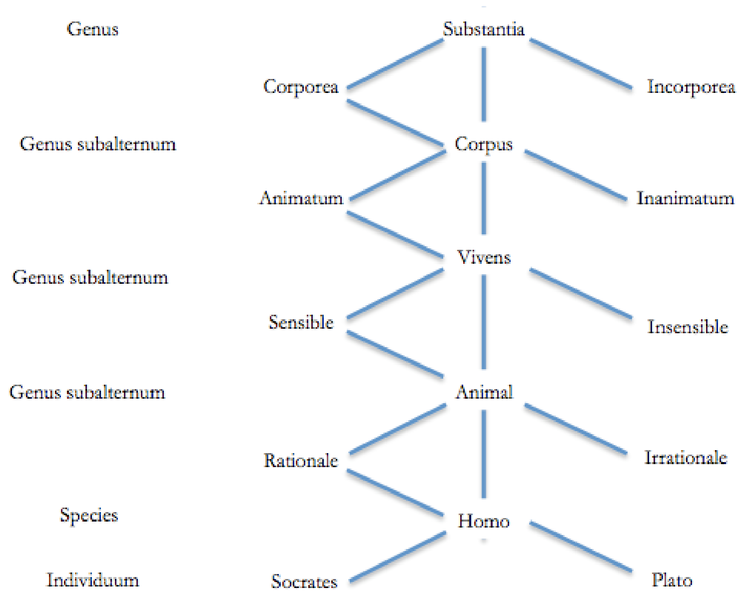
It was actually Aristotle's commentator, **Porphyry** (234-305), who turned Aristotle's divisions into a hierarchical arrangement (Slaughter, 1982). This arrangement, called the Porphyrian tree of hierarchically linked **genera** and species (Figure 4.14), became recognized as the method of classification in the tradition of Aristotelian logic.

In subsequent generations, taxonomy was carried out in accordance with Aristotelian rules (Slaughter, 1982).

The Predecessors of Linnaeus

The principles that Aristotle established retained their authority until the 16th to 17th centuries (Goerke, 1973). This was due to the fact that up until then the rules had proven adequate, since the number of known plants and animals did not increase substantially over the intervening period. Interest in science grew again after the Middle Ages, which was partially due to the

Figure 4.15: The logical classification of the category of substance, Substantia*, as shown in a Porphyrian tree of hierarchical linked genera and species (Slaughter, 1982).*



rediscovery of the intellectual world of Ancient Greece. In addition, the discovery of new continents and regions with unknown and foreign species of plants and animals displayed to naturalists the need for a comprehensive arrangement and classification of life (Goerke, 1973).

During this time of discovery, and more specifically from 1530 to 1542, the so-called **fathers of botany** began publishing their work on plants. The group consisted of **Otto Brunsfels** (1488-1534), **Hieronymous Bock** (1498-1554), and **Leonhard Fuchs** (1501-1566). Their works were essentially a jumble of plant descriptions with no order, although Fuchs' was done alphabetically, but were the first attempt to expand knowledge of plants passed food and medicine (Goerke, 1973). **Charles de L'Escluse** (1526-1609) also extended his study of plants beyond their properties of food and medicine, but in addition grouped them according to their characteristics and place of origin.

In 1594, **Andrea Cesalpino** (1519-1603) published *De plantis*, which described over 1500 species of plants. In it, he divided plants in the manner established by Aristotle: trees, bushes, and herbs (Goerke, 1973). However, he also added a classification based on the appearance of the plant's fruit and flowers, taking the first step towards building a new system.

The founder of natural plant taxonomy was considered to be the Swiss botanist **Caspar Bauhin** (1560-1624). He performed a critical review of all known plant names and arranged plants according to similarities of their outer forms (Goerke, 1973). Bauhin also provided the first descriptions of numerous plants and knew of over 6000 different species. Furthermore, he used an imitation of **binomial nomenclature** in his works (Goerke, 1973).

Later, the Swiss scholar **Conrad Gesner** (1516-1565) published a large number of observations of animals, which is considered to be the start of modern zoology.

At this point in time, science was growing as new technological advances were occurring and an abundance of information about the inner structure and function of living organisms was being discovered. Possibly the biggest advance of the time was the invention of the microscope, which allowed for a large number of observations of morphological structure (Goerke, 1973). In comparison to the anatomical and morphological discoveries being made, there were not very many advances in taxonomy during this time.

However, a significant contribution was made by the pupils of **Joachim Jungius** (1587-1657) who published his works after his death (Goerke, 1973). In his book *Isagoge phytoscopia* (Introduction to the Observation of Plants), Jungius made very precise rules for the description of plants, organized into very concise tables (Goerke, 1973). Like Jungius, **August Quirinus Rivinus** (1652-1723) rejected Aristotle's tree, bush, and herb classification and instead proposed an **artificial system** based on the structure of the **corolla** (Figure 4.15). He also proposed the use of binomials as a method of naming, although he himself did not use them (Goerke, 1973).

Figure 4.16: Corolla is a collective term for the pedals of a flower, and was used in as the basis for early classification systems.

The English pair of **John Ray** (1627-1705) and **Francis Willughby** (1635-1672) conducted research trips throughout England and the continent collecting samples of organisms (Goerke, 1973). However, after Willughby's early death, the compilation and publication of all of their findings fell to Ray. In botany, Ray built a system based on the structure and appearance of flowers, fruits, leaves, and other organs (Goerke, 1973). As this took into account the greatest possible number of similarities, it was a **natural system**. Ray also distinguished plants with and without flowers, and those with flowers he separated into **monocotyledons** and **dicotyledons.** Ray also attempted to try to find the most exact definition of the concept of species, and his criterion of species, which he believed to be unchanging, was similarity of offspring (Goerke, 1973).

The widely acclaimed classification system of **Joseph Pitton de Tournefort** (1656-1708) was based solely on the structure of the corolla. Since his system was simple and easy to use, it spread quickly and became successful even though the tendency of the academic community of this time was more bent towards natural, rather than artificial systems. Tournefort was the immediate

Figure 4.17: A portrait of Carolus Linnaeus (1707 – 1778), by Johan Henrik Scheffel.

predecessor to **Carl Linnaeus** (1707-1778).

The Contributions of Linnaeus

The elaboration and perfection of the system that started with Aristotle culminated in the middle of the 18th century with the work of Linnaeus (Figure 4.16). Linnaeus was the first person to ever try to classify all living organisms, which he did through the creation of the sexual system of classification (Solbrig, 1966; Goerke, 1973). Although the sex of plants was discovered by **Nehemiah Grew** (1641-1712), Linnaeus used Grew's ideas regarding plant physiology as the basis for his own ideas.

In the early part of his career, Linnaeus studied work by Tournefort, but soon began to question whether it was an adequate system. This spurred him to describe all flowers, put them into new categories, and reform the names and families in a new fashion (Goerke, 1973). In his fundamental work, *Systema naturae*, Linnaeus divided nature into three kingdoms: mineral, plant, and animal (Goerke, 1973).

The system Linnaeus proposed had several features which made it famous in its time. It allowed for the placement of new species without disrupting the entire system. The basic taxa, genera, and species were all delineated within it. It introduced the binomial nomenclature that is still used today (Solbrig, 1966). Linnaeus's concept of species was essentially the same as Aristotle's; both were based on morphological similarities. Linnaeus's concept of species also emphasized differences amongst species, rather than similarities.

Linnaeus did not believe that species could change as his practical nature and religious beliefs did not allow him to (Solbrig, 1966). Therefore, he did not attempt to find a grand scheme of nature. It was the next generation of naturalists and botanists who attempted to find the grand scheme at the beginning of the **scientific revolution**; however, they still believed that species were immutable and the scheme was put in place by higher powers (Solbrig, 1966). These naturalists, some of which included **Jean-Baptiste Lamarck** (1744-1829) and **Erasmus Darwin** (1731-1802), actually discovered many evolutionary relationships but did not recognize them as such (Solbrig, 1966). Naturalists in the first half of the nineteenth century were quite close to discovering the theory of evolution, they just lacked the mechanism. This was **Charles Darwin** (1809-1882)'s greatest contribution to taxonomy, not the actual theory of evolution by natural selection but the actual mechanism that evolution provided (Solbrig, 1966).

Interpreting the Fossil Record

A relationship between taxonomy and the fossil record began when fossils were first used to establish evolutionary relationships between species (Kemp, 1999). Initially, many believed that evolving lineages of organisms would easily become apparent as fossils of slightly differing structure were discovered in progressively older rocks. These lineages would trace out the evolutionary history of an organism to their more primitive ancestor, and ultimately lead to the common ancestors of different groups (Kemp, 1999). However, this was a rather naïve assumption. By nature, some species have a more complete fossil record than others, causing them to have a better **phylogenetic reconstruction**.

In the middle of the 20th century, many fossils were discovered that blurred the boundaries of already defined taxonomic groups (Kemp, 1999). The newly discovered fossils, many of which appeared to be fossilized intermediates of species, caused problems in the creation of phylogenetic reconstructions. This posed problems for paleontologists, but they were problems that paleontologists were eager to solve. A new set of rules would allow for the placement of fossils in taxonomic groups to become easier, more precise, and more objective (Kemp, 1999). The taxonomic method of classifying organisms before the explosion of new fossils was that extinct species were grouped together with living species in a formal hierarchical arrangement of **monophyletic groups**. Upon the discovery of the new fossils in the middle of the 20th century, two major complications arose in the naming and placing of new, intermediate specie into existing taxonomic groups. The first complication was that the new fossils were difficult to place in the old taxonomic system. The second complication was that the placing of fossils within old groups altered the definitions of existing groups of living organisms (Kemp, 1999). To address these problems, the concepts of **crown groups** and **stem groups** were introduced into the old taxonomic system. These new groups allowed for the addition of new fossils into pre-existing groups without the disruption of group definitions, and also created a spot for extinct species (Kemp, 1999). This same general outline of the placement of species into taxonomical groups exists today.

The history of taxonomy has also shown to be an influential one. Many concepts rooted in taxonomy have spread to many other areas. Although modern biology would not be the same without taxonomy, the concept of classifying objects in universal and found throughout all disciplines of science.

Taxonomical Bias in the Fossil Record

The fossil record provides the only direct evidence of how species and biodiversity have changed over time (Lloyd, et al., 2011). It also provides a diverse amount of information regarding when and where organisms lived and their modes of life (Bengston, 1985). The fossil record is partial at best, and all of the fossils that have been found today are only a subset of the organisms that actually lived during that time. Therefore, there must be many biases associated with the interpretation of the fossil record, some of which are caused by and through taxonomy.

Partial Fossils

Names in taxonomic nomenclature do not refer to parts on an organism; they refer to the hierarchical groups of organisms (Bengston, 1985). Yet, when interpreting the fossil record, there is often nothing more than a portion of an organism available to study (Figure 4.17). Often the naming of a whole from only the found parts does not create difficulties, but when parts that belong to the same organism are being studied and named as different organisms, this create problems (Bengston, 1985). As a result some taxonomic names for fossil species are based on parts of an organism instead of on whole organisms. Having a naming system based on inconsistent taxonomic rules is unnecessarily confusing for users (Bengston, 1985).

Sampling Bias

An important use of the fossil record is for determining how biodiversity has changed over geologic time (Lloyd, et al., 2011). However, different methods have been developed to determine biodiversity based on the number of fossilized species found. A **diversity curve** is a type of graph that displays the change in biodiversity by graphing the number of species found in different periods of time. Although biodiversity is measured at the species level, higher groups of taxa are often used as a proxy when creating diversity curves. These curves are often found to have small dissimilarities with the actual curves, and the dissimilarities can build up to create biases within the pattern of species biodiversity, which can mask and distort the original pattern of biodiversity (Lloyd, et al., 2011). **Species-to-genus ratios** are another method for determining biodiversity through the fossil record and are used widely as evidence for differences in speciation history caused by life history traits, biogeographical traits, or ecological traits (Lloyd, et al., 2011). However, there are a number of nonbiological factors that can distort species-to-genus ratios. Factors such as the number of workers at a site, number of sites, and taxonomic arbitrariness can contribute to the bias of the ratios. Thus, taxonomy can bias and alter the patterns of biodiversity found through the fossil record.

Figure 4.18: The found remains of a partial skeleton of Masiakasaurus knopfleri, a small predatory theropod from the late Cretaceous period, is an example of the types of partial remains encountered by palaeontologists and taxonomists.

The Development of Paleontology through Time

Since prehistoric times, **fossils** have been a source of fascination for humankind. **Neanderthal** graves have been found to include fossils, and ammonites (Figure 4.19) have been discovered at **Upper Paleolithic** burial sites (Matthew, 1980; Jones, 2006). The intended purpose of these fossils in these contexts has prompted much speculation about their role in prehistoric human life. One explanation is that they were used as decorative ornaments. Support for this hypothesis is given by the fact that many fossils were found strung together with shells and teeth (Donovan, 1968). Another belief is that the fossils were used in religious rituals, for example, the ammonite was thought to be a petrified snake (Donovan, 1968). A number of fossils found in ancient cave shelters and pre-historic dwellings in Europe also suggest the value and usage of fossils in prehistoric life (Matthew, 1980).

Figure 4.19: Ammonite fossil

Many early civilizations used fossils for jewelry and valued artifacts, without understanding the mechanism of their creation, and what they represented. Around the 5th century BCE, the Greek philosophers **Anaximander** (c.610-c.546 BCE), **Pythagoras** (c.570-c.495 BCE), and **Herodotus** (c.484-c.425 BCE) suggested that fossils were the mineralized remains of lithified organisms, left behind from water that had previously covered the land (Corfield, 2001). This was the first known usage of fossils to explain historical processes on Earth. **Aristotle** (384-322 BCE) believed that life could originate from mud or rocks, and as a result, thought that fossils were the failed creation of animals in this process (Marsh, 1879). Although the earlier hypotheses were lost with the fall of Greek civilization, Aristotle's explanation was accepted for many years after his death (Marsh, 1879). Misconceptions about fossils persisted for many centuries; in Europe during the Middle Ages, fossils were thought to be created by the Devil, and in China some fossils found were regarded as dragon bones with special medicinal properties (National Geographic, 2012).

In the 15th century, some of the Greek philosophers' ideas were revitalized, when **Leonardo da Vinci** (1452-1519), explained that fossil marine shells were transported to the places they were found on land by running water (Corfield, 2001). This idea suggests that the sea formerly covered their current location (Matthew, 1980). In the 16th century, the first written observations and interpretations of fossils were documented in a book by **George Bauer** (1494-1555), *De natura fossilum* (Textbook of Mineralogy) (Jones, 2006). Bauer believed that a concreting fluid within the Earth was responsible for the creation of fossils (Thackray, et al., 1990). The earliest illustrations of fossils were published by **Conrad Gesner** (1516-1565) about twenty years later in his book *De rerum fossilium lapidum et gemmarum* (Fossils, Stones, and Gems) (Jones, 2006).

Foundations of Paleontology

With observations and methods of interpreting fossils becoming more systematic, the advance in scientific techniques grew. The 18th century, known as the "**Age of Enlightenment**", brought about the notion of comparing fossils with living forms currently existing on the Earth, and using them to trace the history of life on the planet (Matthew, 1980). **George Cuvier** (1769-1832) contributed greatly to **paleontology**, laying down the foundation for the subdiscipline of vertebrate paleontology. While earlier some had regarded giant fossil bones as belonging to fallen human giants, Cuvier proposed a new idea. When comparing the fossils of the giant elephants to bones of existing elephants, he noticed that they were similar, yet distinct (Marsh, 1879). From this, he concluded that the remains of fossil elephants were from that of a different, extinct species (Marsh, 1879). Cuvier was the first to provide evidence that a succession of different animals inhabited the Earth, specific to the time period in which they lived (Marsh, 1879).

Jean Lamarck (1744-1829) set the foundation for studying paleontology of the invertebrates (refer to *Lamarck, Darwin, and the Geologic Record* on pp.60-62) (Marsh, 1879). He also compared fossils with living organisms, and discovered that fossil shells found in different strata under Paris differed from each other (Marsh, 1879). Invertebrate paleontology is important for the reconstruction of prehistoric aquatic environments (National Geographic, 2012). For example, by examining 200 million year old marine fossils found in the deserts of Nevada, U.S.A, scientists were able to determine that at that time, areas of the state were covered by water (National Geographic, 2012).

Figure 4.20: Fossil excavation site in Spain.

In addition to being applied to trace the evolutionary phylogeny of species throughout time, paleontology also contributes to the field of geology, as clues about the history of the Earth (Figure 4.20) (Matthew, 1980). One such example of this is in stratigraphic geology, which deals with the succession of stratigraphic formations (Matthew, 1980). Using the **Law of Superposition** formulated by **Nicolas Steno** (1638-1686) in the 17th century, fossils used in **biostratigraphy** can be used to measure relative time (Corfield, 2001). **William Smith** (1769-1839), the "father of English geology", was the first of the great Oxford paleontologists, and determined that rock layers could be traced across wide areas. He created the first geological map of South West England, and his work from 1815, *Strata Identified by Organized Fossils,* served as a foundation for biostratigraphy (Corfield, 2001).

Another Oxford paleontologist, **William Buckland** (1784-1856), was an avid fossil and mineral collector and was the author of the first published account of a dinosaur skeleton in the scientific literature (Corfield, 2001). In 1824, he gave the name *Megalosaurus* ("huge lizard") to giant lizard-shaped Jurassic bones (Tattersall, 2010). In 1842 the British anatomist **Richard Owen** (1804-1892) coined Dinosauria ("terrible lizards") to name a group of large fossil animals found in Jurassic and Cretaceous sediments of southern England (Tattersall, 2010). The discovery of the fossils of these great beasts led to a heated rivalry in the late 1800's between two dinosaur bone hunters: **Othniel Marsh** (1831-1899) and **Edward Cope** (1840-1897) (Schopf, 1999). This is discussed in further detail in *Fossil Feuds* on pp.80-83.

The 1859 publication of *On the Origin of Species* by **Charles Darwin** (1809-1882) introduced the proposition that populations evolve over periods of time through the mechanism of **natural selection** (National Geographic, 2012). The advent of the theory of evolution transformed the development of paleontology, as attention was drawn towards discovering fossils that could be identified as 'missing links' (Thackray, et al., 1990). Fossil discoveries have supported Darwin's theory, and paleontologists have used his theory in understanding fossil evidence and applying it to living organisms (National Geographic, 2012).

Recent Discoveries

In the late 19th century, one of the world's most famous fossils was found in Bavaria: the *Archaeopteryx* (Marsh, 1879). What was especially unusual about this creature was that it had many reptilian features typical of a dinosaur, but also wings similar to that of a bird (Marsh, 1879). This prompted many scientists to view it as evidence of an intermediate form between reptiles and birds (see *Archaeopteryx: A Case Study in*

Reconstructing Evolutionary Trees on p.67) (Marsh, 1879). The *Archaeopteryx* is now regarded as one of the first birds (National Geographic, 2012). By examining the physical features of fossil specimens and applying previous knowledge about the evolution of species, scientists can develop a sequence of when species evolved relative to one another (National Geographic, 2012).

Another application of paleontology is through the subdiscipline of **micropaleontology**, which was first recognized in 1883. Micropaleontology looks at the stratigraphic and environmental history of microscopic organisms through time (Lipps, 1981). Microfossils are tiny remains of organisms that usually occur in large quantities in all kinds of sedimentary rocks (Lipps, 1981). These small fossils are very useful in dating rocks recovered from **borehole** cores (Fortey, 2002). Abundant and easily identifiable, they are extremely valuable in the oil, mining, engineering, and environmental industries as **zonal indicators** (Lipps, 1981).

By the end of the 19th century, paleontology was truly established as a science. With the technological and scientific revolution in the early 1900s, paleontology was able to grow and expand as a field. Fossil excavation and analysis continued in the 20th century, with the creation and expansion of many museums to display fossils to the public. Paleontology continued to aid and be aided by advancements in geology, chemistry, biology, and genetics.

There is still much to be uncovered, and new discoveries are still being made. Recently in 2004, a fossil of the Late Devonian fish, *Tiktaalik roseae* was discovered in Nunavut, Canada (Ahlberg and Clack, 2006). A finned crocodile-like animal with shoulder, elbow, and wrist-like limb joints, *T. roseae* represents a link between ancient fish and the first limbed animals that emerged from the water about 375 million years ago (Figure 4.21) (UCM, 2011). Like the *Archaeopteryx*, this creature is a **transitional species**, and provides evolutionary biologists with an understanding of how fins turned into limbs (UCM, 2011; Ahlberg and Clack, 2006).

Paleontology has come a long way from the first speculations of ancient life. With the development of modern tools and techniques, interest in this field continues to expand in the 21st century, as new discoveries and conclusions are made. By applying findings in paleontology to various other disciplines, more information about life as it once was on this planet can be unearthed.

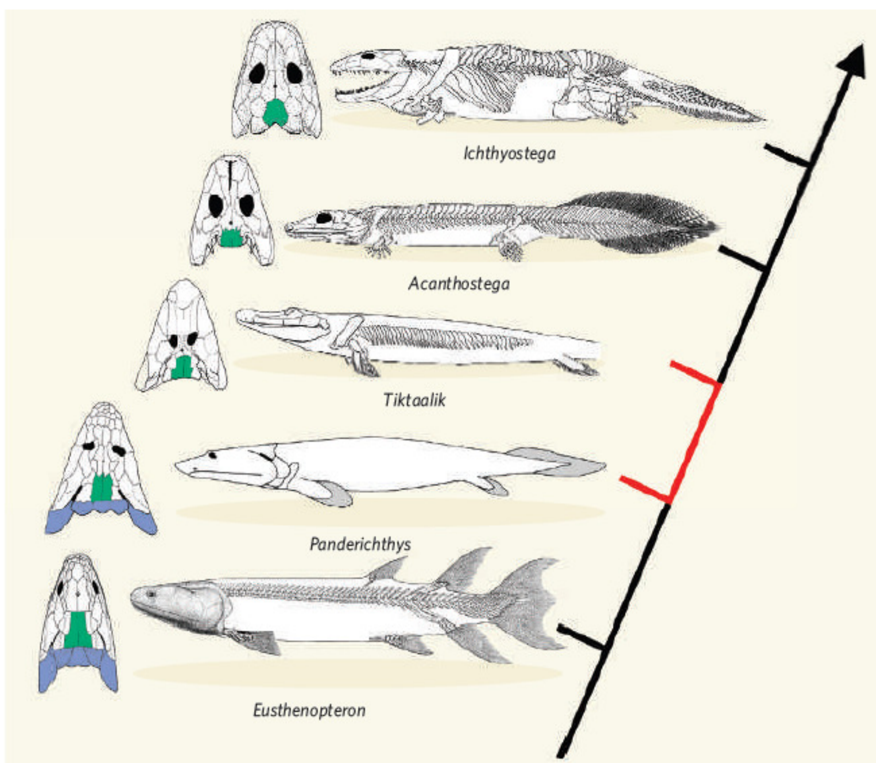


Figure 4.21: The Tiktaalik, or 'fishapod', forms a morphological bridge between the fishes and tetrapods. Over 10 of these 375 million year old specimen have been uncovered to date. They range in size from about 1 to 3 meters in length (Ahlberg and Clack, 2006).

Barriers that once separated paleontology from other disciplines within the earth and life sciences continue to collapse. The continuous developments in paleontology are constantly revealing new information about the history of the Earth.

Radiometric Dating

In order to determine how organisms interacted and evolved in the past, the approximate age of fossils must be determined. Doing so helps scientists understand the processes that have shaped the Earth, and for how long they have occurred (Fortey, 2002). There are a variety of techniques available to measure the age of fossils. Until recently, **relative dating** methods were the only tool available, but it does not provide absolute ages. Thus, relative dating is often used in conjunction with radiometric or isotopic dating, which was developed in the mid-20th century.

Some **isotopes** are unstable, that is, their atomic nuclei spontaneously emit particles or **electromagnetic waves** to reach a stable state (Tattersall, 2010). The time it takes for half the amount of the starting element (mother isotope) to decay in this manner to the product (daughter isotope) is defined as the isotope's **half-life**. The half-life is used to calculate how much of a given isotope will be left at a particular time (as seen in the equation below), since the half-life is specific to the given isotope. The rate of decay is constant, measurable, specific to the isotope, and useful in determining the age of the rocks containing these isotopes (Tattersall, 2010).

$$A_t = A_0 \left(\frac{1}{2}\right)^{t/t_{1/2}}$$

Where A_t is the amount of mother isotope at time t, A_0 is the initial amount of mother isotope before the substance begins decaying, and $t_{1/2}$ is the half-life.

Different isotopes are used to determine the ages of rock or fossil samples of varying geologic periods. Due to the differences in half-lives, an isotope must be chosen such that its half-life is not too short so that it decays to completion, and not too large to provide an imprecise measurement. For example, rubidium-strontium (Rb-Sr) dating measures the amount of radiogenic strontium (^{87}Sr) produced from the radioactive decay of rubidium (^{87}Rb), where '87' refers to the number of neutrons in the isotope (Jones, 2006). The half-life of ^{87}Rb is 49 billion years, which is a long time relative to the Earth's age (Jones, 2006). Thus, this particular method can be used to determine the age of very old rocks or minerals.

Radiocarbon Dating

One popular method of radiometric dating uses the decay of carbon-14 (^{14}C) to date the remains of organic material from **Pleistocene** and younger events. As ^{14}C has a relatively short half-life of 5730 years, samples up to approximately 60 thousand years in age can be dated using this method (Tattersall, 2010). Carbon dating is able to directly date fossil specimens, as opposed to dating the rock around the fossil. Once an organism dies, it stops accumulating carbon, and the amount of carbon-12 (^{12}C) remains stable. However, ^{14}C decays at a constant rate, and by comparing the ratio of ^{12}C to ^{14}C in the sample to a living organism, the age of the sample can be determined (Tattersall, 2010).

Figure 4.22: Machinery like mass spectrometers can be useful in radiometric dating.

There are other methods of dating available to scientists, including **thermoluminescence** and **electron spin resonance** dating (Tattersall, 2010). Currently, paleontologists have a vast toolkit of techniques and machinery (including electron microscopes, x-ray machines, and advanced computer programs) to further the understanding of organisms that existed and events that happened in the past (Figure 4.22).

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Uncovering the Past with Mary Anning

In the early 1800s, geology was dominated by male researchers, but this did not stop British fossil finder **Mary Anning** (1799-1847) from delving into this domain. Anning lived at Lyme Regis on the south coast of England (Figure 4.23) (The Natural History Museum, 2012). The nearby coastal cliffs contained alternating layers of limestone and shale which were deposited as sediment approximately 200 million years ago, yielding a rich fossil record. These cliffs were highly unstable and frequented by landslides due to heavy precipitation in the winter months. Nevertheless, these conditions often exposed fossils, thus attracting amateur paleontologists to the cliffs at Lyme Regis (Goodhue, 2004).

Figure 4.23: A painting of Anning at Lyme Regis, England

Relying on the local resources for income, Anning's father, often accompanied by Anning and her brother, collected and sold fossils along the shore. After the death of her father, Anning sought comfort in roaming the shores whilst reminiscing about their past adventures along this coast (Goodhue, 2004). Serving as more than an emotional refuge, this hobby became a much needed source of income for the family as she began selling her finds (Torrens, 1995).

Anning became extremely passionate about geology and would often scour the seashore for hours despite harsh and perilous weather conditions. As a woman, society viewed such academic fervour as deviant and she was often accused of having psychological disorders (Torrens, 1995). Unwilling to accept the defeat of not being allowed to study at university because she was a female, Anning zealously read and re-wrote papers on the subjects of geology and paleontology (Goodhue, 2004).

Anning's discoveries allowed for advances in several aspects of geology, namely the acceptance of the theory of extinction. Overcoming the obstacles posed by society due to her low social status as a poor and unmarried woman, her dedication to finding fossils and learning their significance has resulted in Anning's standing as one of the most impactful female geologists.

Ichthyosaur Discovery

One of Anning's most noteworthy discoveries was the 17-foot long **ichthyosaur** fossil she found in 1812. While this was not the first ichthyosaurs fossil found, it was the first to be brought to the attention of the scientific community in London (The Natural History Museum, 2012). The animal from which this fossil was created appeared to have fins reminiscent of a dolphin, teeth indicative of a crocodile, a pointed snout like that of a sword fish, the spine of a fish, and the chest similar to a lizard. This mélange of associated animal parts caused a questioning of the more biblical beliefs of Earth's history (Waggoner, 1996). At the time, scientists followed **James Ussher** (1581-1656)'s premise that the Earth was only 4000 years old and that living creatures, made perfectly by God, did not become extinct. Yet as no one living animal matched Anning's find, thoughts about extinction began to arise (Goodhue, 2004).

Continued confusion over the physical attributes of the ichthyosaur led to difficulties in classification of this creature. **Sir Everard Home** (1756-1832) wrote more than six papers describing this fossil to the Royal Society of London, never giving mention to Anning and even referring to its finder as a male (Goodhue, 2004). In these papers Home deemed the fossil to be from a fish, then a platypus, and then a lizard. Finally in 1819, **Charles Konig** (1774-1851) assistant curator of the British Museum, declared it to be half lizard and half fish and called it ichthyosaur, Latin for fish-reptile (The Natural Museum of History, 2012).

Subsequent ichthyosaur discoveries by Anning caught the attention of **Henry De la Beche** (1796-1855) and **William Conybeare** (1787-1857), both members of the Geological Society of London, and strong professional relationships began to develop between the three paleontologists. After analysis, deliberation with Anning, and several papers regarding the fossils, Beche and Conybeare concluded that the creature from which the fossils were derived was a marine reptile. Additionally, through analyzing the differences in teeth morphology, they discovered that there were multiple species of ichythosaurs (Conybeare, 1824).

Plesiosaur

In 1824, Anning had another scientifically significant discovery when she uncovered an intact **plesiosaur** fossil (Figure 4.24). This immediately captured the attention of Beche, Conybeare, and **William Buckland** (1784-1856) (Goodhue, 2004). Conybeare, among other scientists, denied the existence of plesiosaurs as they were believed extremely dissimilar to modern creatures. The pleisiosaur, like the ichthyosaur, appeared to be an aquatic reptile. It is believed to have swum by means of four paddle-like appendages with five digits, each comprised of 10 bones, in every paddle. Its body was described by Conybeare to be that of a turtle without a shell. Fossil evidence shows that the plesiosaur had a short tail, believed to be used only for direction and had a long and thin neck composed of 35 bones. The neck and complex digits of the paddles were unparalleled by any modern-day animal (Conybeare, 1824). In fact, the features of this creature were so strange that geologists such as **Georges Cuvier** (1769-1832) suspected fraud on Anning's behalf. However, her detailed drawings and the support of credited male geologists – Conybeare, Beche, and Buckland – changed Cuvier's opinions. He eventually called the find, "...the most amazing creature that was ever discovered" (Goodhue, 2004).

In disproving Cuvier, Anning gained credibility in the eyes of British geologists. However, Conybeare still did not acknowledge her as the individual responsible for the plesiosaur find in his papers. It was not until years later, at a conference, that Conybeare acknowledged Anning as the person responsible for uncovering the now famous fossil. Subsequently, Anning began to receive credit for her discoveries in *The Bristol Newspaper, The Gentleman's magazine, The Salisbury*, and *Winchester Journal* (Conybeare, 2004).

Moreover, Cuvier relied heavily on Anning's finding for his controversial papers on **catastrophism** and extinction that suggested past organisms differed drastically from those of the present day and also that some species become extinct (Waggoner, 1996). The plesiosaur also played a pivotal role in the theory of **The Great Chain of Being**. Under this theory, each "link" is related, without evolution as the mechanism for creating new species. Plesiosaurs were placed as a link between ichthyosaurs, which were between reptiles and lizards, and crocodiles. Cuvier was one of the few scientists who rejected this theory, as most held it in high regard (Torrens, 1995).

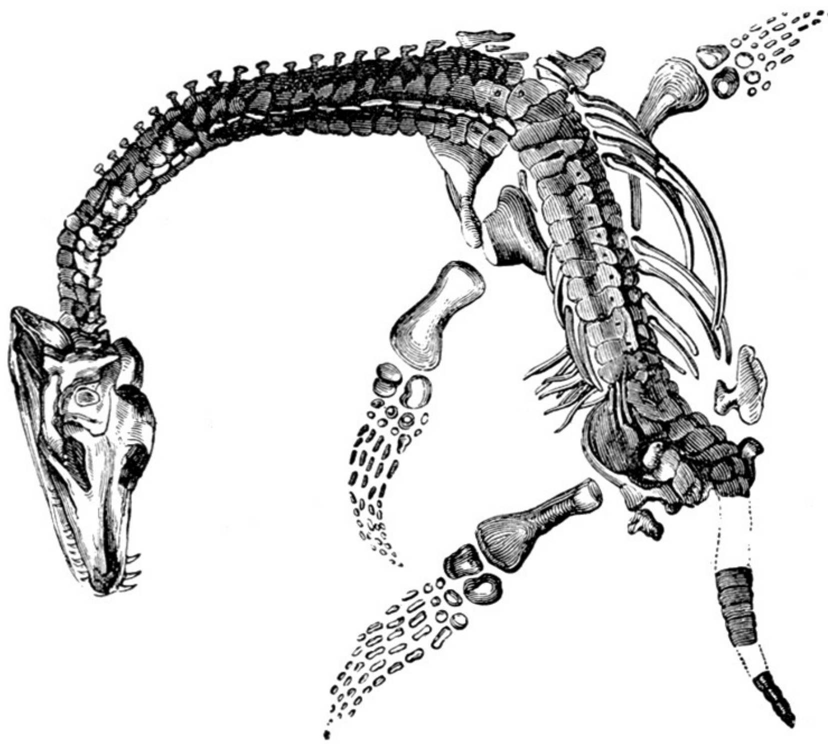


Figure 4.24: A sketch made by Buckland of the plesiosaur fossil Anning found.

Belemnite Fossils

Another instance where Anning changed previous thought is with her discovery of **belemnite** fossils, long, cone-shaped fossils common on the coastline at Lyme Regis. In 1826, Anning cut one of these fossils open and discovered a tiny sac which held dry ink (Goodhue, 2004). Anning quickly noted its similarities with modern day cephalopods, such as squid and cuttle fish. From dissection and analysis of these modern species, she realized that ink served as a defense mechanism for both modern and Jurassic cephalopods as the opaque ink cloud impeded the vision of predators. It was not until years later that Buckland and other male geologists with university educations came to the same conclusion (Torrens, 1995).

Bezoars Stones

In 1824, Annings's thoughts regarding **bezoars** stones led to several heated debates between her and Buckland. These stones ranged in shades of grey, were five to nine centimeters long and two to five centimeters in diameter (Waggoner, 1996). As they were twisted in a corkscrew fashion and contained scales and small remnants of ichthyosaur bones, Anning believed them to be fossilized feces of ichthyosaurs. Buckland, however, thought theses were simply balls of clay, serving no scientific value. Anning soon strengthened her argument when she discovered such stones in the pelvic and abdominal regions of ichthyosaurs (Goodhue, 2004).

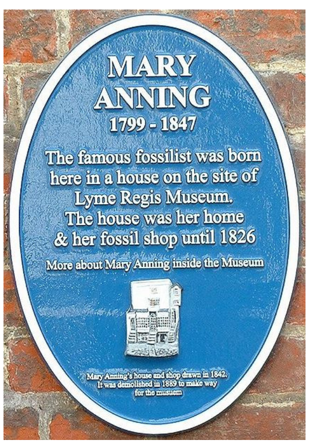


Figure 4.25: A plaque commemorating Mary Anning at her old house in Lyme Regis, which now serves as a museum in her honour.

Finally convinced, Buckland accepted Anning's theory and titled them coprolites. The corkscrew structure indicated that ichthyosaurs had twisted intestines and the varying colours of grey showed that belemnites were within their breadth of diet (Torrens, 1995). Additionally, these fossils showed that ichthyosaurs were cannibals as they contained bones from their own species.

In contrast to previous interactions, Buckland finally gave Anning both credit and praise in his papers and conferences about the conclusions drawn from the bezoars stones (Goodhue, 2004).

Impact

At the time Anning made her discoveries, a strong religious influence on the scientific community caused the notion of extinction to be highly refuted. Relying on the beliefs of creationism, it was believed that God's creations were perfect and thus would never cease to exist (Goodhue, 2004). To explain the bizarre creatures found in fossils, creationists said that they were animals from other regions on Earth. Anning's findings, namely ichythosaurs and plesiosaurs, highlighted the flaws in this belief as these fossils bore so little resemblance to living creatures. Anning, along with other paleontologists of the time, made discoveries which revealed a plethora of extinct marine reptilian fossils, and served as evidence for Cuvier's theories on extinction and **The Age of Reptiles** (Torrens, 1995). Furthermore, Anning's findings, and analysis of these extinct organisms assisted in the development of paleontology as a science (The Royal Society, 2010).

The work of Anning not only changed thoughts regarding Earth's past, but also changed views about women in geology. In the 1800s, women in England possessed very few rights and were not considered to be competent and valuable contributors to science, among other disciplines. Unmarried women were pitied and educated women were rare (Goodhue, 2004). Anning overcame these obstacles of sexism through her persistence and dedication to paleontology. However, her impact for other women in science was not widely felt until decades later. While she began to receive some credit for her work in the latter part of her career, she has only recently received full acknowledgement of her discoveries and associated analysis (Figure 4.25). In 2010, ten women were recognized for their impact on the history of science in celebration of the 350th anniversary of the Royal Society, and Mary Anning was one of those 10 (The Royal Society, 2010).

Female Contributions to Geology

Unlike in the 1800s, women today have the right to receive an education and are more respected for their contributions to science. One woman taking advantage of these rights is **Natalia Rybczynski** (active in 2009), who received her M.Sc. in zoology from the University of Toronto in 1996 and her Ph.D. in biological anthropology and anatomy from Duke University in 2003. Her main areas of study include the morphology of ancient species associated with major evolutionary transitions, relationships between morphology and behaviour in terms of evolution, and the effects of climate on evolution of species at Polar Regions (Canadian Museum of Nature, 2012).

Like Anning, Rybczynski's fossil discoveries have changed previous thought regarding extinct life forms. Of particular interest is a 23 million year old fossil of a seal-like animal, titled ***Puijila darwin,*** which Rybczynski uncovered in 2007 on Devon Island, Nunavut (Figure 4.26). This fossil is described as having a streamlined body approximately 110cm in length and heavy limbs, indicative of a muscular physique. Its long tail is believed to have assisted with movement in its aquatic environment. While it appears to have lacked the presence of flippers, it did possess flattened digits characteristic of webbed feet. *P. darwin* is considered to be a higher order consumer due to its large canine teeth, short snout and muscular jaw (Erikson, 2009). Collectively this array of characteristics and the apparent similarities with modern-day seals led Rybczynski to dub *P. darwin* as the missing link between terrestrial mammals and the modern day seal (Canadian Museum of Nature, 2012). In Rybczynski's own words,

"It fills the gap between the land-living ancestor and the flippered seal-like animal that we see around us today" (Erikson, 2009). While Anning rarely received recognition due to her social status, Rybczynski was credited with the discovery and subsequent analysis of *P. darwin,* in a journal in the April 2009 edition of Nature (Erikson, 2009).

Furthermore, research conducted by Rybczynski and her colleagues helped understand the biomechanics behind the chewing mechanism of ***Suminia getmanovi***, a dinosaur from the **Late Permian**. Using electron microscopy it was shown that the teeth of these beings had horizontal striations, as well as deep pockets between the enamel and dentine. These markings suggest that *S. getmanovi* chewed in a shearing motion (Canadian Museum of Nature, 2012). Similarities between *S. getmanovi* teeth and herbivorous dinosaurs, that they preceded, caused Rybczynski and her team to determine that *S. getmanovi* were also primary consumers. Rybczynski and her team suggest that this would have allowed them to have a broader breadth of diet and also an elevated metabolism (Erikson, 2009).

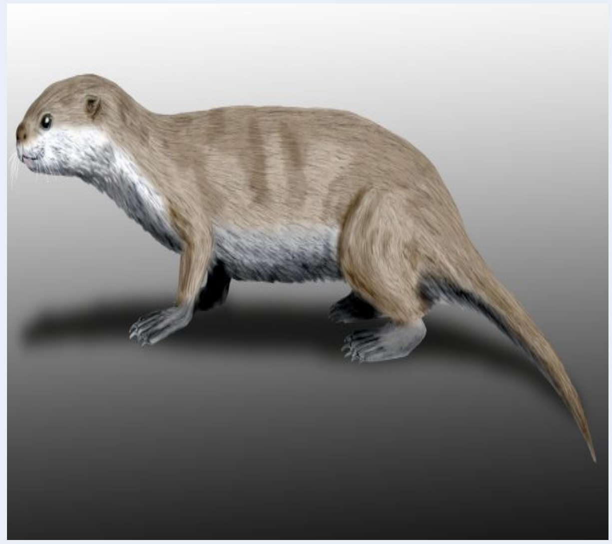


Figure 4.26: An artist representation of P. darwin.

Following in the footsteps of Anning, Rybczynski's work sheds light onto the history of life on Earth through discovery and analysis of fossils. With diminished barriers of sexism, Rybczynski was able to pursue a university education, receive acknowledgment for her research, and also be considered a valuable contributor to the field of paleontology within her lifetime (Canadian Museum of Nature, 2012).

Fossil Feuds

The first known description and illustration of a dinosaur was in 1676 by **Robert Plot** (1640 – 1696), a professor of chemistry at Oxford and a leader in the field of fossil origins. The fossil was a thighbone that was much larger than anything ever seen at that time. The fossil in question was discovered in a quarry near Oxfordshire, England (Oxford University Museum of Natural History, n.d. a).

Figure 4.27 Megalosaur footprints reconstructed on the lawn of the Oxford Museum of Natural History.

At this time, dinosaurs were yet to be discovered and Plot was baffled. At first, Plot believed that the fossil belonged to an elephant brought to Britain during Roman invasions, but when compared to a living elephant brought to Oxford, he concluded that this theory was incorrect (Oxford University Museum of Natural History, n.d. a). He decided that the fossil was that of early man or woman (Oxford University Museum of Natural History, n.d. a).

This fossil was not officially named until 1824, when it was given the name ***Megalosaurus*** (*above*) by **William Buckland** (1784 – 1856). *Megalosaurus* means 'great lizard' which is what Buckland believed the fossil was (Oxford University Museum of Natural History, n.d. b). Today, it is known that a *Megalosaurus* is an enormous carnivorous bipedal dinosaur from the **Jurassic** or early **Cretaceous** period, found in Europe (Princeton, n.d.). However, this fossil was still not classified as a dinosaur, for the term dinosaur would not be created for another 20 years, almost 170 years after the fossil discovery (van Whye, 2012).

In 1842, the term *Dinosauria* (commonly called dinosaurs) was first used by **Sir Richard Owen** (1804 – 1892) a fellow at the Royal Society and a leader of British comparative anatomy (van Whye, 2011). After Owen's introduction of this new taxon, fossils previously classified as large lizards such as the *Megalosaurus* were reclassified as Dinosauria. At this time there were only two other types of dinosaurs ***Iguanadon*** and ***Hylaeosaurus***, both members of the **theropod** family like *Megalosaurus* (University of California Museum of Paleontology, 1993).

These three original dinosaurs are excellent illustrations of how perspectives on dinosaurs change throughout time. Present day, it is known that there are certainly more than three types of dinosaurs and in addition many fossils that were first identified as one of these species were incorrectly identified. From the time of Plot to present day, more and more information is uncovered that changes the scientific community's view of these beasts that used to walk the Earth.

There are many factors that reveal the correct orientation of dinosaur fossils to scientists. Most of these factors are related to discoveries of more complete fossils or other scientific advances, however, some factors are not too scientific.

For example during Plot's time, **Charles Darwin** (1809 – 1882) had not yet been born, and as such had not proposed evolution. In this time it was believed that humans had been present on Earth since its creation and as a result, Plot believed that the fossil very well could have been from an early human (Oxford Museum of Natural History, n.d. a). As the idea of evolution developed, along with dating methods, it was discovered that humans and dinosaurs never shared the earth; dinosaurs went extinct approximately 65 million years ago and the oldest known human lived a little over 200 000 years ago (United States Geological Survey, 2012a; Viegas, 2008).

Another factor that drove dinosaur discoveries forward was competition between palaeontologists, known as 'Bone Hunters' (Lanham, 1973). Since 1842, there has been competition between leading palaeontologists, particularly for recognition for prized fossil finds. In a battle that captivated North America, bringing public interest to dinosaurs for the first time, over 140 different dinosaurs were discovered (Lanham, 1973). This was the fossil feud.

Emergence of the Bone Hunters

The fossil feud started as a friendly rivalry between two friends, **Othniel C. Marsh** (1831 – 1899) and **Edward D. Cope** (1840 – 1896; *right*). Marsh was destined to be a farmer until a rich uncle decided to help him achieve his dream of studying geology. He completed his studies at Yale and in 1861 he published his first paper on a pair of vertebrate fossils he discovered in Nova Scotia (Lanham, 1973). Marsh named the fossils *Eosaurius acadianus* and before publishing the article showed them to **Louis Agassiz** (1807 – 1873) who was the current authority on fossilized fish, which was what *E. acadianus* was thought to be (University of California Museum of Paleontology, 1996; Lanham, 1973).

Agassiz then passed this information around the scientific community, commenting on how remarkable these fossils were. The sharing of his private work angered Marsh who strove to understand the fossil completely. As a result, he discovered that the *E. acadianus* was not a fish but a reptile, making it the oldest known air-breathing reptile at that time (Lanham, 1973). Marsh then went on to create a complete reconstruction of a 15-foot long reptile, adapted for life in the sea. This reconstruction was based on two vertebrae and Marsh was confident there was no error in his creation.

However, as more complete fossils of *E. acadianus* were discovered, it turned out that both Marsh and Agassiz were wrong. *E. acadianus* was not a fish or a reptile but an amphibian and was found within rocks that gave it a geologic age well within the **Age of the Amphibians** (Lanham, 1973). This is an issue that has recurred through dinosaur research, where mistakes of interpretation were made because they were based on incomplete information. As more fossils were uncovered, the mistakes were realized and rectified. However, some mistakes were due to misconceptions of the individual, misconceptions that were smugly pointed out by other scientists.

Bitter Warfare

Edward D. Cope was the victim of one such mistake in 1868. Cope was nine years younger than his rival Marsh, but was not held back by age. Indeed Cope was considered a child prodigy, publishing his first paper at the age of 18 (Lanham, 1973). His father wanted him to become a farmer, as the men in the family had always been, but Cope refused, and decided to pursue academics funded by family money (Lanham, 1973). Both Cope and Marsh were destined to be farmers but academic desire and family money allowed them to follow careers in geology.

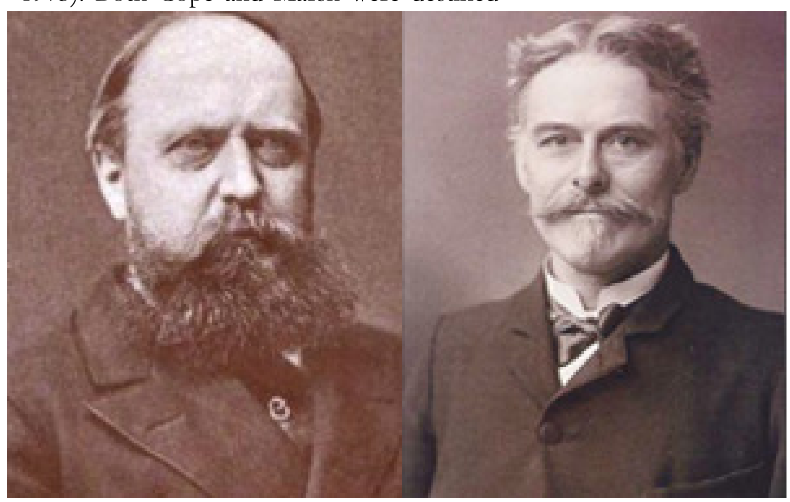


Figure 4.28: Othniel C. Marsh (1831-1899; left) and Edward D. Cope (1840-1896; right).

In 1868, when new dinosaur findings were common, Cope rushed to publish his findings on a new species of **plesiosaur** that had been shipped to his office by an Army surgeon in Kansas, before anyone else could (Lanham, 1973). He named the creature *Elasmosaurus platyurus*, but as he hastily reconstructed the animal, he reversed the vertebrae, thus positioning the skull at the end of the tail. When Marsh inspected Cope's reconstruction, he noticed the error and took pleasure in pointing it out to a devastated Cope. According to a letter written by Marsh, this was when the true rivalry started (Lanham, 1973).

Marsh and Cope were not always enemies; in fact, each named a new species after the other. Cope named an amphibian fossil *Ptyonius marshii* and in response Marsh named a new and gigantic serpent *Mosasaurus copeanus*. Unfortunately, this was the end of their friendly relations (Lanham, 1973). When the rivalry started is not clear, Marsh believed it was when he pointed out Cope's mistake, but Cope believed the rivalry started when Marsh made arrangements with the quarry owner at Cope's dig site to send all fossil finds to himself (Lanham, 1973). After 1868, relations between the two were disrespectful and churlish.

Starting around 1870, both Cope and Marsh were working in the same area of southwestern Wyoming and adjacent parts of Utah. As a result they were both rushing to name fossils, so much so that they both released papers describing the same fossil on the same day, a very rare occurrence (Lunham, 1973). The official name of the fossil is *Limnotherium rostratum*, named by Cope as his description of the fossil was more detailed and included more measurements. *L. rostratum* was a small lemur that belonged to a genus that was given seven different names by Marsh, Cope and **Joseph Leidy** (1823-1891); Leidy was a pioneer of vertebrate anthropology (Lunham, 1973; University of Pennsylvania, 1995). This duplication of names was most likely a result of fragmented fossils. Without more complete fossils, the fragments that the three found quite possibly looked to be from different creatures.

Figure 4.29: Fossil fragments found in mud cracks.

Fragmented fossils (Figure 4.29) were a common reason for species to be incorrectly identified. This leaves an element of guesswork in correctly identifying them, especially in the absence of complete skeletons.

Marsh and Cope continued to battle on the fossil front, at the same time amassing large private collections. At one point, Marsh attempted to obtain Cope's collection by falsely alleging that Cope had used government funds to obtain the fossils. Cope lost patience with Marsh and collected 'proof' of his wrongdoings, giving it to a reporter who published it in an article titled *SCIENTISTS WAGE BITTER WARFARE*. This led to a public battle between the two that lasted for two weeks after which their careers were damaged beyond repair, and they both died impoverished and disgraced (Lanham, 1973).

As the years pass, more and more fossils are uncovered, science moves forward, and more is understood of the history of Earth. This allows scientists to correct past mistakes that were based on limited information. There are quite possibly millions of fossils buried beneath the Earth's surface that have yet to be discovered and which could change scientific perspectives of dinosaurs. In the time of Marsh and Cope, Marsh had named a dinosaur called the **Brontosaurus**. This is a name that is still used today, even though it the Brontosaurus never existed. It was created by Marsh who placed a **Camarasaurus** head on an **Apatosaurus** and called it a Brontosaurus (Viegas, n.d.).

While some may think that there are very few paradigm-shifting discoveries left to be made, in palaeontology may not be the case. Major discoveries have been made as recently as October, 2012 (Zelenitsky, et al., 2012).

What are Feathers for?

For as long as there have been historical records, humans have been fascinated by feathers. They have used them to make weapons, as decoration, and to keep away bad dreams. But until the past decade, scientists have known very little about why birds have feathers. A common belief is that birds have feathers to fly. While it is true that feathers are used for the act of flight, the assumption that they evolved for this purpose is premature. There is a general assumption that since feathers are used to fly they must have evolved for that singular purpose. However, whether or not that is true is still a subject of controversy.

Until recently, feathers were thought to have evolved as a precursor to flight, used for gliding or predatory behaviour (Zelenitsky, et al., 2012). However, the recent discovery of feathered non-avian dinosaurs in Alberta indicates otherwise. Three partial fossils of ***Ornithomimus*** were recovered from the Upper Cretaceous deposits of Alberta: one juvenile (approximately one year old) and two adults (Zelenitsky, et al., 2012). The adult fossils show that the *Ornithomimus* had structures called **pennibrachium**, as well as **filamentous feathers.** This indicates that wing-like structures originated earlier that previously thought. The occurrence of pennibrachium in ground-dwelling herbivores suggests that the wing-like structure did not originate for predatory behaviours or aerial locomotion. In addition, the juvenile *Ornithomimus* appears to only have a plumage of filamentous feathers, different to modern birds whose young have developed pennibrachia within a few weeks of hatching (Zelenitsky, et al., 2012). While the *Ornithomimus* (Figure 4.30) may have used their feathered forearms for terrestrial locomotion in a manner similar to the ostrich, the failure of the juvenile to develop pennibrachia indicates that the feathers may initially have evolved as a secondary sexual characteristic.

This means that these dinosaurs evolved feathers to use in reproductive behaviours such as courtship, display, and brooding. These feathers, once used to attract mates, were later adapted for use in flight by other species such as the ***Archaeopteryx*** (the first true bird). This is quite a shift from previous thought (Zelenitsky, et al., 2012).

The discovery of the *Ornithomimus* fossils also changed the view scientists have on where to find feathered fossils. Before this discovery, feathered fossils were found only in fine-grained deposits, primarily in the Liaoning province of China. The fossils discovered in Alberta were found in **channel sandstones** indicative of a **fluvial depositional environment**. The fact that this **depositional environment** can produce well-preserved feather impressions changes the way fossil preservation and recovery is viewed (Zelenitsky, et al., 2012).

Figure 4.30: An Ornthomimus fossil on display at the Royal Tyrell Museum in Alberta.

Historically, channel sandstones have produced a large number of dinosaur skeletons, several of which could have had feathers. However, these feathers could have gone unnoticed due to the assumption that fine details such as feathers could only be preserved in finer-grained sediments. As a result this assumption would lead to the destruction of any feather impressions around the main fossils during preparation for display (Zelenitsky, et al., 2012).

Fortunately, the potential for feather preservation in coarser-grained deposits has been recognized by the scientific community and could lead to more significant discoveries.

Megafauna and the Discovery of the Ice Age

Ice ages are periods of time characterized by prolonged lowered temperatures and the advance of continental **ice sheets**. During an ice age, global temperatures drop by 5° to 20°, allowing **glaciers** to spread across the higher, middle, and in some cases lower latitudes. Ice ages are not uniform through time; they are composed of **glacial periods** and **interglacial periods** where glaciers advance and retreat respectively (Pidwirny, 2006). The most recent ice age, the **Quaternary Glaciation**, began during the **Pleistocene** period two million years ago, covering much of North America, Europe, and Asia in large ice sheets. The world remains in this ice age today, as ice sheets still exist on Greenland and Antarctica. However, we live in an interglacial period that began with the retreat of glacial ice sheets 14 000 years ago (Pidwirny, 2006). The Pleistocene was also characterized by an extraordinary diversity of mammalian **megafauna**. It was the discovery of megafaunal fossils that inspired the development of the ice age theory, which eventually provided the environmental context needed to understand these remarkable animals.

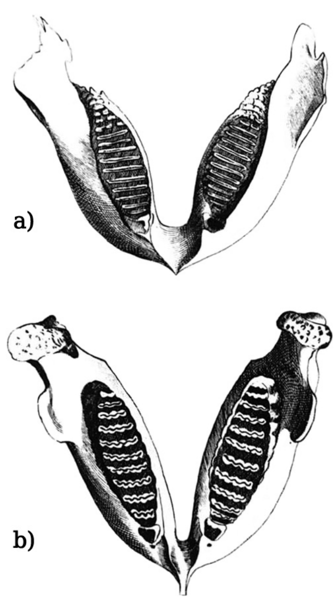


Figure 4.31: Cuvier's sketches of the lower jaws of (a) Mammuthus primigenius *and (b) the Indian elephant* Elephas maximus indicus.

Discovery of Megafaunal Extinctions

The first scientific work that hinted at the possibility of a recent event on the scale of an ice age was **Georges Cuvier's** (1769-1832) examination of mammoth (*Mammuthus primigenius*) fossils in 1796. Cuvier deduced from the differences in mammoth and elephant skeletons (Figure 4.31) that the mammoth must have been a different species that was now extinct. He also compared fossils of the giant ground sloth, now known to belong to the genus *Megatherium*, to modern sloths, and fossils of the woolly rhinocerous *Coelodonta antiquitatis* to the modern rhinoceros. He determined that a catastrophic event must have caused the extinction of these animals, but could not provide an adequate theory for such an event (Fletcher, Henehan and Powell, 2007).

The Development of the Ice Age Theory

Louis Agassiz (1807-1873) was a Swiss naturalist that began his scientific career as an assistant to Georges Cuvier. Agassiz eventually began to make a name for himself when he proposed the original **Great Ice Age theory** to the Swiss Society of Natural Sciences in 1837. Agassiz used his theory to propose a solution to the mysterious mammoth and other megafaunal fossils; he reasoned they were tropical species that were wiped out by an abrupt global cooling period (Agassiz, 1838). The majority of the scientific community, supporting the **Great Flood theory**, rejected his ideas for much of his career. However, Agassiz collected a significant volume of evidence in the field that eventually helped his ideas gain serious traction. Particularly convincing was his discovery of **striations** (Figure 4.32) made beneath **glacial till**. He noted that the striations were parallel to the furrows found in the till, and reasoned that glacial processes abrasively smoothened the bedrock by dragging rocks across the surface, gouging out these formations (Agassiz, 1838).

Agassiz's theory of past global cooling was correct, but many of his ideas were not. He lacked the data that later showed that the global cooling period was much less sudden than he had proposed, and he did not know that periods of global warming and cooling have been occurring for billions of years in a somewhat regular cycle.

The Cyclical Nature of Ice Ages

James Geikie (1839-1915) was the first to propose the idea of multiple ice ages in 1882. Geikie discovered fossils indicating plant life in-between layers of glacial till in Scotland. He thus argued that there must have been warmer periods between glacial periods (Geikie, 1882). These interglacial periods were also thought by others to be connected to the megafaunal extinctions, as the acute shifts in climate would cause great selective stress for species at the time (Coleman, 1926).

A scientist named **James Croll** (1821-1890) proposed a mechanism for this global change in climate based on changes in the Earth's orbit around the sun. Croll also incorporated factors including ocean currents and the Earth's **eccentricity** in his work. He performed the first calculations that approximated the historical pattern of glaciation, however his explanation did not fully explain the proper cycle (Croll, 1885). His contemporaries criticized his approach, as he predicted that the north and south hemispheres would experience different ice ages and over predicted the time lapsed since the last glaciation. Since his predictions did not match the evidence found, the importance of the Earth's orbit in causing ice ages was discarded (Coleman, 1926). Croll's work would eventually be resurrected and improved upon by **Milutin Milankovitch** (1879-1958), who solved the alternating hemisphere problem by recognizing that the majority of the world's land mass is in the northern hemisphere and thus that global glaciation can be driven by cooling in the northern hemisphere (Muller, 2000). With techniques and data that had improved since Croll's calculations were made, he determined a more accurate pattern, called **Milankovitch cycles**, for orbit-driven glaciation. His cycles of 100 000 years were received well by the scientific community, although there was still insufficient field data to confirm his predictions (Muller, 2000).

For half a century various theories cropped up explaining the alternating glacial and interglacial periods. Each theory had its supporters, but the evidence was insufficient to prove any one theory correct. Continental drift suggested to early 20th century scientists that modern equatorial regions might have once been more polar, resulting in many climate changes that could explain glaciation (Coleman, 1926). Ocean currents, which are responsible for many modern differences in climate including the differential harshness of European and North American winters, were also speculated to be major factors in global climate change (Coleman, 1926). The atmospheric greenhouse effects of carbon dioxide and volcanic dust were also considered, as were changes in the sun's radiation output (Coleman, 1926). No proposed cause could account wholly for the glaciations, and the scientific community lacked the precise data needed to test their hypotheses.

Figure 4.32: The scratches in this exposed granite are examples of striations, formed by glaciers dragging rocks across exposed surfaces. Striations like this were the first evidence of a glacial age.

Collecting Historic Climatological Data

Accurate evidence for the history of the global climate was finally found with the development of **deep-sea sediment dating**. From 1947 to 1949 Sweden launched a deep-sea sampling expedition using new coring technologies to collect samples from around the world (Petterson, 1948). Expedition members examined carbonates, microfossils, and general geological trends in samples from the equatorial Pacific and found cyclic patterns. Glacial periods were modeled based on the levels of plankton found in strata, providing the first concrete evidence for multiple ice ages. Palaeontologist **Cesare Emiliani** (1922-1995) demonstrated in 1970 that oxygen fixed into carbonate shells of **foraminifers** could be used to determine the climate of the time (Emiliani, 1970). It had previously been shown that the heavier oxygen **isotope**, oxygen-18, is found more frequently in ocean water while the lighter isotope, oxygen-16, is more common in ice and snow. By analyzing concentrations in core samples with **mass spectrometry** Emiliani showed a regular fluctuation that indicated oxygen-16 had been extracted from oceans during times of glaciation and returned as the world warmed. The cycles found by Emiliani corresponded well with those predicted by Milankovitch (Emiliani, 1970).

Since Emiliani's work the breadth of data detailing past climates has grown immensely, largely due to **ice core** sampling techniques that can determine accurately the atmospheric composition of past periods. By calculating the composition of air found in tiny bubbles in the ice taken from polar ice sheets, a more accurate record has been made of past glaciation than ever before (British Antarctic Survey, 2009). This improved data has demonstrated that Milankovitch's cycles do not fully explain the fluctuations in global temperatures, and show a significant dependence on global carbon dioxide levels (British Antarctic Survey, 2009). Today, no single theory is considered sufficient to explain glacial cycles independently. Rather, many factors including atmospheric composition, astronomical variation, ocean currents, and volcanic activity are thought to be responsible for the patterns seen.

Megafaunal Life during the Pleistocene

During the Pleistocene the world looked dramatically different from today. Excepting interglacial periods, continental ice sheets dominated the planet, although Asia is notable for having little glacial coverage, likely due to its large size isolating it from precipitation-generating oceans. Along with the global decrease in temperature, an ice age is remarkable for the aridity that it brings. This results in many changes for the habitats of organisms at the time. The climate changes were particularly significant for many of the large mammalian species that had spread across the globe since the extinction of dinosaurs.

Scientists in the early 20th century recognized the significance of these environmental changes and suspected that mammalian life could only survive a period of glaciation by one of two strategies: migration to warmer regions or adaptation to colder environments. Now known to have inhabited frigid climates rather than tropical ones, mammoths and woolly rhinoceros (Figure 4.33) were considered examples of the latter. Migrating species found refuge in warmer southern regions, isolated mountain regions, and nunataks: 'islands' surrounded by seas of ice (Coleman, 1926). However, the selective pressures of continuous migration were considered to have been responsible for the widespread extinctions of megafauna including giant sloths and sabre-toothed cats. Even species that were highly adapted to the colder glacial periods such as mammoths and woolly rhinoceros were driven to extinction (Coleman, 1926).

The Pleistocene, however, did not just lead to extinctions, but was also largely responsible for megafaunal propagation throughout the world. **Bergmann's rule**, first proposed in 1847, states that larger-bodied animals are better adapted to cold environments due to their increased volume to surface area ratio. This rule applies well to the megafauna that were successful during the Pleistocene (Larsen, 2011). Recent findings also suggest that some megafauna were **pre-adapted** to ice age life, having developed adaptations in high mountains or other cold regions that allowed them to exhibit great evolutionary success in glacial periods. For example, fossils of *Coelodonta thibetana*, the node species for all woolly rhinoceros, were discovered in the Himalayan foothills and dated to before the Pleistocene. *C. thibetana* possesses adaptions including a warm wool coat and a large, flattened horn that was used to sweep snow out of the way in order to find underlying vegetation. *C. thibetana* and other megafauna including mammoths and yaks are now thought to have rapidly spread to lower altitudes during glacial advance, beginning

Figure 4.33: Although these species would not likely be found in such close proximity, large mammals including the mammoths, woolly rhinoceros, and cave lions pictured were common during the Pleistocene.

their great success throughout the Pleistocene (Deng, et al., 2011).

Now that the Pleistocene is known to be characterized by the proliferation of megafauna during its glacial periods, it seems contradictory that these species also died out during the same age. Today megafaunal extinction is linked mostly to human causes, especially overhunting. However, estimates for the duration of coexistence of humans and the Pleistocene megafauna remain imprecise, and the species likely did not overlap in many cases. The question of megafaunal extinctions remains unanswered, although the fluctuations between glacial and interglacial periods are still a likely factor.

Predicting the Next Glaciation

Milankovitch cycles (Figure 4.34), showing the relationship between variability in the Earth's orbit and changes in global climate, are an effective tool for quantifying the timeline of glacial periods. The expected length of an interglacial period predicted by Milankovitch cycles is 100 000 years, which would place the next interglacial period approximately 90 000 years from now (Muller, 2000). However, these orbital cycles do not take into account many contributors to climate change including ocean currents, vegetation feedback, and most significantly atmospheric effects. The atmospheric effects of **greenhouse gases** require special attention, as the increased levels of carbon dioxide found in the atmosphere today due to human causes have no historical analogue for comparison. Computational climate simulations that consider the effects of these inputs have been made to determine the likely timeline for future glaciation.

As a baseline it is useful to first consider how long the current interglacial period would be without the effects of heightened carbon dioxide levels. A 2012 research paper titled *Determining the Length of the Current Interglacial* predicted the time until the next glaciation under natural circumstances, with carbon dioxide reaching maximum concentrations of 240 ppm (compare to: current concentration of 390 ppm and preindustrial concentration of 280 ppm) in as few as 1 500 years (Tzedakis, et al., 2012). These simulations considered the trigger for the beginning of **glacial inception** to be low **insolation**, determined by the Earth's orbit, during the northern hemisphere's summer. Ocean currents, other greenhouse gases, and other factors are also considered. The duration of 1 500 years was determined by comparing these elements of climate to their analogues in historical interglacial periods (Tzedakis, et al., 2012).

The major difficulty of predicting future climates is that while many causal effects have been linked to global warming, how much impact each has is still unknown (Raymo and Huybers, 2008). Models that show the most significant effects from carbon dioxide predict that glacial inception cannot occur until carbon dioxide levels drop significantly (Tzedakis, et al., 2012). A 2008 study titled *Glacial Inceptions: Past and Future* considered such a situation, in which the Earth experiences a warming period from the present followed by a return in carbon dioxide levels to preindustrial levels around 280 ppm. The simulated results showed a likely glacial inception 50 000 years from now. A parallel simulation in which carbon dioxide levels were not allowed to drop off showed that the greenhouse gas could delay glacial inception for 100 000 to 500 000 years (Mysak, 2008).

In all model scenarios, glacial inception certainly does not appear to be an immediate threat. However, by improving our understanding of glacial and interglacial time frames the methods for predicting climate change can be made more accurate. With the prominence of global warming trends in modern times this is more relevant than ever before.

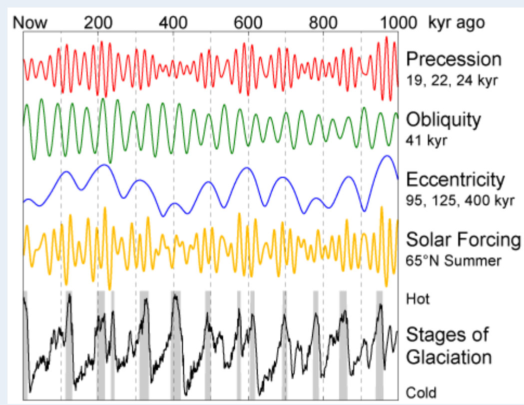


Figure 4.34: Milankovitch cycles account for various aspects of the Earth's orbit and rotation. These combine to accurately predict a cycle closely corresponding to the stages of glaciation observed in the geological record.

Claude Owen Lovejoy and the Origin of Bipedalism

Dr. Claude Owen Lovejoy (b. 1943) (Figure 4.35) is one of the major contributors to the field of **biological anthropology** and human origins, known mainly for his paper *The Origin of Man.* He is most noted for his work with ***Australopithecus afarensis*** and ***Ardipithecus ramidus*** and connecting these **fossil** specimens to human evolution.

Figure 4.35: Portrait of Dr. C. Owen Lovejoy (b.1943) at Kent State University where he is a Professor of Anthropology.

The first appearance of **hominins** was 5-10 million years ago in the late **Miocene epoch** (Larsen, 2011). As new fossils were been discovered and analyzed, **bipedalism** emerged as an important characteristic of human evolution. The geologic record has been very important in identifying fossil **hominids** and the characteristics associated with bipedalism.

In the late 1800s, the fossil record was a very small fraction of what it is today (Larsen, 2011). The first hallmark of human evolution was believed to be from increasing **cranial capacity** and thus, human intelligence. However, this theory has been nullified with the increase in fossil specimens over time. The hominin fossil record shows that bipedalism was undoubtedly the first hallmark for human evolution, not human intelligence (Larsen, 2011). This development is arguably one of the most significant **adaptations** to occur within the lineage of hominins. Furthermore, of all living primates, humans are the only ones who rely solely on bipedalism (Harcourt-Smith and Aiello, 2004).

Bipedalism is distinguished by five characteristics: the **foramen magnum** is positioned on the bottom of the skull, the **pelvis** is short from the front to the back, there is a double arch in the foot, a non-opposable big toe, and long legs relative to the body and arms (Larson, 2011).

Owen Lovejoy's Provisioning Hypothesis

There are many theories as to how bipedalism was selected for, one being **Owen Lovejoy's provisioning hypothesis**. This hypothesis was mostly derived from investigating and researching *A. afarensis,* a hominin that existed 3.6-3.0 million years ago (Lovejoy, 1981; Larsen, 2011). The primary individual he studied was **Lucy** (Figure 4.37), who had some ape but mostly human-like features. The fossil specimen stood 3.5 feet tall and had short legs relative to the size of her torso and length of arms (Larsen, 2011). The **phalanges** of the skeleton are the same size as those of a modern human except they are curved like **pre-australopithecines**, which denote some **arboreal locomotion**. *A. afarensis* is highly **sexually dimorphic** which helped to form Lovejoy's hypothesis. This model for bipedal evolution incorporates social, sexual, and reproductive factors (Larsen, 2011). It states that bipedalism frees up the hands to carry food back to the home base. With the female having obligations of caregiving and gathering of food for herself and her young, there would only be resources and time for one child to be cared for. However, with a **monogamous** father supplying food to the female and her offspring, the mother could invest more into multiple children at one time. The provisioning hypothesis gives a mechanism for increased reproductive rates and success, as the females do not have to move around as much (Larsen, 2011).

Bipedalism vs. Quadrupedalism

Despite the benefits of bipedalism, there are several costs. Due to the upright stance that comes with bipedalism, hominins are more visible to predators than if they were walking as **quadrupeds**. Next, there are burdens on the body associated with upright walking. Chronic back issues and injuries are common, as well as increased difficulty in childbirth. Finally, a burden is placed on the circulatory system, as it is harder to pump blood throughout the body against gravity. However, for bipedalism to have been selected for it must be advantageous to the environment. This means there were more positives associated with it. Bipedalism is fully observed in *A. afarensis*, most notably in Lucy (Lovejoy, 1981). This adaptation allowed for hominins to reach food in tall trees. *A. afarensis* has many features on the hand, shoulder, and torso that correspond with chimpanzees, which stand upright to gather food (Larsen, 2011). Also, bipedality increased viewing distance and the ability to carry tools as well as food (Lovejoy, 1981). Furthermore, tool use, more efficient travel for hunting, and increased thermal regulation are advantages of bipedalism (Hunt, 1994).

There are many physical characteristics that denote bipedalism. The anatomy of the modern human foot is very specialized in its function. As the foot is the only part of the body that continuously comes into contact with the ground, it is under a strong selective pressure to optimize balance and propulsion (Harcourt-Smith and Aiello, 2004). Footprints preserved in volcanic ash in Laetoli, Tanzania 3.5 million years ago provide a unique insight into characteristics of bipedalism in the foot (Figure 4.36). Three important characteristics are rounded heels, non-divergent big toes and double arches from front-to-back and side-to-side (Larsen, 2011). These trace fossils were extensively studied by Lovejoy. The geologic processes that led to the preservation of the world's oldest hominin footprints are dependant on times of immense volcanic activity in the area. These footprints were found in the same sediment layer as *A. afarensis*, which likely makes them their originator. **Tephra layers** add a specific time signature that facilitates in dating these footprints (Larsen, 2011). The footprints were formed as two adults and a child walked through wet volcanic ash, which then dried and preserved the imprints. The volcano erupted again and the footprints were buried by layers of volcanic ash (tephra layers), which protected them for 3.5 million years (Larsen, 2011).

Paleoenvironment for the Evolution of Bipedalism

There are several hypotheses regarding the role environment played in the evolution of bipedalism. Earlier hypotheses state that quadrupedal apes left forest environments for open grasslands (Larsen, 2011). It was thought that here is where bipedal locomotion and posture arose; this is commonly referred to as the **savannah hypothesis of human origins** (Pickford, 2006). This hypothesis is based on the

Figure 4.36: Cast of Laetoli footprints from the Smithsonian Museum of Natural History. The original prints we discovered in Laetoli, Tanzania.

assumption that environmental change drove an adaptation. The savannah hypothesis states that the apes left the forest; however, there are alternative hypotheses such as **Coppens' East Side Story hypothesis** that used geological, chronological, and environmental evidence to say that the forest in fact left the apes (Pickford, 2006). However, fossil evidence shows that an ape lineage became bipedal while still in forest environments. They then spread into the savannah and open grasslands.

Fossil specimens of ***Orrorin tugensis*** discovered in Tugen Hills in Kenya show signs of bipedalism in the femur (Larsen, 2011). Also, animal bones found at this site indicate that *O. tugensis* inhabited wooded and forest environments. This indicates that the **paleoenvironment** in which bipedalism evolved is a forest or woodland area (Pickford, 2006). This well wooded environment is likely to have been a very wet rainforest (Larsen, 2011).

4.37 Skeleton of Lucy the A. afarensis from which many conclusions about early hominid bipedalism have been drawn from.

Major skeletal characteristics serve as indicators for bipedality in hominins; however, there are more specific characteristic that must be explained further. These skeletal indicators are found in the **postcranial** skeleton and the skull (Larsen, 2011). The major postcranial characteristics of bipedalism are observed in the pelvis. In a quadruped or ape the pelvis is located toward the back on the body and is very long. Meanwhile the pelvis of a bipedal hominin is short and directed toward the side of the body (Larsen, 2011). Another major difference is the location of the skull on the body. On humans, the skull is located on top of the body while quadrupeds have the skull more on the front. Also, in humans, the foramen magnum (the large opening for the spinal cord to connect to the brain) is located at the bottom of the skull. In apes and other quadrupeds this is at the back of the skull (Larsen, 2011). Furthermore, the medius and minimus gluteal muscles that attach across hip joints also differ between quadrupeds and bipeds. In bipeds, these muscles pull the thigh away from the midline of the body when the leg is in an extended position. When the leg abducts there is an inward rotation that provides hip stability for walking. In quadrupeds the medius and minimus pull the leg backward which extends the leg at the hip joint (Larsen, 2011).

Ardipithecus ramidus

Chimpanzees, gorillas, and bonobos are all part of the family **Hominidae**, the same which humans belong to. This makes them the closest living relatives to humans today. Prior to Lovejoy's work on *Ar. ramidus*, a newly discovered link in human evolution and bipedality, *Australopithecus* was thought to be the transition between ape-like ancestors to early *Homo*. Owen Lovejoy was part of the anthropological team that studied the 4.4 million year old fossil. *Ar. ramidus* is a **species** that shares many traits with later hominins compared to apes, which nullifies the hypothesis that *Australopithecus* is the transition (Lovejoy, 2009). *Ar. ramidus* shows the anatomy of present day apes and how they evolved specifically within extant lineages of apes. This provides a base line for reconstructing the **last common ancestor** between ape and human lineages (McHenry, 2012; Lovejoy, 2009). This is the first major adaptive transition that *Ar. ramidus* helps us to understand. The skeleton shows a modified pelvis and foot that is useful for both climbing and walking. However, the appearance of a grasping big toe and powerful hip and thigh muscles denote a greater dependence on climbing than *Australopithecus* hominins (Lovejoy, 2009). This ties to the second critical adaptive transition: *Ardipithecus* to *Australopithecus*. *Australopithecus* hominins have a pelvis and lower limb structure that is associated more closely with upright walking and running, with little use for climbing (Lovejoy, et al., 2009). Unlike *Australopithecus, Ardipithecus* had no energy advantage for upright walking (Lovejoy, 2009).

Owen Lovejoy's contribution to field of biological anthropology has been influential. From *The Science of Man* with his provisioning hypothesis and work on *A. afarensis* to *Reexamining Human Origins in Light of Ardipithecus ramidus* to find the missing last common ancestor between apes and humans, Loveyjoy has been critical to the study of human origins and is highly respected within the field.

Hominid Taxonomy

Taxonomy is an important and useful tool for interpreting variation (Larsen, 2011). Taxonomic classifications are refined to make nomenclature and understanding as succinct as possible. **Carl Linnaeus (1707-1778)** first used **binomial nomenclature** and taxonomy as mentioned previously in *Taxonomical Bias in the Fossil Record.* Traditional hominid classification has been reevaluated and changed, as there has been new evidence that chimps and gorillas diverged from orangutans on the evolutionary tree before they diverged from humans (Larsen, 2011).

Furthermore, the close genetic relationship between the three African apes (chimpanzees, bonobos, and gorillas) and humans has also caused the revision of taxonomic groupings (Flammer, 2006).

A major revision from previous taxonomic breakdowns is the definition of the word hominid. Previously, this referred to humans and all their extinct bipedal ancestors whereas now hominid encompasses humans and all African apes. The term hominin is now used to refer to only humans and their bipedal predecessors (Flamer, 2006).

There is still a taxonomic debate between anatomical and genetic classifications. Due to the genetic similarity of humans and chimpanzees, genetic classification has linked them under the same subfamily **Hominine** (Larsen, 2011). This encompasses the **genus** Pan (chimpanzees and bonobos) and Hominin (human). When focusing on adaptations, an anatomical classification is observed. The most widely accepted phylogenetic tree is depicted (Figure 4.38).

The superfamily **Hominodiea** encompasses all apes and humans with three distinct families beneath it (Flammer, 2006). These are: **Hylobatidae** (gibbons and siamangs), **Pongidae** (orangutans), and Hominidae (African apes and humans). Hominidae can then be broken down further into three sub families: **Gorillinae** (gorillas), **Paninae** (chimpanzees and bonobos), and **Homininae** (humans and all past bipedal hominins; Flammer, 2006). Both of these are widely accepted and neither is wrong at this point in time.

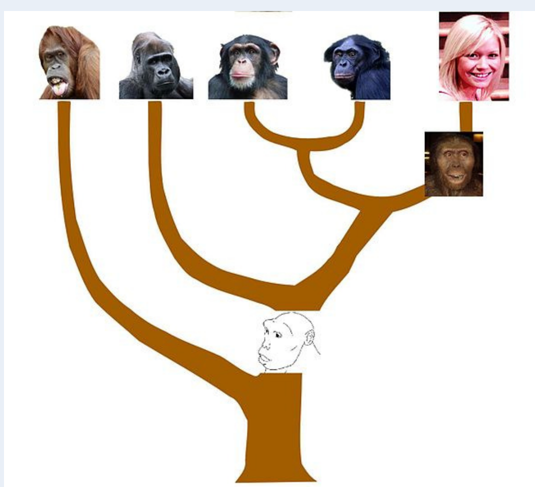


Figure 4.38: Ape and human evolutionary tree depicting both Ar. ramidus (white image) and A. afarensis (hominid below anatomically modern human).

Taxonomy is important to understanding the classification of living and once living things on Earth. Genetics and the fossil record are used to modify evolutionary trees and update them to reflect current understanding. Although evolutionary trees are widely debated it is undeniable that they are useful to enhancing understanding of evolutionary processes. The taxonomy of hominids is complex and anthropologists are continuously searching for new evidence to make understanding of human evolution exact and undisputed.

Figure 5.1: Machu Picchu is one of the few well preserved centers from the Incan Empire. Located in the Andes Mountains, the city was developed around and with Earth's resources.

Chapter V: How the Earth Defined the Development of Humanity

Humans, despite their intellectual prowess, often fail to recognize the influence of the Earth on the ways their civilizations have risen, evolved, and thrived. The planet on which these primates stand has not only shaped their progress in the past, but also continues to do so in the present.

From the earliest records of crop domestication and livestock to the latest in synthetically designed salt and nylon clothing, humans have been able to clothe and feed themselves only through the use of the Earth's natural resources. To access these resources, humans have formed unique and intricate societies in a great variety of environments. Whether upon the sheer slopes of the Andes, or in the coal mines of England, the Earth's geological features and distribution of resources have influenced how civilizations have formed, flourished, and fallen.

The progression of knowledge, discovery, and understanding has been influenced greatly by the unique relationships humans share with the Earth. From making hellish war on one another, to flying through the skies, to discovering the history of ancient civilizations, the Earth has directed human learning for millennia. Bearing in mind that humanity's ability to learn has been paramount to its development, the Earth's influence on human learning cannot be overlooked.

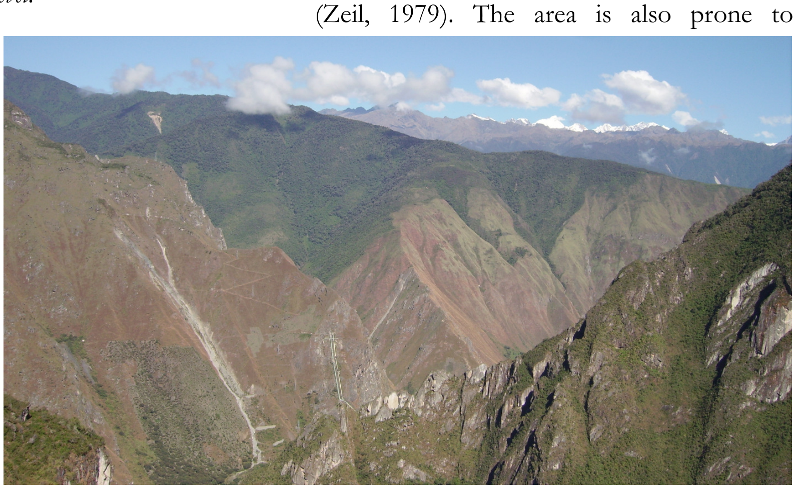
Agriculture in the Andes

Modern *Homo sapiens* have been on this planet for at least 160 000 years (Larsen, 2011). For much of this time the species existed solely as hunter and gatherers; the land and its animal were utilized for feeding the rapidly growing population. However, the development of domesticated plants and crop cultivation sparked the beginning of the agricultural revolution 10 000 years ago (Larsen, 2011). Agriculture emerged after *H. sapiens* had already populated every continent, except Antarctica. This means that the progress of agriculture varies between geographic regions, as a result of different environmental and climatic conditions. The development of agriculture is a case in which geologic processes and structures have greatly influenced human civilizations around the world. The emergence of agriculture in the Andes provides an excellent case study of how location greatly influences the societal and scientific development of human populations in an area.

The Andes

The Andes mountains extend approximately 7 500 km along the west coast of South America and reach peaks of just under 7 000 m above sea level (Zeil, 1979). A broad spectrum of climates is a direct result of the mountain range spanning over 65 degrees of latitude and having large changes in elevation (Zeil, 1979). The area is also prone to earthquakes and volcanic activity while the land is comprised mainly of igneous rocks. The climate itself is highly variable, with multiple glacial episodes in the past 10 000 years, though temperatures can vary upwards of 20 degrees in a single day (Clapperton, 1988). The higher altitudes are also prone to long drought periods. The harsh landscape and climate of the Andes makes it a challenging environment for sustaining human life based on agriculture, but the people in this region have found ways of adapting.

Figure 5.2: The Andes Mountains span the west coast of South America. Steep slopes and rock exposures are common characteristics of environments as high elevations, such as the surrounding area of Machu Picchu, located over two thousand meters above sea level.



The Emergence of Domesticated Species

It is estimated based on archaeological records that *H. sapiens* first arrived in the Peruvian Andes 12 000 years ago (Rick, 2012; Larsen, 2011). During this time the area was experiencing a glacial episode, which began to subside around 9 000 years ago (Rick, 2012; Clapperton, 1988; Larsen, 2011). This caused the shift from cool, arid conditions to a more warm and moist environment. It was during this major change in climate that the Andes experienced a rapid increase in the amount of natural vegetation growth (Markgraf, 1989). Comparison of various archaeological sites in the Peruvian and Bolivian highlands indicate that the cultivation of plants began in approximately 8 000 BCE, with potatoes being one of the first confirmed domesticated species in the area (Pearsall, 2006). There is a distinction between cultivated plants, which are any wild or domesticated plants cared for by humans, and domesticated plants, which have been modified by the interaction with humans (Landon, 2008). Further, the cultivation of wild plants often leads to the domestication of certain species which have higher yields and are more resilient (Landon, 2008).

Intercropping

After the initial leap to plant domestication, one of the first major contributions to agriculture in the Andes was the concept of intercropping. **Intercropping** is a technique in which multiple types of crops are grown interspersed on the same plot of land. The most common grouping has been given the name ‘the three sisters’ and refers to maize, beans, and squash grown in conjunction (Landon, 2008). Analysis of the pollen record in sedimentary deposits gives an indication of when these crops began to appear in the Andes. There is evidence of squash and beans emerging between 8 000 and 4000 BCE; however, the first introduction of maize into South America is a highly debated topic among archaeologists (Pearsall, 2006). Remains that date to approximately 1 000 BCE have been found; although some professionals still suggest maize was present as early as 5 000 BCE (Pearsall, 2006). Regardless of the precise timing of crop emergence, it is believed that intercropping has been present in the mountains for thousands of years (Gianoli, 2006; Landon, 2008). The establishment of intercropping was not unique to the Andes, though it is well suited for the harsh mountain environment and allowed for the establishment of a sustainable agricultural system. This technique is still used by rural Andean farmers today (Gianoli, 2006; Landon, 2008). The precise inspiration of intercropping is unclear but there are many proposed causes based on today's known benefits of the system. Specific to the maize-beans-squash combination, the maize can act as support for the bean plants while the beans are nitrogen-fixing plants and provide essential nutrients for its neighbours. Additionally, the squash protect the soil from excessive water loss, erosion from both wind and water, and their presence prevents the establishment of weeds (Hart, 2008). It is believed that growing the three crops together makes them more resilient to sporadic climates such as those found at high elevations (Hart, 2008). Another theory suggests crops were grown together due to limited space; land was often allotted to each family and thus a variety of foods needed to be grown on the same plot. Maize is a sufficient source of carbohydrates but is lacking in essential amino acids that are present in the beans and squash (Hart, 2008). A diet consisting of all three crops provides a complete set of calories, vitamins, and proteins (Hart, 2008; Landon, 2008). Current research has investigated the efficacy of intercropping with respect to pest reduction. A 2006 study done on the effects of growing maize in solitude or with the addition of beans and weeds was conducted to see if the number of pests was significantly reduced (Gianoli, 2006). The study was conducted in the Peruvian Andes and found that there was a significant decrease in the maximum abundance of two local pest species when the maize was grown with beans and weeds (Gianoli, 2006). Although the first farmers may not have been aware of these nutritional and protective benefits of intercropping, they may be responsible for the prevalence of this system for thousands of years.

Figure 5.3: Intercropping is a common practice in modern rural communities throughout the Andes, where a family's main food source comes from their own fields. In the Ccaccaccollo village in Peru, it is the woman's role to tend to the crops since the men work in the city.

Agropastoralism

In addition to the characteristic slopes of the Andes, a defining feature of the region is the abundant presence of **camelids**, such as llamas and alpacas. Although not a direct feature of the environment, the domestication of llamas found in the area is believed to have influenced the agricultural success in the higher regions (Chepstow-Lusty, 2011). **Agropastoralism** is the act of combining agriculture with the rearing of animals by using the animals for transport of goods, as well as fertilizer for the fields. Additionally, the dried excrement could be used as fuel for fires, as trees are scarce at high elevations (Chepstow-Lusty, 2011). By tracking the amount of mites in a soil sample, a relative number of llamas can be inferred, as increased mite populations correspond to abundance of llama excrement (Chepstow-Lusty, 2011). Comparison to the pollen record indicates a relationship between increases in llama herding and crop yields between 1 500 and 500 BCE (Chepstow-Lusty, 2011).

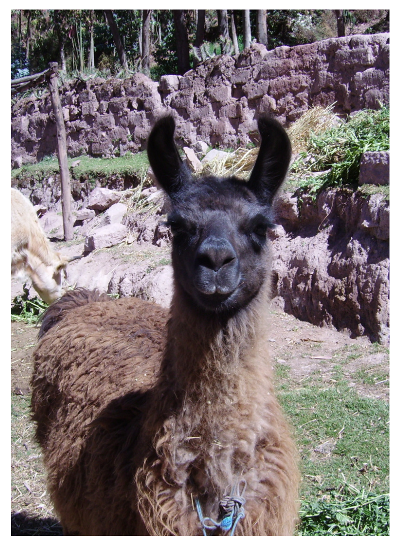


Figure 5.4: A llama is a frequent sight in the Andes. Llamas are believed to have enabled agricultural development and expansion in the higher regions.

Irrigation & Terraces

Precipitation is highly variable throughout the Andes, ranging from long drought periods to unpredictable flooding due to **El Niño** events (D'Altroy, 2003; Hastorf, 2009). By about 200 CE, sophisticated farming techniques had been developed in the Titicaca Basin to accommodate for the inconsistency in water supply (Hastorf, 2009). At 3 800 m above sea level, the basin features the highest lake in the Andes. However, the salt content in Lake Titicaca is too high for direct use in farming and trapped rain water had to be channeled to the fields (Hastorf, 2009). These elaborate channel based **irrigation systems** would carry water between many different settlements up to 12 km apart and indicate the societal organization of the people (Hastorf, 2009). This region is also associated with the development of raised fields, which had the potential to produce crop yields comparable to those achieved with today's technology (Hastorf, 2009). The **Incan empire** (c. 1400 – 1533) brought many changes to the central region of the Andes, consisting mainly of Ecuador, Peru, and Bolivia. Although the foundations of irrigation systems were present prior to the reign of the Incas, there was rapid expansion during the early 13th century until the Spanish invasion in 1533 CE (D'Altroy, 2003; Hastorf, 2009). It is believed that the gradual increase in temperatures beginning in 1 100 CE was also a factor in Incan success (Chepstow-Lusty et al., 2009). This major climatic change allowed them to establish civilization at higher elevations than ever before, with the construction of **terraces** which employed glacier-fed irrigation systems (Chepstow-Lusty et al., 2009). The Incan society valued order while considering the mountains, rock, and water to be sacred (Hastorf, 2009). These views are displayed in their construction as they focused on the distribution of water to linear stone terraces, which still preserved the mountains natural topography (D'Altroy, 2003; Hastorf, 2009). Remnants of these agricultural centers can be seen throughout the Andes, especially in the Urubamba Valley near Cuzco.

Figure 5.5: The remnants of Incan terraces found near Cuzco in Peru, preserve agricultural areas used for mass production of staple crops, such as maize. Refer to the upper right corner for people as a scale.

The extreme climatic and topographic features of the Andes have provided a great challenge to the local societies and still affect the area today. Since the first domestication of plants, the Andean people have found ways of channelling the few resources they had while still respecting the natural system. The people were often inspired by their environment and modelled their systems after observation of existing systems. This motivation lead to concepts like intercropping, which mimicked the dispersal of natural vegetation, and elaborate canals, which channeled the water commonly flowing long distances through the mountains. The Andes have been a defining feature of human civilizations along the western coast of South America for the last 12 millennia and continue to exhibit the influence of Earth processes on the development of *H. sapien* societies.

Predictive Soil Mapping

Societal success around the globe depends greatly upon agricultural sustainability, to which soil quality is fundamental (Scull, 2003). **Pedology**, the study of soils, has become a major field of research which integrates concepts from many scientific disciplines including geology, physics, and chemistry to classify soils (Brady and Weil, 2008). This information can then be used in **Predictive Soil Mapping** (PSM), by which a predictive map of soil type is generated based on statistical models of environmental factors and their relationship to soil properties (Martha, 2010; Florinsky, 2012a).

Soils are sorted according to a wide variety of characteristics, ranging from physical and chemical properties, to process of formation and geographic location. Alternatives to intrusive, and often expensive, soil analysis methods of the past, such as **bore holes**, are now available. An example of a commonly used technique is **Ground Penetrating Radar** (GPR) (Brady and Weil, 2008). GPR emits a series of oscillating electromagnetic waves as the instrument is pulled across the ground. The waves are then reflected off the layers of soil and return an energy signal to the instrument. Based on how the energy was reflected, the data can be interpreted to indicate moisture content, salinity, and density of the various layers up to 30 meters underground (Brady and Weil, 2008).

Although the classification of soils can provide information about their geologic and environmental location, the transition between different soil types within an environment can provide insight into changes in microenvironments. **Topography** is an important factor for soil formation as it influences moisture content and temperature of soils and can control the distribution of certain soil characteristics, such as chemical or biological properties (Florinsky, 2012a). The development of a **Digital Elevation Model** (DEM) is a crucial step in creating an accurate reconstruction of the soil property distributions within an environment (Florinsky, 2012a; Martha, 2010; Scull, 2003). A DEM can be created by taking elevation and slope measurements at various points within the environment, and reconstructing the plane of the Earth's surface with the use of computer modelling (Florinsky, 2012a). Alternatively, satellite images can be used to develop an automatic DEM. A comparison done in 2010 by Tapas Martha et al. found that values "derived from automatic DEMs showed a reasonably good match" to those made from manually collected data (Martha, 2010). However, at slopes steeper than 50° the automatic DEMs were "prone to error" and so the process that accurately captures all types of landscape is still under development (Martha, 2010).

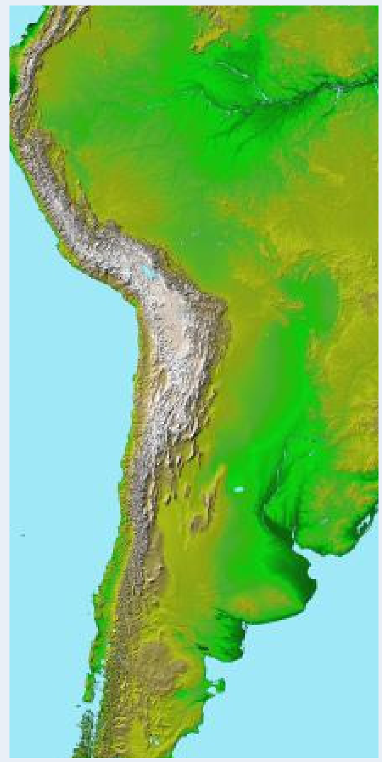


Figure 5.6: An understanding of the topography of regions such as the Andes can be gained from the generation of images based on DEMs. The above image was generated by NASA based on satellite radar data.

Combining information about the topography and soil types can lead to comprehensive models of the relationship between soil properties and spatial distribution. In 1886 **Vasily Dokuchaev** (1846-1903) proposed the hypothesis that "soil is always and everywhere a mere function" of the various factors of soil formation (Florinsky, 2012a; b). However, it was not until the late 20th century that his mathematical approach to soil properties was explored by pedologists around the world. Many mathematical models have been developed for the purpose of PSM, one of which is the concept of **fuzzy logic** (Florinsky, 2012a). Fuzzy logic is based on the theory of allowing an element to fit partially into a certain classification (Scull, 2003; Florinsky, 2012a). This approach is highly applicable to soils, where it is often difficult to limit a sample to a specific class, and describing the sample as a combination of a series of characterizations can give a more accurate representation of its specific properties (Florinsky, 2012a; Scull, 2003).

Integrating concepts from fields such as mathematics and physics can aid in the understanding of geologic processes, such as the formation and distribution of soils, and even be used to predict conditions that have not been directly observed.

The Development of the Usage, Understanding, and Production of Fossil Fuels

Fossil fuels are naturally occurring fuels which are found within the Earth's crust. They are composed of varying amounts of hydrocarbons, compounds made up of hydrogen and carbon which react readily with oxygen in a process known as combustion, creating heat and energy. The three main types of fossil fuels are **coal**, **petroleum**, and **natural gas**. Fossil fuels were formed from the anaerobic decomposition of organic matter, such as plants, algae, and zooplankton, a process which takes millions of years to occur (Fossil Energy Office Of Communications, 2012). The fossil fuels utilized today are composed of matter from organisms living from 200 – 650 million years ago (Fossil Energy Office Of Communications, 2012). Fossil fuels have been used by human civilization for millennia; however, the past few centuries have seen a dramatic rise in the use of fossil fuels, which are now an integral part of a person's day to day life.

Figure 5.7: Coal, a naturally occurring fossil fuel. Coal is formed of decayed terrestrial plant matter, compressed over a period of millions of years. Typically, coal has a much higher carbon content than other fossil fuels, though more impurities.

Early History: c. 2000 BCE – 1600 CE

The history of fossil fuel usage dates back four millennia to the time of the construction of Babylon, in which asphalt, a very crude form of petroleum, was used in the construction of the walls (Chisholm, 1911). The first major concerted effort to mine fossil occurred sometime around 1 000 BCE, from the **Fushun mine** in northeastern China (Encyclopedia Brtiannica, 2012). Coal was also mined by the Romans in Roman Britain in the year 200 CE, where it was used for funeral pyres and the heating of homes and public buildings. The importance of coal in Europe declined during the middle ages, and would not be mined regularly until the 13th century (Encyclopedia Brtiannica, 2012). The earliest oil wells were dug in China as late as 347 CE; by the 10th century, in parts of China and Japan, these simple wells had turned into complex bamboo pipeline networks used to evaporate salt water for the production of salt, as well as heating and lighting in buildings (Chisholm, 1911). Fossil fuels up to this point were not utilized, and were only used as rudimentary heat sources. This began to change when the Persian alchemist **Muhammad ibn Zakariyā Rāzī** (865 – 925 CE) performed the first distillation of petroleum, producing kerosene (Chisholm, 1911).

Beginning of the Industrial Revolution

In the early parts of the 17th century, there was a shortage of firewood in England, causing the government to place restrictive measures on the harvesting of wood (Encyclopedia Brtiannica, 2012). As a result of this, people began to turn to the use of coal as an alternative heat source. In 1603, **Hugh Plat** (1552 – 1608) suggested that coal could be super-heated to make a new fuel, in a similar to the process of heating wood to make charcoal. The practice was not put in place until 1642, when it was used to roast malt in Derbyshire (Nersesian, 2006). The new fuel produced was **coke**; similar to coal, but much higher in carbon content due to the removal of containments such as sulfur. In 1709, **Abraham Darby I** (1678 – 1717) began to use coke inside blast furnaces made for smelting iron. Because coke is chemically more pure than coal, it burns at a much higher temperature, allowing blast furnaces to increase in size and production capabilities (Weissenbacher, 2009). This increase in blast furnace size, coupled with the fact that coke was an easily produced and cheap fuel, meant that the production of iron increased exponentially (Weissenbacher, 2009). This abundance of easily available and cheaply produced iron was a major contributor to the industrial revolution.

Planes, Trains, and Automobiles

The mining of coal had become a major industry in England, although it faced two major issuess: frequent flooding of mines, and the lack of an easy method of transporting coal around the country. The first problem was solved by **Thomas Newcomen** (1664 – 1729), who invented the Newcomen steam engine in 1712, a coal powered device which could be used to remove water from mines (Chisholm, 1911). This device was adapted and improved upon by **James Watt** (1736 – 1819) in 1763, whose designs ultimately led to the practical steam engine (Chisholm, 1911). Watt's steam engine helped greatly in the development of the rail system as a solution to the second problem mentioned above. The first commercially successful rail system was developed by **John Blenkinsop** (1783 – 1831) who used a steam powered locomotive (Chisholm, 1911). By 1850, England had over 7 000 miles of railway, routinely used to transport people, coal, and other goods throughout the country. Meanwhile in North America, in 1858, **Edwin Drake** (1819 – 1880) drilled the first petroleum well in Titusville, Pennsylvania (Chisholm, 1911). This began a major boom in oil drilling throughout North America, in locations including Petrolia, Ontario. In 1886, **Gottlieb Daimler** (1834 - 1900) and **Wilhelm Maybach** (1846 -1929) attached their prototype model of an internal combustion engine to a four wheeled carriage, effectively making the world's first automobile

(Chisholm, 1911). This was the start of a legacy of personal transportation deveices that would revolutionize the way people travelled. In 1903, the **Wright Brothers** made the first powered flight, using a gasoline powered engine. In just over two centuries, humans had gone from using coal as a simple heat source to using highly refined petroleum to power human flight.

Outside of Combustion: Medicines and Plastics

As the chemical knowledge of hydrocarbons began to grow, fossil fuels became an

Figure 5.8: A petrochemical refinery found in Grangemouth, Scotland, UK. At refineries like these, petroleum is separated using distillation into its component parts: many different important chemicals, including acetone, benzene, napthas, and gasoline are produced at plants like these.

important source of raw materials necessary for the production of thousands of different compounds. Medicines such as ethers, used to anaesthetize patients for surgeries, could be refined from drilled petroleum. To this day, solvents and pre-cursors found in almost every scientific lab are synthesized using fossil fuels extracted from the earth.

End of the Fossil Fuel Bubble

As time progressed into the latter half of the 20th century, it was realized that the fossil fuel bubble would have to "pop". Fossil fuels as an energy source are non-renewable: this means that the rate at which humans are harvesting and using fossil fuels far exceeds the rate at which the fuels are being regenerated (Nersesian, 2006). Society had formed a deep reliance on the use of fossil fuels for power: from transportation, to energy, to food production and medicine, modern human civilization now relies on fossil fuels to what is considered by many to be an unsustainable degree (Nersesian, 2006). Current Human civilization has experienced numerous scares over how to deal with the results of its reliance on fossil fuels. There exist two main problems with dependency on fossil fuels as a fuel source: i) fossil fuels, as explained above, are a non-renewable energy source which will run out eventually, leaving civilization with useless infrastructure that will need to be adapted to a new energy source; ii) the use of fossil fuels results in the

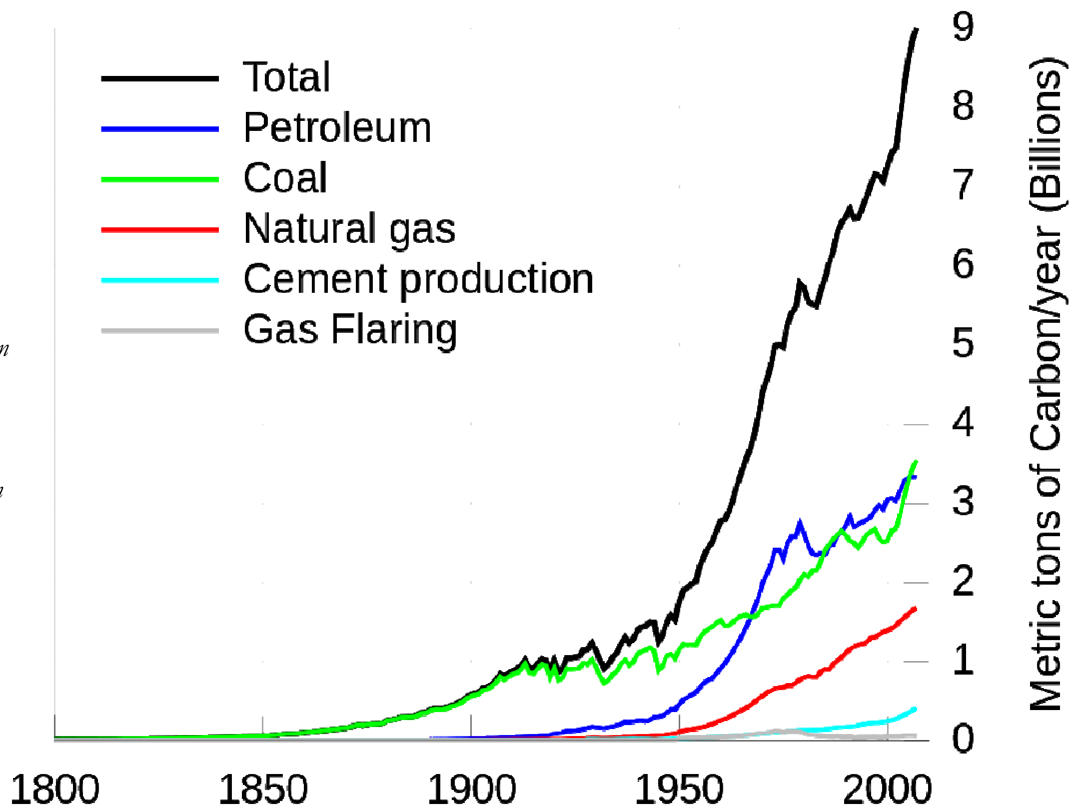


Figure 5.9: In this graph, amount of carbon emissions in billions of metrics tonnes is shown. Not that as time moves into the early 21st century, the amount of carbon emissions increases exponentially.

After World War I, the full scale development of synthetic plastics from derivatives of fossil fuels began (Freinkel, 2011). Examples of some of these plastics include **Nylon**, **polystyrene**, and **polyvinyl chloride**. This major boom in production of plastic products allowed consumers to buy products they had never seen before or had been unable to afford. Nylon stockings, cheaply and easily made, replaced old fabric stockings; pipes could now be constructed of lightweight and cheaply made polyvinyl chloride; polystyrene could be made into a foam like material, known as Styrofoam (Freinkel, 2011). The usage of plastics quickly spread throughout developed nations, forming a society reliant on their usage.

creation of billions of tonnes of pollution every year (Weissenbacher, 2009). One major component of this pollution is carbon dioxide, a main contributor to the **greenhouse effect** and **global warming**; however, there exist numerous other sources of pollution, including sulfur and nitric acid, major causes of acid rain (Nersesian, 2006). Human civilization must begin looking for alternatives to fossil fuel energy and find ways to reduce the impact of the pollution which it has caused.

Development of Algal Produced Biofuels

The use of **algae** to produce **biofuels** is one possible source of fossil fuels for the future, a source which offers many benefits and few drawbacks. This method of biofuel production has been suggested as early as the 1950, although it has only been recently seriously considered as a viable method.

All types of algae, more correctly referred to as microalgae, contain lipids and oils which can be extracted for the purpose of creating biodiesels; useful fuels which can be burned for production of energy (Beer et al., 2010). By composition, algae is typically 10-30% oils, though this figure varies from species to species, with some species reaching as high as 73% lipid content by dry weight (Beer et al., 2010). The benefit of the use of algae for the production of biofuels is that the entirety of the produced algae can be used for productive purposes: For example, lipids and oils can be converted into biodiesels, protein residues can be refined utilized for human foodstuffs, and other precious materials can be extracted and used as fertilizers (Beer et al., 2010; Hossain et al., 2008). Other benefits of using algae to produce biofuels include its ability to grow in normally toxic environments, such as high salt concentration, contaminated waters, or high CO_2 concentrations, and its ability to utilize waste materials as energy sources (Beer et al., 2010; Sheehan, 1986). What this means is that algal species could be selected or genetically modified to be able to utilize brackish or ocean waters as a growth medium, and exhaust from production plants such as coal burning power plants as a source of CO_2 (Beer et al., 2010; Ono and Cuello, 2001; Arizona Public Service Company, 2006). In one particular example, emissions from a coal burning power plant in Arizona were used to grow microalgae in a laboratory; the algae experience higher than expected growth rates, peaking at 174 $g/m^2/day$ (Arizona Public Service Company, 2006).

There are two major ways to produce algae fuels: an open pond system, or a closed photobioreactor (Ono and Cuello, 2001). Open pond systems involve the use of large, open bodies of water in which populations of algae are cultured, grown, and subsequently harvested; nutrients and waste CO_2 would be injected directly into the system (Ono and Cuello, 2001; Sheehan, 1986). This system has come under criticism due to its poor utilization of land area, as well as its susceptibility to external weather conditions and temperature (Sheehan, 1986; Ono and Cuello, 2001). A closed photobioreactor is similar in concept to an open pond system, though the entire system is closed; this means the system is less susceptible to external weather conditions and temperature, and utilizes land far more efficiently (Ono and Cuello, 2001; Sheehan, 1986). However, the costs of setting up a system like this are quite high compared to an open pond system, and typically require more maintenance to function properly (Ono and Cuello, 2001). Alternative methods of culturing systems for microalgae have been proposed, including a hybrid controlled pond system (Ono and Cuello, 2001). In this system, an open pond would be used, though in a location where ambient climate and temperature can be controlled to some extent, such as a greenhouse (Ono and Cuello, 2001).

Human civilization relies too much on fossil fuels right now to completely stop using them all at once. Algae fuels present a viable option for producing the hydrocarbons needed by society in a renewable fashion. With the use of responsible technologies like algae fuels, human civilization can sustain itself on Earth for years to come.

Salt Through the Ages

Salt may seem harmless enough sitting on the dinner table. But consider, for a moment, that the salt in front of you has saved lives, started wars, and revolutionized society.

Discovery

While the discovery of this familiar seasoning can be traced back to ancient times, it is difficult to pinpoint a date without first fixing a location. Salt was discovered before travel and communication were simple feats. Because of this, salt was discovered at different times depending on location. Initial encounters of salt are thought to be the result of early peoples following animals to **salt licks** (Kurlansky, 2002) As cultures began to develop, people noticed that crystallized salt films formed on the surface of water bodies, and developed the first known method of salt harvesting: the 'dragging and gathering' method. This method, a simple harvesting of the crystals on the water surface, is thought to have occurred as early as 6000 BCE in Ancient China (Kurlansky, 2002)

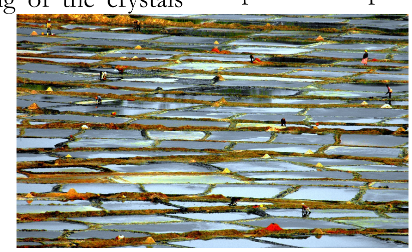


Figure 5.6: Workers harvesting salt from brine ponds, located in Queen Elizabeth National Park, Uganda.

Origin

Salt is mainly found in salt water bodies, brine springs, and deep underground in the form of halite deposits (Kurlansky, 2002; Multhauf, 1978). The general presence of salt can be attributed to the fundamental chemical composition of the Earth (Plummer et al., 2007). One may question how it made its way into deposits and seas. Geology allows for stratigraphic analysis, where salt formations can be attributed to ancient salt water deposits (Plummer et al., 2007). This brings about the second question of how saltwater gains its saltiness. Early theories suggested a giant salt bed at the bottom of the ocean, volcanic origin, or even the ability of certain rocks to generate salt (Multhauf, 1978; Kurlansky, 2002). **Edmond Halley** (1656 - 1742) thought that rivers carried salt from deposits to the oceans. **René Descartes** (1596 - 1650) thought that seawater had hard and soft parts, and that the soft parts pass through earthen pores to form springs, leaving the hard parts behind (Multhauf, 1978). Descartes' ideas of evaporation and deposition were quite close to those views held today. **Robert Hooke** (1635 - 1703), a pioneer in cell biology, postulated that salt comes from the air (Kurlansky, 2002). A common 18th century view held that gypsum changed into salt, keeping the seas salty (Multhauf, 1978). Modern theories suggest that geochemical weathering adds salinity to water, but a definitive answer is yet to be found (Jurinak, 1990).

Production

While every culture has adopted its own variations on salt production, there are three main avenues. The first is simply salt harvesting, as mentioned earlier. When evaporation processes form salt films on water surfaces, these films can be collected by hand. This is how *fleur de sel*, or 'salt flour' is obtained, a light, fine crystal (Kurlansky, 2002).

The second method is similar to that used to produce maple syrup: evaporation. There are many different techniques of evaporation. The earliest records of Chinese salt production, approximately 800 BCE, describe the boiling of seawater in clay vessels. The Romans used the same method around 200 CE (Kurlansky, 2002). The Chinese later tried replacing the clay pots with iron pans around 450 BCE, which became one of the leading methods in salt production and is still used today. Ancient Egyptians also used evaporation, although they had access to salt flats which are created in an arid environment (Plummer et al., 2007; Kurlansky, 2002).

Another evaporation technique, still used today, is to build brine ponds (Figure 5.6) and remove precipitated crystals following solar evaporation. The Venetians improved on this between the sixth and ninth centuries, creating a series of ponds ranging from low salt concentration to high salt concentration (Kurlansky, 2002). This allowed for a continuous process, where new brine could always be added, and the formed crystals continuously removed (Kurlansky, 2002).

The final technique, and certainly the most applicable to Canadian culture, is salt mining (Figure 5.7). Mining for brine, which could be treated by evaporation, went back to 252 BCE in Ancient China. Coincidentally, these workers also uncovered natural gas deposits (Kurlansky, 2002). After a few unfortunate accidents, they learned to pipe out the natural gas, which gave a source of heat for the evaporation process. Thus evaporation could be conducted conveniently close to the mine (Kurlansky, 2002).

Initial interest in deposit mining emerged in Europe, where it was discovered that salt was in fact much more common than once thought. By the end of the 18th century, so many underground deposits had been found that European geologists believed that nearly all of central Europe was underlain with salt (Kurlansky, 2002). Drilling was popularized around the same time, with the invention of a new type of drill by **Johann Lehmann** (1719 - 1767). He displayed a keen interest in demonstrating his drill as a method of salt excavation (Multhauf, 1978).

A discovery crucial to mining was made in 1867 by **Charles Goesmann** (1827 - 1910). Geologists had wondered for some time about the origin of the massive salt deposit forming **Avery Island**, Louisiana, a large **salt dome** where the salt deposits deep underground became pushed to the surface. (Kurlansky, 2002). Goesmann hypothesized that this was due to brine springs coming up through much older deposits (Kurlansky, 2002). He thought that brine comes from deep within the Earth and crystallizes near the surface. This lead to much deeper drilling than had been done before. In 1866, **Samuel Platt** (1812 - 1887) took on the arduous task of drilling 964 feet into limestone at **Goderich**, Ontario (Sifto Canada Corporation, 2012). Initially looking for oil, he drilled until finally hitting a massive deposit of rock salt. This mine is now as deep as the CN Tower is tall, making it the largest salt mine in the world (Sifto Canada Corporation, 2012; Ontario MNR, 2012).

Figure 5.7: A tunnel in a modern salt mine.

Preservation

Salt's initial use in preservation of food has all but faded out in developed countries. While many still enjoy sauerkraut or pickles, salting food for preservation is no longer needed with modern pasteurization and refrigeration. The Ancient Egyptians were thought to be the first to cure food using salt, with preserved fish and birds found in tombs dated before 2000 BCE (Kurlansky, 2002). They also took advantage of salt's natural preservation abilities in the mummification process (Kurlansky, 2002). The realization that food could be preserved and eaten later sparked an entire industry and significantly advanced societies.

The Celts took advantage of this fact, trading salted foods as opposed to trying to trade the salt itself. Unlike other cultures which did not eat pork due to religious or cultural restrictions, the Celts discovered the joy of salted pork, and may have developed the salt-cured hams still eaten today (Kurlansky, 2002).

The Romans used a considerable amount of salt in their food. They also salted their pork products, such as sausage. Items such as olives and wine also benefited from preservation with salt (Kurlansky, 2002). They even salted their greens, giving rise to the term *salad*; and the Romans also began to pickle vegetables in brine. The origins of cheese are somewhat of a mystery, but it should be noted that at some point, someone discovered that soft curds can be treated with brine to give hard cheese (Kurlansky, 2002).

In the Middle Ages (c.476 – 1500 CE), the Irish started salting beef, well on their way to their famed corned beef. The Italians also developed their own salted foods, which have stood the test of time to today, such as salami and different cheeses (Kurlansky, 2002). The Germans made their own contributions, a prime example being sauerkraut (Kurlansky, 2002).

Seasoning

While salt was used liberally in foods as a preservation method, its use as a seasoning did not occur until later in the history of salt. It is thought that the Romans were the first to have a container of salt on the table (Kurlansky, 2002). **Archestratus** (active fourth century BCE), a Greek poet, gave one of the first recorded recipes using salt as a seasoning. Rather than eating a caught tuna immediately, or salting it for later, he suggested baking tuna tail with salt and oil, and dipping it in brine (Archestratus, Wilkins and Hill, 2009). The idea must have caught on, as later a salted fish sauce caught on as a new condiment.

Fish sauce is mainly made of fish and salt, and was also popular in ancient parts of Asia, becoming the fish sauce one can still purchase today in Vietnam, and soy sauce (which originally had fish in it) in China (Kurlansky, 2002). These fish sauces often took the place of salt as a condiment, prior to its popularization for sprinkling over food (Kurlansky, 2002).

Figure 5.8: An elaborate French nef, or salt container, shaped like a ship and made of gold.

During Medieval and Renaissance times, many cultures adopted the custom of having salt cellars on the table as well. The French called their salt containers *nefs* (Figure 5.8), which were very large and ornate, covered in gold and jewels (Kurlansky, 2002). These *nefs* could even have secret compartments holding substances as innocuous as pepper, or more exotic powders such as **'unicorn' horn**, a supposed poison antidote. Some dinner plates had a cavity designed to be filled with salt, as touching salt with one's fingers was not good table manners (Kurlansky, 2002).

Salt-Fueled Disputes

With salt becoming such an important commodity, it is no wonder that people began to fight over it. When the Dutch fought for independence from Spain, starting in 1568, they were cut off from Spanish salt. The Dutch would land at Araya, a lagoon on the coast of Venezuela, and steal salt from the beach where the seawater had evaporated (Brushaber and Brushaber, 1997). The British also illegally gathered salt on the island of **Tortuga**. Salt ships had to travel together in convoys, as their cargo was considered so valuable that they risked attack not only from the Spanish, but from pirates (Jarvis, 2010).

By the early eighteenth century, the American colonies held by Britain began to flourish in the fishing industry. However, they were producing salted fish at a greater rate than the British could provide them with salt, and turned to other resources (Kurlansky, 2002). By 1759, the British felt that an independence of trade could lead to the colonies desiring independence, and began imposing fees and taxes (Breen, 2004). Colonial merchants became angered at this, and the relations between the American colonies and Britain grew very strained (Breen, 2004). Following many struggles, the colonies were declared in rebellion, and the British sent in a naval blockade, which in turn caused a salt shortage (Kurlansky, 2002). The British worsened the shortage by destroying many **saltworks**. However, as the struggle for independence continued, the Americans learned to make their own salt (Breen, 2004).

Until the end of the eighteenth century, India produced salt in **Orissa** (Choudhury, 1979). Under British rule, in 1790 the British offered to buy all Orissa salt. The governor of Orissa turned it down, as he realized that the British were simply trying to gain a monopoly on salt (Kurlansky, 2002). However, the British responded by banning Orissa salt in **Bengal**. Salt smuggling began, which caused British occupation of Bengal (Choudhury, 1979; Samal, 1990). Finally in 1804 Orissa salt fell into the hands of the British, with strict laws and high prices. Things escalated to the point where the British ordered local salt production to cease, causing pain and famine for those who lost their jobs in the Orissa salt industry (Choudhury, 1979; Samal, 1990). The legislature and taxes associated with the **British salt policy** became more and more outrageous.

Finally, in 1885 the **Indian National Congress** was founded, with **Mahatma Gandhi** (1869 - 1948) at the helm (Gandhi, 2006). An independence movement was in the works, and Gandhi wanted to focus this movement on salt. In 1930, he wrote to the **Lord viceroy** of India, saying that if the misrule was not dealt with, he would take it upon himself to break the law (Gandhi, 2006). The **viceroy** stayed firm, and so Gandhi and his followers marched 250 miles to **Dandi**. On April fifth, he picked up a piece of salt out of the Arabian Sea (Gandhi, 2006). This started mass salt protests and eventually led to the independence of India (Gandhi, 2006).

Though the Earth holds a great variety of minerals, there are few that have been more intertwined with civilization than salt. Its uses may have changed with scientific understanding, but its importance to daily life remains unchanged. Whether at war or a great feast, salt has always been something worth fighting over.

Designer Salt

Salt has been used as a seasoning dating back to ancient civilizations. However, recent concern by public health boards regarding the high sodium content of processed foods has led to commitments by food companies to reduce sodium content in their products (Desmond, 2006). For many companies this means reducing the actual amount of salt in recipes, which can detrimentally alter flavour. Salt alternatives, flavour enhancers, and masking agents such as **potassium chloride** or **monosodium glutamate** are an option, but can present similar or more severe health problems (Desmond, 2006). Natural substitutes, for example seaweed granules, can also compromise flavour. However, some companies have taken a more scientific approach, particularly for potato chips. While some flavours can be modified by replacing salt with other seasonings, plain chips require a different tactic: **designer salt** (Desmond, 2006).

Figure 5.9: Salt in its common cubic crystal form.

One way to preserve the flavour experience with smaller amounts of salt is to grind the salt particles into smaller pieces. These contact the tongue in more places at once, due to more exposed surface area. This allows less salt to give the taste of more (Desmond, 2006; Miller and Barringer, 2002). Eating salty snacks provides the experience of a **flavour curve**, which starts with an initial spike of saltiness, moves to a full-bodied flavour, and ends by leaving an aftertaste (Pålsgård and Dijksterhuis, 2000). The problem with this smaller-particle approach is that while the initial burst of flavour is identical, there is a significant reduction in aftertaste, or the lingering saltiness after swallowing.

A better approach examines the effect of crystal structure on **dissolution** rate. In the digestion of salty snacks for a typical human, only twenty percent of salt dissolves on the tongue, while the remainder is swallowed and not tasted (Desmond, 2006). Different crystal shapes have different rates of dissolution. An ideally designed salt would completely dissolve in the mouth during chewing. This quality is called taste bioavailability (Desmond, 2006).

One designer salt, **Star Flake** from Morton Salt, uses **dendritic crystallization** to address this problem (Desmond, 2006). The crystals form a branched, star-shaped structure (Figure 5.10). This form has a low **bulk density** (less sodium per unit volume) and high surface area, optimizing dissolution rate (Davidson and Slabaugh, 2003). This also reduces clumping, a problem with common table salt's cubic, easily stackable form (Figure 5.9). Dendritic crystallization can occur when **ferrocyanide ions** are added to salt brine prior to evaporation (Davidson and Slabaugh, 2003). This addition is approved for food grade salts, as ferrocyanide ions are nontoxic at the required concentration. Crystal growth becomes suppressed on the crystal face, and focused at the corners, resulting in the dendritic form (Davidson and Slabaugh, 2003).

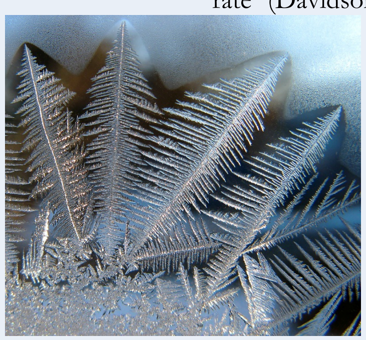


Figure 5.10: The dendritic crystal formation of ice, which is very similar to dendritic salt growths.

For those who wish to consume salty snacks without all the sodium, designer salt has come to the rescue.

The Influence of Geologic Knowledge on Subterranean Military Tactics

Knowledge about the geologic and geographic features of a given battlefield has been paramount to the formation of effective military strategies across the ages. In reference to geography and geology, **Sun Tzu** (c. 544-496 BCE) himself said in ***The Art of War*** that "He who knows these things, and in fighting puts his knowledge into practice, will win his battles" (Tzu 1994, p.100). Therefore when scientific developments allow a given civilization to recognize these features more effectively, their military tactics often improve proportionally.

One of the greatest challenges for any army is taking a heavily fortified position, which puts assailants at a distinct disadvantage. An interesting tactic used to mitigate this disadvantage is **subterranean warfare**, where soldiers venture underground in attempts to damage an enemy's defenses. Every fortification has a foundation, and that foundation can be compromised by digging a tunnel through and collapsing it (Wiggins, 2003). This causes the fortification to sink, shatter, or collapse, which provides an opening for assault. Digging these tunnels, however, can be very dangerous or nearly impossible in certain areas due to geological factors. For example, certain rock layers can be prone to premature collapse and flooding, or simply too hard to dig through (Wiggins, 2003). Increases in the geologic knowledge of a civilization are therefore invaluable to the success of subterranean tactics, which can be seen in Assyria, Ancient Greece, and 18th century Britain.

Figure 5.15: An ancient relief (right) depicting Assyrian siege warfare. Note the bottom left corner, where soldiers are shown underground passing debris from siege mining.

Assyria & the Siege of Lachish

The **Assyrians** are a shining example of how war and science interact. Estimated to have existed between 2 000 and 605 BCE, Assyria was greatly feared as a military superpower in ancient **Mesopotamia** (Saggs, 1984). The Assyrians realized early on that, with some of the most fertile lands for hundreds of kilometres, they were an ideal target for conquest. Adopting the mindset that the best defence is a good offence, the Assyrians became obsessed with conquest themselves. It was this obsession that fueled scientific development, notably the use of iron in weapons (Saggs, 1984). This advancement not only gave the Assyrians a distinct advantage over enemies with bronze weapons, but also opened the door to subterranean warfare.

Congruent with the military focus of Assyrian science, a popular pursuit was the classification of objects with respect to their applications (Thompson, 1936). In addition to the classification of iron as a harder metal than bronze, the Assyrians also classified certain stones based on their perceived medicinal applications (Thompson, 1936). Many of these classifications persisted into Roman times, but they were limited through the influence of religion. As the Assyrians believed that the earth was created using half the body of a former god, they had no reason to investigate how rocks formed (Hincks, 1849). In this way, the Assyrian contributions to geology were limited to classification and applications of iron.

As **siege warfare** is essential to conquest, the Assyrians were constantly improving current tactics and developing new ones. The use of iron weapons and tools, for example, made **siege mining** a much more viable tactic as they could cut through rock much more quickly than with bronze tools (Campbell, 2006). Depicted in the bottom right corner of the pictured relief, siege mining involves soldiers digging beneath the walls of a fortress or city and collapsing the tunnels. Considering that soldiers only had access to simple tools or weapons and that time is of the essence in a siege, the use of a harder metal that allowed them to dig efficiently was key (Campbell, 2006).

The efficiency of Assyrian siege warfare is exemplified by the siege of **Lachish** in 701 BCE (Ussishkin, 1990). In response to a rebellion, **King Sennacherib of Assyria** (d. 681 BCE) reclaimed over 40 Judean towns and cities by force. To avoid a prolonged siege, the Assyrians used siege mining from the beginning against Lachish (Ussishkin, 1990). Although iron weapons and tools were not limited to the Assyrians at this time, their early application of iron gave the Assyrians more extensive experience in subterranean warfare. This experience was made clear as the city's fortifications were successfully undermined in a matter of weeks, and Lachish fell to the Assyrians (Ussishkin, 1990).

Ancient Greece & the Siege of Mount Parnassos

The Ancient Greek philosophers are well-known for their insights into the sciences, and geology is no exception. Some of the earliest thoughts of geology can be traced back to **Empedocles** (c. 490-430 BCE), who postulated that the four elements fire, air, water, and earth make up all the materials in the world (Kingsley, 1995). All of these elements were thought of as indestructible, and it was their varying proportins that produced different materials. Following this way of thinking, a philosopher named **Theophrastus** (c. 371-287 BCE) was curious about what would happen to a rock if the proportion of one of the elements was increased (Richards, 1956). He chose fire as the element to be added, and as such his research involved observing the behaviour of different rocks when heated.

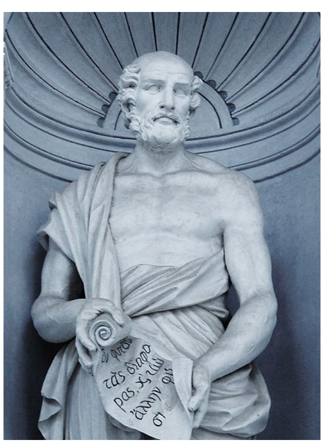


Figure 5.16: A sculpture of Theophrastus (c. 371-287 BCE), a Greek philosopher who investigated the effects of heat on rocks.

Theophrastus recorded his findings in his book ***On Stones***, where he classified different rocks based on properties such as hardness after being heated (Richards, 1956). For example, Theophrastus contrasted the hardness of different kinds of **sedimentary rocks** found in Greece, such as sandstones and limestones. Although he made no mention of how these sedimentary rocks formed, Theophrastus did demonstrate knowledge that **pumice-stones** originated from volcanoes (Richards, 1956). This difference in understanding could be attributed to his experimental design, as he only observed the effects of fire on rocks.

Like most philosophers of the time, Theophrastus taught about his findings frequently. *On Stones* was no exception, and was particularly well received as it followed the popular four elements view (Richards, 1956). In fact, the classification of rocks that he postulated became common knowledge not only for the upper class in Greece, but also in surrounding kingdoms (Richards, 1956). This open sharing of knowledge contributed greatly to the development of science, but also eliminated the chance of using it for a military advantage. In fact, **Macedonia**, a neighbour of Greece, used that very knowledge against them.

Philip V (c. 238-179 BCE) was a young Macedonian king whose goal was to gain influence in Greece before the Romans could (Walbank, 1967). He laid siege to a town on **Mount Parnassos** and began digging a siege mine, but unfortunately the limestone-rich ground was far too hard to tunnel. Philip recognized that there were different, softer rocks that he was familiar with nearby, however, and formulated an ingenious plan (Walbank, 1967). Under the cover of night he ordered his troops to find the nearby rocks, break them, and throw them near the tunnel's entrance to make it appear that the tunnels were almost finished. In the morning, Philip V announced that large parts of the town were undermined and that they could collapse the tunnels at any time. The citizens promptly surrendered, allowing a near bloodless victory for Philip V (Walbank, 1967).

18th Century Britain & the Battle of Messines

The field of geology saw great developments in 18th century Europe, with Britain, Germany, and France at the forefront. Many of these developments can be attributed to the **Industrial Revolution**, where the mining of precious metals and ores such as coal became crucial to a nation's economic success (Jardine, Secord and Spary, 1996). Britain, as the provider of five-sixths of the world's coal, had significant interest in resource exploitation research (Jardine, Secord and Spary, 1996). With that in mind, it is not surprising that some of the greatest geologic strides in the 18th century were made by a British coal surveyor.

Figure 5.17: A photograph of a destroyed German trench at Messines in 1917. The cause of this destruction was an explosion from a British mine.

William Smith (1769-1839) is known as the father of English geology, and with good reason (Winchester, 2001). Smith observed in his work as a coal surveyor that the order of the rock layers, or **strata**, in a particular coal pit was consistent across its perimeter. He hypothesized that strata would be consistent in their relative positions across greater distances, and spent the majority of his life travelling across England drawing **cross-sections** and mapping locations of various strata to prove this (Winchester, 2001). This turned out to be accurate, and Smith demonstrated it by publishing the first ever nationwide **geologic map**. Smith's work greatly improved understanding of stratification world-wide, which became invaluable in the **First World War**.

Until the First World War in 1914, the application of formal geology for military purposes was very rare (Rose and Nathanail, 2000). With great developments in the field of geology and the importance of digging trenches, however, military geological service became a significant asset. The American, British, and German forces recognized this, and each formed military geology units that used their specialized skill-sets to help turn the tide of the war (Rose and Nathanail, 2000). This can best be illustrated by the Battle of Messines, where the efforts of British **military geologists** helped break the stalemate of trench warfare on the Western Front.

Messines was a battlefield near **Ypres** where the Germans had heavily fortified positions on the high ground, making a straightforward assault by the Britsh nearly impossible (Rose and Nathanail, 2000). To counteract this advantage, the British constructed 20 mines between 1916 and 1917 that completely undermined German positions (Rose and Nathanail, 2000). This was by no means easy as certain strata were prone to flooding, but these issues were avoided through the work of British military geologists. These geologists took what samples they could on the battlefield, estimated the depths and positions of problematic strata and planned a route that could avoid them (Rose and Nathanail, 2000). German counter-mining operations, on the other hand, had no geologists advising what areas to avoid and promptly failed due to flooding. With no opposition and the mines directly below German positions, over 450 tonnes of high explosives were detonated on June 7th, 1917 (Rose and Nathanail, 2000). This not only decimated the German forces at Messines, but also set the stage for the monumental Allied victory at **Passchendaele**. Though this was the last major military mining operation in history, it remains a testament to the power of geologic knowledge in warfare.

Scratch Hardness & Field Geology

Modern science provides many methods that help identify minerals, but hardness persists as a useful measure. Although the field of materials engineering has expanded on the formal definition of hardness to account for differences at very small scales, **scratch hardness** remains as a favoured measure among field geologists (MSA, 2012).

Scratch hardness is the measure of how resistant a sample is to **fracture** due to friction (Broz et al., 2006). It is one of the oldest measurements of hardness, as Theophrastus himself described the method of scratching one stone against another to determine their relative hardnesses (Theophrastus, 1956). That being said, we now have a much better understanding of the mechanism behind this technique. Every surface has imperfections, which can be visualized as spikes. If this surface is rubbed against another one, which also has imperfections, movement across is only possible if the spikes of one surface break. The spikes with the greatest resistance to fracture will remain, whereas pieces of the others will break off. This leads to an indentation in the softer material, which we perceive as a scratch (Broz et al., 2006).

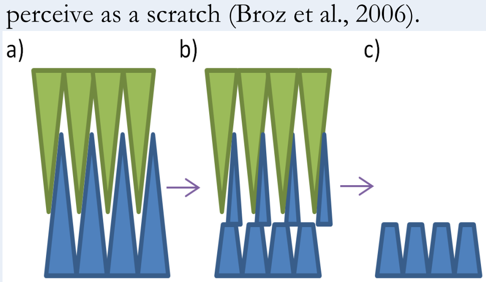


Figure 5.19: A diagram depicting how scratch tests work, with the surface with the greatest resistance to fracture in green. a) shows the two surfaces pressed against one another, b) shows the movement across due to rubbing and the fracture of the least resistant surface, and c) shows what remains of the least resistant surface, which we perceive as a scratch.

This method was used as the basis of the **Mohs scale of hardness**, where **minerals** can be classified on a scale of increasing scratch hardness from 1 to 10 (Broz et al., 2006). Each integer on the scale is representative of a particular mineral, and the scratch hardness of a sample is expressed in relation to the hardness of these minerals. For example, a mineral that scratches quartz (7 on the scale) but not topaz (8 on the scale) would be described as having a scratch hardness between 7 and 8. There has also been the addition of everyday objects to Mohs scale such as pencil leads (1.5), fingernails (2.5), and copper pennies (3.5), which allows field geologists to use the scale without carrying ten minerals around (Broz et al., 2006).

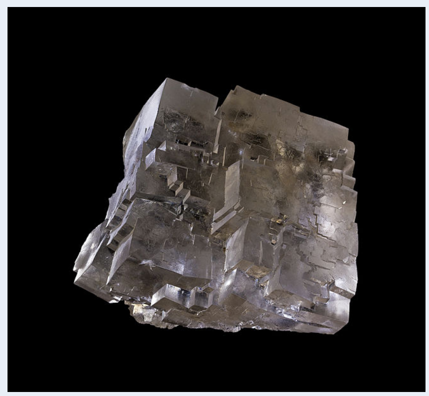


Figure 5.18: A photograph of a piece of halite.

Modern geologists use the Mohs scale to help with quick identification of minerals they find in the field (MSA, 2012). As certain minerals only form under very specific conditions, identifying them can give great insight into the geologic history of a given area (Plummer et al., 2007). One of the best examples of this is the presence of large **halite** deposits, which often result from the evaporation of enclosed lakes (Plummer et al., 2007). This would not only tell the geologist that there was a former lake or sea in the area, but also that the environment was most likely **arid** at the time. Although halite has other properties such as color and **opacity** that are easy to identify, these are shared with other minerals such as quartz. As halite is categorized as between 2 and 2.5 on the Mohs scale and quartz is 7, halite could be distinguished using only a pencil lead and a fingernail.

Despite the presence of more accurate techniques for measuring hardness, the Mohs scale is more than sufficient for modern field geologists. This may change if scientific development greatly reduces the size of more accurate instruments, but for now, field geologists will just have to keep scratching.

Figure 6.1: The Northern Lights as seen from Kluane National Park in the Yukon Territory. This reserve possesses some of the most unpopulated space on the Earth and provides a chance to see this phenomenon in a completely clear sky.

Chapter VI: How Humanity Defines the Earth

The Earth is a dynamic place, constantly changing over time. In its recent history, a new species has had a dramatic impact. The presence of humankind has undeniably altered the Earth's landscape, biosphere, and atmosphere, and therefore, is an important player in its history.

Many processes on Earth rely on delicate balances or equilibria. However, with the rapid growth and expansion of mankind as a species, there have been instances of disruption, negligence and failure of these equilibria. Sometimes this has led to drastic consequences. An example of this is the production of ozone depleting substances, which resulted in the destruction of atmospheric ozone, a vital molecule responsible for shielding the biosphere from harmful ultraviolet radiation. Understanding the history behind mankind's mistakes is the best place to start in minimizing and remediating detrimental effects on the Earth.

Humanity has always felt the urge to rationalize nature and its own existence. Scientific advancements throughout the ages have not only improved the quality of life for the general populace, but have allowed mankind to better understand its surroundings. In order to satisfy their curiosity, humans have developed tools – both conceptual and physical – to define the world around them.

Conceptual tools are theories, models and definitions that comprise humanity's present system of knowledge. Driving the growth of humankind's knowledge was the development of scientific methods – procedures for analyzing and synthesizing facts about nature. These methods have been applied by scientists throughout history, including Charles Lyell and Charles Darwin in the Victorian era.

Physical tools are devices that were created to test predictions and allow in-depth study of various phenomena. Seismometers, maps, X-ray machines and spectroscopy are examples of tools used by scientists to quantify and categorize Earth's features.

Environmental impacts as well as humanity's conceptual and physical tools are all parts of how the human species has defined its home – the planet Earth.

Development of Scientific Methods

While specific sciences such as geology or biology can be traced to their historical foundations, science itself has no distinct origin; it gradually branched off from **empiricist** traditions. The development of science's methods can be traced back through the ideologies of noted empiricists. This path follows a history of observational, inductive, and critical techniques of inquiry.

Phenomena and Endoxa

Unlike Plato, who distrusted the senses, **Aristotle** (384-322 BCE) lauded perception as a means of acquiring knowledge. For this reason, the objects of his studies were **phenomena**, the appearances of the world to human senses. He began working by categorizing and contrasting phenomena in an effort to find puzzles: where does a river get water? how did the ground rise to a mountain's height? Next, he found reasonable explanations for the phenomena. Most of these came from the credible opinions, ***endoxa***, of his contemporaries but Aristotle is famous for his unique takes on common beliefs (Shields, 2012).

One accurate explanation in Aristotle's *Meteorology* is that most rivers originate from groundwater sources, which are continually refilled by the atmosphere. This *endoxori* opposes the view that rivers were fed by massive reservoirs or subterranean lakes that held all the water for one river. Selecting one *endoxori* over another was done through **syllogistic logic**, Aristotle's own invention. No body of water could be large enough to feed a river all year long, and therefore, flows of water must be part of a continuous water cycle that includes seas, rivers, the air and groundwater. Aristotle's only error in this theory was that he thought groundwater came from condensation and rain rather than only rain and surface water (McKeon, 1941).

By logically critiquing endoxa and comparing them to observed phenomena, Aristotle created a systematic worldview covering all the fields of knowledge known today as the sciences. Unfortunately, Aristotle had no rigorous observational techniques (Shields, 2012). His experiments were qualitative instead of quantitative and often involved superficial observation of relevant phenomena. There were many things left wanting by Aristotle's methods but a suitable alternative would not be presented for over a millennium (McKeon, 1941).

A New Instrument of Science

As Europe entered the Renaissance, natural philosophy, something moderns call natural science, experienced renewed growth. Its greatest leap forward came from "the most powerful mind of modern times", the unique scientist **Francis Bacon** (1561-1626) (Durant, 1926).

Figure 6.2: Francis Bacon, father of the inductive method of science.

Bacon lamented the stagnation of human knowledge under the weight of antiquated methods, a result of zealous **scholasticism**. He dreamed of leading a reconstruction of philosophy and science, imbuing them with utility over speculative beauty. His was a truly modern outlook on science.

The contributions Bacon made to science are too numerous to list but he pioneered some broad perspectives and techniques which would become ubiquitous to scientists (Durant, 1926).

First, Bacon critiqued unreflective belief in dogma and popular opinion. While *endoxa* were a boon to Aristotle's nascent type of science, they had become obstacles to the growth of knowledge. Even Aristotle's theories held back independent thinking by inspiring complacence in those views. If no one questioned Aristotle it would still be believed that the Earth is the center of the universe and its interior is cold. Destroying these **idols** of antiquated thinking was a key part of Bacon's reconstruction (Durant, 1926).

Second, he outlined how to experiment in practice. In his words, the "true method of experience first lights the candle", that is, presents the hypothesis. Then, "by means of the candle [it] shows the way," that is, shows how to design the experiment. Finally, it asks the scientist to "put nature on the rack and compel her to bear witness", that is, gather data from the experiment (Durant, 1926).

The revolutionary final component of Bacon's method is the way in which data about nature is to be gathered. Scientists should not simply collect data en masse. It is necessary for them to classify what they gather and look for distinct **correlations**. One of the tools Bacon favored for this was his "table of more or less". This organizes phenomena by which ones increase or decrease together, such as soil pH with occurrences of acid rain. What Bacon expects to reveal by this method are the hidden regularities in nature. Correlations could not be consistently found if there were not actual relations – **causal relations** in his view – between phenomena which varied in conjunction with each other. The crucial step in this new logic of discovery is the move from consistent correlations in data to a statement of general laws of nature. Taking this step is the practice of **logical induction** (Durant, 1926).

An eminent application of Bacon's inductive method was the formulating of the **doctrine of uniformitarianism**. The geologists **James Hutton** (1726-1797) and **Charles Lyell** (1797-1875) presented and elucidated this theory respectively (Sigurdsson, 1999).

Hutton purports to explain "from principles of natural philosophy", namely Bacon's method, how landmasses were produced from consolidation of materials from the sea and that this could only happen over long periods of time, since **sedimentation** acts so slowly. His hypothesis opposes a more biblical view that the land was created rapidly. Uniformitarianism posits that observed geological phenomena, such as coastal sedimentation or volcanic eruptions, were also happening in the past. Since these are seen to gradually modify the land, they could drastically change the face of the Earth if allowed to operate for thousands or even millions of years. In order to justify the theory one must accept that present observations of geological change show regular natural phenomena – not merely chance occurrences. If these events reflect laws of nature, which statement Bacon and Hutton would justify by induction, then it is sound to extrapolate geological events in the past from this information (Hutton, 1785).

Hypotheses like Hutton's uniformitarianism, Newton's laws of motion, and Descartes' optics owe a debt to Bacon. But for all the utility of his inductive method, one criticism severely hampered its credibility.

The Problem of Induction

Over a century after Bacon presented his reconstruction of science, a Scottish librarian by the name of **David Hume** (1711-1776) tore away its logical foundations. While induction justifies science's drawing of general laws of nature from specific phenomena, it must be asked what justifies the principle of induction. The easy answer is to say that induction has generated useful knowledge in practice before and will therefore generate useful knowledge in the future.

Unfortunately for scientists, the only way that past observations, of the usefulness of induction, can justify a general law, that induction works, is to apply the principle or method of induction. Hume points out the obvious to say this is circular reasoning.

More than merely critiquing induction, Hume sought to explain why people are wont to accept inductive conclusions and to

Figure 6.3: David Hume, ardent skeptic and brilliant empiricist philosopher.

show of what use they are (Hume, 1739).

Central to the **problem of induction's circularity** are the causal relations that Bacon thought scientists could discover. He agreed that the cause of a phenomenon could only be identified by observation which is to say it is not deducible from definitions. One issue is that there is no source of generalizations, and general laws, from human perception. The senses solely present specific things and can only provide knowledge of individual phenomena. Causal relations, in Bacon's view, are found by comparing simultaneously varying phenomena in many instances so if nothing general can be garnered from such collections of observations then no amount of correlated variations can show that causes are present in nature (Hume, 1739).

What repeated observations do provide is confidence – confidence in a belief that phenomena are causally related. In Hume's view, a belief that two phenomena are connected strengthens itself every time the two are observed together or observed to vary simultaneously. These observations do not logically strengthen a statement that they are causally related, but give the scientist confidence in his belief in the statement (Hume, 1739). Far from hurting the practice of science, Hume thought his conclusions forced a necessary humility on the theories of science. For all that scientists can discover by observation, they must be willing to accept that their theories can always be proven wrong and will always incorporate something of their biases. The utility of their theories, however, was not put into question.

Logical Positivists

Despite Hume's criticism, the inductive method of science stayed, attested to by Hutton's reference. With the turn of the 20th century, its firmest proponents were a group of philosophers and scientists under the banner of **Logical Positivists**. Their creed was that a scientific theory could only be grounded on empirical or observable facts, for which their term was **sense-data**. For these academics, induction was the only means of drawing general laws of nature from specific sense-data (Popper, 1935).

Their supplement to induction was a **practice of verificationism**. It follows from this position that a statement or theory qualifies as scientific by the possibility of verifying it with observation. In other words, whatever theory makes an observable prediction is a scientific theory. This single criterion handily excludes the far-flung metaphysical ideas of early modern philosophers like Leibniz and Spinoza from the recognition of scientists. Presenting such ideas as non-empirical and meaningless was the intention of the positivists. With these kinds of theories gone, they thought that science could continue grow without the hindrance of obscure **metaphysics**.

One of the metaphysical ideas which were thrown away in the advance of the positivists was that of causal relation; they attacked the very notion of a cause. **Bertrand Russell** (1872-1970), an influence of the positivists, demonstrated that modern scientific theories had already dispensed with causal relations in practice and did not logically rely on their existence. Instead, the connection of phenomena could be quantitatively explained by functional relations, ones which are entirely describable by a series of algebraic equations and can be presented graphically (Russell, 1956). For example, Lyell knew that there was a relationship between a depositional environment's flow velocity, the size of deposited sediment and the resulting sedimentary structure. Modern geologists can express the correlations of these factors as accurate quantitative graphs, like the one below, without mentioning cause and effect (Plummer et al., 2007).

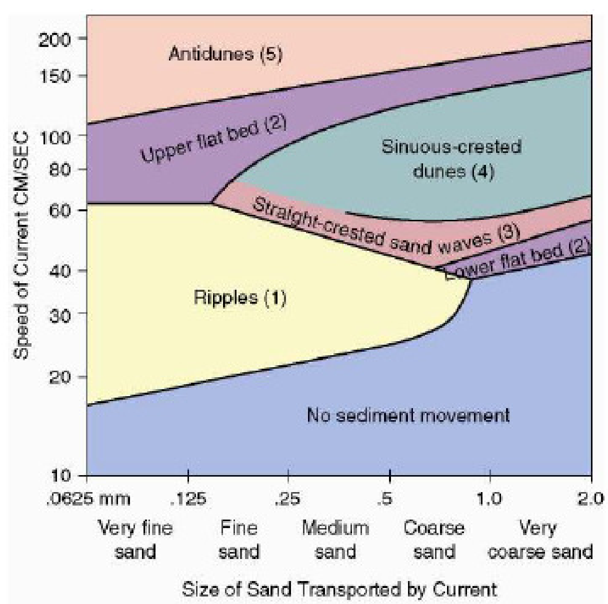


Figure 6.4: Bedform stability diagram for flows approximately one meter deep.

Falsifiability and Modern Science

Deductive Method

Scientists and philosophers held dogmatically onto the logic of induction, in its new mathematical form, like the scholastics clung to their theological doctrines. There were no viable alternatives to induction until the 20th century. It was then that **Karl Popper** proposed a new scientific method, one free of inconsistencies like that of Bacon while keeping its practicality. His was the **deductive method** of science.

In a sense, Popper was returning to Aristotle's techniques. The ancient philosopher thought that *endoxa* and theories should be kept unless contradicted by phenomena. More rigorously, this asserts that if certain predictions are deducible from a scientific statement then the statement is proven wrong by a failure of any of these predictions to come true. Aristotle took this aspect of his theory for granted but Popper resolved himself to defending its importance to the practice of science (Popper, 1935).

While Popper had in mind to resolve the problem of induction, his primary motive was a distinct but relevant issue in the sciences – the **demarcation problem**. He focuses in his *Logic of Scientific Discovery* on the question of how people distinguish science from non-science or **pseudoscience** (Popper, 1935).

For example, biblical **creationism** fits into science by the criterion of verification. With enough effort, a creationist can fit modern data to a theory where the Earth is only 6412 years old. However, the creationist can never present a theory which is **falsifiable** and by consequence, the logic of creationism keeps it from being a scientific alternative to the doctrine of uniformitarianism under Popper`s **falsificationism**. The ability to exclude intuitively unscientific practices like creationism, Marxism or astrology is a reason Popper presents for accepting a convention of falsificationism for science (Popper 1935).

Falsifiability applies to the problem of induction by dissolving the inductive method entirely. Under this convention, a scientific theory is always a hypothesis that can be subjected to further experiment. Every hypothesis presents specific quantifiable predictions that, if contradicted by statistically significant experimental data, must be rejected or falsified. This is the modern accepted method of science.

Statistically significant data is essential to falsifying or failing to falsify a hypothesis. When data presents a correlation between two **variables**, there are a large variety of statistical tests which can determine the significance of the data to the correlation. Failing to meet these standards leaves the hypothesis open to further experimentation.

Falsifiability and Global Eustacy

In analysis of **stratigraphic** evidence around the world, the **global eustacy** model of **Peter Vail** (b. 1930) has come into disrepute. Geologists following Vail supported the hypothesis that cycles of worldwide flooding created stratigraphic patterns over long geological timescales. Successful oil surveys consistently validated Vail's model and it gained a reputation in businesses for utility (Miall, 2000) .

Seismic stratigraphic evidence corroborating the global eustacy model piled up. **Unconformities** in geologic data could be fitted to Vail's global cycle chart and patterns in **sequences** from around the world could be collated through the same cycles (Miall, 2000). Under a verificationist methodology, one that still has influence outside the scientific community, it would be reasonable to view global eustacy as one of modern geology's eminent theories (Popper, 1935).

The conflicting **complexity model** attributes the same stratigraphic evidence to regional as well as global sea level changes. Both models fit the data well. Vail's model, however, is partly the result of bias from business interests and is falsified by 2 out of 17 boundaries in stratigraphic sequences, while the other 15 verify it (Miall, 2000).

The strength of the falsificationist method is in the capacity for anomalies within a fog of corroborative data to still reject a hypothesis. The debate between these models continues but it is certain the methods of science will have the final word.

How Geoscience and Mathematics Invented Each Other

STREPSIADES: And what's this?

STUDENT: Geometry.

STREPSIADES: So what's that useful for?

STUDENT: For measuring land.

STREPSIADES: You mean land for cleruchs?

STUDENT: No, land generally.

STREPSIADES: A charming notion! What a useful and democratic device.

This excerpt from *The Clouds,* a comedy by the celebrated ancient Athenian playwright **Aristophanes (c. 427-386 BCE)**, satirizes the usefulness of geometry to Athenian society. The pun employed here is lost in translation as cleruchs, members of a class of settler-soldier, received land as payment for military service to Athens. The Greek expression "land generally" is also used as "land for everybody," exaggerating the importance of geometry as if it were a tool by which politicians can grant land to all people in Athens (Cuomo, 2001).

Geometry and Land Generally

Geometry is often attributed to the Greeks, the word itself derived from Greek, literally meaning 'Earth measure'. This attribution is entirely justifiable as the surviving works of Greek mathematicians describe the explicit study and refinement of geometric principles (Boyer and Merzbach, 2011). However, the beginnings of geometry are ancient and mostly unknown. Evidence suggests that early peoples of the **Indus Valley** and ancient **Babylonia (c. 3000 BCE)** developed early principles concerning lengths, angles, areas, and volumes (Boyer and Merzbach, 2011).

It is suspected that early understanding of geometry was applied to support construction, astronomy, and land surveying practices of these ancient civilizations (Cuomo, 2001). Evidence of early geometry can be found in Egyptian artefacts, such as the famous **Rhind Papyrus**, which supports the theory that versions of the Pythagorean theorem were developed as early as ancient Egypt, 1500 years before **Pythagoras (c. 570-495 BCE)**, and likely even earlier (Boyer & Merzbach, 2011).

The surviving works of Greek mathematicians suggest that their study of geometry perfected and refined the concepts into explicit mathematical laws. **Euclid (c. 325-265 BCE)** provides the most prolific definition of early geometry in his treatise *Elements of Geometry*. His definition of pure geometric theory was so influential that it remained a primary textbook until the early 20th century (Boyer & Merzbach, 2011). Euclid, now considered the "Father of Geometry," provided the principles which serve as the foundation of geometric mathematics for future generations.

Although it is almost certain that geometric principles arose from early geographic and architectural application, it was **Eratosthenes of Cyrene (c. 276-195 BCE)** who formally applied it to the study of Earth science, or at the very least, his work on the subject survived where others did not. Eratosthenes, a Greek mathematician, astronomer, and philosopher, was the first person to use the word 'geography,' from the Greek verb 'to write the Earth,' in his treatise *Geographika* (Roller, 2010).

This influential work is mostly lost, not surviving intact past the second century CE, but existing today in 155 fragments. **Strabo of Amaseia (64 BCE-24 CE)**, who quoted Eratosthenes extensively thorough his own work, *Geography*, provided most (105) of these fragments (Roller, 2010).

Eratosthenes' *Geographika* developed the foundation for what is the modern study of geography. Here he synthesized the previous three centuries' thoughts on geometry and the nature of the Earth, and used these concepts to describe his understanding of Earth science. The topics covered in this work are diverse and integral to modern geology, including sea depth, geologic history, climate history, and global measurements including circumference (Roller, 2010). Most academic study of geography and geology that followed refined the thoughts that were laid out by Eratosthenes.

Much of the other works by Eratosthenes are completely lost, including his earlier treatise *On the Measurement of the Earth,* in which he provided the first known calculation of the circumference of the Earth (Boyer & Merzbach, 2011).

Fortunately, his method for the earliest circumference calculation was preserved by later authors and is now a famous example of the union of geometry and geography, an area of mathematics that evolved into its own branch known as **geodesy**, derived from Greek *geodaisia*, literally 'division of the Earth'.

In an anecdote of his famous calculation, Eratosthenes observed that the shadow of a building in Syene, modern Aswan, Egypt, disappeared at noon, when the sun was directly overhead, but at that same time in his hometown of Alexandria he knew that a building cast a shadow (*Figure 6.5*). From trade practices, he knew the distance between Syene and Alexandria to be 5000 Stadia (the length of a stadium). He used the shadow in Alexandria to calculate the angle between the vertical building and the direction of the sun (recall that this is the vertical at Syene during noon). Using geometric principles he concluded that the angle between the sun and the building in Alexandria is equivalent to the angle between Alexandria and Syene on a sphere. The angle, approximately 7°, is $1/50^{th}$ of a circle's circumference. He used this in conjunction with the known distance between the two cities to generate the full circumference of a circle, which he estimated as the circumference of the Earth, 250 000 stadia (Roller, 2010).

Unfortunately, it is not know how precise Eratosthenes was compared with the current value of circumference, as the exact unit of measure for a stadion is no longer known. Historians suggest that his estimate was somewhere between 60-75 thousand kilometers, which is accurate in magnitude to the modern measure of Earth's circumference at 40 thousand kilometers (Roller, 2010).

Although Eratosthenes' procedure and reasoning, not his exact number, is the importance of the story, it is a tragedy that the value was lost due to unit conversion error. This problem, however, remained uncorrected for thousands of years, providing another great example of geodesy in the history of science.

"For All People, For All Time"

Those were the words of **Marquis de Condorcet (1743-1794)**, a French politician and mathematician, concerning what may have been the most important outcome of the **French Revolution** (Alder, 2003).

Prior to the revolution, the **Ancien Régime of France** employed an estimated 250 000 different units of measurements (Alder, 2003). This included multiple units for length, weight, volume, and temperature among others. A travelling Englishman in France commented on the issue, complaining, "the infinite perplexity of the measures exceeds all comprehension. They differ not only in every province, but in every district and almost every town" (Alder, 2003).

This was true not only France, but globally. Units of measure differed between cities, countries, religious orders, and government regimes. Scientists, politicians, conquerors, and tradesmen alike were affected by the confusion between the units as it hindered the communication of information and the accessibility of trade (Alder, 2003).

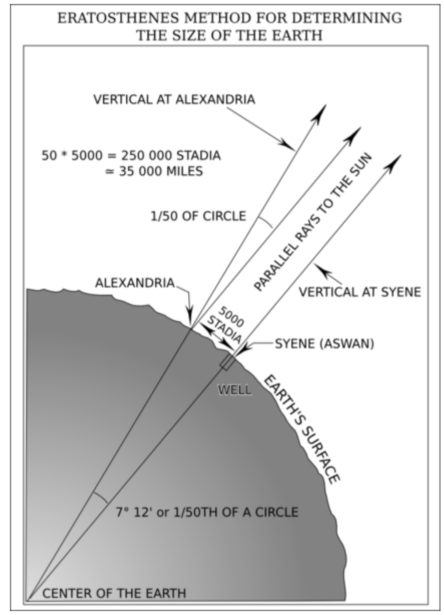


Figure 6.5: Eratosthenes' method for calculating the circumference of the Earth by comparing the verticals of two cities to the direction of the sun.

In June 1792, just months before the Republic was declared and the execution of King Louis XVI, two astronomers left Paris to embark on one of the most enterprising missions of the French Revolution, the creation of a global unit of measure (Cox, 1956).

The two astronomers left Paris in opposite directions, one North to Dunkirk and the other South to Barcelona, along the **Meridian of Paris**. The North-going astronomer **Jean-Baptiste-Joseph Delambreand (1749-1822)** and the South-going astronomer **Pierre-Francois-André Méchain (1744-1804)** forever changed the scientific process and the definition of science itself (Cox, 1956). Befitting the ideology of the French Revolution, the two astronomers set out to define a unit of measure based on the values of reason and universality. It must be a global unit, they decided, that belonged to all people, regardless of nationality. They resolved to base their measurement on the size of the Earth, a value shared by all humanity. A metre, then, would be one ten-millionth of the distance between the North Pole and the equator. It was a hidden agenda, however, that they also wished to settle the debate of the Earth's shape for all time (Frangsmyr, Tore, Heilbron and Rider, 1990).

Following the Meridian of Paris, the astronomers used geometric principles of triangulation to collect vast quantities of data regarding the length of the circumference and the shape of the Earth (Alder, 2003). The results of their work not only changed the principles of geodesy, but the nature of science.

The data they collected succeeded in bringing a conclusion to a centuries-old debate regarding the shape of the Earth. As their measurements were plotted, it was evident that no simple geometric description of the Earth could be applied. It was neither a perfect sphere nor an egg-shaped ellipsoid. The results of this study finally defined the shape of the Earth as that of an irregular spheroid, today known as a **geoid** (Alder, 2003).

Something even more profound, however, resulted from this work. As Méchain, the South-going astronomer, attempted to fix the southern endpoint of his line, he experienced multiple discrepancies in his data (Frangsmyr et al., 1990).

For years Méchain worked to clean the data, trying to account for 'an error' in his calculation. He repeated his methods and scrutinized the data searching for his mistake. His struggle to correct this error forced him to question morality of altering scientific data, and it drove him close to madness until his death in 1804 (Alder, 2003).

His 'error', discovered long after his death, exemplified one of the most fundamental concepts of science. Méchain's discrepancies were not a result of an error, but rather the phenomenon of error itself. It was not until the early 19th century that mathematicians created theories to address measurement error, but this early example of error defined the importance of objectivity and the morals inherent to the scientific process (Alder, 2003).

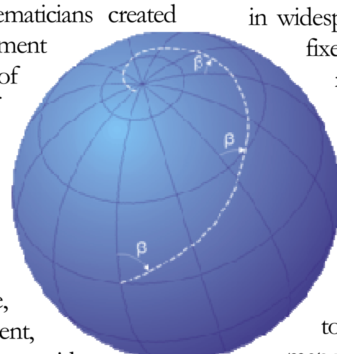


Figure 6.6: Rhumb line shown as a spiral on the globe intersecting longitudinal meridians at the same angle.

Ultimately, their work was successful. When they presented their result, the metre, to the French government, Emperor Napoleon Bonaparte said, "Conquests will come and go, but this work will endure" (Alder, 2003).

Today that truth is evident. After a long history, the metric system is the official method of measurement for over 95% of the world's population (Cox, 1956). Only one industrialized nation does not officially use the metric system, as Thomas Jefferson failed to convince the United States Congress to adopt the French measurements (Cox, 1956). Despite this, the metric system remains the exclusive unit for scientific measurement and an extraordinary testament to globalization.

This discovery not only defined the shape of the Earth, solidifying many principles of geodesy, but also provided a basis for early mathematic theory in error statistics, a study that is foundational to the modern scientific process. The metre, and the process by which it was discovered, succeeded in being 'for all people, for all time.'

Mathematics for a Flat Earth

The idea of globalization and the debate of the Earth shape were both understandable by-products of the **age of exploration**, which started in the early 15th century, 300 years before the French Revolution. This period of discovery was characterized by advancements in navigational astronomy and nautical technology which, in conjunction with the printing press, allowed explorers and cartographers to print and share maps, encouraging European exploration and colonization of the globe.

Although much can be said, both positive and negative, about this period, one cannot argue against its importance in Earth science history and its impact on our understanding of the planet.

A less celebrated contribution by the age of exploration to science is the work done in the field of mathematics in conjunction with geodesy and geography.

Since the 13th century, magnetic compasses were in widespread use for sea navigation. Lines of fixed compass direction were named **rhumb lines**; each intersecting longitudinal meridians at a constant angle. On a globe, rhumb lines are spirals *(Figure 6.6)*, but on a plane they are curves, and navigators had difficulty understanding and using those curves. It was **Gerardus Mercator (1512-1594)** who resolved to address this problem by designing a map where rhumb lines were represented by straight lines on a plane (Rickey and Tuchinsky, 1980).

He attempted to do this while also maintaining both angles and distance, but discovered that this is mathematically impossible. Instead he altered his design by utilizing a conformal system, which preserves angles but distorts areas.

The resulting mapping system, named **Mercator projections**, is characterized by increasing distances between parallel latitude lines as the map describes land further from the equator. This results in increasing area distortion at greater latitudes. Over short distances, such as exploration within the Mediterranean, this distortion was negligible, but with advancements in global exploration it was important to determine the exact factor by which distortion was increasing.

The work produced by **Edward Wright (1561-1615)** in his 1599 publication, *Certaine Errors in Navigation*, finally allowed for the production of accurate Mercator maps (Rickey and Tuchinsky, 1980). Not only did he calculate the factor by which area is distorted to be exactly the secant of the latitude degree.

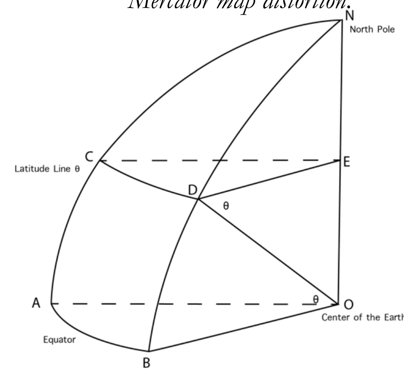
Using principles described in geometric texts, such as Euclid's *Elements*, Wright observed that latitude lines, being parallel lines on sphere, such as the segments AB and CD (*Figure 6.7)* are related by the geometric equality:

$$\frac{AB}{CD} = \frac{BO}{DE} = \frac{DO}{DE} = \sec\theta$$

This shows that the change in horizontal length of parallel lines on a sphere change by a factor of secant θ, providing the formula for the integral of a secant before the work of either **Sir Isaac Newton (1642-1727)** or **Gottfried Leibniz (1646-1716)** (Rickey and Tuchinsky, 1980).

Mercator projections are still common in modern maps, as they allow the spherical globe to be described on a flat plane. The mathematics incorporated by Wright, prior to the invention of calculus, is a testament to the powerful interconnectedness between geographic applications and mathematic progress.

Figure 6.7: Length relationship between parallel lines on a sphere used by Edward Wright to determine Mercator map distortion.



Modern Geodesy

In the late 19th century, German geodesist **F. R. Helmert (1843-1917)** redefined the study of geodesy to "the science of measurement and mapping of the Earth's surface." This new definition proved necessary in the coming century where the nature of the science was permanently transformed by major advancements in technology (Rundle, 1990).

A Perspective Stolen from the Gods

Humans went to space for the first time in the late 20th century, forever changing the understanding of Earth. *The Blue Marble*, possibly the most widely distributed photograph, is an image of the fully illuminated Earth taken by the crew of the *Apollo 17* spacecraft (Petsko, 2011).

Since that photograph was taken, satellites have been collecting vast quantities of data with precise details on the measurement of the Earth. Modern geodesists utilize the tools provided by the space age to obtain precise positioning and elevation information in a continuing effort to construct the most accurate model of our globe (Rundle, 1990).

The shape of the surface of the Earth is now known to be heavily dictated by interior processes. Geodesy has evolved to include extremely precise measurement of the Earth's magnetic field. Technology such as supercomputing, satellite measurement, and global surveying networks are allowing scientists to describe the Earth's magnetic field in detail never before possible furthering the understanding of Earth's internal and surface processes (McNutt, 1990).

An extraterrestrial perspective is not the only advancement that technology has provided for geodesy. Continuing the work of Eratosthenes, over two millennia after his time, geographers and geodesic scientists are now able to survey the deep ocean basins. Today these areas represent something akin to a 'final frontier' in geodesics research. With satellite imagery providing increasingly accurate descriptions of the Earth's lands, the seafloor still remains largely unknown (Spiess, 1990).

Over the next century, technological advances both for space and aquatic surveying will continue to alter the science of geodesics in unpredictable ways. Oceans cover over 70% of the planet's surface. With only 3% of the sea floor currently mapped, the majority of the Earth remains effectively undiscovered (Friel et al., 2000). This situation provides the opportunity for exciting scientific research that may have far-reaching implications. Deep ocean organisms have already contributed invaluable data regarding early biology and the origins of life. It is likely that vast quantities of fossil fuel reservoirs are undiscovered below the ocean floors.

Modern geodesy is nowhere near the end of the task it set out to complete. Humans' understanding of the planet Earth will likely be transformed as the ocean floors are mapped for the first time. In conjunction with precise land analysis and globally accessible world maps, the science of geodesy has made great contributions to our view of the planet, and it will likely continue this practice in the decades to come.

The Victorian era: Science and Politics

The Victorian era (1837-1901) saw major developments in numerous fields which grew to greatly affect British attitudes. To this trend, science was no exception, having seen advances in medicine, physics, politics, and invention (Roth, 2012). This time period saw the creation of numerous scientific inspectorates throughout various fields, in addition to much political debate.

The government in the promotion of science

Prior to the Victorian era, science was not conducted by government-funded scientists, but rather independent individuals who were curious about the world and eager to learn. These individuals found that communicating and discussing their findings was important in order to achieve understanding of the world, and so started to form societies featuring regular meetings of members for scientific discussion. One such society was called the Royal Society, founded in London in 1660 (O'Connor and Robertson, 2004).

It was around the 1820s that **Sir David Brewster** and **Charles Babbage** started to argue that British science needed governmental assistance in order to be competitive against the rest of Europe. Their campaign was responsible for some honours and pensions granted towards British science, the creation of the British Association of Science, as well as a reform of the Royal Society. It was during this period that the British government began to favourably look upon scientific discovery and exploration (Macleod, 1971).

Almost two decades afterwards in 1849, the Royal society was given its first £1000 grant by the British parliament. Although this grant did help the average scientist pay some of his expenses, it could not do much for men studying science without any money of their own. This caused the universities of Oxford and Cambridge to be heavily criticized by prominent scientists such as **Charles Lyell** (1797-1875) (Figure 6.8) regarding their lack of support for natural science (focusing instead on theology, Macleod, 1971).

In the following years, several men of science, among them **Thomas Huxley**

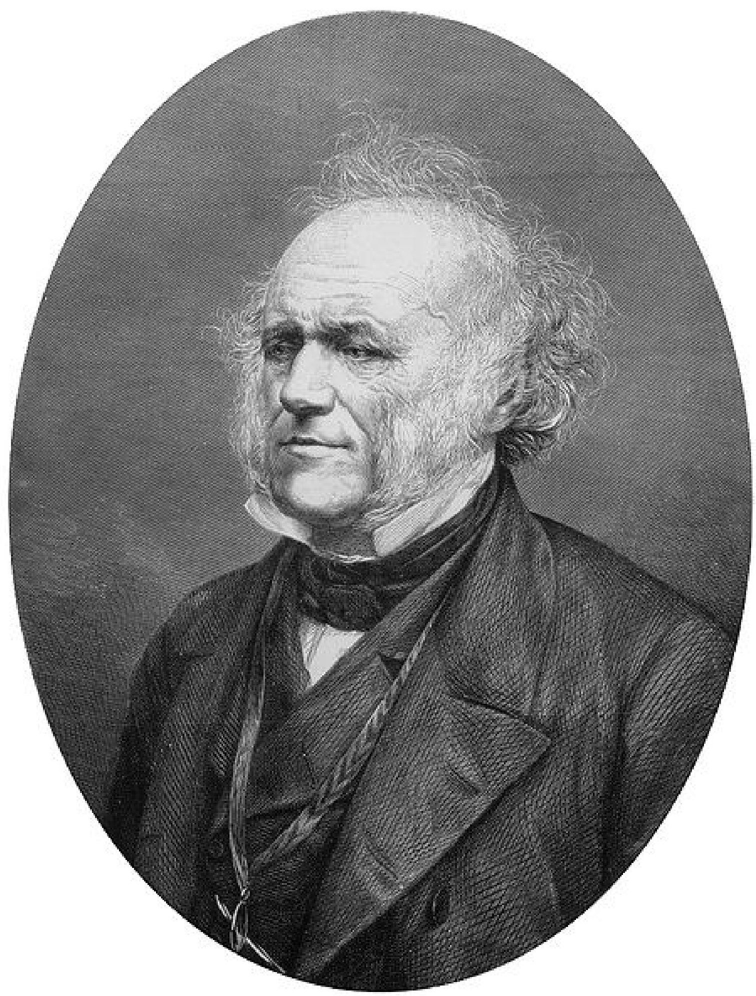


Figure 6.8: Charles Lyell in 1875

shaped scientific development. The Victorian era was when several of the most famous geologists in history were in their prime. This included names like Charles Lyell, **Edward Sabine** (1788-1883), (Figure 6.9) and John Tyndall. All these men had their own parts to play in the political situation in the scientific world.

Figure 6.9: Edward Sabine in 1873.

Sir Charles Lyell, arguably the most well known of the trio, was responsible for the development of uniformitarianism. Lyell was involved in the transformation of science in Victorian Britain because he was one of the more prominent scientists

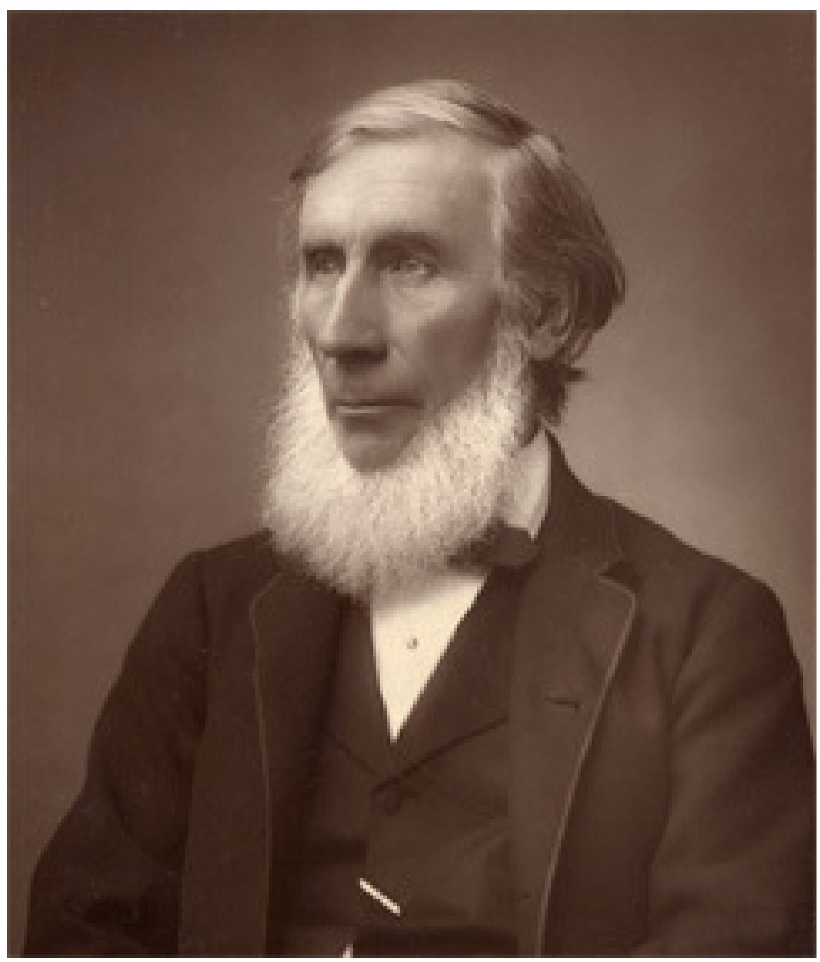


Figure 6.10: John Tyndall ca. 1885.

(1825-1895) and **John Tyndall** (1820-1893), had started to gather regularly in London through the British Association of Science. These men were in positions of power in the scientific world by the 1860's, and nine of them had come together to create an organization famously known as the "**X-Club**". They were united in their belief that a career as a scientist was a largely financial matter and that public support of science was a worthy cause to campaign for. It was this collection of men that was responsible for the creation of journals such as the *Quarterly Journal of Science* and *Nature* (Macleod, 1971).

After decades of pressure from the Royal society and the British association, the British government was convinced that the funding of science in Britain was an important endeavor, as the academic community began to make scientific progress one of its top priorities. By the 1880's, the scientists had succeeded in convincing the government to give them substantial grants for their research as well as increased job opportunities in universities (Macleod, 1971).

The effect of scientific developments on geology

Geology was important in the way that it to speak out against Oxford's disproportionate allocation of resources towards the studying of the natural sciences. It was shortly after Lyell criticized Oxford via the publishing of a book known as *Travels in North America* (Lyell, 1845), in which he outlined his feelings on the broken system at Oxford. This publication was one of the reasons that Oxford decided to introduce honours programs in natural sciences in 1850 (Macleod, 1971).

Edward Sabine was an explorer and geophysicist who was a famous proponent for a movement known as the **magnetic crusade**. In the 1800's, the Royal Navy was troubled with navigation issues, which were caused by variations in the earth's magnetic field. Sabine began to rally physicists to his cause to conduct a magnetic survey of the entire globe. This was known as the magnetic crusade, and it led to the British government looking much more favourably on science. It also led to the government better recognizing the importance of surveying for scientific data (Cawood, 1979).

Figure 6.11: Charles Darwin in 1830.

John Tyndall (Figure 6.10) was a geophysicist and one of the members of the X-Club. Tyndall was responsible for giving popular science lectures at the Royal Institution in London (Wyhe, 2002) and was responsible for numerous advances in physics at the time (Reville, 2001). He was famous for giving a historic address in Belfast, 1874. In his address he passionately argued for the important of science and reason over religion and called for men of science to prize rationalism and natural law. This address influenced the British Association and rallied them under his words. (Wyhe, 2002).

Evolution and Politics

In the field of biology, the Victorian era was an extremely important time. This is primarily due to the fact that it was during these ages that **Charles Darwin** (1809-1882) (Figure 6.11) published his magnum opus, *On the Origin of Species*. The politics involved in the biological sciences was different than the politics involved with the scientific community, in biology, it was less of a clash between scientists and universities and more of a clash between religion and evolution.

It was not until 1859 that all theories regarding the evolution of species and man stopped being **teleological**. This meant that they all were thought to favour perfection, with humans being superior to all other species. Humans were also thought to be special, due to the descriptions of their consciousness by genesis (Diniejko, 2010).

However, after Darwin observed that there was a continuing struggle for survival between species, he concluded that animal evolution did not have any preference towards a "perfect form" of any sort. He concluded that animals evolved such that the fittest members of any species were the ones who would come to dominate the population of that species. Many people applied Darwin's theory to philosophy and politics, and this altered many thoughts on the human condition to deprive humans of a special position in the world. Many people concluded, as a result of Darwin's theory, that humans were little more than an extremely intelligent variant of apes (Diniejko, 2010).

This philosophy and re-evaluation of the human condition manifested itself in peculiar political opinion later deemed social Darwinism. Social Darwinism attempted to apply the concepts of natural selection to sociological situations. This line of thought led many to conclude different things and use the conclusions of Darwin to support their claims. Throughout history, the idea of survival of the fittest has been used to support eugenics, racism, imperialism, capitalism, and several more ideas about society (Leonard, 2009).

The theory of evolution had mixed responses by the religious of England. While there were several clergymen who were friendly to the idea of religion, there were others who expressed hostility towards scientists, accusing them of impudence. Alternately, scientists exposed several ignorant beliefs held by members of the clergy. This resulted in the mid-late Victorian period being known for great appreciation of the value of scientific development by both the people and the government. This eventually led to natural philosophy, a field previously dominated by amateurs, to develop into natural science, dominated by professional scientists (Diniejko, 2010)

Evolution and Education in the United States

In the United States, the teaching of creationism in schools is a topic that has sparked much controversy throughout certain parts of the nation, even reaching as high as the US senate. The issue has been discussed and argued about extensively over the past century, with different movements arising in stark opposition to teaching evolution in government funded schools (Scott and Matzke, 2007; Wexler, 2003).

In 1987, the supreme court of the United States decreed that the teaching of creation science would not be given equal weighting to the teaching of evolution in public schools throughout the nation. This was based on the court's conclusion that it was religious and therefore unconstitutional to teach in public schools (Scott and Matzke, 2007). However, several politicians and individuals remained firm opponents of the teaching of evolution following this, and their beliefs are still alive and well in several creationist movements happening in the modern United States (Scott and Matzke, 2007).

It is important to note, however, that scientists are in unanimous agreement regarding the validity of evolution and there is absolutely no scientific debate in modern academia regarding the validity of intelligent design or creation science over that of Evolution (Scott and Matzke, 2007). Unfortunately for science educators throughout the United States, their efforts to teach evolution in biology classrooms have been greatly hindered by the religious in certain states. Antievolutionists have been known to cite a student's right to knowledge in order to make legal cases, in addition to passing off intelligent design as a valid scientific theory (Scott and Matzke, 2007).

The efforts of antievolutionists have reached the United States senate in 2001. It was during this year that for the first time, the United States Senate contemplated the passing of a bill that would lend equal merit to the idea of teaching intelligent design in government schools. This issue sparked

debate on an issue that had began to die down at the time, and as a result there are today still numerous antievolutionists and antievolutionist organizations in the United States government as well as their populace (Wexler, 2003).

According to a 2012 poll, approximately 46% of US citizens currently hold the view that human origins are a result of a divine being as opposed to evolution (Newport, 2012). Denial of evolution was also found in higher frequencies among religious people. This is a situation similar to that in Britain around the time that Darwin first published his theory, and is an excellent example of the impact that the theory of evolution has had on the religious community (Newport, 2012).

The History of Ozone Depletion

The Discovery of the Ozone Layer

Individual scientific discoveries by contributors from all over the globe culminated in the final discovery of ozone. Scientific knowledge of ozone dates back to the days of ancient Greece. Texts from this time, such as the ***Iliad*** and the ***Odyssey***, noted a peculiar odour that arose after a lightning strike (Andersen and Sarma, 2002). It was not until centuries later that the cause of this smell was actually understood and given a name. In 1785, **Martinus van Marum** (1750 - 1837) passed electrical sparks across oxygen and noted the same peculiar scent (Andersen and Sarma, 2002). However, he falsely attributed the odour to the electricity. Despite this misunderstanding, he did successfully characterize some of ozone's chemical attributes, such as how it reacts strongly with mercury. Eventually, in 1840 the Swiss chemist **Christian Schönbein** (1799 - 1868) determined that this gas was a constituent of the lower atmosphere (Andersen and Sarma, 2002). As a result of its distinctive scent, he named it 'ozone', based on the Greek word *ozein*, meaning 'to smell'. He was also the first to realize that the mysterious, aforementioned odour arose from the gas itself, and not from any electrical source. Shortly after, **Jacques-Louis Soret** (1827 - 1890), also of Swiss origin, identified ozone as an unstable triatomic oxygen-containing molecule (Figure 6.12; Andersen and Sarma, 2002).

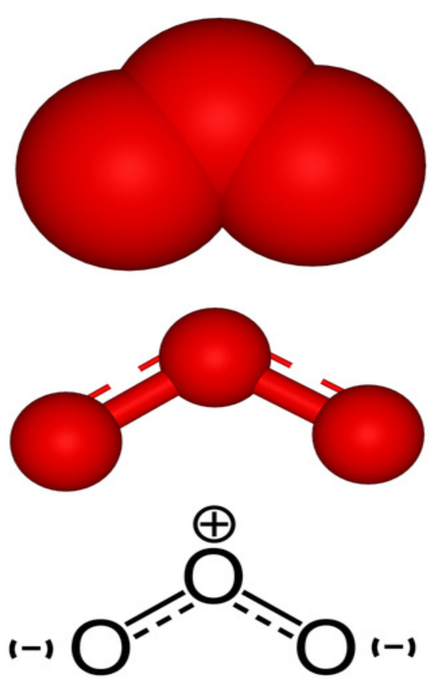


Figure 6.12: The molecular structure of ozone (left). Ozone is a triatomic oxygen-containing molecule (Andersen and Sarma, 2002). On top is a space-filling model, followed by a bond-line structure, and lastly a resonance hybrid diagram illustrating ozone's delocalization of charge, where the colour red represents oxygen molecules.

Mari-Alfred Cornu (1841 - 1902), was the first scientist to identify the role of an ultraviolet (UV) light-absorbing substance within the atmosphere (Andersen and Sarma, 2002). He accomplished this by measuring the sun's spectrum with novel techniques for UV **spectroscopy**, and found that UV light intensity decreased dramatically at wavelengths lower than 300 nm. Although he correctly attributed the drop-off to a substance absorbing UV light, he did not identify that substance as ozone.

One year later, an Irish scientist named **Walter Noel Hartley** (1845 - 1913) ascertained that the substance was indeed ozone (Andersen and Sarma, 2002). Hartley also speculated that the majority of ozone must be located in the upper atmosphere. He based this on studies revolving around UV absorption by ozone. Hartley and Cornu then collaborated and discovered that ozone was able to absorb wavelengths of electromagnetic radiation in the range of 200 - 300 nm, which we now know corresponds to UV-B light (Andersen and Sarma, 2002).

Alfred Fowler (1868 - 1940) and **Robert J. Strutt** (1875 - 1947) confirmed Hartley's findings in 1917, when they ran an experiment demonstrating that the absorption bands in the solar spectrum corresponded with ozone's absorption bands as observed in the laboratory (Andersen and Sarma, 2002). Strutt also made the important contribution of discovering that the majority of ozone is located in the upper atmosphere (Andersen and Sarma, 2002). He accomplished this by quantifying the amount of absorption by ozone from a light source positioned four miles away. Because he could detect no absorption, he was able to conclude that absorption does not occur in the lower atmosphere, and hence deduced that ozone is primarily located in the upper atmosphere (Andersen and Sarma, 2002).

The Discovery of Ozone Depleting Substances

Many times throughout history, scientific inventions have had unintended and unforeseen detrimental consequences which the inventor could not have predicted. The history of ozone depleting substances (ODSs) is a prime example of this. In 1928, **Thomas Midgley Jr.** (1889 - 1944), an industrial chemist, was employed by **General Motors** to find alternatives for harmful substances such as sulphur dioxide and ammonia that were, at the time, being used in home refrigerators (Andersen and Sarma, 2002). He invented a chlorofluorocarbon (CFC) containing chlorine, fluorine, carbon, and hydrogen that was non-flammable and non-toxic to solve this problem. He even inhaled the compound and blew out candles with it to prove it was harmless (Andersen and Sarma, 2002).

CFCs subsequently found many uses such as in automobile air conditioners, as propellants for aerosol sprays, in manufacturing plastics, and as industrial solvents (Andersen and Sarma, 2002). At this time, the atmospheric chemistry responsible for forming and destroying ozone was characterized. **Sydney Chapman** (1888 - 1970) was the scientist who first proposed a photochemical theory of stratospheric ozone formation and destruction (Andersen and Sarma, 2002). He based his mechanism on the chemistry of pure oxygen, and described how UV light could create ozone by inducing photolysis of diatomic oxygen. He realized that if one of these free oxygen molecules was then to react with another diatomic oxygen, a triatomic ozone molecule would be created.

The Implications of ODSs

By the 1950's and 60's, CFCs and other ODSs were being hailed as 'wonder chemicals'. However, their usage came at a price. In 1970, a scientist by the name of **Paul Crutzen** from the Netherlands demonstrated the significance of catalytic loss of ozone (Andersen and Sarma, 2002). He theorized that chemical processes occurring on Earth's surface could affect atmospheric ozone detrimentally, by showing that nitric oxide and nitrogen dioxide are able to react in a catalytic cycle that destroys ozone (Andersen and Sarma, 2002). These volatile chemicals are formed in the atmosphere through reactions with nitrous oxide, which in turn is formed by microbes in soil (Andersen and Sarma, 2002). Although his hypothesis did not extend so to include CFCs, he speculated that increasing levels of atmospheric concentrations of nitrous oxide as a result of increased usage of agricultural fertilizers could lead to ozone depletion (Andersen and Sarma, 2002). Around this time, **James Lovelock**, a researcher from the UK, invented an electron-capture device capable of measuring extremely miniscule organic gas levels in the atmosphere (Andersen and Sarma, 2002). With this device, Lovelock analyzed air samples across the North and South Atlantic. In 1973, he revealed that in every single sample he collected, he had detected CFCs, and that CFCs had spread globally throughout the atmosphere (Andersen and Sarma, 2002). In a direct response to this astounding find, the **DuPont Company** organized a panel called The Ecology of Fluorocarbons, which included all the major producers of CFCs. To provide context, at this time, CFCs were being discharged into the atmosphere at a rate of almost a billion pounds a year (Andersen and Sarma, 2002). Although the goals of this panel were to examine the biological consequences of CFCs and not their effects on climate change, it was a step forward in determining the extent to which these compounds were damaging the Earth (Andersen and Sarma, 2002). In 1974, two researchers associated with Harvard University named **Steven C. Wofsy** and **Michael B. McElroy**, published two very influential papers (Andersen and Sarma, 2002). One paper examined the effects of supersonic transport aircraft, a major depositor of atmospheric nitric oxide, and found that their emissions would result in a significant decrease in atmospheric ozone of about 2% by 1990 (Andersen and Sarma, 2002). Their second publication concluded that chlorine could deplete ozone, and specifically, that one chlorine atom was capable, through a catalytic chain reaction, of destroying tens of thousands of ozone molecules (Andersen and Sarma, 2002). Bromine was also found to be approximately fifty times more efficient at destroying ozone than chlorine (Hewitt and Jackson, 2009). In 1975, McEroy stated that bromine "appears to be so effective at ozone depletion that it could be used as a weapon" (Andersen and Sarma, 2002).

Although Wofsy's and McElroy's findings were vital pieces of evidence describing the ozone depleting characteristics of chlorine, they did not realize the implications their findings had on CFC usage (Andersen and Sarma, 2002). Two chemists at the University of California at Irvine were responsible for making that connection. **Mario J Molina** and **Frank Sherwood Rowland** (1927 - 2012) were the first to research CFCs as a potential source of atmospheric chlorine (Hewitt and Jackson, 2002). They found that CFCs were the major source of atmospheric chlorine and they deduced a mechanism for their ozone depleting action (Figure 6.13). They proposed that UV light could break the chlorine-carbon bond in CFCs, resulting in the release of free chlorine (Hewitt and Jackson, 2002). This free chlorine could then react with ozone to form chlorine monoxide (ClO) and diatomic oxygen (O_2). ClO could then react with free oxygen atoms to form O_2 and atomic chlorine, which could then decompose another ozone molecule (Hewitt and Jackson, 2009). The same traits of chemical inertness and high volatility that make CFCs so useful also meant that they could reside in the atmosphere for extended periods of time. Molinda and Rowland estimated that the lifespan of CFCs in the atmosphere could range from 40 - 150 years (Andersen and Sarma, 2002). Based on Rowland and Molina's findings, it was calculated that even a 10 % decrease in ozone levels would result in 80 000 additional cases of skin cancer each year in the US, and that if CFC production increased at the then current rate of 10 % per year until 1990 and then plateaued, approximately 50 % of the ozone layer would be depleted by 2050 (Andersen and Sarma, 2002).

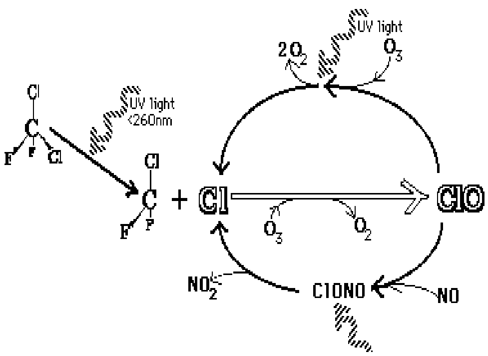


Figure 6.13: The catalytic destruction of atmospheric ozone by CFCs (left). Notice how a free chlorine atom is able to catalyze the destruction of an ozone molecule and is subsequently regenerated. As a result, only a small amount is needed to catalyze the destruction of a lot of ozone (Andersen and Sarma, 2002).

The Beginning of a Solution

The scientific community realized that any action with the goal of regulating the production and use of CFCs would have to be a worldwide effort. In September of 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer was signed by 24 countries, and proposed the phasing out of eight ODSs (Andersen and Sarma, 2002). Due to ongoing doubts of some countries about the gravity of the situation, only moderate measures were taken to reduce production and consumption of ODSs (Andersen and Sarma, 2002). Although scientists knew that the Protocol was insufficient, periodic assessments of the control measures provided opportunities for the Protocol to be strengthened in the future. Eventually, the Protocol resulted in the phasing out of about 85 % of ODSs and the support of almost every national government (Figure 6.14). A technology transfer was necessary in order to achieve this success. In June of 1975, the **S.C. Johnson Company** was the first enterprise to entirely abandon the use of CFCs (Andersen and Sarma, 2002). This transfer of technologies from the environmentally harmful to the

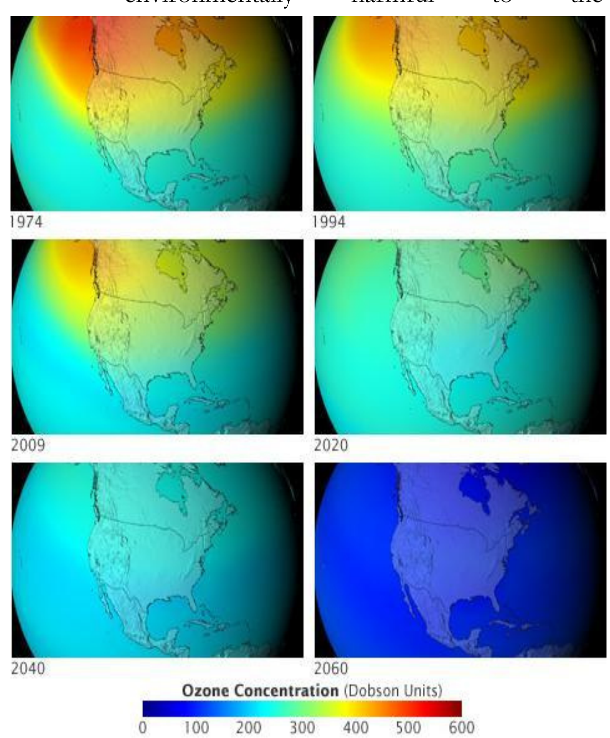


Figure 6.14: What the ozone layer would look like if the Montreal Protocol had not banned ODSs based on a computer model created by NASA (right). The model starts in the year 1974, when CFCs had not yet caused significant damage to the ozone layer (NASA, 2009). A blue colour in this model indicates an ozone hole with ozone concentrations below the threshold of 220 Dobson Units. By 2040, this model predicted that a global ozone hole would exist (Lindsey, 2009).

environmentally friendly was unprecedented. Many see this transfer as an instance where public and private stakeholders cooperated, putting selfish interests aside, to promote actions facilitating the survival of the human race (Andersen and Sarma, 2002).

Current Ozone Status

Although the molecule ozone itself accounts for only approximately three out of every 10 million molecules present in the atmosphere, it plays the crucial role of shielding the Earth's surface and inhabitants from harmful UV light (Andersen and Sarma, 2002). UV radiation is harmful because of its ability to disrupt chemical bonds, such as those in DNA (Hewitt and Jackson, 2009). The most significant form of UV radiation is called UV-B, and includes light with wavelengths between 280 - 320 nm (Firor, 1990). Light of longer wavelengths is able to penetrate the atmosphere to reach the Earth's surface but does not possess as much energy, and is therefore not as damaging. Although light of shorter wavelengths has a higher potential for damaging effects, it is almost completely absorbed by the atmosphere. As a result, ozone's main protective role is to absorb UV-B, which is a principal cause of sunburns, skin cancers, reduced crop yields, damage of surface-dwelling aquatic organisms, and weakening of human immune defences (Firor, 1990).

The atmospheric layer containing the largest proportion of ozone is the stratosphere. In a natural system without anthropogenic influences, the amount of ozone created in the stratosphere should equal the amount destroyed. However, if a chemical **catalyst** is introduced that fascilitates the destruction of ozone but not its formation, the equilibrium will be altered so that there is a reduction in the quantity of ozone (Makhijani and Gurney, 1995). Today, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) have largely replaced CFCs (Makhijani and Gurney, 1995). HFCs contain no chlorine or bromine, and HCFCs contain less chlorine atoms per carbon atom compared to CFCs, and instead contain more hydrogen. The presence of more hydrogen in the structures of HFCs and HCFCs results in an increase in their chemical reactivity (Makhijani and Gurney, 1995). Consequently, they undergo chemically decomposition in the lower atmosphere, namely the troposphere, before they can reach the stratosphere causing them to have a lower impact on the ozone layer (Makhijani and Gurney, 1995). However, these compounds are not a perfect replacement because they are potent **greenhouse gases** (Makhijani and Gurney, 1995).

The Montreal Protocol has been extremely successful thus far, and has extinguished ODS consumption in nearly all sectors. However, despite this success, it is predicted that it will take decades for the ozone layer to recover. To quantify this, Antarctic ozone levels are expected to return to pre-1980 levels as late as 2060 - 2075 (Hewitt and Jackson, 2009). Tropical column ozone levels are expected to return to their 1980 values by approximately 2070, and stratospheric chlorine levels are not expected to return to their low 1960 values until the end of the century (Bekki, S. and Bodeker, G., 2010).

There is still much work to be done to solve the ozone problem. The aforementioned chemical alternatives still harm the ozone, just to a lesser extent, so new, cost-effective alternatives must still be developed. Also, other sources of ODSs such as nitric oxides emitted in the exhaust of subsonic aircraft are being released into the stratosphere at increasing rates. Since aircrafts usually cruise at altitudes of 10 - 12 km, which is within the stratosphere, their emissions can have direct impacts on ozone destruction. It is predicted that approximately 44 % of nitric oxide from exhaust emissions from subsonic aircrafts end up in the stratosphere (Hewitt and Jackson, 2009). Industry projections also predict a 5 % per annum increase in this subset of air traffic from 2005 - 2015, raising major concerns that the impact of subsonic aircraft emissions on the ozone layer is likely to increase dramatically (Hewitt and Jackson, 2009). Time is of the essence in dealing with this critical global issue.

Development of Earthquake Detection Methods

Earthquakes are defined as the shaking of the ground caused by the movement of rocks beneath the Earth (Plummer, et al., 2004). **Tectonic forces** within the Earth place stress on the rocks causing them to deform. Over time, this strain builds up as energy until it exceeds the strength of the rock resulting in a sudden break or movement that releases the stored energy in the form of **seismic waves**. These waves spread either on the surface or through the interior of the Earth resulting in the deadly effects of earthquakes. These effects, which include ground motion and displacement, fire, **landslides**, and **tsunamis**, make earthquakes one of the most dangerous natural disasters.

History's Deadliest Earthquakes

In 1556, China experienced history's deadliest recorded earthquake (USGS, 2012c). On the morning of January 23rd, the Shaanxi province awoke to a magnitude 8 earthquake as classified on the **Richter Scale** (Houa, 1998). It killed 830 thousand people and damaged towns as far as 800 km away. Towns reported the collapse of buildings, waters gushing out of ground fissures, and landslides (USGS, 2012c). Due to the lack of knowledge about earthquakes, the Chinese believed the earthquake was a punishment for angering the heavens (Needham, 1959).

Moving into modern times, Haiti experienced the second deadliest recorded earthquake on January 12th, 2010 (USGS, 2012c). A magnitude 7 earthquake took the lives of about 316 thousand people and injured 300 thousand others. The earthquake occurred inland due to the rupture of multiple **blind thrust faults** along the **Enriquillo-Plantain Garden** fault system (Hayes, et al., 2010). Haiti experienced damage to infrastructure along with uplifts along its coasts and localized tsunamis (Figure 6.15) (USGS, 2012c). These effects were felt as far away as Jamaica, Puerto Rico, Florida and Venezuela. Following the earthquake, the **United States Geological Survey (USGS)** recorded eight **aftershocks** within two hours of the main quake and a total of 52 after 12 days. Though smaller in magnitude, the aftershocks made relief efforts more difficult.

Seismology and Seismometers

These two examples illustrate how dangerous earthquakes can be. However, they represent only a tiny fraction of the millions of quakes that have occurred in history. On average, the **National Earthquake Information Center** (NEIC) locates approximately 50 earthquakes per day or around 20 thousand in a year (USGS, 2012b). Although most earthquakes are only minor tremors, their common occurrence and potentially deadly effects make them an important area of study. This has led to the development of **seismology**, a branch of **geophysics** that studies earthquakes and seismic waves.

Though the use of the term 'seismology' was

Figure 6.15: An aerial photograph taken in 2010 depicting the devastation and collapse of infrastructure caused by the earthquake in Haiti.

not commonly accepted until the 1890s, humans had been studying earthquakes for thousands of years (Kozak and Cermak, 2010). In order to study the location, depth, and size of earthquakes, humans invented the **seismometer**; an instrument that measures seismic waves (Plummer, et al., 2004). This novel invention was an important scientific advancement that has greatly changed from its creation in Ancient China to its use in the 20th century.

The Early Seismometer

In 1831 BCE, ***Bamboo Annals*** described the tremoring of the mountain Taishan in the Shandong province of China (Kozak and Cermak, 2010). This is the first documentation of an earthquake. Later in 780 BCE, there were reports of a powerful earthquake in North China (Kozak and Cermak, 2010). The Ancient Chinese began regularly documenting earthquakes due to concerns over their destructive force.

Figure 6.16: A replica of Chang Heng's seismometer. The direction of the earthquake can be determined from which dragon drops a ball (Dewet and Byerly, 1969).

It was not until the year 132 CE that Chinese philosopher **Chang Heng** (b. 78 CE) invented the earliest seismometer to detect earthquakes and their **azimuths** (Dewet and Byerly, 1969). The basis of this invention came from his belief that earthquakes were caused by wind and air (Needham, 1959). Chang believed that events on Earth could be predicted using the direction, force, and timing of the winds.

The first seismometer was documented as resembling a wine jar about 2 m in diameter (Figure 6.16) (Dewet and Byerly, 1969). The outside of the vessel was decorated with eight dragon heads that faced in the directions of a compass rose. The dragon heads each held a ball and had a toad directly below it. When an earthquake occurred, one dragon released its ball in the direction of the shaking. Thus, the approximate location of the earthquake could be determined. The instrument was reported to be sensitive enough to detect an earthquake about 640 km away even though the earthquake was not felt at the seismometer's location.

Unfortunately, Chang's original seismometer is lost and so the exact mechanism of how it worked is unknown (Dewet and Byerly, 1969). However, modern seismologists have attempted to deduce its internal structure. Seismometers need an **inertial system** that is arranged such that an earthquake can cause it to move relative to the ground. Many interpretations assumed a pendulum was used to sense direction. Its motion would activate one of the dragons to release its ball.

Mercury Based Seismometers

Late 18th to early 19th century Europe saw a surge of interest in the construction of seismometers (Dewet and Byerly, 1969). This was likely due to the **Calabrian earthquakes** of 1783 that caused great devastation and loss of life. Like Chang's seismometer, the instruments detected the presence of an earthquake and gave an indication of direction. However, these new devices could record the time of an earthquake.

Atanagio Cavalli (active in 1784) suggested a model where two bowls were filled with mercury and placed over rotating platforms (Dewet and Byerly, 1969). As the platforms spun around, cavities that corresponded to the hour and the minute of the day would pass beneath notches on the bowls' sides. If an earthquake occured, the mercury would overflow through the notches and fall into the cavities. While this seismometer was never built, it was the first design that could record the timing of an earthquake.

1n 1856, **Luigi Palmieri** (1807-1896) succeeded in developing and using a seismometer that could record the duration of an earthquake. The device was also able to detect both horizontal and vertical ground movements (Dewet and Byerly, 1969).

To detect vertical motion, a conical mass was suspended on a spring over a bowl of mercury (Dewet and Byerly, 1969). Movement would cause the tip of the cone to touch the mercury, completing an electric circuit that stopped a clock to indicate the time of shock. To detect horizontal motion, a mass was suspended from a wire on a column (Plummer, et al., 2004). When the ground moved horizontally, the mass swung like a pendulum and completed the circuit (Dewet and Byerly, 1969).

In both motions, completing the circuit also caused a pencil to be pressed against a moving paper (Dewet and Byerly, 1969). Every time the circuit was completed, there would be a pencil dash. Thus, the duration of the quake was recorded. The earthquake's size could also be determined by looking at the spring and pendulum's oscillations.

Horizontal Pendulum Seismograph

Another major development in seismology was made towards the end of the 19th century. **John Milne** (1850-1913), **Sir James Alfred Ewing** (1855-1935), and **Thomas Gray** (1850-1908) developed the first **seismograph** which could record ground motion as a function of time (Dewet and Byerly, 1969). Known as the horizontal pendulum seismograph, the device allowed scientists to first study the propagation of seismic waves, and the behavior of the ground during earthquakes.

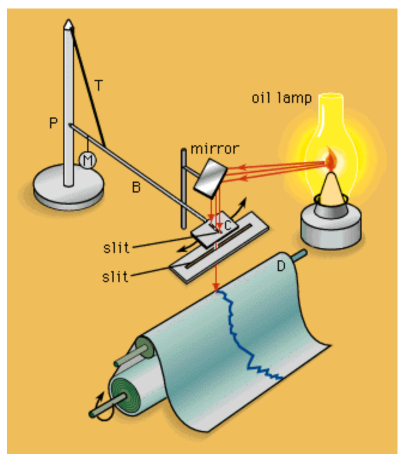


Figure 6.17: Milne's seismograph was made the standard earthquake detector in his time (Dewet and Byerly, 1969). It consists of a weighted rod that shifts a slitted plate when tremors occur. The plate's movement allows light to shine through its slit and a stationary slit below it. Falling onto light-sensitive paper, the tremor is recorded.

To conduct experiments on the propagation of waves, Milne and his colleagues used dynamite explosions as artificial sources (Dewet and Byerly, 1969). The results recorded a normal, a transverse, and a slight vertical motion. Milne believed the normal motion and transverse motion were **compressional** and **distortional body waves** respectively. He also suggested the vertical displacement was due to **surface waves**. These observations helped develop the modern understanding of seismic waves. In another experiment, Milne placed seismographs at different locations to study how ground type affects earthquake motion. Milne determined stronger earthquakes had larger amplitudes on soft ground (marshy land with a high **water-table**) than on rock.

While the experiments were conducted using a seismograph developed by Ewing and Gray, Milne's 1895 version was more famous and was used all around the world (Figure 6.17) (Kozak and Cermak, 2010). Its wide spread use allowed Milne to locate earthquakes by plotting **travel-time curves** for different seismographs and triangulating them (Dewet and Byerly, 1969). For his work, Milne is regarded as a founding father of modern seismology (Kozak and Cermak, 2010).

Inverted Pendulum Seismograph

In 1898, **Emil Wiechert** (1861-1928) modified seismographs by introducing viscous damping to reduce the effects of pendulum **Eigen-oscillations** (Dewet and Byerly, 1969). After studying other seismometers, he invented the inverted pendulum seismograph in 1900. He used an inverted pendulum that was stabilized using restoring springs applied to the top of the inertial mass. This kept the pendulum in stable equilibrium for smaller oscillations. At the base of the pendulum was a joint that allowed the pendulum to oscillate in any direction horizontally.

In 1904, Wiechert modified his own model in order to resolve the motion of the mass into its components (Dewet and Byerly, 1969). In addition, he amplified the signal by a factor of 200 using a mechanical lever system, and had the pendulum mechanically record oscillations on smoked paper. This seismograph is still in use some places around the world.

Using his device, Wiechert explored the interior of the earth by measuring artificially produced earthquakes (Mulligan, 2000). In 1907, he wrote a pioneering paper on how seismic waves propagate through the Earth. Later in 1910, he studied the depth of the Earth's liquid core and confirmed its depth to be at 2 900 km (Dewet and Byerly, 1969).

21st Century Seismometers

Modern seismometers are electronic such that the motion between the weight and frame creates an electrical voltage that can be recorded by a computer (IRIS, n.d.). They are more sensitive to ground movement and can detect a larger range of earthquakes. Seismograph stations are now located all over the world (Plummer, et al., 2004).

Over the years, seismometers have not only allowed scientists to better understand earthquakes, but to explore the interior of the Earth and its processes. Its uses are still expanding, namely into its role in Space.

Seismometers – From Earth to Space

Seismometers serve the important purpose of measuring seismic waves. The data collected has allowed scientists to locate and categorize earthquakes as well as determine features of the Earth's interior. Over the last 40 years, seismometers have also proven to be useful in the study of Space, as shown in the Apollo Passive Seismic Experiment and in the InSight Mars Mission.

Apollo Passive Seismic Experiment

In the 1970s, the National Aeronautics and Space Administration (NASA) ran a series of manned Apollo missions to the Moon (LPI, 2012). One of the many experiments that ran during these missions was the Passive Seismic Experiment (LPI, 2012). Scientists sought to detect lunar '**moonquakes**' using the seismometers deployed by astronauts at various landing sites in order to determine the internal structure of the Moon (Figure 6.18). Most seismic events detected were from moonquakes and meteoroid impacts. There were also man-made events where several superfluous rockets were crashed into the Moon at specific times and locations. Data from four seismometers were transmitted to Earth until 1977.

*Figure 6.18: During the Apollo 11 mission on July 21st, 1969, Edwin "Buzz" Aldrin (b. 1930) deploys a seismometer on the Moon at the **Sea of Tranquility** (LPI, 2012).*

The Passive Seismic Experiment resulted in two important scientific discoveries. The first is knowledge about the Moon's interior structure which consists of a mantle, core, and crust (LPI, 2012). Scientists were also able to deduce the chemical components of the layers. They suggested the crust is composed of **plagioclase**, the mantle consists mostly of the minerals **olivine** and **pyroxene**, and the core is likely composed mostly of iron and sulfur.

The second discovery yielded information on the **attenuation** of seismic waves (LPI, 2012). Scientists found the reduction of seismic waves was significantly less in the mantle of the Moon compared to the Earth. As attenuation is enhanced at higher temperatures and with water; the Moon's lower attenuation indicates a cold, dry interior. This reveals that the Moon cooled more rapidly than the Earth which produced a cold interior. However, the attenuation increases at depth of 1000 km indicating the potential presence of molten rock.

InSight Mars Mission

While the Apollo Passive Seismic Experiment explains how seismometers have been used in the past, the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) Mars Mission shows how they will be used in the future. InSight is an upcoming Mars lander mission scheduled for launch in 2016 (NASA, 2012). Using a stationary lander equipped with a seismometer and **heat flow probe**, scientists will study Mars' interior structure, tectonic activity, and the effects of meteorite impacts. The data from this mission will hopefully bring new understanding to the formation and development of the Terrestrial planets.

The Apollo Passive Seismic Experiment and InSight Mars Mission illustrate the versatility of seismometers and how they have transcended beyond their role of detecting earthquakes. With their modern applications, seismometers will help unlock the secret of how our solar system evolved.

Cartography through the Ages

Throughout history, the map has served as one of the most fundamental forms of human communication, providing a medium that portrays a perceptual interpretation of the physical world. In theory, everything that can be spatially conceived can also be mapped. The ability to portray the physical world in the form of a map is so primitive to human cognition that it existed long before written language or numbers. In fact, it is rare to find a society in history that did not use some type of cartographical technique, even though the use of the map did not become routine until the European Renaissance (Harley and Woodward, 1987).

Figure 6.19: The Babylonian World Map (500 BCE), considered to be the first attempt at a map of the world. The map is mythological in nature and shows Babylonia in the centre surrounded by water. The map includes key geological features of Babylonia, all labeled in Cuneiform inscription.

Not only are maps reputable works of art, but they also encompass a high degree of intellectual effort and accomplishment. It is interesting to appreciate the use of maps throughout history, as they often portray useful information about the people who produced them. The study of **cartography** provides an interesting window for historical research, particularly when considering the progression of civilization and science. The development of cartography throughout the ages is correlated with the progression of scientific thought, as the growth of the understanding of the world has been reflected in the intricacy of cartographic representation (Harley and Woodward, 1987).

Maps of the Primitive Peoples

The history of cartography can be traced back to some of the most primitive societies in human history. The earliest cartographic evidence is in the form of rock paintings found throughout parts of Europe and Africa, which may be up to 25 000 years old. These paintings mostly consist of rough linear networks, which were possibly attempts to map out travel routes, as these primitive peoples were mostly hunters and gatherers (Bagrow and Skelton, 1964). The indigenous peoples of North America also produced evidence of early cartography. These people used wood from tree bark to record their travel routes and would carry these maps during their wanderings. The Inuit tribe are the first recorded society to have attempted the delineation of **relief features** on wooden surfaces. Varying landscapes on the Earth's surface due to hills, mountain ranges, and coastlines were carved in wood, which perhaps assisted these people in the planning of hunting expeditions (Bagrow and Skelton, 1964).

It is interesting to note that these early societies began utilizing cartographic techniques long before the existence of written language, mathematics, or true scientific thought. It can be seen that the ability to form spatial relationships between objects is something very primitive to human intellect. In recording the relationships of the outer world on stone or on wood, it can be suggested that these people were beginning to consider methods in which spatial data could be collected and displayed to further understand the natural world. In turn, these early progressions may suggest that the gradual development of scientific thought may have had its roots in even the most primitive societies (Harley and Woodward, 1987).

Contributions of the Ancient Near East

The earliest attempts at what would be considered real maps were produced by the ancient civilizations of the Near East. Cartographic works produced by the **Babylonian empire** as early as the 25th century BCE have been discovered in the form of engravings on clay tablets. These maps were generally simple and were produced for military purposes, merchant routes, and land distribution. What sets these maps apart from older works is the labeling of key characteristics. The Babylonians are credited as one of the first societies to use a form of written language, known as **Cuneiform inscription**. This language consisted of a system of wedge-shaped pictographs, carved into clay tablets. These pictographs were used to annotate cartographic features such as mountain ranges or bodies of water (Bagrow and Skelton, 1964). Babylonia is also credited for attempting the first map of the world in 500

BCE, called the **Babylonian World Map** (Figure 6.19). This map is unique in the sense that it is purely symbolic and is a clear representation of Babylonia's mythological perspective of the universe. The map shows Babylon engraved as a rectangular island surrounded by water, with labeled mountain ranges and water bodies. Interestingly, the surrounding Persian and Egyptian empires are not included, suggesting that Babylonian knowledge of distant lands was limited (Bagrow and Skelton, 1964).

Like Babylonia, there are few surviving maps from **Ancient Egypt**. In fact, most geographical evidence from Egypt is in the form of **hieroglyphs** on temple walls. However, the limited Ancient Egyptian cartographic evidence that does exist is particularly interesting and shows insight into their scientific understanding. For example, the **Turin Papyrus map** (Figure 6.20), created around 1150 BCE, is considered to be the earliest geological map. This map shows a fifteen square-kilometer area of the Wadi Hammamat region, and is believed to show travel routes for mining expeditions. The most interesting feature of the map is that it uses colour to distinguish between different rock types found throughout the area, suggesting that the Ancient Egyptians were showing geological thought through rock classification (Harrell and Brown, 1992).

Ancient Greece and the Birth of Geography

The origins of some of the most influential scientific breakthroughs in human history are rooted in **Ancient Greece**. The contributions of early Greek thinkers to mathematics, science, and philosophy were pivotal to the current understanding of the Earth, as well as the development of cartography. There are very few surviving cartographical artefacts from Ancient Greece. Most of the current knowledge of Greek cartography is found only in literary form, such as in the works of **Strabo** (64 BCE-24 CE), whose seventeen volume encyclopaedia **Geographica** outlines the development of cartography throughout Ancient Greece (Harley and Woodward, 1987).

The origin of cartographic thought in Ancient Greece is credited to **Homer** (c. 700-600 BCE), who is considered to be the founding father of geographical science. Strabo describes Homer's contributions as a poetic expression of the general beliefs regarding the universe and the role of man within it. In his poetry, Homer uses imagery to describe earthly observations such as the sea, the sky, the sun, and the moon. While it is not known as to whether any physical cartographic evidence existed at his time, Homer's poetry provides insight into how the Ancient Greeks were beginning to show scientific thought through their observations of the physical world (Harley and Woodward,1987).

The **Classical Period of Ancient Greece** (510-323 BCE) gave rise to the true emergence of Greek science. At this time,

Figure 6.20: A segment of the Turin Papyrus Map of Ancient Egypt, the oldest geological map. Different coloured circles represent locations of different types of gravels that were mined throughout the Wadi Hammamat region (1150 BCE).

academics were starting to take a more naturalistic approach to studying the world, rather than focusing on the supernatural. Even though most Greek science was focused on **astronomy**, it was at this time that some Greek thinkers were beginning to take an interest in the world beneath their feet. Perhaps one of the most important Greek scientists from the Classical era was **Anaximander** (610-546 BCE), who was credited for developing the first map of the inhabited world, containing an outline of land and sea. What is particularly interesting about this map is that it was round and contained both Europe and Asia, surrounded by ocean (Harley and Woodward, 1987). The spherical shape of the Earth was not suggested until **Pythagoras** (570-495 BCE), who was inspired by the geometric perfection of the sphere. He therefore hypothesized that the Earth was also spherical, even though this was not proven scientifically until later. The first attempt at the construction of a globe was credited to the philosopher **Eudoxus** (410-355 BCE). This globe included the main celestial circles, along with the equator, the tropics, and the Arctic Circle (Harley and Woodward, 1987).

Figure 6.21: A medieval ideal portrait of Ptolemy, innovator of the principles of map-making and author of Geographia. He also created one of the first true geographical information systems.

The progression of science and mathematics throughout the **Hellenistic Period** (323-146 BCE) helped define the field of cartography as it is known today. One of the most important individuals from this time period was **Eratosthenes** (276-195 BCE), who is noted for inventing geography based on the technique of **surveying**. As a renowned mathematician, he invented the concepts of **latitude** and **longitude**, as well as accurately calculating the circumference of the Earth (Harley and Woodward, 1987). All of the geographical progress made throughout Ancient Greece was compiled by **Ptolemy** (90-168 CE) (Figure 6.21), who laid down the principles of map-making in **Geographia**. In his work, Ptolemy outlines the process of how a map can be created using a **coordinate system**. He refined the concepts of latitude and longitude by stating coordinates in degrees, as well as showing how geographical features such as mountain ranges and localities can be arranged according to this system (Bagrow and Skelton, 1964).

The Age of Enlightenment: Paving the Way for the Modern Era

The scientific approach to cartography laid out by the Ancient Greeks was embraced centuries later by academics in the European **Renaissance era** (1400-1600 CE). Perhaps the greatest scientific contribution to cartography during this time of intellectual enlightenment was the development of the printing press. German publisher **Johannes Gutenberg** (1398-1468 CE) invented **movable type printing** in 1450, which quickly spread throughout Europe. This technology allowed for maps to be published and distributed among the general public, facilitating widespread knowledge of the subject (Bagrow and Skelton, 1964). The development of sailing techniques along with the discovery of the **New World** lead to the emergence of the modern world atlas. In 1570, Flemish cartographer **Abraham Ortelius** (1527-1598 CE) published ***Theatrum Orbus Terrarum***, the first modern world atlas, which included seventy maps. At this point, exploration of the Americas was underway and map-making played a key role in the discovery of new land and trading routes (Bagrow and Skelton, 1964).

Throughout the remainder of the Age of Exploration and into the 20th century, cartography continued to grow along with knowledge of the surrounding world. As technology continued to advance, surveying techniques mapping accuracy, and distribution improved. However, there was probably no scientific breakthrough more important to cartography in the 20th century than the development of computational technology, a phenomenon that would revolutionize the face of the map forever (Foresman, 1998).

GIS: Cartography in the Technological Age

Technological innovations of the modern era have drastically shaped the face of cartography. The most important system of geographical analysis today is **the geographic information** system (GIS). In the most general sense, a GIS is defined as a system that captures, stores, analyzes, and presents geographical data. The most primitive example of a GIS dates back to Ptolemy and his pioneering principles of map-making. In Geographia, Ptolemy described a system in which spatial data could be effectively recorded and analyzed. Throughout history, the progression of technology has facilitated the ability to analyze the physical world, allowing for GIS to develop into an interdisciplinary navigational tool (Foresman, 1998).

Development of GIS

GIS as it is known today was shaped by the convergence of cartographic and computational concepts. While the exact lineage of GIS is complex, there are several key technological contributions that lead to its development. The earliest modern influence on GIS is the landscape planning of Europe and North America in the early 20th century. Landscape planners produced overlaying thematic maps of geographical areas in order to analyze the spatial environmental, and social implications of urban planning. This "layered cake" approach to mapping geographical areas paved the way for the future development of computerized GIS systems, which are based on superimposed layers of maps (Figure 6.22) (Foresman, 1998).

The development of computational GIS is a Canadian accomplishment and is credited to **Dr. Roger Tomlinson** of Ottawa, Ontario. In 1960, Tomlinson developed the first industry scale GIS, known as the **Canada Geographic Information System** (CGIS). The CGIS was originally developed as a way for the government to gather data about natural resources in order to monitor changes. Later on, the development of the Internet allowed for GIS to become available for commercial use, and it is now used for a wide range of applications (Foresman, 1998).

Application of GIS

One of the most important roles of GIS today is its use as a **location-based service** (LBS). Mobile networking allows for individuals to use GIS as a navigational tool. Through mobile devices, individuals have access to geographic databases, enabling them to locate their current or desired destinations. The benefits of LBS are revolutionary in the sense that individuals are able to decrease travel time and reduce environmental costs. LBS also allows people to be easily located in emergency situations (Nyerges, Couclelis and McMaster, 2011).

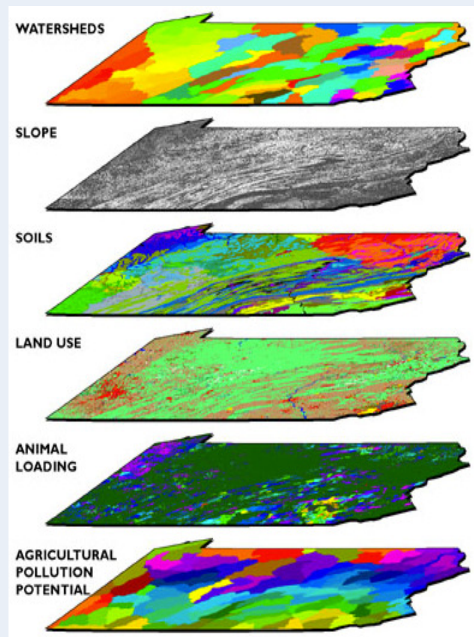


Figure 6.22: A diagram showing the map overlay process of GIS. A series of thematic maps are superimposed on each other. This overlay shows an area's susceptibility to agricultural pollution caused by watershed. This is an example of how GIS can be used to model environmental changes.

The role of GIS in **sustainability science** is being explored in order to determine how the Earth's environment is changing and what the consequences of these changes are for human civilization. GIS can model climate and environmental changes, which can then be analyzed and correlated with human activity (Nyerges, Couclelis and McMaster,2011).

GIS also has valuable implications in understanding and communicating trends in **population health**. Within a population, health status can be quantified by generating population health models showing relationships between population health and socioeconomic, environmental, and other factors. (Nyerges, Couclelis and McMaster 2011). The importance of GIS technology in healthcare and sustainability science suggests that it will remain an essential tool for countering the scientific problems of the future.

Historical Topic

Minerals are an important area of research. They are scientifically important, as they compose much of the Earth, and they are important to the economy as mining of important minerals plays a large role in modern society. The interest in minerals is not a new concept – investigation into the properties, composition, purification of, and origin of minerals is an ancient practice, along with the manipulation of minerals for human use. **Gold-washing**, the process of sifting through sand or mud to collect gold particles, was practiced as early as the 20th Dynasty of Egypt (1187 to 1064 BCE) by Egyptians (Healy, 1999). **Pliny the Elder** (23 – 79 CE) makes note of the Roman Empire's mining practices in his time, also noting the abundance of gold mines in Spain, as well as other precious minerals (Mason and Berry, 1959; Healy, 1999). Gold is an elemental mineral that has been continuously exploited throughout time for its rarity and evident beauty, and thus has been a target of research for many regarding its composition, origin, and mining practices.

Modern scientists, in contrast to many early scholars, do not support the theory of geologic processes continuously making more of a certain mineral. For example, Ancient Greeks believed that the Sun's rays transformed more common metals on Earth into gold (State Library of Victoria, 2011). Rather, most scientists now support the **nebular theory** of formation of the Earth, which dictates that all present minerals were formed and solidified from elements present in the Earth during initial formation (Cessna, 2009; State Library of Victoria, 2011). This is one of the defining characteristics of minerals. Minerals are also necessarily solid, have **crystalline atomic structures**, are **inorganic** substances, and have a definite chemical composition (Drummond, 2011). Pliny categorized minerals by mineral properties such as colour, **cleavage**, hardness, **tenacity**, **density**, magnetic and electric properties, and **streak** of minerals can be investigated (French and Greenaway, 1986). These classifications have been further developed over time, some of which will be discussed here. The history of the study of minerals and mineralogy can be tracked through various scholars that contributed to the developing field.

Theophrastus

Theophrastus (372 – 286 BCE) was a Greek scholar and one of Aristotle's pupils (Eichholz, 1965). Aristotle had established the Peripatetic School as an early form of what we identify as universities, teaching philosophies of a variety of disciplines, including humanities, scientific research, natural sciences, political science, ethics, logic, **metaphysics**, and literature (Eichholz, 1965). Upon Aristotle's death, Theophrastus took over as head of Aristotle's school, making lecturing at the school part of his life (Eichholz, 1965). Theophrastus also spent much of his time researching almost all of the subjects taught at the school, avoiding specialization and researching a breadth of topics.

Evident from his book, ***De Lapidibus*** (On Stones) written c. 315 BCE, Theophrastus' early research on formations of the Earth includes mineralogy and other earth aspects such as rocks and **organic** materials (Eichholz, 1965). In *De Lapidibus*, Theophrastus' theory on formation of earth materials is that stones and minerals are formed by 'earth' that has become purified over time, rather than 'earth' in its natural state. He expands his argument by suggesting that this pure matter is formed through **filtering** or through a **conflux**. Theophrastus explains filtering through the examples of gold and stones; he states that gold is formed by water that has compacted after filtering through rock, and that stones are formed by earth filtering through water. Next, a conflux is described as water containing suspended earthy mass, and pure matter forms as a deposit of this mass when the water is still. In his descriptions of filtering and conflux, Theophrastus relates these to **veins** and large deposits of minerals, respectively, as the governing process that creates these in the Earth. Theophrastus' reasoning is flawed because he mainly examined how the matter travelled and compacted, rather than the original source, which does not provide a good explanation for his "formation of earths" inquisition.

This is due to his belief in an eternal Earth, rather than a formation of one; this led him to study formation of elements in the Earth rather than with, and as a part of, the Earth (Eichholz, 1965). Furthermore, Theophrastus' reasoning is not similar to modern scientific method – he mainly speculates and philosophizes, rather than experimenting. Nonetheless, his research provided an early basis for future research into the origin of minerals.

Pliny the Elder

Pliny, born in northern Italy in 23 CE, was a knight belonging to a wealthy family of the governing class (Healy, 1999). Healy indicates that after Pliny served his time in knighthood, he was promoted to the status of a procurator, with the task of governing smaller provinces as a state official. This gave him time to research and write. Pliny's work in mineralogy is significant in that he introduces and correctly identifies most of the properties of minerals we use in modern classification. In addition, Pliny outlines the areas of the Earth that gold may be found in, and gives detailed descriptions of the refining of gold.

Pliny, in his encyclopaedia ***Historia Naturalis*** (Natural History), conveys an understanding of cleavage in minerals as rocks splitting at certain planes (French and Greenaway, 1986). He recognized the magnetic properties of magnetite and used streak as an identifier of minerals. For example, he states in *Historia Naturalis* that a mineral's streak colour is generally consistent and when a softer mineral is rubbed on a harder one, it leaves a certain tint (French and Greenaway, 1986). Furthermore, in *Historia Naturalis*, he correctly identifies gold as the most malleable material and makes note of the brittle nature of emeralds. Pliny thus demonstrates extensive knowledge of mineral properties and identifies many in his research.

Pliny also investigated gold in terms of mining and refining processes. He communicates that gold can be obtained from the Earth in three ways. He states in *Historia Naturalis* that gold can be found in rivers, and this is the most refined type of gold naturally available, as fluvial currents have polished the mineral (Healy, 1999). The second method is to sink shafts into the Earth, and the last is to search for gold in the rubble from collapsed mountains (Healy, 1999). Pliny also provides numerous examples of where these sources can be found in Europe and Asia and gives a detailed description of how to refine gold. Although he was not familiar with densities, he states that "Gold is first heated with twice its weight of salt, three times its weight of copper pyrites, and then again with two parts of salt and one of alum. This process removes the impurities when the other substances have been burnt away in an earthenware crucible; the gold itself is left behind pure and uncorrupted" (Healy, 1999).

Pliny thus shows a high level of understanding of the processes of refining gold and of the chemicals used in this process. However, he incorrectly suggests that all forms of gold are impure and always contain some silver (Healy, 1999). In fact, deep-vein gold only needs to be separated mechanically from the matrix surrounding it – it is pure otherwise (Healy, 1999). **Alluvial deposits** (of gold), on the other hand, do need to be refined in the way Pliny described. Pliny thus accounts for many mining and refining processes, describes the chemicals involved in these reactions. This provides a detailed account of how advanced these processes were in his time.

Georgius Agricola

Approximately 500 years later, **Georgius Agricola** (1494 – 1555 CE) made a significant contribution to the field of mineralogical research. He was a German doctor and an expert in mining (Mason and Berry, 1959).

Mason and Berry state that he is known by many scholars as the "Father of Mineralogy" for his exceptional works ***De Natura Fossilium*** (On the Nature of Fossils) in 1546, and ***De Re Metallica*** (On the Nature of Metals) in 1556. In his books, Agricola records the mineralogical, geologic, and metallurgic knowledge of that era and incudes detailed diagrams of mining processes and machinery. This allows modern scientists and engineers to trace their area of work back to previous developments in the 16th century. *De Re Metallica* focuses specifically on locating, mining, and refining minerals (Dibner, 1958).

Early forms of streak tests were referred to as **assaying** by use of a **touchstone** (Dibner, 1958). In the previous section, it was mentioned that Pliny the Elder made note of certain softer minerals leaving a streak of colour when rubbed onto a harder one (French and Greenaway, 1986). A few centuries later, Agricola records a more sophisticated form of touchstone that is used to determine the ratio of minerals in a gold and silver **alloy**. He states in *De Re Metallica* that the best touchstone is composed of lydite that is black and does not contain sulphur (Dibner, 1958). Gold or silver can be rubbed onto the touchstone and compared with standardized needles that differ in ratios of gold to silver (Figure 24). 24 needles are provided as reference; the first needle has 1 part gold and 23 parts silver. The ratio of gold increases until the 24th needle is of pure gold. Our modern characterization of metallic purity in "**carats**" of gold stems from this method of classification (Dibner, 1958).

Another major contribution of Agricola's to research on metals is his chapter in *De Re Metallica* on recovery of precious metals from base metals (Dibner, 1958). Prior to Agricola's account and explanation of separating metals by acid, written works regarding alloying techniques were scarce. In this chapter, Agricola puts forth that the recommended method of separation of gold from silver is through ***aqua valens***, a broad term accounting for nitric, hydrochloric, and sulphuric acid, although Agricola only mentions examples using nitric acid. To separate gold from silver, he suggests adding lead and heating this mixture in a **cupel,** to evaporate the lead and copper. Next, the nitric acid is added to the remaining metals in a glass **ampoule** until the silver dissolves and only gold remains at the bottom. The acid is poured out into a copper bowl, causing the silver to precipitate out, this providing one with purified, separated gold and silver.

Evidently, from Theophrastus' time, to Pliny's, and finally, Georgius Agricola's, ideas on formation and treatment of gold have developed greatly. Theophrastus proposed an early theory on the formation of minerals, which Pliny developed through his methods of refining gold. He introduces an earth science perspective in terms of where gold is found, and in what form. Pliny also identifies many mineralogical properties we still consider important today. Agricola takes Pliny's research one step further in providing precise methods of chemical and physical treatment of metals, mainly alloying and refining. He provides detailed instructions for separating gold from other metals and establishes a basis for determining metallic purity, which we predominantly use today. Thus, the mentioned scholars set a base for modern researchers to develop the field of mineralogy.

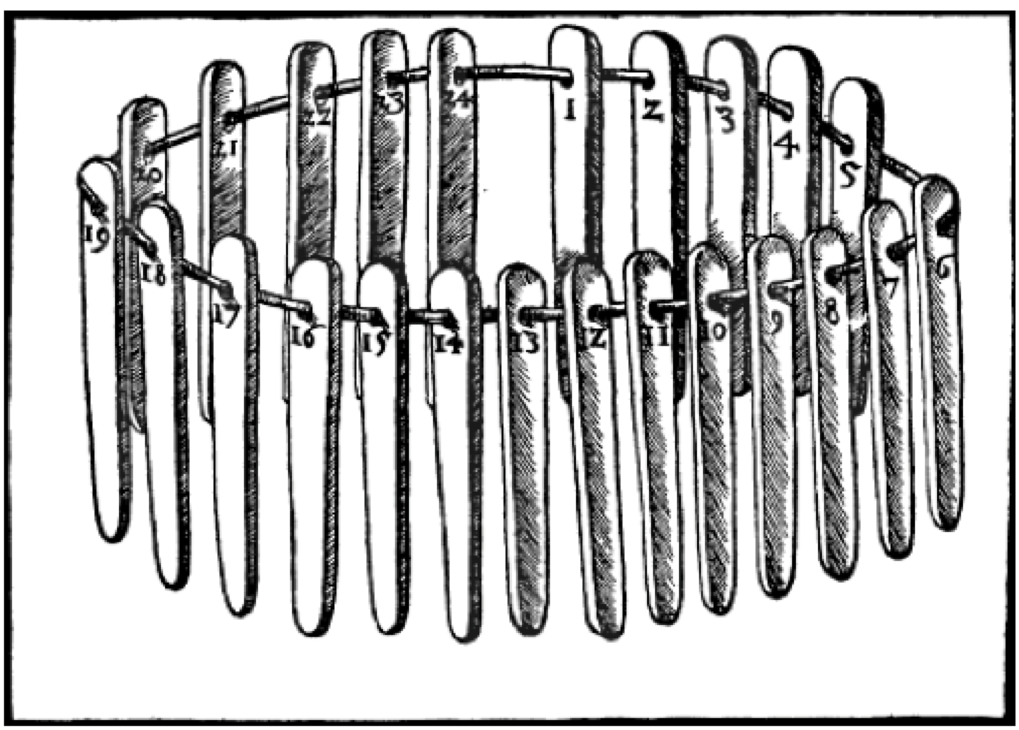


Figure 6.23: A diagram provided in Book VII of Agricola's De Re Metallica. The picture depicts a set of standardized needles used to compare gold and silver alloys with for the purpose of determining gold to silver ratio (Dibner, 1958).

X-ray Diffraction of Crystals

Max von Laue (1879 – 1960) was motivated to research the passing of X-ray waves through crystals because he was researching passing of light waves through crystal arrangements of particles (Eckert, 2012). Unfortunately, Laue could not get a definitive answer for the nature of the waves and came up with the hypothesis that interferences would be seen if X-rays, rather than light waves, were passed through crystals themselves (Eckert, 2012). He came to this conclusion because he recognized the lattice structure pattern of a crystal is approximately ten times larger than the X-ray wavelengths, and thought this would create a diffraction pattern. When Laue ran the experiment, he saw a series of spots created by interference of wavelengths in the primary beam, although they were not entirely consistent (Eckert, 2012; Cambridge Physics, n.d.a). However, **Sir William Lawrence Bragg** (1890 – 1971) of Cambridge was not satisfied with Laue's explanation that X-rays must have certain wavelengths to make all the spots appear. Bragg thought that X-rays might have a continuous spectrum of all wavelengths like white light has a spectrum of all colours (Cambridge Physics, n.d.a). Bragg's hypothesis was that the X-rays reflecting off the surface of a crystal travels less distance than reflecting off the atomic planes in the crystalline structure (Cambridge Physics, n.d.a). Bragg created a mathematical equation to explain crystal structure, which forms the basis of Bragg's law. Bragg's law is now used to calculate the crystal structure of atoms in a solid (Cambridge Physics, n.d.b). The joint effort by Laue and Bragg in the discovery of X-ray diffraction by crystals is very significant to mineralogical research. Laue's discoveries created two new areas of research, X-ray crystallography and X-ray spectroscopy, which are the basis for modern mineralogical research. As well, Bragg's revisions to Laue's original theories allow modern crystallographers to correctly calculate the arrangement of atoms in solid crystals. Mineralogical research has taken a completely new turn now that the crystal structure of minerals can be analyzed and documented through X-ray crystallography. An example is the use of an X-ray spectrometer in the MESSENGER spacecraft to analyze the elemental surface composition of Mercury (Figure 25)(Weider et al., 2012). Laue and Bragg's discoveries have thus provided the scientific community with a tool that can be used in various areas of research.

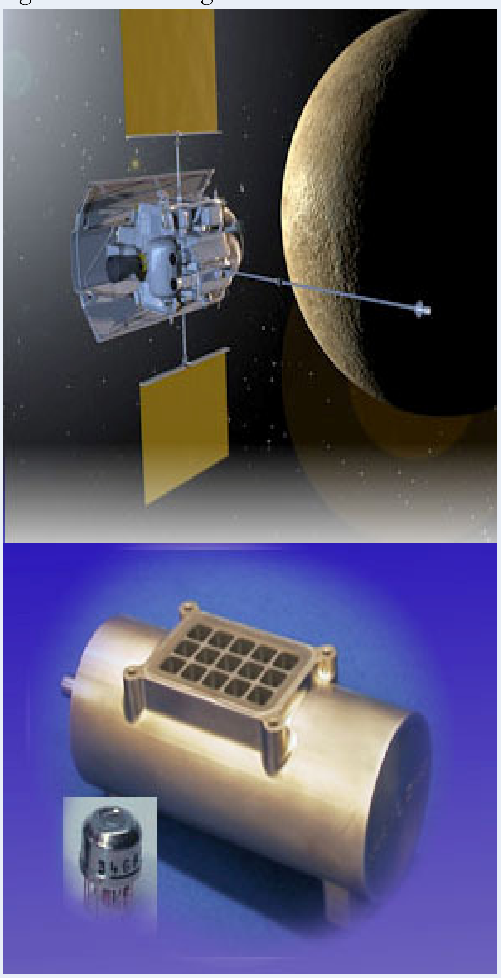


Figure 6.24: The X-ray spectrometer aboard the MESSENGER spacecraft.

Changing Methods of Quantifying Iron with Improved Equipment Availability

Banded iron formations (BIFs) are sedimentary structures that formed most often near mid ocean ridges (MORs). BIFs were created primarily during the existence of early Archean oceans when iron was abundant and the creation of BIFs effectively stored and trapped this element in sedimentary rocks (Klein, 2005). The iron in these layers was sourced from hydrothermal vents within the MOR and was deposited as a combination of minerals (Figure 6.25). BIFs are extremely important to the understanding of Earth history because they indicate the presence of oxygen in the early atmosphere (Klein, 2005). This promoted early life and can help scientists understand the organisms that could survive at a certain stage in the geological past. Today, BIFs are a major source of iron mined for industrial operations (Klein, 2005).

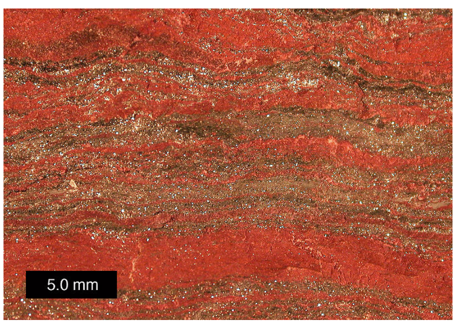


Figure 6.25: Hematite, the product of mineralized ferric hydroxide ($Fe(OH)_3$). Iron can also be retained within the fossil record through hydromagnetite ($Fe_3O_4 \cdot H_2O$) that becomes magnetite.

To determine good locations for stratigraphic analysis or iron ore mining, earth scientists often turn to chemists to understand the amount of iron contained in a given rock sample. Putting together a modern, widely respected method to measure iron came together over a long period of time, with puzzle pieces contributed by many analytical chemists. This story posed no clear-cut trailblazer who singlehandedly spearheaded the process, instead people did an inspiring job of learning from each other by working together to take small steps to gain the understanding we have today. It is important to note that all of the researchers mentioned below worked in a variety of universities in the United States, where they had access to lab resources and were often financially motivated by agricultural or health interests.

The first methods for detecting iron began in the late 1800s and were purely qualitative, because instruments and **assays** for **sensitive** or **specific** quantification were not commonplace anywhere in the world (Elvehjem and Hart, 1926). Chemists were forced to take advantage of iron oxidizers and spontaneous reactions with a **chromophore** that produced a visible colour change if iron was present above a certain threshold concentration (Elvehjem and Hart, 1926). One of the most challenging problems to overcome using this process was the ability of an assay to distinguish between **ferrous iron** and **ferric iron** content in a sample. The first chemical method with this ability was developed in the late 1800s by **Thomson (active in 1885)** (Elvehjem and Hart, 1926). This early scientist does not have a documented first name or life span, although he is widely cited and well respected in his field. His method for measuring iron content focused on homogenous samples, so that it could be applied when the analyte is contained in soil, milk or water samples. In fact, his method gained enough popularity to become the American Public Health Association's recommendation for testing drinking water by 1923 (Elvehjem and Hart, 1926). To keep all iron in the ferric state, the reaction conditions were acidic and potassium permanganate was chosen as an **oxidizing agent**. Positive iron bonded with negatively charged thiocyanate to produce ferric thiocyanate. The resultant colour was red and Thomson intended for the intensity to be distinguishable even with small amounts of iron (Elvehjem and Hart, 1926). However, the colour was extremely light sensitive and immediately disappeared, making any form of quantification or further analysis difficult.

Since iron was often part of homogenous samples such as soil or rock debris, it was vital for any colourimetric change be to be well defined and detectable by the human eye. In an effort to improve upon Thomson's ideas, thioglycolic acid became a viable alternative to thiocyanate. This method was in development for years, but conformational studies and further information only became available around 1924 from **Robert Keith Cannan** and **George Maxwell Richardson (both active in 1929)**. Their interpretation of thioglycolate's redox reaction with ionic iron was that it produced ferric thioglycolate (Cannan and Richardson, 1929). Unfortunately, this colour is also short lived because people believed that it was oxidized to the colourless ferro salt (Cannan and Richardson, 1929).

Edward J. Lyons Sr. (1901-1969) also worked with thiogylcolic acid as an alternative to thiocyanate, but he proposed a contrasting colour change mechanism with ferrous thioglycolate in 1927 (Lyons, 1927). Unlike the thiocyanate method, this reaction was run in alkaline conditions to further destabilize thioglycolic acid. In Lyons' discussion, all iron was reduced to the ferrous form and colourless ferrous thioglycolate was formed, which quickly dissociated to the coloured ferrothioglycolate ion in basic reagents (Lyons, 1927). Impressive attributes of this development included the fact that total iron (both ferrous and ferric) content was detected with thioglycolate, and that minute amounts (1: 12 million fold dilutions of iron) could still be detected. In fact, a colour gradient existed that enabled changes in iron concentration produced entirely different colours in this reaction. Highest amounts yielded an intense reddish-purple, and more dilute samples were pink (Lyons, 1927).

At this stage in development, American chemists began to realize that a quantitative understanding of iron concntration was much more important to develop. Until this time, people were limited by the amount, cost, availability, and type of equipment in chemistry labs (Lyons, 1927). Both of the methods described above only required beakers and droppers. No measurements needed to be exact; error, **accuracy**, specificity, sensitivity, and **precision** were not considered. In subsequent years, people focused on looking to new tools and more analytical methods for iron measurement. Major developments included the use of **transmittance** or **absorbance** data, **redox titrations**, **chelation titrations**, **amperometry**, **coulometry**, and **ion specific electrodes (ISEs)** for the measurement of iron content.

The start of transmittance measurements in 1938 by **William Brooks Fortune (1913-2005)** and **Melvin G. Mellon (1893-1993)** marked a huge leap in the iron detection process because this was one of the first ways to think quantitatively and strive to measure iron amounts, instead of simply identifying its presence (Fortune and Mellon, 1938). Fortune's legacy as a chemist and philanthropist continued as he established a prominent scholarship at Purdue University after being awarded an honourary Ph.D. in science and was the chair of the Philanthropy President's Council from 1990-1991 (Purdue University, 2011). Mellon also became a very well respected chemist after his developments in colourimetric readings. He published over 200 scientific papers, was a chemistry professor for over 50 years at Purdue University in Indiana and was the Fischer award recipient in 1952 (Murphy, 1952). As a result, there remains a chemistry library at Purdue University in Mellon's name (American Chemical Society, 1993).

Despite the use of very different chemicals, coloured iron complexes remained important in Fortune and Mellon's analytical assays. Here, the focus was on the transmittance properties of a red compound produced when ferrous iron bound to o-phenanthroline (Fortune and Mellon, 1938). The properties of this compound were widely researched and it became a standard for iron transmittance detection after conformational studies. New equipment used in this assay consisted of a spectrophotometer for transmittance readings and a potentiometer for maintenance of a constant pH (Fortune and Mellon, 1938). Results were graphed by a calibration curve of percent transmittance as a function of varying visible spectrum wavelengths with a variety of parts per million (ppm) iron concentrations (Fortune and Mellon, 1938). Their calibration curve (Figure 6.26) displays the results of these spectrophotometric readings and further calculations by the authors even indicated an

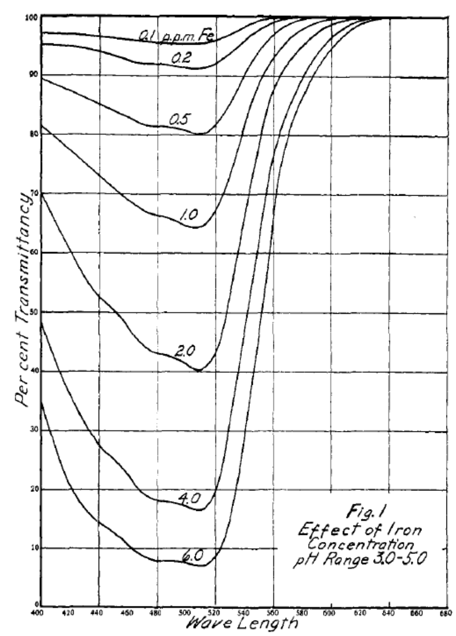


Figure 6.26: Calibration curve for percent transmittance as a function of wavelength for varying iron concentrations.

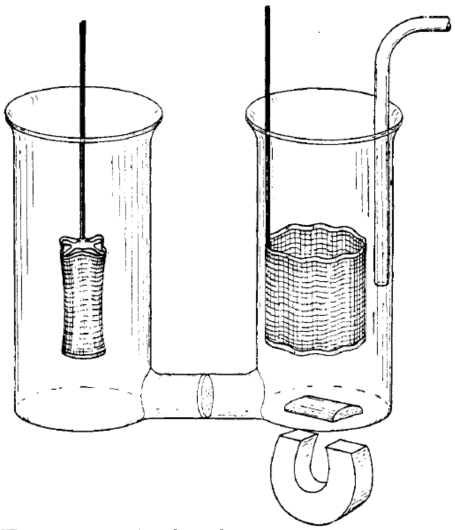


Figure 6.27: An electrolysis cell that contained two electrodes; one reference and the other working. The large horseshoe magnet represented an old form of magnetic stirring bars.

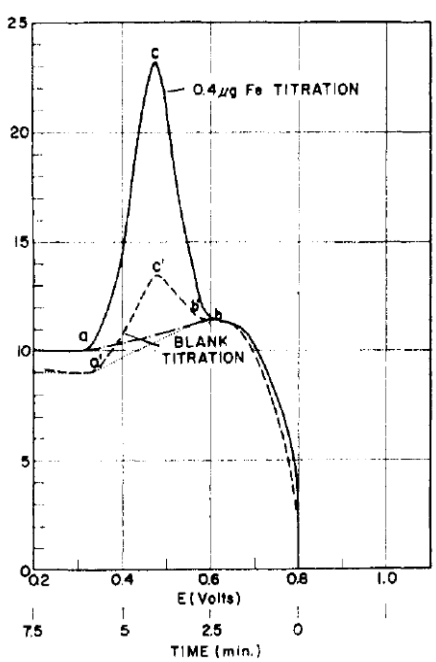


Figure 6.28: Titration curve for a redox titration of iron. The large jump in current at point C represents the ***endpoint****, where all iron has reacted.*

interest in experimental error, termed "apparent error" at this stage (Fortune and Mellon, 1938).

The next few decades showed an amazing advancement in human understanding of colourimetric measurements to quantify iron. Flaws in the 1938 work included many chemical interferences that can also interact with the chosen chromophore. These **matrix** effects contributed to extensive bias in the assay. In 1955, **John H. Yoe (1892-1975)** and **Arthur Letcher Jones (1915-1985)** looked for another chromophore that would bind to iron with a higher affinity to build in specificity (Yoe and Jones, 1944). In addition to their shared paper, Yoe and Jones were well accomplished professors who lived in a world very similar to that of Fortune and Mellon. Yoe was a distinguished author and, like Mellon, received the Fischer Award in 1957 (Yoe, 1957). Jones was an established author, publishing a book called *Studies in Organic Analytical Reagents* with help from the University of Virginia in 1943 (Jones, 1943).

Yoe and Jones' new reagent was disodium 1,2-dihydroxybenzene-3,5-disulfonate, sensitive enough to account for the presence of fluorides, phosphates, tartrates, citrates, or oxalates in solution with iron analyte (Yoe and Jones, 1944). Another issue to be addressed was that neither titration method from Fortune and Mellon or Yoe and Jones could distinguish ferrous and ferric oxidation states. This was dealt with by **Aubrey E. Harvey Jr.**, **John A. Smart**, and **Edward S. Amis (all active in 1955)** who returned to the use of 1,10-Phenanthroline and accounted for interferences with a standard addition curve (Harvey, Smart and Amis, 1955). Their main goal of simultaneous detection of ferric and total iron content in a sample was accomplished through a combination of spectrophotometric measurements and the understanding that absorbance values for Fe^{2+} and Fe^{3+} are maximal at different wavelengths within the visible spectrum (Harvey, Smart and Amis, 1955).

A second type of assay for iron quantification involved looking at electrochemical interactions that iron can have and applying this knowledge to potential redox measurements. In 1952, **William M. MacNevin** and **Bertsil B. Baker (both active in 1952)** were one of the first teams to use coulometry, the recording of change in charge throughout a reaction, for iron detection (MacNevin and Baker, 1952). Coulometry was only possible at this stage because equipment recently became available. Often in research, people were actually more restricted by materials and technology available than by knowledge in a given subject area. A typical electrolysis cell at this stage in history (*Figure 6.28*) looked drastically different from tools of today. The MacNevin and Baker study focused specifically on ferrous iron, with a reaction done in acidic solution with a platinum electrode. Their method returned to the use of calibration curves, with an external calibration to interpolate for unknown values using the slope-intercept method (MacNevin and Baker, 1952).

An additional application of coulometry examined voltage scanning coulometry with **redox titration**s through a titration cell to increase sensitivity while lowering the **limit of detection (LOD)**. Titrations were a great method for any lab around the world because they involved inexpensive equipment such as burettes and Erlenmeyer flasks that were readily available by this time. Also, earth science samples rarely exceeded trace amounts of iron, so new ideas from **F.A. Scott, R.M. Peekema,** and **R.E. Connally (all active in 1961)** proved very helpful in understanding soil components (Scott, Peekema and Connelly, 1961). Areas under each region of their redox titration curve (*Figure 6.29*) represented the total charge delivered by any given time point in the reaction.

Expanding on titrations to measure iron, **Claude A. Lucchesi** and **Clyde F. Hirn (both active in 1960)** posed a final viable analytical method that is accurate, precise, sensitive, and specific through chelation titrations. Endpoint detection in this case only required readings by the human eye; this made chelation titrations feasible without further significant instrumental discoveries. Here, **Lucchesi** and **Hirn** used **(ethylenedinitrilo)tetraacetic acid (EDTA)** as an initial chelating agent because it is **hexadente** and could bond to many positive metal ions with a relatively strong affinity (Lucchesi and Hirn, 1960). Use of Eriochrome black T as an indicator built in excellent selectivity because this compound chelates to iron with a much higher affinity than other possible agents. Eriochrome black T was powerful enough to replace EDTA in its coordination bonds with iron. Beyond past chelation titrations for iron, this method also aimed to separate ferric and ferrous forms because they each chelate with Eriochrome black T at unique pH levels (Lucchesi and Hirn, 1960). This assay showed substantial thought in how to design an effective assay; even matrix effects were accounted for and discussed (Lucchesi and Hirn, 1960).

Overall, the development of iron detection chemistry in the 20th century illustrates that did not always involve the creation of entirely new methods, but the improvement of existing ideas as better analytical tools became available. In this sense, titrations became substantially more accurate with the invention of volumetric glassware, burette calibration, and magnetic stir plates. Other researchers worked on conformational studies to illustrate or refute the precision of a given assay. The biggest overall advances came from changes in technology. However, the level of communication between scientists at a time when papers were not instantly available with a university prescription or a quick trip to the library is astounding. Therefore, development rates only continue to increase and higher levels of technology will mean the arrival of a standard method that results in a consensus among all researchers involved.

Iron Measurement with Spectroscopy for Economic Profit

During the development of early quantification strategies for iron, chemists worked to develop analytical methods that were later tailored to earth science applications within sedimentary stratigraphy. In recent years, the input of analytical chemists drastically decreased because interest in measuring iron shifted to a biological context. The technology for high throughput measurements to test many samples at once or ISEs for trace analysis of iron exist, but the demand for production in these areas was not present. As a result, geochemists developed specific methods that were directed to hematite or magnetite in BIFs. Current knowledge in this area remains very similar to that of the 1990s (Namduri and Nasrazadani, 2008). Once the correlation between BIFs and valuable energy sources was realized, many mining, power generation, and petrochemical companies became involved in the iron assaying process. These companies were great sources of financial support because the development of an effective method for quantifying iron content meant huge profits for them (Namduri and Nasrazadani, 2008).

In contrast to past techniques, most current options use diffraction or spectroscopy to measure ferrous and ferric iron through hematite or magnetite. In addition, modern studies were not conducted exclusively in the United States because they involved samples specific to geologic site locations.

For example, **Junfeng Ji**, **William Balsam**, **Jun Chem**, and **Lianwne Lu (all active in 2002)** worked with hematite and goethite in Chinese sedimentary sequences (Ji, Balsam, Chen and Liu, 2002). Their analytical method of choice was **diffuse reflectance spectroscopy** because it posed a low **LOD** and is highly sensitive to iron oxides (Ji, Balsam, Chen and Liu, 2002).

Future goals are to further improve analytical devices by limiting sample preparation to minimize error and increasing sensitivity.

Figure 7.1: Humanity exploring an Icelandic canyon where the view shows endless possibilities.

Final Thoughts

Humanity has always been driven to improve, to innovate, and to explore. Humans have always searched, without border, end, or restraint. They have looked into the Earth's inner core, up to the skies, and at all of the life that exists in between. This search has been driven by a power greater than any single obstruction or restraint, humanity's curiosity, its unquenchable thirst for knowledge. The people of modern planet Earth are privy to a scientific understanding that has been earned through the hard work, personal sacrifice, and dedication of those who came before them. Without those many passionate and inquisitive men and women, the world would be a much poorer place. A great thanks is owed to all those who gave themselves to the discipline of science. Those who trekked through mountains, dove the depths of the ocean, lived in inhospitable climates, and spent hours dwelling over mathematical formulae. This volume of History of the Earth has aimed to respect and acknowledge their incredible dedication in the pursuit of scientific knowledge.

Looking to the past, reviewing current techniques, answering new questions, and finding those still unasked have brought humanity closer to the science that defines and describes the surrounding universe. This is the beauty of science; there will always be new avenues and adventures awaiting exploration by each and every generation of scientists. With each new revelation, a slightly better understanding of the universe is handed down, progressively scratching the surface of the unknown and adding direction to humankind's future. The only future we have is one which we build for ourselves: one in which each new generation will be able to discover the beauty and wonder that comes from exploration and innovation

Glossary and Index

Absorbance 141
The fraction of light taken up by a molecule at a specific wavelength

Academie Royale des Sciences 7
A society in Paris founded in 1666 by Louis XIV. It was a society of intellectuals at the forefront of scientific research during the 17th and 18th centuries.

Accretion..5
The process of growth through gradual accumulation of matter.

Accuracy... 141
This refers to the closeness of a calculated value to the true value. A sensitive and specific assay leads to accurate results. It is important to maintain both precision and accuracy.

Adaptation 61,88
Any characteristic that is inherited by an organism that gives it higher reproductive success in an environment to those lacking the characteristic.

Aftershock... 129
A smaller earthquake occuring after a larger earthquake and generated within the same vicinity as the main shock.

Agassiz, Louis (1807-1873)..................... 84
A Swiss scientist who proposed the first ice age theory.

Age of Enlightenment.................... 7,24,72
A movement that took place in the 18th century in Europe. A historical period after the Rennaissance when science and reason were promoted. Also known as the Enlightenment or the Age of Reason (Sigurdsson, 1999).

Age of Reptiles 3
A term coined by Georges Cuvier to describe the extreme prevalence of reptiles in the the Devonian to Cretaceous period.

Age of Exploration............................... 118
Also know as the Age of Discovery, this period from 15th to 17th century describes the period of global exploration by Europeans.

Age of the Amphibians 81
The Age of the Amphibians is a common name for the late Palaeozoic era from approximately 290 to 354 million years ago, when the most common creatures on Earth were amphibians; the first reptiles were also seen here.

Agricola, Georgius (1494-1555)..... 138,139
Born with the name George Bauer, he was a German doctor and expert in mining. Authored *De Natura Fossilium* and *De Re Metallica.*

Agropastoralism 95
Technique in which agriculture and herding animals are combined. Occurs most often in areas with restricted land availability or less advancement in farming technology, such as rural communities in mountainous regions.

Airfall Volcanic Deposits 29,30
Fragments of volcanic rock which travelled in an eruption column prior to falling to the Earth's surface. Grain size decreases with distance from the volcanic vent. These deposits are often well-sorted and well-layered. The dispersal of these fragments may be impacted by winds (see *tephra*).

Alchemist...24
Early chemists and scientists often associated with attempts to transmute base metals to gold. The practice was present until the eighteenth century (Sigurdsson, 1999).

Algae 101
A microorganism which can be utilized to produce biodiesels and other hydrocarbons. Important in developing a sustainable method of producing hydrocarbons for human use.

Alighieri, Dante (1265-1321) 14
An Italian poet best known for penning the *Divine Comedy*, which influenced European cultural development and is considered by many to be Italy's crowning literary achivement.

Alloy 137,139
A metal composed of two or more elements in various ratios.

Alluvial deposits 137
Sediments deposited by rivers.

Alpine Orogeny.....................................20
Range of mountains located along the Mediterranean coast and into southern Asia. These mountains were formed during the late Mesozoic and Cenozoic periods.

Altman, Sidney (b.1939) 59
Canadian molecular biologist and winner of the 1989 Nobel Prize in Chemistry for his discovery of ribozymes, independent from Thomas Cech.

Alvarez, Luis (1911-1988) 52
A physicist, who found high levels of iridium in samples from the Cretaceous-Paleogene boundary, provding convincing evidence that an asteroid impact caused the Cretaceous-Paleogene mass extinction.

Alvarez, Walter (b.1940) 52
Earth scientist found irridium in the Cretaceous-Paleogene boundary rocks, providing convincing evidence that an asteroid impact caused the Cretaceous-Paleogene mass extinction.

Amis, Edward S. (Active in 1955)......... 142
Worked at the Univeristy of Arkansas with Smart, and Harvey, posed a drastic improvement in spectrophotometric measurements by silmultaneously detecting ferric and total iron (Harvey, Smart and Amis, 1955).

Amperometry 141
The measurement of changes in electric current over the course of a reaction.

Ampoule 139
A sealed container used to preserve a material.

Anaximander (610-546 BCE)...7,64,72, 134
Pre-Socratic Greek philosopher of the Classical era and pupil of Thales who developed the first map of the known world in Ancient Greece. Anaximander proposed that the Earth was a cylinder with mankind inhabiting the top, circular face.

Ancien Régime of France..................... 117
Aristocratic social and political system that lasted from the 15th to 18th century until overthrow by the French Revolution (see *French Revolution*).

Ancient Egypt (3150-30 BCE) 133
An ancient civilization located in northeastern Africa. This land makes up present-day Egypt.

Ancient Greece (800 BCE-400 CE) 133
A period in Greek history lasting from Archaic Greece to Classical Antiquity. It was followed by the Middle Ages.

Andes, The 94
A mountain range spanning the west coast of South America. With rapid changes in elevation and close proximity to the Pacific Ocean, the climate in the Andes is highly variable and often unpredictable (see *El Niño*).

Anning, Mary (1799-1847)..................... 76
One of the first female paleontologists, she was self-taught and found several fossils, notably ichthyosaur and plesiosaur fossils, along the Lyme Regis cliffs in Britain.

Antibiotic 63
Drugs used to counteract diseases caused by infection of microorganisms such as bacteria, funghi, and viruses. These drugs generally stunt the growth of microorganisms by attacking specific mechanisms of survival used by the organism.

Apatosaurus.. 82
Apatosaurus was a large quadrupedal herbivorous dinosaur common in North America during the late Jurassic period.

Aqua valens.. 137
A broad term accounting for nitric, hydrochloric, and sulphuric acid.

Aquifer 41
A body of rock or sediment which can hold and transmit significant amounts of water.

Arboreal Locomotion............................ 88
Adapted to living and travelling in trees.

Archaeopteryx................................. 67,83
Archaeopteryx is a genus of extinct bird from the Jurassic Period that has lizard like characteristics, leading some scientists to believe that it is a transitional form between dinosaurs and birds.

Archestratus (active fourth century BCE)... 104
A Greek poet who also wrote recipes.

Ardipithecus ramidus 88
A late pre-australopithecine hominin species from the late Miocene to early Pliocene epoch that shows evidence of both bipedalism and arboreal locomotion.

Arid 109
A type of environment that lacks liquid water.

Aristophanes (c.427-386 BCE)............. 116
Celebrated Athenian playwright known for comic, often satirical dramas. Known as the Father of Comedy.

Aristotle (384-322 BCE)............................. 2,6,38,56,68,72,112
A Greek philosopher, student of Plato and teacher of Alexander the Great. Aristotle studied many areas, including physics, poetry, theatre, music, logic, linguistics, politics, government, ethics, and biology; considered one of the great thinkers of his time. However, many of his specific conclusions have been called into disrepute over the millennia and his experimental methods, though certainly empirical, are antiquated by modern scientific standards.

Artificial System 69
A system of classification based on only a few characteristics that do not indicate natural relationships.

Assaying 137,140
Determining the content or quality of a metal or ore through quantitative or qualitative analysis.

Assyrians 106
A civilization in ancient Mesopotamia (see *Mesopotamia*) that existed between 2000 and 605 BCE. Known for their warlike nature, their early use of iron in weapons, and their early use of siege mining (see *siege mining*).

Astronomy 134
The study of celestial objects, particularly referring to phenomena outside of the Earth's atmosphere.

Atlas 134
A collection of maps of the world or of a certain region, usually in the form of a book; although, electronic atlases now exist.

Attenuation..131
The loss of energy in waves as they propogate through various media.

Austin, Steve (active)..............................4
A Creationist that believes in the new Earth theory placing the Earth at a very young age; also an opposer of *uniformitarianism*.

Australopithecus afarensis 88
An early australopithecine hominid that is thought to be a direct human ancestor (3.9-2.9 mya).

Avery Island 103
An island located in Iberia Parish, Louisiana, United States. Home of Tabasco Sauce. The structure of the island is a giant salt dome (see *salt dome*). Home to many exotic flora and fauna.

Azimuth...129
The direction or horizontal angle of a compass bearing.

Babbage, Charles (1791-1871) 120
A Victorian mathematician responsible for mathematical code breaking in addition to many other ideas and technical innovations (Wyhe, 2007). Charles Babbage was important to Victorian scientific development because he called for government funding towards the sciences. (Macleod, 1971).

Babylonia 116,133
Ancient city-state which declared independence c. 1894 BCE, although the capital city of Babylon dates much earlier (c. 3000 B.C.E.) Located in present-day Iraq.

Babylonian World Map (500 BCE)........134
Considered to be the earliest recorded map of the world; shows a mythological representation of the nation of Babylonia as a rectangle surrounded by water

Bacon, Francis (1561-1626)............ 20,112
English philosopher and scientist who had a prominent position in the Elizabethan and Jacobean royal courts. He systematized the first rigorous scientific method.

Baker, Bertsil B. (Active in 1952)..........142
Paired with MacNevin at the Ohio State Univeristy to begin coulometric assays for iron detection after an increase in available technology to allow for this method (MacNevin and Baker, 1952).

Balsam, William (Active in 2002) 143
Performed one of multiple diffuse reflectance spectroscopy assays for the measurement of iron through hematite with Ji, Chem, and Liu. This study was was done to further understand BIF stratigraphy in China (Ji, Balsam, Chen and Liu, 2002).

Bamboo Annals 129
A chronicle of Ancient China beginning in 5th century BCE to 221 BCE. It describes the first documented earthquake in the mountain Taishan.

Banded Iron Formations (BIFs) 140
Ancient sedimentary deposits that contain well defined bands of silica and iron in the form of minerals such as hematite or magnetite. Formed between 3 and 1.8 billion years ago.

Basaltic Rocks 25
Volcanic rocks largely composed of ferromagnetic minerals. These rocks make up the ocean crust (Plummer et al., 2007)

Bauer, George (1494-1555) 72
Also known as Georgius Agricola. Physician and apothecary from Saxony. Author of *De re metallica libri xii*, which was important to the development of the science of geology.

Bauhin, Caspar (1560-1624) 69
A Swiss botanist known as Gaspard Bauhin. Described thousands of plants and classified them based on their outer form. Used an imitation of binomial nomenclature.

Becker, Luann (active in 2000) 52
A scientist who found evidence of an asteroid impact around the time of the Permian Triassic mass extinction, in the form of fullerenes containing helium and argon isotopes commonly found in space.

Belemnites..78
Cephalopods of the Mesozoic era that were similar in shape to squids, possessing an internal skeletal structure but lacking tentacles, while possessing an internal skeletal structure.

Bengal 104
A historical region of the Indian Subcontinent. Divided in present day between the People's Republic of Bangladesh, and West Bengal.

Bergmann's Rule...................................86
The tendency for larger sized species and populations to be found in colder environments, and smaller sized specied and populations to be found in warmer environments. The rule is named after Carl Bergmann (1814-1865), the biologist who first described this tendency.

Bezoars 78
A mass of partially ingested material that does not pass through the intestines.

Big Bang theory 4
The theoretical explosion of matter that marked the beginning of the universe about 14 billion years ago.

Binomial Nomenclature...................69,91
A formal system of naming organisms by giving a name composed of two parts. Usually uses Latin grammatical forms. First part of the name identifies the genus to which the organism belongs and the second part identifies the species within the genus.

Biodiversity...63
The amount of variation of species within an ecosystem. Biodiversity is affected by many factors, including weather, competition with other species and human impact.

Biofuel 101
Hydrocarbon based fuel produced from living plant or algal matter. A sustainable energy source.

Biological Anthropology 88
The study of humans and their past relatives through examination of evolution, variation and adaptation.

Biological Species 65
A group of naturally interbreeding organisms capable of producing viable offspring.

Biostratigraphy 73
A paleontological subdiscipline in which rock strata are identified on the basis of the fossils they contain.

Bipedalism 88
Walking on two feet in an upright position.

Blenkinsop, John (1783-1831) 2,99
Developer of the first successful rail system; utilized a steam powered locomotive.

Blind Thrust Fault 128
Occurs when a thrust fault terminates before reaching the Earth's surface. Its lack of visibility on ground makes its detection difficult (see *Thrust fault).*

Bock, Hieronymous (1498-1554) 69
A German botanist, physician, and Lutheran minister. Known as one of the fathers of botany.

Borehole 74,97
A shaft drilled into the earth. Can be used to collect cores, which reveal the contents of the ground below. Upon analysis of the cores, different stratigraphic layers can be identified.

Bores.. 32
Steep fronted water waves caused by the meeting of two tides, or by the constriction of a tide rushing up a narrrow opening.

Bouguer, Pierre (1698-1758) 8,10
A French mathematician, astronomer, geophysicist, and member of the Academie Royale des Sciences. Bouguer was a member of the party of scientists who travelled to Peru to determine the true shape of the Earth.

Brewster, Sir David (1781-1868).......... 120
A Victorian mathematician, writer, and physicist responsible for the invention of the kaleidoscope and influencial work in optics(Carradice, Waddel, Philip and Edwin, 1996). He was important for Victorian scientific development because of his advocay of government funded science (Macleod, 1971).

British Salt Policy 104
Policy referencing the 1882 British Salt Act (see *British Salt Act*).

British Salt Act (1882)......................... 104
A set of rules and taxes governing Indian salt import and transport. Established in 1882.

Brontosaurus 82
The Brontosaurus was believed by Othniel Marsh to be a new species of large quadrupedal herbivore, when it was simply a Camarasaurus head on an Apatosaurus body.

Brunsfels, Otto (1488-1534) 69
A German theologian and botanist. One of the fathers of botany.

Buckland, William (1784-1856) 73,76
English theologian, geologist, and paleontologist. Professor of Geology and Minerology at the University of Oxford. He wrote the first full account of a fossil dinosaur.

Bulk density..105
The amount of substance per unit volume.

Calabrian Earthquakes.........................129
Sequence of five strong eathquakes that affected the Calabria region of the south of Italy in 1783.

Camarasaurus.......................................82
The Camarasaurus was one of the most numerous sauropods (large quadrupedal dinosaurs) and one of the few dinosaurs of which scientists have discovered all bones.

Camelids...95
Family of quadrupedal mammals; there are four species native to the Andes: llamas, vicuñas, alpacas, and guanacos. Of these, llamas and alpacas have been domesticated.

Canada Geographic Information System (CGIS) 134
The first computerized geographical information system, developed by Dr. Roger Tomlinson in Ottawa, Ontario in 1960. Its purpose was to assist the government in developing land use and resource management policies.

Cannan, Robert Keith (Active in 1929).140
Worked at the University College in Londeon to develop an interpretation of thioglycolate's reaction with ionic iron where the colour change results from the production of ferric thiogylconate (Cannan and Richardson, 1929).

Cantica 14
A religious or narrative poem. A cantica is divided into multiple cantos.

Carat 138
A unit of purity to describe gold alloys. 24 carats is pure gold. Any ratio below 24 parts gold : 0 parts silver is impure.

Cartography 132
The study and practice of map-making .

Catastrophic Theory 50
The theory that an extraterrestrial agent such as a cosmic or solar ray hit the Earth causing the Permian-Triassic mass extinction.

Catastrophism 77
The theory that the Earth changed due to sudden and violent events.

Catalyst 127
A catalyst is a chemical compound capable of increasing the rate of a reaction without being consumed by the reaction. It does this by lowering the activation energy barrier.

Catastrophism 3
A theory that postulates changes in the Earth's features happen suddenly and rapidly over short periods of time.

Causal Dilemma...................................59
A common philosophical issue, in which it is not possible to logically determine which of two events has

taken place first, because each must be present for the other to exist.

Causal Relation 113
Correlation where one phenomena necessarily produces, or is a condition for the existence of the other phenomena. It is thought of as a force that turns one phenomena into another, as in fire causing a pot of water to boil.

Cavalli, Atanagio (active in 1784) 113
Italian seismologist who developed he mercury bowl seismometer that could record the time of an earthquake.

Cavendish, Henry (1731-1810) 11
British scientist, experimentalist, chemist, and discoverer of hydrogen who attempted to determine the weight of Earth.

Cech, Thomas (b.1947) 59
American chemist and winner of the 1989 Nobel Prize in Chemistry for his discovery of ribozymes, independent from Sidney Altman.

Central Sun Model 15
A Hollow Earth model consisting of a single shell with access points to the interior of the Earth at the poles and a star at the center of the Earth.

Cerberus 14
A Greek mythological three headed dog that guarded the underworld. Dante adapted Cerebus for his own work, *Inferno*, in which Cerebus was an overseer of the third circle of Hell, Gluttony.

Cesalpino, Andrea (1519-1603) 69
An Italian physician, philosopher, and botanist. Theorized the circulation of blood. Classified plants according to their fruit and seeds instead of alphabetically or by medicinal properties.

Channel Sandstones 83
Channel sandstone is sandstone that was deposited in a river channel. Deltaic deposits of the middle Jurassic contain numerous examples.

Chapman, Sydney (1888-1970) 125
A British geophysicist and mathmetician who studied the Earth's ozone layer and the kinetics of gases.

Chelation Titrations 141
A titration method that takes advantage of multiple chelators to form different coordinate bonds with the analyte. Endpoint is determined with a colourmetric indicator that reacts with a chelator once all analyte is consumed.

Chem, Jun (Active in 2002) 143
Performed one of multiple diffuse reflectance spectroscopy assays for the measurement of iron through hematite with Balsam, Ji, and Lu. This study was was done to further understand BIF stratigraphy in China (Ji, Balsam, Chen and Liu, 2002).

Chondrites 5
Stony meteorites that have not been changed due to melting and were formed at the start of the formation of our solar system, making them about 4.6 billion years old.

Christianity 2
A religion based on the teachings and readings of *Jesus Christ*.

Chromophore 140
A molecule, or part of a molecule, that is resposible for absorbing specific wavelengths of light. A chromophore can quantitatively transmit or flouresce with resultant light enery.

Classical Period of Ancient Greece (510-323 BCE) 134
A period of Ancient Greece following Archaic Greece (800-480 BCE) and preceding Hellenistic Greece (323-146 BCE).

Clear-Cutting 63
A method of harvesting trees used in the forestry industry that involves cutting down large groups of trees at one time. This method is quite destructive to the environment, leading to a great loss of biodiversity.

Cleavage 136,137
Tendency of minerals to break along definite planes of weakness.

Climate Change 63
A statistically significant and lasting change in the distribution of weather patterns over a period of time. This period of time could be decades to millenia.

Climate Proxy 42
Preserved characteristics from the past that enable scientists, with the right tools, to reconstruct climatic conditions.

Coal 98
A solid fossil fuel which has a high carbon conent. Contains many other trace elements. Used as a fuel and heat source throughout the world.

Coke 98
A derivative of coal, formed by removing impurities through super heating. Burns at a higher temperature than coal.

Complexity Model 115
Theory that local rises and falls in sea level are attributable to a combination of regional and global factors.

Compressional Body Wave 130
One type of seismic wave that travels through the Earth where rock vibration is parallel to the direction of wave propagation. Also known as a Primary or P wave.

Concave Model 15
A Hollow Earth model in which the surface of the Earth surrounds and points inwards towards the universe, and underground areas extend outwards and away from the surface.

Concentric Sphere Model 15
A Hollow Earth model that viewed the Earth as a series of hollow shells terminating in a solid core.

Condamine, Charles-Marie de La (1701 – 1774) 8
A French mathematician, geographer, and member of the Academie Royale des Science. La Condamine was a

member of the party of scientists who travelled to Peru to determine the true shape of the Earth.

Conflux... 137
Theophrastus describes conflux as the process where pure matter is formed as a deposit of earthy mass in still water (Theophrastus, 315 BCE, p.24). He states that this process creates large deposits of minerals on Earth.

Connally, R.E. (Active in 1961)............ 142
Together with Scott, and Peekema, through General Electric, introduced voltage scanning coulometry to detect traces amouns of iron. This assay lowered detection limits for higher sensitivity (Scott, Peekema and Connelly, 1961).

Convection Cell 21
A volume of material which flows in a characteristic circular pattern as the result of a temperature gradient.

Convergent Plate Margin 23
Boundary between two or more tectonic plates where the plates are moving towards eachother.

Conybeare, William (1787 – 1857)......... 77
A British clergyman, geologist, and paleontologist who is best known for his work on marine reptilian fossils.

Coordinate System............................. 134
A system that uses nimbers to determine the position of points in space. For example, the Cartesian coordinate system consists of two perpendicular number lines, and the two-dimensional position of a point can be determined by its distance from these lines.

Cope, Edward (1840-1897).............. 73,81
American paleontolgist and comparative anatomist. Competed against Othniel Marsh in a feud known as the Bone Wars. Discovered and named many vertebrate species.

Coppens' East Side Story Hypothesis..... 90
Variant of the Savannah Hypothesis that states the environment that the apes inhabitted changed around them. More specifically the fragmentation of forest habitats due to uplift of the Eastern Africa rift system caused open grasslands.

Cornue, Mari-Alfred (1841-1902) 124
A French physicist who worked in the fields of optics and spectroscopy (see *Spectroscopy*).

Corolla 69
Collective term for all the petals of a flower.

Correlation... 113
Conjunction of two distinct phenomena in experience. Change in one phenomenon, e.g. river flow velocity, occurs with change in a correlated phenomenon, e.g. size of deposited grains. Does not imply a causal relation (see *Causal Relation*).

Coulometry 141
A method for determining the quantity of analyte, by which the total amount of charge to bring a reaction to completion is proportional to analyte concentration.

Cranial Capacity 88
Measure of the volume of the interior of the cranium.

Creation Science.................................. 123
A pseudoscience created by fundamentalist christians in an attempt to scientifically reason for the validity of the bible. Creation Science is not really science and is generally disregarded by the scientific community (Scott and Matzke, 2007).

Creationism (Biblical) 115
Theory claiming that the Earth was created 6,412 year ago by an act of God.

Cretaceous Period 80
The Cretaceous period was part of the Mesozoic era, spanning from 145 to 66 million years ago. Rocks of this period contain the first fossils of flowering plants.

Crick, Francis (1916-2004)...................... 59
English molecular biologist and neuroscientist, most well known for his discovery of the structure of DNA with James Watson. Crick was among the first supporters of the RNA-World hypothesis, even prior to the discovery of ribozymes.

Croll, James (1821-1890) 85
A Scottish scientist that proposed that variations in the Earth's orbit could be responsible for climate change and glacial periods.

Cross-cutting 3,25
Disturbances to the sedimentary rock record, caused for example, by magmatic intrusions (Plummer et al., 2007)

Cross-section 108
A geologic representation of the stratigraphy of an area identifying successive layers of strata (see *strata*). Symbols or colours are used to distinguish different strata.

Crown Group 71
A collection of species which consists of all the living relatives of the collection along with all of their ancestors back to the common ancestor. Also consists of all the common ancestor's descendants.

Crutzen, Paul 125
A Dutch Nobel prize winning atmosheric chemist is most notable for his reasearch on ozone depletion and its correlation to nitrous oxide emissions.

Crystalline atomic structure 136,139
Repeating atomic pattern throughout a structure.

Cubit.. 46
Unit of measurement from the Middle Ages, described by the Egyptian hieroglyphics. Measured from the elbow to the tip of ones middle finger.

Cuneiform Inscription............................ 132
A written language developed in Ancient Mesopotamia, consitsting of wedge-shaped pictographs.

Cupel 139
A flat dish, with pores, that can withstand high heat.

Cuvier, Georges (1769-1832) 72,77,84
A French natuarlist and zoologist notable for his contributions to anatomy and palaeontology, and especially the establishment of concepts relating to extinction.

da Vinci, Leonardo (1452-1519) 38, 72
A well known Italian painter, sculptor, engineer, architect and scientist of the Italian Renaissance.

Daimler, Gottlieb (1834-1900) 99
Co-inventor of the first internal combustion engine, along with Wilhelm Maybach. Made major contributions to the development of the automobile.

Dandi.. 104
A village along the coast of the Arabian Sea. Located in Gujurat, India. The end destination of Gandhi's Salt March (see *Mahatma Gandhi*).

Darby I, Abraham (1678-1717) 98
Improved blast furnaces to utilize coke as a fuel source instead of coal, allowing larger blast furnaces to be built and produce more iron.

Dark Ages (Middle Ages) 24
A historical period that lasted from the fall of the Roman Empire (400 to 1000 CE) until the fifteenth century. The period was chracterized by a lack of scientific inquiry and religious domination in the West (Sigurdsson, 1999).

Darwin, Charles (1809-1882) ....
.... 57,60,64,70,73,80,112
British naturalist creditted for the development of the theory of evolution through natural selection. Along with evolution, Darwin made significant contributions to many other fields of science, one of which was the study of the origin of life. Darwin was the author of *On the Origin of Species*.

Datum 9
A system used to connect a graticule to a spheroid by relating the position of a spheroid to the center of the Earth. It defines how a graticule will sit over the desired spheroid.

de Condorcet, Marquis (1743-1794) 117
A French philosopher, mathematician, and political scientist at the time of the French Revolution. He wrote on ideals of the rationalism which are influential today.

de L'Escluse, Charles (1526-1609) 69
A Flemish physician and botanist. First to group plants based on their characteristics and place of origin.

De la Beche, Henry (1796-1855) 76
A British geologist and paleontologist whose work focused on geological surveying techniques.

***De Natura Fossilium* (On the Nature of Fossils) 138**
A book written in 1546 by Georgius Agricola. (*see Agricola, Georgius).* Categorizes rocks, sediments, and minerals.

***De Re Metallica* (On the Nature of Metals)**
.. 138
A book written in 1556 by Georgius Agricola. Describes the mining, refining, and smeling processes of metals.

de Tournefort, Joseph Pitton (1656-1708)
...69
A French botanist. Made the first clear definition of the concept of genus. Created a classification system based on the structure of the corolla.

Deductive Method..............................115
In reference to Popper's new logic of scientific discovery, the deductive method contrasts with the inductive method of science (see *Inductive Method*). Places the validity of scientific theories in their capacity to make predictions that can, in principle, be falsified by experiments (see *Falsificationism*).

Deep-sea sediment dating 85
A collection of techniques used to date sedimentary rocks sampled in deep waters.

Delambre, Jean-Baptiste-Joseph (1749-1822) 117
French mathematician and astronomer. Served as director of Paris Observatory and authored books on the subject of astronomy. Lead the Northern leg of the expedition to define the metre with colleague Pierre-Francois-André Méchain.

Demarcation Problem.........................115
Dilemma in the philosophy of science in designating a suitable criterion for what constitutes a scientific theory. On the one hand, a loose criteria will include theories which are intuitively unscientific (astrology, creationism, etc.) but on the other hand a strict criteria will exclude commonly accepted areas of science like theoretical physics.

Dendritic crystallization 105
A crystal formation characterized by the development of long branches and starlike shapes.

Dendrochronology................................42
Method of scientific dating by analyzing the patterns of tree rings.

Density 136
Mass per unit of volume. Water has a density of 1000 kg/m^3.

Depositional Environment 83
A depositional environment is the physical, chemical and biological processes present in an environment that become associated with sediment deposited at that time.

Descartes, René (1596–1650)..............102
A French philosopher and mathematician. Known for Cartesian planes.

Descent with Modification 61
A model for evolution proposed by Charles Darwin stating that offspring vary from their parents in regards to certain traits and those with favourable traits will succeed and produce more offspring. These offspring will then, in turn, produce new offspring with different variations and this pattern continues.

Designer salt.......................................105
Salt crystals designed for a specific purpose.

Dicotyledons 69
Also known as dicots. Grouping of flowering plants whose seeds have two embryonic leaves, or cotyledons.

Differentiation 3
Separation of parts of a mixture so that the parts can be identified as distinct units. The Earth is considered to be a differentiated planet with a dense core, intermediate density mantle and low density crust.

Diffuse Reflectance Spectroscopy 143
A geochemical detection method that is popular because it is very sensitive to iron oxides (Ji, Balsam, Chen and Liu, 2002).

Digital Elevation Model (DEM) 97
Computer generated model of the topography of an area used in predictive soil mapping (see *Topography* and *Predictive Soil Mapping*).

Dis 14
A Roman mythological ruler of the underworld, named as such in Virgil's *Aeneid.* Dante adapted the name to his work *Inferno* by naming the walled city of Dis, which contained the inner most four circles of Hell.

Discharge 39
The volume of water flowing downstream over a unit of time.

Dissolution 105
The dissolving of one substance into another.

Distortional Body Wave 130
One type of seismic wave that travels through the Earth where rock vibration is perpendicular to the direction of wave propagation. It is also known as a Shear or S wave.

Divergent Plate Margin 23
Boundary between two or more tectonic plates where the plates are moving apart from each other.

Diversity Curve 71
Type of graph which shows the number of taxa that are counted in different time periods.

Dixon Oldham, Richard (1858-1936)...... 16
A British geologist who was the first to identify earthquake P-waves, S-waves, and surface waves arriving separately on a seismogram, and later provided the first evidence of a central core.

Dokuchaev, Vasily (1846 – 1903)........... 97
Russian mathematician and geologist. Proposed that soil type is a function of various environmental factors (Florinsky, 2012).

Douglass, Andrew Ellicott (1867-1962).. 42
American astronomer who first discovered the relationship between sunspots and tree rings (*see dendrochronology).*

Drake, Edwin (1819-1880) 99
Drilled the first oil well in North America. Initiated an age of major oil production in North America.

Du Toit, Alexander (1878-1948)............. 21
South African geologist. Compiled evidence and arguments in support of the theory of continental drift.

DuPont Company 125
An American company that was a leading producer of chlorofluorocarbons. DuPont is one of the largest cheimcal manufacturing companies in the world.

Dust Veil Index (DVI) 29
A quantitative method developed by Hubert H. Lamb (1913-1997) to compare the magnitude of volcanic eruptions through analysis of the amount of sunlight passing throught the atmosphere after a volcanic eruption. Based on the idea that a decrease in sunlight after an eruption is due to the injection of volcanic dust into the atmosphere, DVI gives a reference value of 1000 to the 1883 CE eruption of Krakatau, Indonesia (see *Lamb, Hubert H.*).

Dynamo Effect 17
A geophysical theory that explains the magnetic field of planets by attributing it to the rotation of a convecting and electrically conductive fluid. The fluid is commonly an outer core layer comprised of a molten metal.

Earthquake 128
The trembling of the ground caused by the displacement of rocks beneath the Earth.

Eccentricity 42,85
A measure of how much an elliptical orbit deviates from a circular one.

Eigen-Oscillation 130
An oscillation that occurs in the absence of external action.

El Niño 96
Irregular cycle of warming of the Pacific Ocean resulting in extreme flooding across South America.

Eldredge, Niles (b. 1943) 65
An American paleontologist most famous for proposing the theory of punctuated equilibria with Stephen Jay Gould. Eldredge's research has focused on the study of trilobite fossils.

Electromagnetic Wave 75
Sinusoidal energy wave associated with electric and magnetic fields. Includes light, microwaves, and x-rays.

Electron Spin Resonance 75
Also called electron paramagnetic resonance. Technique used to study materials with unpaired electrons. Can be used for dating (ex: dating teeth).

Elysium 14
A location in Greek afterlife described as a paradise for souls who had lived a virtuous life. Also known as the Elysian Fields.

Emiliani, Cesare (1922-1995) 44,85
An Italian-American scientist responsible for the founding of the discipline of palaeoceanography. Emilliani was an oceanographer who predicted that the lighter oxygen-16 isotope was more common to colder regions than the heavier oxygen-18 isotope.

Empedocles (c.490-430 BCE) 107
An Ancient Greek philosopher. Proposed that all materials are formed by different proportions of the four elements of fire, air, water, and earth.

Empiricism..112
Philosophical school which says that the human senses are the final and only grounds for knowledge. An empiricist is a follower of this school and rejects any beliefs that cannot be traced back to sensory experience or experimentation. The word, empirical, from which the name is derived, means "related to experience".

Endoxa 112
Credible opinions, often presented by expert sources. Only criteria for an opinion to be an endoxori are that the belief is non-contradictory and does not widely diverge from common experience.

Endpoint..142
The experimentally determined equivalence point, the stage in a titration where all analyte has reacted and the reaction is complete.

Enlightenment..................................3,56
An intellectual movement in Europe during the 1700's that moved toward reason to explain events, commonly referred to as the scientific revolution.

Enriquillo-Plantain Garden 128
A system of strike slip faults that runs along the southern side of Hispaniola Island on which the Dominican Republic and Haiti are located.

Epoch 88
Subdivision of a Period of geologic time.

Eratosthenes of Cyrene (c.276-195 BCE)....
...7,116
Greek mathematician, geographer, poet, and astronomer. First person to calculate the circumference of the Earth, tilt of the Earth's axis, and first to use the word geography. Provided the basis for early work in geography, geology, and geodesy.

Eruption Column 28,30
A pillar of hot gases and ash expelled during a volcanic eruption. This body of gas and ash has the ability to rise to a height several kilometers above a volcano.

(Ethylenedinitrilo)tetraacetic Acid (EDTA) .
...143
The most commont titrant for complexometric chelation titrations because it forms complexes with any cation of charge two or more (Lucchesi and Hirn, 1960).

Eudoxus of Cnidus (410-355 BCE) 116
An Ancient Greek philosopher and mathematician of the Classical era who constructed the first globular map of the world.

Euclid (c.325-265 BCE) 134
Greek mathematician, the Father of Geometry, provided the most comprehensive work on early Geometry, *Elements of Geometry,* which remains influential in mathematics today.

Euphotic Zone 53
The top layer in a body of water that allows sufficient light penetration for photosynthesis to occur. The depth of this layer changes based on a variety of factors including location and weather.

Evolution 60,64
The change of gene frequencies in a population over time. The word is more commonly used to denote any physical or behavioural changes in a population over time. The theory that species alive today are descendants of ancient species with differing characteristics.

Evolutionary Tree 64,67
A graphic representation of the interconnectedness of species. An evolutionary tree or "tree of life" or phylogenetic tree depicts the progression from ancenstral species to descendants.

Ewing, Sir James Alfred (1855-1935) 130
Scottish physicist and engineer who worked with John Milne and Thomas Gray to develop the horizontal pendulum seismograph.

Eyles, Nicholas (active in 2004) 45
Canadian geologist who proposed the zipper-rift hypothesis to account for near equatorial ice. (see *zipper-rift*)

Falsifiability 115
Property of statements or systems of statements if they imply predictions that can be proven untrue by experiments.

Falsificationism...................................115
Doctrine that makes falsifiability the criterion of science for hypotheses.

Far-Field *Tsunami* 33
A *tsunami* that occurs at least 1000 km away from its source (see *Tsunami*).

Fathers of Botany 69
Began the transition from medieval botany to the modern scientific worldview by arranging plants based on their resemblance and relation.

Fault Motion..33
Movement along a fracture in a volume of rock.

Ferric Iron 140
The highest oxidation state of iron, corresponds to Fe^{3+}.

Ferrocyanide ions 105
Charged particles of the chemical formula $Fe(CN)_6^{4-}$.

Ferrous Iron 140
The lower oxidation state of iron, corresponds to Fe^{2+}.

Fidelity..59
Accuracy of the replication of nucleic acids.

Filamentous Feathers 83
Filamentous feathers are small tufts that project a few millimeters above the surface of the skin. They resemble what is hypothesized to be early stages in avian feather development (Eastern Kentucky University, n.d.)

Filtering 137
Theophrastus describes filter as the process where water percolates through rock, or earth travels through water (Theophrastus, 315 BCE, p.20).

devices can also be used to map out a route to a desired location.

A point in the Arctic Ocean where the Earth's axis of rotation intersects the Earth's surface.

Irregular surface that represents a non-idealized ellipsoid used to describe the mean surface of the Earth.

Layers of rock strata formed through the cooling of igneous and metamorphic rocks, and deposition of sediments, and impacted by various earth processes. Analysis provides much information on climatic, geological, and biological conditions in the past.

The study of the Earth, rock composition and changes in composition.

Ernst Mayr's theory that new species result from the evolution of small populations which are spatially separated from the main population.

A depiction of an area that shows the spatial arrangement of geologic features such as strata (see *strata*) with colour or symbols.

The study of the Earth and its environment in space using quantitative physical methods.

A type of data that is linked to a location on the Earth's surface.

A Swiss naturalist and bibliographer. His *Historiae animalium* has been considered the basis of modern zoology.

Glacial development and advance at the beginning of a glacial period.

A colder period within an ice age during which ice sheets advance and cover large areas of the continents.

Unsorted glacial sediment collected by abrasion and plucking and deposited directly by glacial ice without subsequent disaggregation.

A moving body of ice.

Theory that sea levels around the world follow a universal pattern of rising and falling over time.

A progressive warming of the Earth's climate. This may be caused by the Earth's inability to disapate heat caused by a build up of carbon dioxide, methane, and other gases in the atmosphere.

A beach town in Southwestern Ontario, Canada. Home to the largest salt mine in the world.

A French astronomer and member of the Academie Royale des Sciences. He lead an expedition to Peru in order to measure a degree of latitude to determine the true shape of the Earth.

An American Earth scientist specializing in manure and fertilizer.

The process of sifting through sediment to collect gold particles.

Subfamily of gorillas.

Co-inventor of the first internal combustion engine, along with Wilhelm Maybach. Made major contributions to the development of the automobile.

An American paleontologist and evolutionary biologist. Gould conducted much of his research with land snails and published the theory of punctuated equilibria with Niles Eldredge in 1972.

The theory that the P-T extinction took place over a long time period due to local irregularities sea level and increased competition.

A grid created by lines of longitude and latitude that is used to assign coordinates to locations on the Earth's surface.

An empirical constant used to determine the force of gravity on two objects with known mass and separated by known distance.

Scottish engineer who worked with John Milne and Sir James Alfred Ewing to develop the horizontal pendulum seismograph.

The belief that all living creatures were arranged in a hierarchical structure by God.

A theory that a global flood was responsible for past extinctions and the formation of many landforms.

Louis Agassiz's theory that there was, in the past, a single glacial period. He also thought that this period was responsible for the extinction of mammoths and other mammilian megafauna

Gases including water vapour, carbon dioxide, and methane that absorb and emit thermal radiation. These gases effect global climate change by absorbing radiation coming from the Earth and emitting it back towards the Earth, increasing the Earth's temperature.

Greenhouse Effect.................................. 3
An important climatic effect caused by excess amounts of carbon dioxide and other greenhouse gasses (e.g. methane, water vapour) being present in the atmosphere. Heat from solar radiation enters the Earth's atmosphere and is trapped due to the presence of these gases in the atmosphere.

Greenland Ice Sheet Program................ 44
Program created following the International Geophysical Year (1957-1958) to explore the history of Greenland's ice sheets (see *International Geophysical Year*).

Grew, Nehemiah (1641-1712) 70
An English plant anatomist and physiologist. Known as the father of plant physiology. Discovered that plants had sexes.

Ground Penetrating Radar (GPR) 97
A nonintrusive method to determine the moisture content, salinity, and density of near-surface sedimentary layers.

Groundwater 41
Water beneath the surface of the Earth which fills cracks, cavities and pore spaces.

Hadean Eon.. 58
The earliest and most violent stage in the history of Earth, between 4.4 and 4.0 Gya.

Hades... 1
The God of the underworld in Greek mythology. In time, Hades became a term used to refer to an underworld in general.

Haldane, John Burdon Sanderson (1892-1964)... 58
British geneticist and molecular biologist, independently proposed the modern theory of abiogenesis in 1929.

Half-life 5,43
Amount of time for an object to decrease to half of its original amount.

Halite 109
A mineral (see *mineral*) composed of the chemical compound sodium chloride. Commonly known as salt.

Hallam, Anthony (b.1933) 51
A British geologist and paleontologist who hypothesized that sea level was rising 250 million years ago during the P-T transition.

Halley, Edmond (1656-1742) 2,38,102
An English astronomer, geophysicist, mathematician, meteorologist, and physicist best known for calculating the orbit of the eponymous Halley's Comet. Halley also developed a very popular Hollow Earth model.

Hamilton time 65
A span of eight million years during the Middle Devonian period. Niles Eldredge studied trilobites from Hamilton time to formulate the theory of punctuated equilibrium.

Harland, Brian (1917-2003) 65
British geologist who invented the theory of a fully glaciated Earth in order to explain the existence of ancient glaciers near the equator (*see Snowball Earth*).

Harvey Jr., Aubery E. (Active in 1955)..142
Worked at the University of Arkansas to pose a drastic improvement in spectrophotometric measurements by silmultaneously detecting ferric and total iron (Harvey, Smart and Amis, 1955).

Hartley, Walter Noel (1845-1913)........124
A British physicist noted for being the first scientist to discover the relationship between an element's position on the periodic table and the wavelength of its spectral lines.

Hays, Jim (active 1976) 44
British geologist who developed the theory of a fully glaciated Earth in order to explain the existence of glaciers near the equator (*see Snowball Earth*).

Heat Flow Probe 131
Surveys the heat flow either in water or below the Earth's surface.

Hellenistic Greece (323-146 BCE).........134
A period in Ancient Greece following Classical Greece and leading up to the rise of the Roman Empire (27 BCE-476 CE).

Helmert, F. R. (1843-1917)..................119
German geodesist and writer on theory of errors. His work provided the foundation for modern geodesy (see *Geodesy).*

Heng, Chang (b.78 CE) 129
A leading scholar in astronomy, cartography, mathematics, philosophy, and literature in Ancient China. He is credited for creating the first seismometer.

Heritable 60
The property of a trait that indicates it can be passed down from parent to offspring.

Herodotus c. (484-425).........................32
An ancient Greek historian who wrote one of the first histories of the world.

Hess, Harry (1906-1969) 22
American geologist and navy officer who proposed that new ocean floor was formed at volcanically active ocean ridges (see *sea-floor spreading*).

Heterogenesis 56
An obsolete theory which proposes that new life forms are spontaneously derived from others, in spite of a lack of physical similarity between the organisms.

Hexadente 143
Refers to the number of possible coordination sites on a chelating agent. More sites on an agent leads to a more effective and versatile compound.

Hieroglyphs 133
A writing system invented by the Ancient Egyptians, commonly used for religious purposes.

Hirn, Clyde F. (Active in 1960)............. 142
Posed an EDTA complexometric, chelation titration for the Sherwin-Williams Company as a recent method to quantify iron with excellent specificity and sensitivity. Ferric and ferrous iron were quantified separately by taking advantage of their separate ideal chelation pHs (Lucchesi and Hirn, 1960).

***Historia Naturalis* (Natural History)..... 137**
An encyclopaedia written by Pliny the Elder *(see Pliny the Elder)*.

HMS *Beagle*.. 60
The name of the ship that Charles Darwin sailed on during his trip to South America where he formulated his theories on evolution.

Holmes, Arthur (1890-1965) 21
British geologist who developed rock-dating techniques based on radioactive decay of uranium isotopes. Also developed a realistic mechanism for continental drift based on convection cells in the Earth's mantle.

Home, Everard (1756-1832).............. 4, 76
A British anatomist and surgeon. He was one of the first scientists to describe the ichthyosaur fossil which Anning found and thought it had relations to fish. He was also elected into the BiFellowship of the Royal Society in 1787. He performed extensive *radiometric dating* of rocks.

Homer (c.800 BCE)........................... 1, 133
An Ancient Greek poet best known for writing the epics *Iliad* and the *Odyssey*. His works influenced many following classical writers.

Hominidae.. 90
Family consisting of hominids (see *hominids*).

Hominids.. 88
All extinct and living bipedal primates of the human and African ape lineages.

Hominins.. 88
Humans and their past ancestors.

Homininae.. 91
Subfamily of humans and all past bipedal hominins.

Hominine 91
Subfamily of chimpanzees and humans.

Hooke, Robert (1635 – 1703).............. 102
An English physicist and polymath. Known for his work in microscopy and on gravity.

Horizontality 3
The ability to lay parallel with the horizon.

Hubble, Edwin (1889-1953CE) 4
An American astronomer known for his work with the *Big Bang* theory as well as movement of other celestial bodies including galaxies.

Hume, David (1711-1776)................... 115
British empiricist (see *Empiricism*) who critiqued the method of induction and tried to dispel metaphysics by an analysis of human nature.

Hutton, James (1726-1797CE) 3,115
Geologist known for his theory of *uniformitarianism* and theory of the Plutonic Earth (see *Plutonism*).

Ice age 84
Also called a glacial age. A geological age with decreased global temperatures resulting in the growth of continental ice sheets. Colloquially refers to the most recent ice age spanning from the beginning of the Pleistocene to modern times.

Ice core 44,85
A core taken from a glacier or an ice sheet that can be analysed and used to construct a record of historical climates. Air bubbles found in the cores are indicative of the atmosphere and climate at the time of formation.

Ice sheet 84
A large ice mass covering an area of at least five million square kilometres.

Ichthyosaur...76
A diverse order of marine reptiles of up to 15m long, depending on the species, which lived during the Mesozoic era. Their morphology suggests they were rapid swimmers.

Idols..112
Beliefs that people hold due to personal biases of certain kinds.

Iliad124
An ancient Greek compilation of poems written during the 8th century BCE. It is one of the oldest works of Western literature, and one of two works ascribed to Homer (see *Odyssey* and *Homer*).

Imbrie, John (b. 1925)...........................44
American paleoceanographer who helped make connections between oxygen isotope ratios and the climate model developed by Milankovitch. Later he and Nicholas Shackleton generated an extensive marine chronology based on oxygen isotope ratios.

Incan Empire..96
South American empire which conquered much of the central Andes during the beginning of the 15th century until their downfall by the Spanish in 1533 (D'Altroy, 2003).

Indian National Congress....................104
Also known as the Congress. A major Indian political party.

Inductive Method 113
Logical technique for going from specific observations to general conclusions. It relies on a principle of induction: uniformity or regularity in experience demonstrates a uniformity in nature. As Hume shows in *A Treatise on Human Nature* and other texts, the inductive method can only be demonstrated with the principle of induction, making it circular and unjustifiable.

Indus Valley 116
Fertile river valley in the middle east. Provided water and other resources for early civilizations to develop the area.

Industrial Revolution (1750 – 1850) 108
A period in which changes in mining, transportation and technology made coal a very valuable resource. Originated in Britain and spread to the rest of the world.

Inertial System 129
A reference frame within which objects can only be subject to acceleration by external forces.

Inorganic 136
A compound that lacks carbon and hydrogen atoms. Formed by geologic processes.

Insolation 42, 87
Measure of solar radiation energy received by a unit area.

Intercropping 94
Agricultural technique in which multiple crops are grown interspersed on the same plot of land.

Interglacial period 84
A warmer period within an ice age during which ice sheets retreat.

Intergovernmental Panel on Climate Change (IPCC).. 48
Scientific panel initiated by the World Meteorological Organization and the United Nations Enivronmental Programme – both United Nations organizations in order to provide information about climate change and human activity. Co-won 2007 Nobel Peace Prize with Albert Arnold Gore Jr.

Intermediates 62
Refers to transitional forms of species not present in the fossil record but that should be found between two forms present in the geologic record.

International Geophysical Year (1957-1958)... 44
Program created following World War II by 67 nations to deve into the unexplored Earth sciences. These included ionospheric physics, seismology, meterology and oceanography.

Ion Specific Electrodes (ISEs) 141
An analytical tool that detects changes in voltage as they correspond to one ion in solution as opposed to any other components of solution.

Irrigation System................................... 96
Anthropogenic control of water reaching crop fields.

Isochron Dating.................................... 47
Radiometric dating technique using events such as crystallization to determine age. Data ploted onto a graph for analysis. No assumptions made about initial daughter quantity.

Isopach Map 30
A map composed of contour lines joining deposits of equal thickness. Isopach maps can be used to calculate the minimum volume of material ejected from a volcanic eruption (see *pyroclastic debris, tephra,* and *airfall deposits*).

Isotope......................................43, 75, 85
A variant of a chemical element. Different isotopes have different molecular masses due to different numbers of neutrons in the nucleus, but have unchanged numbers of protons and neutrons and thus unchanged periodic numbers.

Isozaki, Yukio (active 2006) 52
Geologist who proposed the theory that the Permian-Triassic extinction was caused by a massive anoxic event resulting from a lack of ocean mixing and stagnation of the deep oceans.

Jackson, Andrew (1767-1845).................2
The seventh president of the United States of America. Was rumored to be involved with the Flat Earth Society following the cancelation of support for Symees Jr.'s arctic expedition.

Jagger, Thomas (1871-1953).................26
Was sent on a US government mission to Mount Pelée after it erupted in 1902. Wanted volcanoes to be continually monitored to be able to predict eruptions. Spent from 1912 to his death ensuring an unbroken record of observations at Kilauea (Lockwood and Hazlett, 2010).

Jesus Christ (c. 2BCE-36CE) 2
The central figure of many religions including *Christianity* who follow his teachings and readings; also believed to be the son of God.

Ji, Junfeng (active 2002) 143
Performed one of multiple diffuse reflectance spectroscopy assays for the measurement of iron through hematite. This study was was done to further understand BIF stratigraphy in China (Ji, Balsam, Chen and Liu, 2002).

Jones, Arthur Letcher (1915-1985).......142
Collaborated with Yoe at the University of Virginia to improve on the Fortune and Mellon assay by changing the chromophore to improve specificity for iron (Yoe and Jones, 1944).

Judeo-Christian 1
Being historically connected to both Judaism and Christianity.

Jungius, Joachim (1587-1657)...............69
A German mathematician, logician, and philosopher of science. Believed that science was based on mathematics. Made precise rules of how to describe plants.

Kircher, Athansius (c. 1601-1680) 3
A German Jesuit Scholar who published a number of works in geology, medicine, and oriental studies. His book, Mundus Subterraneusm, is a culmination of his geological and geographical investigations that combined physical observations with mythological elements.

Konig, Charles (1774-1851) 76
German-born, he came to Britain in the early 1800s and eventually became an assistant within the Department of Natural History in the British Museum, with work of several other colleagues at The Museum, he published several papers regarding fossils.

Lachish 107
An ancient Judean city. Citizens rebelled against King Sennacherib of Assyria (see *King Sennacherib of Assyria*) in 701 BCE, but the city was later recaptured.

Lacroix, Francis (1863-1948) 26
A French minerologist present after the 1902 eruption of Mt. Pelée. Lacroix coined the term *nuées ardentes* to describe pyroclastic flows (Lockwood and Hazlett, 2010).

Lamarck, Jean Baptiste (1744-1829) 60,70,73
A botanist from France with the full name Jean-Baptiste Pierre Antoine de Monet, Chevalier de Lamarck, but known as Lamarck. Lamarck was an early advocate of the idea that evolution occurred in accordance with natural laws, but his theory of the inheritance of acquired charactersitics as a form of evolution was proven to be incorrect (see *Theory of Inheritance of Acquired Characteristics*). Lamarck is credited with coining the term *invertebrates*.

Lamb, Hubert H. (1913-1997) 28,29
A leading scientist in the field of climatology in the late twentieth century. Lamb created the Dust Veil Index (see d*ust veil index*) to classify volcanic eruptions based on the decrease in sunlight passing through the atmosphere after the release of a large amount of volcanic ash. In his lifetime, Lamb had a long career at the UK Meteorological Office and become the first Director of the Climatic Research Unit at the University of East Anglia, Norwich, England (Kington, 2008).

Landslide 128
The rapid sliding of a large mass of earth and rock down a slope. Landslides are commonly triggered by earthquakes.

Land subsidence 41
The lowering of a natural land surface due to water, oil, or gas extraction.

Last Common Ancestor.......................... 90
The last common organism within varying evolutionary lineages.

Late Permian 79
A subdivision of the Permian epoch which occurred 260 – 251 million years ago (see *Permian Period*).

Latitude 134
A geographical coordinate system ranging from 0-90° that determines north-south positioning on the surface of the Earth.

Law of Superposition............................ 73
Developed by Nicolas Steno, the law states that the most recently deposited sediments overlay older sediments (see *Steno, Nicolas*).

Law of Universal Gravitation 10
First stated by Sir Isaac Newton in his *Principia*, the Law of Universal Gravitation dictates that all objects in the universe attract each other with proportion to their masses and inverse proportion to the distance between them (see *Newton, Sir Isaac*).

Law of Use and Disuse 60
Also known as Jean Baptiste Lamarck's "Second Law", this law states that change in the environment that an organism lives in results in behavioural changes that increase or decrease the use of a certain organ, causing the organ to grow or shrink depending on whether or not its use is increased or decreased (Campbell, et. al., 2007).

Leagues... 39
A historical unit of measurement, typically the distance a person could walk in one hour. One league is roughly 4.8 km.

Lehmann, Johann (1719-1767).............103
A German geologist. Lehmann specialized in mining.

Leibniz, Gottfried (1646-1716) 119
A German mathematician and philosopher. Leibniz independently developed calculus at the time of Newton (see *Newton, Sir Isaac*).

Leidy, Joseph (1823-1891)......................82
Joseph Leidy was a pioneer of vertebrate anthropology in North America. He was also a prominent fossil hunter at the same time as Othniel C. Marsh and Edward D. Cope (see *March, Othniel C.* and *Cope, Edward D.*).

Lemaitre, Georges (1894-1966)............... 4
A Belgian priest, astronomer, and professor known for his contribution to the *Big Bang* theory by proposing the expanding universe.

Libby, Willard (1908-1980).....................43
An American physical chemist who developed radiocarbon dating.

Limit of Detection (LOD) 142
The smallest value of analyte that a given assay can distinguish from noise and interferences in solution. The goal is to minimize the LOD as much as possible.

Linnaeus, Carl (1707-1778)................70,91
A Swedish botanist, physician, and zoologist. Linnaeus is known as the father of modern taxonomy and one of the fathers of modern ecology, and developed binomial nomenclature.

Location-Based Services.......................135
A mobile system sensitive to location, allowing a user to relate their location to the surrounding environment in order to complete spatiotemporal tasks.

Logical Division 68
An Aristotelian term describing the process by which genera are distinguished into species.

Logical Positivism 114
A philosophical school which attacked all knowledge not based on the scientific method of Bacon and his successors (see i*nductive method* and *Bacon, Francis*). Positivists declared non-empirical concepts and theories meaningless and useless – including those of ethics and metaphysics (see *metaphysics*).

Longitude 134
A geographical coordinate system that determines east-west positioning on the surface of the Earth.

Lord Kelvin (1842-1907).......................... 3
See *William Thomson*.

Lord Viceroy 104
A lord who is also a viceroy (see *viceroy*).

Lovecraft, H.P. (1890-1937) 15
A multi-genre American fiction author. Lovecraft was one of the most influential horror writers of the 19th century.

Lovejoy, Dr. Claude Owen (b.1943) 88
An influencial anthropologist who developed the provisioning hypothesis (see Owen Lovejoy's provisioning hypothesis) and worked with *A. afarensis* and *Ar. Ramidus* (see *Australopithecus afarensis* and *Ardipithecus ramidus*).

Lovelock, James 125
An English scientist who proposed the Gaia hypothesis. In 1973, he discovered that chlorofluorocarbons had spread through the atmosphere.

Lu, Lianwne (active 2002).................... 143
Lu performed one of multiple diffuse reflectance spectroscopy assays for the measurement of iron through hematite with Balsam, Chem,and Ji (see *diffuse reflectance spectroscopy*; *Balsam, William*; *Chem, Jun*; and *Ji, Junfeng*). This study was was done to further understand BIF stratigraphy in China (Ji, Balsam, Chen and Liu, 2002) (see *banded iron formations*).

Lucchesi, Claude A. (active 1960) 142
Lucchesi posed an EDTA complexometric, chelation titration for the Sherwin-Williams Company with Hirn as a recent method to quantify iron with excellent specificity and sensitivity (see *(ethylenedinitrilo)tetraacetic acid*; *chelation titrations*; *Hirn, Clyde F.*; *specific*; and *sensitive*). Ferric and ferrous iron were quantified separately by taking advantage of their separate ideal chelation pH ranges (Lucchesi and Hirn, 1960) (see *ferric iron* and *ferrous iron*).

Lucy... 88
One of the most important fossils in tracing human origins. A female specimen of *A. afarensis* believed to have lived 3.2 mya.

Lunar Orbiter 1.. 6
A spacecraft launched in 1966 as part of the Lunar Orbiter Program with the purpose of taking pictures of the Moon's surface to help determine a landing site for future missions. The spacecraft also took the first photographs of the Earth from space.

Lyell, Charles (1797-1875) 3,113,120
A prominent Victorian geologist and Britsh lawyer noted for his observations of changing landscapes, his work in developing uniforimtarianism (see *uniformitarianism*), and less so for his harsh critism of Oxford University for not emphasizing the study of the natural sciences enough (Lyell, 1845; Macleod, 1971).

Lyons, Edward S. Sr. (1901-1969) 141
Lyons proposed a unique mechanism for the reaction of ionic iron with thioclycolate where the colour comes from the production of a ferrothioglycolate ion (Lyons, 1927).

Macedonia 107
An ancient kingdom near Greece. This country was the birthplace of Alexander the Great and was both an ally and an enemy to Greece at certain time periods.

MacNevin, William B. (active 1952) 142
MacNevin paired with Baker to begin couloemetric assays for iron detection after an increase in equipment to allow for this method (MacNevin and Baker, 1952) (see *Baker, Bertsil B.*).

Magma Chamber 31
See *magma reservoir*.

Magma Reservoir 31
A long-lived, magma-filled chamber beneath the Earth's surface which forms as new magma from the mantle is added at a rate greater than the rate of cooling of pre-existing magma. Magma reservoirs may be various shapes and may be composed of several interconnecting dikes (see *volcanic dike*). Also refered to as magma chamber.

Magmatic evolution 26
The compositional change in a magma body, determined from the temporal changes in the mineral compostion of volcanic deposits produced.

Magnetic Crusade 121
A campaign which focussed on encouraging scientific surveying in order to understand more about the earth's magnetic field. This effort was spearheaded by Edward Sabine and caused a newfound appreciation for science in the British Government (Cawood, 1979; see *Sabine, Edward*).

Magnetic Declination 15
The angle between true north and magnetic north on a compass (see *Magnetic North*).

Magnetic North 22
A point located in Northern Canada where the Earth's magnetic field points straight down towards the center of the Earth.

Mariotte, Edme (1620-1684) 38
A French physicist and priest, known for his quantitative analysis of the hydrologic cycle.

Marsh, Othniel C. (1831-1899).......... 73,80
Othniel C. Marsh was an American geologist active in the mid to late 1800s, who along with Edward D. Cope was responsible for naming over 140 new dinosaurs. He was also part of the First Great Dinosaur Rush (see *Cope, Edward D.*).

Maskylene, Reverend Dr. Nevil (1732-1811) 11
An English astronomer, mathematician, and minister. Maskylene served as England's fifth Astronomer Royal.

Mass Extinction 52
The extinction of more than 20% of marine species, over a short period of geologic time.

Mass Spectrometry 85
A technique used to identify the ratio between mass and charge in particles. Mass spectrometry can be used to identify elemental isotopes.

Matrix 142
All components of solution except the analyte.

Maupertuis, Pierre Louis (1698-1759)......8
A French philosopher, mathimatician, and member of the Academie Royale des Sciences. Maupertuis was one of the first French philosophers to support Newton's theories and he helped bring these ideas into French society (see *Newton, Sir Isaac*). He also participated in an expedition to measure the length of a degree of latitude in Lapland to determine that the Earth is an oblate spheroid (see *oblate spheroid*).

Maybach, Wilhelm (1846-1929)..............2
A co-inventor of the first internal combustion engine, along with Gottlieb Dailmer (see D*ailmer, Gottlieb*). He made major contributions to the development of the automobile.

Mayr, Ernst (1904-2005).......................65
A 20th century evolutionary biologist and zoologist. Mayr is best-known for his definition of a biological species and the theory of geographic speciation.

McElroy, Michael B. (active 1985) 125
A leading atmospheric scientist at both Harvard and Columbia. He is noted for his research on ozone layer depletion and his contributions to the development of the Montreal Protocol.

Méchain, Pierre-Francois-André (1744-1804)..117
A French astronomer and surveyor who studied deep sky objects. Méchain led the Southern leg of the expedition to define the metre with colleague Jean-Baptiste-Joseph Delambre (see *Delambre, Jean-Baptiste-Joseph*).

Megafauna...84
Large animals exceeding 100 kg. Mammillian megafauna were especially prevalent during the Pleistocene (see *Pleistocene*). Examples include mammoths and ground sloths.

Megalosaurus **......................................80**
The *Megalosaurus* was an enormous carnivorous bipedal dinosaur present in the Jurassic to early Cretaceous periods; mainly found in Europe. It was the first dinosaur ever described and one of the three creatures Sir Richard Owen used to define dinosaurs (see *Owen, Sir Richard*).

Mellon, Melvin G. (1893-1993)...........141
Mellon worked with Fortune at the Purdue University to develop one of the first assays for transmittance measurements to quantify iron (Fortune and Mellon, 1938) (see *Fortune, William Brooks* and *transmittance*).

Mercator, Gerardus (1512-1594) 118
A cartographer, philosopher, and mathematician. Mercator is known for his world map which represents rhumb lines as straight (see *rhumb lines* and *Mercator projections*)

Mercator Projections..........................118
Created by Gerardus Mercator, this map type depicts rhumb lines as straight causing area distortion at higher latitudes (see *rhumb lines* and *Mercator, Gerardus*).

Meridian of Paris................................117
The meridian line through Paris, which was used to measure the size of the Earth and to define the metre (see *Delambreand, Jean-Baptiste-Joseph* and *Méchain, Pierre-Francois-André*).

Mesopotamia 106
An area of the Tigris-Euphrates river system that correponds to modern-day Iraq. Mesopotamia is known as the site of the emergence of early civlizations such as the Assyrians (see *Assyrians*) in ancient times.

Metaphysics 114,136

An area of philosophy which inquires into the nature of reality, God, minds and causality (see *causal relation*). Metaphysics is distinguished from physics and other natural sciences by seeking justifications on non-empirical grounds.

Meton of Athens (active 432 BCE) 42
A Greek mathematician and astronomer who first observed that the presence of spots on the sun had some relation to the weather on Earth (see *sunspots*).

Michell, Reverend John (1724-1793).11,33
An English philosopher, geologist, and inventor of the Earth-weighing apparatus, which was gifted to Cavendish upon Michell's death. He proposed that earthquakes and tsunami might be caused by "subterraneous fires" (Cartwright and Nakamura, 2008; see *Cavendish, Henry* and *tsunami*).

Microorganism 63
An organism that can only be viewed under a microscope, and can be either univellular, multicellular or form clusters of cells.

Micropaleontology 74
The study of microfossils.

Midgley Jr., Thomas (1889-1994). 124
An American chemist and engineer who was a key member of the team who developed the first chlorofluorocarbons.

Mid-Ocean Ridge 22
Long underwater mountain chains found along the boundary of diverging tectonic plates.

Migration..63
The movement of a population from one habitat to another, usually in response to changes in the environment during different seasons.

Milankovitch Cycles 85
The mathematical determination of patterns in global climate based on variations in the Earth's orbit and rotation.

Milankovitch, Milutin (1879-1958)....42,85
A Serbian mathematician, astronomer, geophysicist, and writer who proposed that periodic changes in the Earth's orbit around the sun affect incoming solar radiation and account for global climate changes leading to the development of glacial-interglacial cycles.

Military Geologists 108
Military units that applied geology to the battlefield, first created in the First World War (see *First World War*). Military geologists partnered with engineers to plan trenches and subterranean warfare (see *subterranean warfare*).

Miller, Stanley (1930-2007) 58
An American chemist and biologist, and the student of Harold Urey (see *Urey, Harold*). Conducted the Miller-Urey experiment in 1952 to determine the accuracy of the Oparin-Haldane model (see *Miller-Urey experiment* and *Oparin-Haldane model*).

Miller-Urey Experiment........................ 58
An experiment performed in 1952 by Stanley Miller and Harold Urey, to determine the accuracy of the Oparin-Haldane model in a laboratory setting (see *Miller, Stanley*; *Urey, Harold*; and *Oparin-Haldane model*).

Milne, John (1850-1913)..................... 130
The British geologist and mining engineer considered to be a father of modern seismology. In the 1900s, the British Association for the Advancement of Science declared his horizontal seismograph to be used as the standard device around the world.

Mineral 109,136-139
A naturally occuring, solid inorganic substance with a specific chemical composition and crystalline structure (see *crystalline atomic structure*).

Minotaur.. 14
A Greek mythological creature with the head of a bull and the body of a man that dwelt at the center of the Cretan Labyrinth. Dante adapted the Minotaur for his own work, *Inferno*, in which the Minotaur was a guardian of the seventh circle of Hell, Violence.

Miocene 88
A geological epoch spanning the time between 23.03 and 5.3 million years ago.

Mohorovičić, Andrija (1857-1936) 16
A Croatian meteorologist and seismologist known for the discovery of the eponymous Mohorovičić discontinuity. He is considered to be a founder of modern seismology.

Mohs Scale of Hardness 109
A scale from 1 to 10 used to determine the relative scratch hardness (see *scratch hardness*) of a mineral (see *mineral*). Each integer on the scale is representative of a particular mineral, and the scratch hardness of a sample is expressed in relation to the scratch hardness of these minerals. The scale is based on the concept that a harder mineral will scratch a softer mineral.

Molina, Mario J. 126
A Mexican chemist noted for making discoveries that helped in the discovery of the Antarctic ozone hole.

Monocotyledons 69
Also known as monocots. The grouping of flowering plants whose seeds have one embryonic leaf, or cotyledon (see *diicotyledons*).

Monogamous 88
A social group that includes one adult male and one female, and their offspring.

Monophyletic Group 70
A group of organisms containing an ancestor and all its descendants. These groups are characterized by shared derived characteristics.

Monosodium glutamate 105
A food additive common to Asian cooking. Monosodium glutamate is known for an addictive taste and unpleasant side effects.

Moonquake 131
Ground movement caused by displacement of rocks on the moon (see *Earthquake*).

Morris, Henry (1918-2006) 46
A young Earth creationist who is known as "the father of modern creation science". Morris co-wrote *The Genesis Flood*, and has received a Bacholor degree at Rice University in civil engineering and a Ph.D. at the University of Minnesota in hydraulic engineering.

Mount Parnassos 107
A mountain of limestone in central Greece. A town on Mount Parnassos was the subject of a siege by Philip V (see *Philip V*).

Mount Pelée 26
A volcanic mountain located on the island of Martinique. In 1902, it erupted, devastating the nearby city of St.Pierre (Lockwood and Hazlett, 2010).

Movable Type Printing 134
A method of printing that uses movable components to produce text documents. It was originally invented by the Chinese in 1040 CE and independently invented in Europe by Johannes Gutenberg in 1430 (see *Gutenberg, Johannes*).

Muids 39
A french unit of measurement used to record fluid volume before the metric system. One muid is equivalent to roughly 275 L.

Multi-Phased 16
Multiple phases of matter existing concurrently. For example, the Earth's core is multi-phased; it has a solid and liquid component.

Murchison, Sir Roderick Impy (1792-1871) 50
British geologist who first identified rocks of the Permian period (see *Permian period*).

Mutations 66
Random alterations of an organism's DNA. Genetic diversity caused by mutations is considered a requirement of evolution.

National Earthquake Information Center 128
An organization that compiles and maintains a global database on earthquakes.

National Oceanic and Atmospheric Administration (NOAA) 49
An information center for ocean and atosphere data and issues. NOAA is part of the United States Department of Commerce.

Natural Gas 1
A gaseous fossil fuel which is high in simple hydrocarbons (see *fossil fuels*). Natural gas is important as a modern heating fuel.

Natural Selection............................. 61,64
Commonly known as survival of the fittest, a process where organisms that have traits that are more favourable to the environment in which they live will survive and reproduce more than those lacking the trait. This increases the prevalence of the trait in subsequent generations. Natural selection was Charles Darwin's proposed mechanism for descent by modification (see *Darwin, Charles*).

Natural System..................................... 69
A natural system reflects a situation as it appears to exist in nature and utilizes information available at the time.

Neanderthal 72
An extinct variety of humans, much stronger than modern humans, present on Earth from approximately 300 000 to 30 000 years ago. Neanderthal skulls were first discovered in Belgium and Gibraltar in 1848.

Nebular Theory 136
A theory which states that our Solar System was formed 4.6 billion years ago when materials within a nebula, a cloud of interstellar dust and gas, amalgamated in concentric zones to form the planets. The theory suggests that minerals were formed and solidified at the time of formation of the planet.

Needleham, John (1713-1781).............. 57
An English theologian and supporter of spontaneous generation. Needleham used a flawed and highly biased experiment to disprove the works of Francesco Redi (see *Redi, Francecso*).

Neptunism.. 25
A geological theory popular in the eighteenth century that proposed all rocks were deposited in a marine setting. This theory strongly correlated with religious views of the time, concerning the Biblical Flood described in the book of Genesis (Sigurdsson, 1999).

New World 134
A term describing the Americas, after their discovery by European explorers in the 16th century CE.

Newcomen, Thomas (1664-1729) 2
The inventor of the Newcomen steam engine, which allowed water to be pumped out of mines.

Newell, Norman (1909-2005) 50
The geologist who proposed the gradual theory as the cause of the Permian-Triassic mass extinction, and later proposed decreasing global sea level as the mechanism of gradual extinction (see *gradual theory,* and *Permian Triassic mass extinction*).

Newhall, Christopher G. (active in 1982) 30
The current group leader of volcanic research at the Earth Observatory of Singapore, Christopher G. Newhall is a co-author of the Volcanic Explosivity Index (see *volcanic explosivity index* and *Self, Stephen*). In the past, Newhall worked in the US Geological Survey's Volcano Hazards Program for several years. Newhall was also co-leader of a crisis response team responsible for forecasting the 1991 eruption of Pinatobu (Earth Observatory of Singapore, n.d).

Newton, Sir Isaac (1642-1727) 3,7,10,15,119
An English physicist, mathematician, astronomer, natural philosopher, alchemist, and theologian whose 1687 work *Philosophiæ Naturalis Principia Mathematica* (commonly known as the *Principia*) laid the foundation for most of classical mechanics. His work identified many principles of physics, including the theory of gravity, and he is credited with the invention of calculus. He also was the first to note that the Earth was not a perfect sphere but instead flattened at the poles. Newton was one of the most influential thinkers in the Enlightenment (see *Enlightenment*), and changed the way scientists thought about the world using his theories.

Niche 63
The interaction of an organism with its environment and with other organisms in the environment.

Nor'easter 49
A large scale storm (similar to a hurricane) formed on the east coast of the Americas. Nor'easter describes wind direction of the storm from the east coast towards northeast land. Storm conditions include flooding, high winds, and blizzards.

Nylon 3
A synthetic plastic made from refined petroleum (see *petroleum*). Famously used to make stockings.

Oblate Spheroid...................................... 7
An imperfect sphere with a shorter polar axis and longer equitorial axis (see *prolate spheroid*).

Oblateness..17
A property describing the flatness of a spherical object.

Obliquity...42
A parameter that describes the tilt of an object relative to its rotational axis.

***Odyssey* 124**
An ancient Greek compilation of poems written during the 8th century BCE. It is one of the oldest works of Western literature, and one of two works ascribed to Homer (see *Iliad*).

Olivine 131
A mineral of the silicate group that has been found on the Moon.

***On Stones (De Lapidibus)* 107,136**
A book written between 315 – 305 BCE by Theophrastus (see *Theophrastus*) on the formation of earth and stones, especially of minerals and metals. Rocks and minerals (see *mineral*) were classified based on various properties such as hardness, and the process of rubbing stones against one another to determine scratch hardness (see *scratch hardness*) was described.

***On the Origin of Species*........................61**
A book published by Charles Darwin in 1859 outlining his theories on descent with modification and natural selection (see *Darwin, Charles*; *Descent with Modification* and *Natural Selection*). *On the Origin of Species* was one of the most influential and controversial books ever published.

Opacity 109
A measure of the amount of light blocked by a mineral (see *mineral*). The greater the opacity of an object, the more light that is blocked.

Oparin, Alexander (1894-1980) 57
A Russian biochemist, who independently developed the modern theory of abiogenesis in 1924 in *Origin of Life* (see *theory of abiogenesis*).

Oparin-Haldane Model......................... 58
The modern model of abiogenesis (see *theory of abiogenesis*), independently proposed by Alexander Oparin and J.B.S Haldane (see *Oparin, Alexander* and *Haldane, John Burdon Sanderson*). The model suggests that the early terrestrial environment gave rise to a colloidal structure known as the primordial soup, in which life first developed (see *primordial soup*).

Organic 136
A compound containing carbon atoms.

Orgel, Leslie (1927-2007)...................... 59
A British chemist and fervent supporter of the RNA-World hypothesis (see *RNA-World hypothesis*).

Orissa 104
A state of India.

***Ornithomimus*...................................... 83**
The *ornithomimus* is a genus of birdlike dinosaurs found in the Late Cretaceous period of what is now North America.

Oro, Joan (1923-2004).......................... 58
A Spanish biochemist and proponent of abiogenesis (see *theory of abiogenesis*). In 1961, he performed an experiment similar to that of Miller and Urey (see *Miller-Urey experiment*) and determined that nucleic acids could have formed on the early Earth.

***Orrorin tugensis*.................................. 90**
A pre-australopithecine hominin that showed early evidence of bipedalism.

Ortelius, Abraham (1527-1598)........... 134
A Flemish cartographer who developed *Theatrum Orbus Terrarum*, the first modern atlas (see *Theatrum Orbus Terrarum*).

Overdraft 41
The removal of more water from an aquifer than can be readily replaced. This often leads to consequences such as ground subsidence (see *land subsidence*).

Owen Lovejoy's Provisioning Hypothesis 88
States that monogamous, bipedal fathers are beneficial to the success of a species as it frees up the hands for gathering food while the mother can take care of the young (see *Lovejoy, Dr. Claude Owen*).

Owen, Sir Richard (1804-1892)......... 73,80
Sir Richard Owen was an English biologist, paleontologist, and a leader in British comparative dinosaur anatomy. He coined the term *Dinosauria* or 'dinosaur' in 1842 (van Whye, 2011).

Oxidizing Agent 140
A chemical that takes electrons, to become reduced and help another species lose electrons in a reaction.

P-Wave...16
A type of seismic wave emitted by an earthquake in which rock vibration is parallel to the direction of wave propagation. Also known as a primary wave (see *s-wave*).

Paleoclimatology..................................42
The study of previous climates by means of proxy methods (see *Climate Proxy*).

Paleoenvironment................................90
The past environment of an area.

Paleomagnetism.............................. 22,45
The study of the Earth's past magnetic field by means of signature orientations of magnetic minerals in the rock record.

Paleontology 72
The study of ancient life forms, especially through the use of fossils.

Palisades Sill 47
A tilted intrusion of igneous rock, which is found between layers of other rocks in New York and New Jersey. This layer of rock dates back to the Triassic age (200 Ma.), and is composed of diabase (see *diabase*).

Palmieri, Luigi (1807-1896) 129
The Italian physicist and meterologist well known for creating a seismometer that could record earthquake duration and measure horizontal and vertical motion of the Earth.

Paninae 91
The subfamily of Hominidae that refers to chimpanzees and bonobos.

Passchendaele....................................109
A battle of the First World War (see *First World War*). The Allied victory at Passchendaele is widely known as a turning point in favour of the Allies in the war.

Pasteur, Louis (1822 – 1895).................57
A French chemist and microbiologist, and one of the founding figures of medical microbiology. In 1859, Pasteur used an elaborate experiment to disprove spontaneous generation and simultaneously prove that bacterial growths are produced by microbes.

Pedology 97
The study of soils.

Peekema, R.M. (active 1961) 142
Together with Scott, and Connally, at General Electric, Peekema introduced voltage scanning coulometry to detect traces amouns of iron (see *Scott, F.A.* and *Connally, R.E.*). This assay lowered detection limits for higher sensitivity (Scott, Peekema and Connelly, 1961) (see *sensitive*).

Pelvis...88
A large structure of bone near the base of the spine where the legs are attached.

Pennibrachia 83
Pennibrachia are forelimbs that bear long feathers. These feathers form planar, wing-like surfaces but are not necessarily used for aerial locomotion (Williams, 2012).

Permian Period...................................... 50
The last period of the Paleozoic era that lasted between approximately 299 and 251 million years ago (see *Late Permian*).

Permian Triassic (P-T) Mass Extinction .. 50
Also known as the Great Dying, it is the largest extinction in documented history, killing approximately 96% of marine species in addition to terrestrial organisms including insects.

Perrault, Pierre (1608 – 1680)................ 38
A Receiver General of Finances for Paris who later became a scientist and helped develop the concept of the hydrologic cycle.

Perret, Frank (1867–1940)..................... 26
Perret had no formal training in geology, but was interested in volcanoes after visiting the aftermath of the 1902 eruption of Mount Pelée. He was involved in 1909 study of lava temperatures (Lockwood and Hazlett, 2010).

Petroleum 1
A liquid fossil fuel containing many different forms of hydrocarbons (see *fossil fuels*). Petroleum is mined in many nations throughout the world. It can be refined into chemical products and gasoline.

Phalanges.. 88
A bone of a finger or toe.

Phenomenon...................................... 112
An object as it appears to the senses; an object of perception. Phenomena are the things with which a theory is compared to verify it empirically (see *Empiricism*).

Philip V (c.238-179 BCE)....................... 107
A king of Macedonia (see *Macedonia*) from c. 221 to 179 BCE. He is known for an unsuccessful struggle against the emerging power of Rome.

Phillips, John (1800-1874)...................... 50
An English geologist who separated the geologic time scale into the Paleozoic, Mesozoic, and Cenozic Eras based on the fossil record.

***Philosophie Zoologique* 60**
A book published in 1809 by Jean Baptiste Lamarck outlining his theories on evolution, including the theory of inheritance of acquired characteristics (see *Lamarck, Jean Baptiste* and *Theory of Inheritance of Acquired Characteristics*).

Philosophy of Essentialism 68
The philosophy that essence characterizes a substance or a form, which is unalterable, permanent, eternal, and present in every possible world.

Phlegthon... 14
A Greek mythological river of flame that flowed into the depths of Tartarus. Dante adapted Phlegthon for his own work, *Inferno*, in which the Phlegthon was a river of boiling blood within the seventh circle of Hell, Violence.

Phyletic Gradualism............................... 64
The theory that evolution occurs continuously, and that new species arise from the slow splitting of ancestral lineages. It is often contrasted with the theory of punctuated equilibria (see *punctuated equilibria*).

Phylogenetic Reconstruction 70
The creation of a phylogenetic tree.

Phytoplankton 53
Algae that photosynthesizes in the euphotic zone of water bodies to release oxygen into the water (see *euphotic zone*).

Picard, Jean (1620-1682)......................... 7
A French astronomer, most well known for measuring the size of the Earth with resonably accurate equipment. He also incorrectly measured a degree going North from the equator, providing evidence for the prolate sphere model of the Earth (see *prolate spheroid*).

Plagioclase... 131
A mineral of the feldspar group that is the main constituent of the Earth's crust.

Planetary Differentiation....................... 16
The process by which a planetary body develops compositionally distinct layers, with denser layers underlying lighter layers. This process is driven by gravity when the planet is in a molten state.

Planetesimal 5
A planet-like body that forms from dust in the early solar system, large enough to exert gravitational influence on nearby bodies.

Plat, Hugh (1552-1608) 1
Plat suggested that coal could be super heated in the way wood was to form charcoal (see *coal*). This led to the development of coke (see *coke*).

Plato (427-347 BCE) 6
A greek philosopher who taught Aristotle (see *Aristotle*). Plato published many works and helped lay the foundation for many scientific concepts.

Platt, Samuel (1812-1887).................... 103
An independent Member of Parliament for Toronto East, in 1875 and 1878. Platt owned his own distillery.

Pleistocene 75,84
A geological subdivision, lasting from approximately 2.6 million to 11.7 thousand years ago.

***Plesiosaur* 77,81**
A *Plesiosaur* was a large marine reptile of approximately 20 metres in length that had paddle-like limbs. It was common to Europe and North America during the Mesozoic Era.

Pliny the Elder (23-79) 136-138
Born with the name Gaius Plinius Secundus. A Roman scholar and philosopher. Author of *Historia Naturalis* (Natural History) (see *Historia Naturalis*).

Plot, Robert (1640-1696)....................... 80
Robert Plot was a pioneer in the field of fossil origins and he was the first recorded person to describe a dinosaur fossil.

Plutonism... 25
A geological theory developed by James Hutton in the 18th century. This theory states that volcanic rocks come from hot molten materials in the subsurface (Sigurdsson, 1999).

Pohlflucht 21
Force proposed by Wegener. He suggested that the slightly flattened shape of the Earth caused gravity to be stronger at the equator, pulling continents slowly away from the poles.

Polystyrene 3
A synthetic plastic made from refined petroleum (see *pertroleum*). Famously used to make styrofoam.

Polyvinyl Chloride 3
A synthetic plastic made from refined petroleum (see *pertroleum*). Famously used to make piping.

Pongidae 91
A subfamily of orangutans.

Popper, Karl (1902-1994) 115
A British philosopher who was at odds with the Vienna School of philosophy, a contemporary name for the main Logical Positivists, regarding methodology. Popper presented the falsificationist criterion of science (see *Falsificationism*).

Population Health 135
The study of the health outcomes of a population of individuals, as well as the distribution of health outcomes within a population.

Porphyry (234-305) 68
A Neoplatonic philosopher and commenter of Aristotle (see *Aristotle*). Porphyry introduced in his book *Isogoge* (Introduction) logic and how the categories of substance could be broken down into the five components of genus, species, difference, property, and accident.

Postcranial 90
Refers to the skeleton apart from the skull.

Potassium chloride............................. 105
A chemical compound commonly used in fertilizer. Also known as potash.

Pre-adapted 86
The use of a preexisting evolved characteristic for a new or unrelated function.

Pre-australopithecines 88
Refers to hominids before the time of the *Australopithecines*.

Precession.. 42
A parameter that defines the orientation of a body around a rotational axis.

Precision 141
A measure of the reproducibilty of measurements in an assay. Results can be precise, while still inaccurate.

Predictive Soil Mapping (PSM) 97
Combination of known soil properties, their relationship to environmental factors, and known topographic features to create a model for the prediction of soil type (Florinsky, 2012)

Primeval 2
Refering to the earliest beginning's of the world; raw and elementary.

Primordial Soup................................58,64
A term describing the accumulation of carbon-containing compounds in the oceans of the early Earth. It is thought that life first developed in this primordial soup.

Problem of Induction...........................114
Inconsistensy in the inductive method, namely that the validity of induction cannot be justified without circular reasononing.

Progenitor 62
Also known as ancestor, an organism from which another organism descends.

Prolate Spheroid......................................7
An imperfect sphere with a shorter equitorial axis and longer polar axis (see *oblate spheroid*).

Protoplanet 5
A developing planet that is formed from accretion of multiple bodies through gravitational attraction.

Pseudoscience 115
A system of beliefs which pretends to be scientific while not satisfying the criteria of a science. For Karl Popper, a pseudoscience is an ideology that makes verifiable but not falsifiable predictions (see *Popper, Karl*).

Ptolemy (90-168).................................134
Ptolemy invented the principles of map-making by compiling the cartographic discoveries of Ancient Greece; author of *Geographia* (see *Ancient Greece* and *Geographia*).

Puijila darwini 79
An ancient seal species that lived 23 million years ago. From fossil evidence, it is suggested to be a transitional species for seals returning from terrestrial life to marine life.

Pumice 28,30,107
A porous, low density volcanic glass formed through the rapid cooling of gas-rich felsic lava. Often forms stones that have a pattern of holes created by air bubbles during cooling.

Pumice Rafts 28
A large accumulation of pumice floating on the surface of a body of water. Pumice rafts may result from ocean-based or near-ocean volcanic activity.

Punctuated Equilibria 65
Eldredge and Gould's theory of evolution derived from their interpretation of the fossil record. This theory suggests that a species remains in a prolonged period of stasis before changing rapidly via geographic speciation (see *Eldredge, Niles*; *Gould, Stephen Jay*; and *geographic speciation*)

Pynchon, Thomas (b.1937) 15
An American novelist whose works ranged wildly in genre but were often complex and contained in-depth social and philosophical commentary.

Pyroclastic Debris 29
Fragments of volcanic material produced in an explosive eruption. This may include dust and ash, fragments less than 2 mm in diameter; cinders, 2-64 mm in diameter; or blocks and bombs, greater than 64 mm in diameter. Pyroclastic debris may be deposited as airfall depostis or by a pyroclastic density flow (see *tephra, airfall volcanic deposits,* and *pryroclastic density flow*).

Pyroclastic Density Flow 29,30
A dense mixture of gases and hot rock fragments which travels downslope from a volcano at very high velocities. Often triggered by the collapse of an eruption column, pyroclastic density flows travel at high velocity as pyroclastic debris flows over a thin layer of hot, expanding and escaping gases (see *pyroclastic debris*).

Pyroxene 131
One of a group of minerals composed of chain silicates that is found in many igneous and metamorphic rocks. Pyroxene has been found on the Moon.

Pythagoras of Samos (c.570-495 BCE)........ 6,72,116,134
An Ancient Greek mathematician and philosopher (see *Ancient Greece*). Pythagoras founded a religious sect called the Pythagoreans and taught mathematics. He is often attributed with the geometric principle Pythagorean theorem ($c^2 = a^2 + b^2$), although he is likely not the founder. He and his followers believed that a sphere is the perfect shape and therefore, that the Earth must be spherical. His proposition of a spherically shaped Earth contributed to cartography.

Quadrupeds 88
Organisms that walk on four legs.

Quaternary Glaciation 84
The glacial period extending from the beginning of the Pleistocene to the present day (see *Pleistocene*). Colloquially referred to as the ice age.

Ra (Atum-Ra)... 2
An Ancient Egyptian god of the sun, said to have given rise to the sky gods.

Racemic Mixture 58
A mixture of compounds of the same molecular structure but distinctive chirality.

Radar equipment (Doppler theory) 49
Used for doppler radar equipment. Analyzes signal frequency in microwave signals in order to determine distance and velocity data.

Radar equipment (Wave theory) 49
Measured wind waves create oscelating movement that transfers energy.

Radiometric dating.................................. 4
A process by which ratios of radioisotopes are measured to give approximate ages of a rock.

Ray, John (1627-1705) 69
An English naturalist. Referred to as the father of English natural history. Classified plants according to similarities and differences. First person to give a biological definition of species.

Rāzī, Muhammad ibn Zakariyā (865-925 CE) 98
Persian alchemist. Notable for being the first to distill kerosene from naturally occruing petroleum in the early 10th century.

Redi, Francesco (1626-1697) 57
Italian physician and naturalist, who performed the first true scientific experiment to prove that spontaneous generation was not a legitimate process.

Redox Titrations 141
A titration method that uses an oxidizing or reducing agent to consume analyte. This method involves having an analyte that is readily oxidized or reduced.

Refining 136-139
Purifying an impure material.

Relative Dating 75
Method of determining the relative order of past events. Used prior to the discovery of radiometric dating.

Relief Structures 132
Areas of varying elevation on the surface of the earth, such as hills or mountains.

Renaissance Era 24,134
A historical period in Europe approximately beginning in Italy in the 14th century and lasting until the 18th century. Period of significant changes in cultures and advances in human intellect as the result of the transition from theology-dominated thought into the beginnings of modern science (Sigurdsson, 1999).

Rhind Papyrus.....................................116
An Egyptian mathematical document dated to c. 1650 BCE scribed by the earliest named mathematician Ahmes.

Rhumb Lines 118
Also known as loxodrome, a rhumb line is defined to cross all meridians of longitude at the same angle.

Ribozyme 59
A molecule of RNA capable of catalysing its own replication, and the replications of other, similar strands.

Richardson, George Maxwell (Active in 1929) 141
Worked with Cannan at the University College in London to develop an interpretation of thioglycolate's reaction with ionic iron where the colour change results from the production of ferric thiogylconate (Cannan and Richardson, 1929).

Richter Scale 128
A quantitative measure of an earthquke's magnitude. It was developed in 1935 by Charles F. Richter, an American seismologist.

Ridge-push, Slab-pull Hypothesis...........23
A pair of forces thought to play a role in the movement of tectonic plates. Ridge push occurs as the

accumulating weight of mountains at mid-ocean ridges pushes the plate down and towards the subduction zone. Slab-pull occurs when the weight of older, denser ocean crust subducts at a trench area and pulls the rest of the slab along with it.

Rittman, Alfred (1893 – 1980) 26
A Swiss geologist who developed a graphical method to describe volcanic eruptions and published the influential book *Volcanoes and their Activity* (1936) (Lockwood and Hazlett, 2010).

Rivinus, August Quirinis (1652-1723) 69
A German physician and botanist also known as August Bachmann. Introduced several important innovations in taxonomy, including the classification of plants according to the structure of their flower, use of dichotomous keys, and the instigation of the rule that names of all species belonging to the same genus should start with the same word.

RNA-World Hypothesis 59
A postulate which suggests that the first molecules of life were composed of RNA, since this molecule is capable of both information storage and reaction catalysis. Evolution by natural selection would later differentiate these functions to create DNA for information storage, and enzymes for reaction catalysis.

RNA Replicase 59
An enzyme designed to catalyse the replication of RNA. According to the RNA-World Hypothesis, this enzyme eventually evolved from early ribozymes.

Rock cycle 3
Process by which the major different types of rocks form and change over time.

Rotation curve method 13
Method for calculating the mass of a galaxy. Invokes Kepler's Third Law, and can be used when both of a star's rotational speed and distance from the centre of mass of the galaxy are known.

Rowland, Frank Sherwood (1927-2012) 126
An American Nobel Prize laureate who researched atmospheric chemistry. He is best known for discovering that chlorofluorocarbons are a major cause of ozone depletion.

Royal Society... 7
A society in London founded in 1660 by King Charles II. It functioned as a center for science and ideas during the Enlightenment and remains in existance to this day.

Russell, Bertrand (1872-1970) 114
Famous British philosopher known for critiquing a wide range of metaphysical and theological ideas.

Rybczynski, Natalia (active)................... 79
A Canadian female paleontologist and paleobiologist at the Canadian Museum of Nature in Ottawa, Canada. She discovered the *Puijila darwini* fossil in Nunavut and has done extensive work on the morphology of several extinct species, including Sumina *getmanovi.*

S-Wave 16
A type of seismic wave emitted by an earthquake in which rock vibration is perpendicular to the direction of wave propagation. Also known as a Secondary Wave.

S.C. Johnson Company......................... 126
An American company that is one of the largest manufactures of consumer chemicals and that is also involved in scientific research.

Sabine, Edward (1788-1883)................ 121
Edward Sabine was the geophysicist that spearheaded the magentic crusade, which eventually led to the establishment of magentic observatories throughotu the British empire in the Victorian era.

***Sakoku* 33**
Japanese foreign policy in practice from 1633-1853, wherein immigrants were punished by death and emigrants were exiled.

Salt 102
A chemical compound of the form NaCl. Also known as sodium chloride, or the mineral halite. Characterized by its distinctive 'salty' taste, and white to transparent appearance.

Salt dome 103
A large domelike protrusion of salt.

Salt licks 102
A naturally occuring salt deposit frequented by animals, who lick the salt. Can also refer to artificial salt licks provide by farmers to their animals.

Saltworks 104
An establishment for the manufacture of salt.

Savannah Hypothesis of Human Origins 89
States that a quadrupedal ape lineage left a forest environment and spread out into more open grasslands where bipedalism evolved.

Schindewolf, Otto (1896-1971)............. 50
Geologist who proposed the catastrophic theory as the cause of the P-T extinction.

Scholasticism...................................... 112
Philosophical school which followed the works of Aristotle and reconciled them with traditional Christian dogma. Among its most notable members were Thomas Aquinas, Duns Scotus and St. Anselm.Scholasticism was most active in the Middle Ages.

Schönbein, Christian (1750-1837)........ 124
A Swiss chemist who is famous for inventing the fuel cell and discovering guncotton and ozone.

Schulman, Edmund (1908-1958)........... 42
American dendrochronologist who created a 9 000 year record of the climate in the South-western United States.

Scientific Revolution.................... 15,56,70
Period in the history of science where development in astronomy, biology, chemistry, mathematics, and physics transformed views of society and nature. Modern scientific inquiry was also developed during this period.

Thought to have begun at the end of the Renaissance era in Europe and continued until the late 18th century.

Through General Electric, introduced voltage scanning coulometry to detect traces amouns of iron. This assay lowered detection limits for higher sensitivity (Scott, Peekema and Connelly, 1961).

The measure of how resistant a sample is to fracture and scratching. Currently measured using Mohs scale of hardness.

A field volcanologist who published the first modern volcanology textbook (Lockwood and Hazlett, 2010).

Process whereby new oceanic crust is formed at oceanic ridges and slowly migrates away to eventually subduct back into the mantle at convergent plate margins.

Large, dark, basaltic plain within the Tranquility basin on the Moon.

Rocks formed by the deposition of material at the Earth's surface, most commonly within bodies of water. Composed of combinations of mineral grains (see *minerals*).

Deposition of particles out of a fluid.

The ability of an assay to detect and respond to small changes in analyte concentration. A higher sensitivity corresponds to a higher slope on a calibration curve.

A pendulum that can be used to calculate the force of gravity by measuring the period of its swing.

Scientific practice of identifying layers of rock by reflections from earthquakes.

Low frequency wave of energy caused an earthquake, explosion, or volcanic activity that travels either on the surface or through the Earth.

Instrument that measures seismic waves in relation to time (see *Seismic wave*).

The scientific study of earthquakes and seismic waves.

Instrument that measures seismic waves (see *Seismic wave*).

A co-aurthor of the Volcanic Explosivity Index, Professor Stephen Self is currently the head of the Volcano Dynamics Group in the Department of Earth Sciences and the Centre for Earth, Planetary and Astronomical research at The Open University, UK (Open University, 2012)(see *volcanic explosivity index* and *Newhall, Christopher G.*).

Direct knowledge from the senses, before the perceiver has evaluated it.

A king of Assyria that reigned from c. 705 to 681 BCE. Reclaimed over 40 Judean towns and cities, notably Lachish (see *Lachish*), by force.

A difference in physical appearance of a male and female within a species.

British geologist who was first to postulate that the ratio of isotopes oxygen-18 to oxygen-16 in marine records can determine the approximate quantity of planetary ice. Later he helped correlate oxygen isotope ratios from deep marine cores with the cliamte model developed by Milankovitch. He also generated an extensive marine chronology with John Imbrie.

Igneous rock structure formed in Siberia during the P-T as a result of extensive volcanic activity. These flood basalts provides evidence to support a volcanic kill mechanism for the Permian-Triassic mass exteniction event.

The process of mining under the walls of a city under siege (see *siege warfare*). Once mined, support structures are burned away to collapse the walls and allow entry to the attackers.

A type of warfare where walled cities or castles are attacked without entry being provided. Involves strategies revolving around cutting off supplies to the defender and destroying fortificiations.

A thick fluid-like mixture of a solid and a liquid, similar to mud.

Worked at the University of Arkansas with Harvey, and Amis, posed a drastic improvement in spectrophotometric measurements by silmultaneously detecting ferric and total iron (Harvey, Smart and Amis, 1955).

Called the "Father of English Geology". A coal surveyor that hypothesized that the relative positions of strata were consistent across great distances. Credited with the creation of the first nationwide geologic map.

French scientist who proposed that the presence of identical fossils on either side of the Atlantic could be the result of the Americas, Africa and Europe having once been connected.

Hypothesis of a fully glaciated Earth during the Neoproterozoic era (1 000 to 541 million years ago) to explain the existence of ice near the equator.

Soddy, Frederick (1877-1956)................ 43
British radiochemist who first proposed the existence of isotopes (*see isotope*).

Soret, Jacques-Louis (1827-1890) 124
A Swiss chemist who discovered the chemical composition of ozone. He is also noted for codisovering the chemical element holmium.

Species.. 60,90
A group of organisms that can mate successfully to produce viable, fertile offspring but cannot mate with organisms of another group to produce viable, fertile offspring.

Speciation 64
The process for the development of new species.

Species-to-genus ratio........................... 71
Ratio comparing the number of species with the number of genera during a length of time.

Specific.. 140
The ability of an assay to distinguish the analyte from interferences in the solution. A greater specificity means a higer signal to noise ratio.

Spectroscopy...................................... 124
The study of the interaction between electromagnetic radiation and matter.

Stanley, Steven (b.1941) 51
An american paleontologist and evolutionary botanist who proposed continental glaciation as the cause of sea level regression associated with the P-T extinction event.

Star Flake 105
A dendritic form of salt (see *salt*, *dendritic crystallization*) manufactured by the Morton Salt company.

Stasis... 66
The absence of morphological change in a species over an extended period of geological time.

Stem Group.. 71
Taxonomic group containing the group above minus the crown group, which leaves the primitive relatives of the crown group all the way to the last common ancestor. All the members of a crown group are extinct. Purely a way to classify fossils.

Steno, Nicolas (1638-1686)................ 3,73
Danish Catholic bishop and scientist. Developed the Law of Superposition, Principle of Original Horizontality, and Principle of Lateral Continuity.

Strabo of Amasia (64 BCE-24 CE) 133
A philosopher and geographer of Greek descent who lived in Ancient Rome; author of *Geographica*.

Strata 3,108
A layer of sedimentary rock with distinguishing characteristics. Makes up the stratigraphy of the Earth's crust.

Stratigraphic Sequences..................... 115
Branch of geology studying patterns in sedimentary deposits to look for uncomformity bound units and explanations of these patterns.

Stratospheric Aerosol Layer..................29
The layer of small water droplets in the second layer of the Earth's atmosphere in which volatile gases may dissolve. Of particular concern is the dissolving of sulfurous gases released from a volcanic eruption (see *volcanic aerosol layer*).

Streak..136-138
The colour a mineral produces when it is rubbed onto a surface harder than itself.

Striations..84
Scratches or gouges made in bedrock due to abrasion by debris embedded in the base of overriding glaciers.

Strutt, Robert J. (1875-1947) 124
A British physicist noted for his research involving the atmosphere. He was the first scientist to understand how nitrogen can cause the night sky to glow.

Styx14
A Greek mythological river that separated the underworld from the surface world. Dante adapted Styx for his own work, *Inferno*, in which Styx made up the entire fifth circle of Hell, Wrath.

Subduction Zone 23
Regions of the Earth's lithosphere where one tectonic plate is slowly forced beneath another plate and into the mantle. Usually results in the formation of deep trenches.

Subsidence 62
Downward motion of the earth materials.

Subterranean Fiction 15
A sub-genre of adventure fiction set in which part or all of a story is set in an underground location

Subterranean warfare 106
A type of warfare where miltary operations are conducted underground. Examples include siege mining (see *siege mining*).

***Suminia getmanovi* 79**
Living 260 million years ago in the late Permian, these early vertebrates are believed to have lived in deltaic regions and could climb trees due to their complex hand morphology.

Sunspots...42
Dark spots visible on Sun caused by high magnetic activity.

Superbug..63
A microorganism, such as bacteria, that has evolved to become resistant to all antibiotics.

Supercontinent.....................................21
Hypothetical former land mass formed by the convergence of multiple continents. Thought to undergo cycles of aggregation and separation.

Superposition 3
To be placed on or above another giving relative time of placement.

Surface wave 130
One type of seismic wave that travels along the surface of the Earth. It is slower than a body wave but can cause severe damage.

Surveying 134
A scientific technique for determining the position of points on the surface of the Earth, as well as the distances and angles between them.

Sustainability Science 135
A scientific discipline focusing on the understanding of global change and how humans are affected.

Syllogistic Logic 112
Method of reasoning for drawing inferences (conclusions) from statements (premises) that are certainly true if the premises are true.

Symees Jr., John Cleves (1780-1829)...... 15
An American Army officer who created a highly notorious Hollow Earth model.

Taxon 80
A taxon is a category for grouping or classifying organisms such as phylum, class, genus or species.

Taxonomy 68-71,91
The branch of science concerned with defining and classifying groups of organisms on the basis of shared characteristics and giving names to those groups.

Taylor, Frank Bursley (1860-1938) 20
American geologist remembered primarily for developing the idea of continental drift independently of Alfred Wegener.

Tectonic forces 128
Forces from within the Earth that cause movement and structural deformation of the crust.

Teleological 122
In science, teleological thought is generally accepted to mean the analysis of scientific phenomena through contemplation of what purpose it might serve humans.

Tenacity... 136
Describes the physical reaction of a mineral to force. Common examples are: brittle, malleable.

Tephra... 29,30
Airborne volcanic rock fragments blasted from a volcano during its eruption, or carried into the atmosphere by a convecting column of hot gases. These particles are carried downwind from the volcano before their deposition. Larger particles fall close to the volcanic vent, while smaller particles travel further, creating layers of volcanic deposit which gradually thin with increased distance from the volcanic vent (see *eruption column, volcanic vent,* and *pyroclastic debris*).

Tephra Layers 89
Layers of volcanic material (ash) which originated as solid matter ejected from an erupting volcano. Tephrochronology is the science of using tephra layers as a dating tool.

Terrace 95
Refers to Incan structures which modify slopes by the construction of flat sections of land resembling stairs. Used to provide a platform for agriculture.

Theory of Abiogenesis 56
Theory concerning the origin of life, which postulates that life develops from previously non-living compounds.

Theory of Inheritance of Acquired Characteristics 60
Also known as Jean Baptiste Lamarck's "First Law", this thoery proposed that behavioural and physiological characteristics acquired in an organism's lifetime could be passed on to offspring (Campbell, et al., 2007)

Theory of Spontaneous Generation 56
Obsolete theory which suggests that certain animals are generated spontaneously from certain materials such as hay or feces.

***The Art of War*....................................106**
A classic book about military strategy. It emphasizes the importance of terrain in war, and was written in Ancient China by Sun Tzu (see *Sun Tzu*).

Thales (625-547 BCE) 6
A greek philosopher, sometimes referred to as the first of his time. Thales tried to step away from mytholodgy to develop alternative explanantions for natural phenomena. He described the Earth as a circular disk.

***Theatrum Orbus Terrarum*...................134**
The first modern atlas including the Americas. Developed in 1570 by Abraham Ortelius.

Thematic Map 135
A type of map that displays a particular theme associated with a geographical area, such as soil types, slopes, or watershed.

Theophrastus (371-287 BCE) 107,136,137,139
An Ancient Greek scholar and philosopher. Observed the behaviour of different rocks when heated and recorded findings in a book called *On Stones* (see *On Stones*).

Thermoluminescence 75
Emission of light from certain crystalline materials after absorbing ionizing radiation. Can be used for dating samples not able to be dating using radiocarbon dating, for example, sediments..

Theropod..80
A theropod is a group of diverse liz6ard-like carnivorous bipedal dinosaurs of all sizes.

Theropods 67
A suborder of bipedal dinosaurs within Dinosauria. Modern birds are the descendants of theropods.

Thomson (active 1885) 140
One of the first analytical chemists to work on iron identification. Credited with the ferric thiocyanate method for qualitative iron determination (Elvehjem and Hart, 1926).

United States Geological Survey (USGS) 128
US federal agency that provides scientific information about the Earth in regards to its resources and natural hazards.

Upper Paleolithic.................................. 72
Subdivision of the Paleolithic Age from approximately 50 thousand to 10 thousand years ago.

Urey, Harold Clayton (1893-1981) 44,58
American physical chemist and winner of the 1943 Nobel Prize in Chemistry. Showed that different oxygen isotopes are more abundant at different temperatures. Well known for 1952 experiment with Stanley Miller, which tested the Oparin-Haldane model (see *Miller-Urey Experiment*).

Ussher, James (1581-1656)................. 2,76
A scholar and archbishop of Ireland known for his chronology that established the creation of the Earth, according to the Bible, to be Sunday October 23, 4004 BCE.

Vail, Peter (b.1930).............................. 115
Geologist who proposed the global eustacy model.

van Marum, Martinus (1750-1837)...... 124
A Dutch scientist who is famous for his experiments involving electricity and chemistry.

Variable.. 115
In the sciences, a measurable quantity that changes, often in conjunction with changes in other measurable quantities.

Vein (of mineral) 137,138
A long body of crystallized minerals in ore.

Verificationism................................... 114
Doctrine that makes the capacity for predictions to be verified experimentally the criterion of science. This was favored by the Logical Positivists (see *Logical Positivism*).

Verne, Jules (1828-1905) 15
A French author who is considered by many to be the grandfather of science fiction. Verne popularized subterranean fiction with his book "*Voyage au centre de la Terre*" (Journey to the Center of the Earth).

Viceroy 104
An official who runs a country in the name of a monarch.

Virgil (70-19 BCE).................................. 14
A Roman poet best known for writing the *Eclogues*, *Georgics*, and *Aeneid*. Virgil strongly influenced Western Literature and notably appeared in Dante's *Divine Comedy*.

Volcanic Aerosol Layer 29
The layer of sulfurous gases and volcanic ash particles injected into the stratosphere during a large eruption. This layer has the potential to alter global climate by scattering solar radiation back into space while also heating the stratosphere by absorbing some solar and terrestrial radiation (see *stratospheric aerosol layer*).

Volcanic Conduit............................. 30, 31
A passage or set of passages through which magma travels from the Earth's mantle to the surface of the Earth. (see *volcanic dike*).

Volcanic Dike 31
A type of igneous intrusion which is often tabular in form and cuts across the planar structures of pre-formed adjacent rocks. A dike is formed as magma ascends through a vertical or sub-vertical facture in the Earth's crust, then cools to form a sheet of rock (see *volcanic conduit*).

Volcanic Explosivity Index (VEI) 29,30
A scale developed in 1982 by *Christopher G. Newhall* and *Stephen Self*, and used to classify volcanic eruptions by their size. The VEI ranges for 0 to 8, with 8 being the greatest magnitude. Classification is based upon all available information on a volcano's column height, magnitude, intensity, destructiveness, dispersive power, violence, blast duration, and energy release rate (see *Newhall, Christopher G.* and *Self, Stephen*).

Volcanic Fumaroles................................31
Vents at which volatile gases from the interior of a volcano reach the ground surface. These gases include, but are not limited to, steam (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen sulfide (H_2S). Deposits may be formed as these gases cool and settle to the ground.

Volcanic Vent...30
An opening in the surface of a planet, through which volcanic materials are released during an eruption.

Volcanology 24
A scientific field focussing on the study of volcanoes and their activity.

von Humboldt, Alexander (1769-1859) 20
Prussian geographer credited with being the first to scientifically describe Latin America during an exploratory expedition. Also recognized for his work *Kosmos*, a comprehensive compilation of the various branches of science.

von Laue, Max (1879-1960)..................139
A German physicist who discovered the diffraction of X-rays when passing through crystal structure. He won the 1914 Nobel Prize for Physics for this.

Water stratification 50
Occurs when layers of water are separated. This can be caused by differences in density, salinity levels, or oxidation.

Water-table 130
Upper surface of ground water where the pressure of water in soil is equivalent to the atmospheric pressure.

Watt, James (1736-1819) 99
Inventor of the first practical steam engine. Made improvements on Newcomen's original design, allowing the engine to be used in numerous novel ways.

Wegener, Alfred (1880-1930)............20,26
A German meteorologist and geophysicist who proposed the theory of continental drift. Also made

many significant contributions to the field of meteorology.

Werner, Abraham (1749-1819)............. 25
An influential German geology teacher who developed the Neptunian Theory of the Earth (see *Neptunism)*.

Whitcomb Jr., John (b.1924).................. 46
Influencial young earth creationist. Co-wrote *The Genesis Flood.*. Studied historical geology and paleontology at Princeton University. Graduated with B.D. degree at Grace Theological Seminary.

Wiechert, Emil (1861-1928)................. 130
German geophysicist who constructed the first damped seismograph as well as the inverted pendulum seismgograph.

Wignall, Paul (active 1990).................... 51
Geologist who, with partner Anthony Hallam, hypothesized that sea level was rising 250 million years ago during the P-T transition.

Willughby, Francis (1635-1672)............. 69
An English ornithologist and ichthyologist. Participated in various expeditions with friend John Ray until his sudden death.

Wofsy, Steven C. (active)..................... 125
A professor at Harvard University and is noted for his research into the exchange of gases between the biosphere and the atmosphere.

Woolley, Sir Charles Leonard (1880 – 1960).. 46
He is condsidered the first modern archaeologist and knighted for his efforts. Famous for discovering royal tombs in Ur, Mesopotamia.

World War II (1939-1945)...................... 43
Global war between opposing military alliances, the Allies and the Axis, which became the most widespread war in history.

Wright Brothers 99
First humans to successfully complete a powered flight using a gasoline powered internal engine.

Wright, Edward (1561-1615) 119
English mathematician and cartographer. His work showed the exact distortion of area caused by Mercator projections with respect to degree of latitude (see *Mercator Projections*).

Xiaotingia.. 67
A bird-like dinosaur recently discovered in China. The study of *Xiaotingia* contributed to the relocation of *Archaeopteryx* on the evolutionary tree.

X-club... 120
A collection of scientists who gathered in order to discuss science and progress. The X-club developed into a voice for the scientists of the Victorian era through which they could adress matters in the philosophy of science (Macleod, 1971).

Yoe, John H. (1892-1975) 142
Worked at the University of Virginia to improve on the Fortune and Mellon assay by changing the chromophore to improve specificity for iron (Yoe and Jones, 1944).

Young, Davis (active 1995) 46
Studied engineering at Princeton University and mineralogy and geochemistry at Pennsylvania State University. Doctorate earned at Brown University in geological science. Won Mary C. Rabbitt History of Geology Award in 2009. Author of many publications including *Creation and the Flood: An Alternative to Flood Geology and Theistic Evolution.* President of the Affiliation of Christian Geologists.

Ypres 108
An area in West Flanders, Belgium. Known as a battlefield in the First World War (see *First World War*).

Zeitgeist 14
The dominant mode of thought representative of a period's culture.

Zerefos, Christos (b.1943)......................29
Professor of Atmospheric Physics at the Universities of Thessaloniki and Athens, and Post Doctoral researcher at the National Center for Atmospheric Research, Christos Zerefos worked with colleagues at the Observatory of Athens to categorize over 500 historical paintings by the level of volcanic aerosols present in their sunsets (Biomedical Research Foundation Academy of Athens, 2012) (see *volcanic aerosol layer*).

Zipper-rift...45
Theory proposed by Nicholas Eyles, that explains the existences of near equatorial ice during the Neoproterozoic by means of rifting along continental margins, which forms plateaus suitable for hosting glaciers.

Zonal Indicator 74
Fossils which are used to identify geologic priods.

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Cover
Pool in Cub Run Cave, Kentucky. Mabee, M., 2012.

Table of Contents
Moraine Lake. Moor, B., 2001.

Introduction
p.ii Divergent Plate Boundary. Kasper, A., 2008.

Chapter I
p.1 Earth Rise. Wikimedia Commons, Anders, B., 1968.
p.2 The Ancient Egyptian sun god Ra. Wikimedia Commons, Kompak, K., 2010.
p.3a A portrait of Nicolas Steno. Wikimedia Commons, Manske, M., 2004.
p.3b The differentiated Earth model. Wikimedia Commons, Halldin, M., 2005.
p.4 A photograph of the Grand Canyon. Wikimedia Commons, Galuzzi, L., 2007.
p.5 A chondrite found in North Africa. Wikimedia Commons, Meteorite Recon, 2007.
p.6 A timeline of the dominant model of the Earth. Englert, E., 2012.
p.7 Portrait of Isaac Newton. Wikimedia Commons, Unknown, n.d.
p.9a GPS devices come in many forms. SmugMug, Tong, S., n.d.
p.9b GPS devices come in many forms. Arte&Fotografia, Jorge, E., 2012.
p.9c GPS devices come in many forms. Englert, R., 2012.
p.10a Planet Earth.. Wikimedia Commons, NASA, 2000.
p.10b Sir Isaac Newton. Wikimedia Commons, Kneller, G., 1669,
p.11 World-weighing apparatus. Wikimedia Commons, Cavendish, 1798.
p.12 Timeline of events in Earth's density's discovery. Martin, H., 2012.
p.13 A galaxy. Wikimedia Commons, NASA, 1995.
p.14 Dantes Werke. Wikipedia, Ritter, A., 1922.
p.15a Halley with diagram. Wikimedia Commons, Unknown, 1736.
p.15b Concentric spheres hollow Earth. Wikimedia Commons, Croquant, 2006.
p.15c Inner sun hollow Earth. Wikimedia Commons, Croquant, 2006.
p.15d Concave hollow Earth. Wikimedia Commons, Cesa, J., 2010.
p.16 Speed of seismic waves versus depth into the Earth. Wikipedia, Ohrea, B., 2010.
p.17a Earth layers model. Wikimedia Commons, Halldin, M., 2006.
p.17b Mars interior. Wikimedia Commons, NASA, 2005.

Chapter II
p.18 Mount Rinjani eruption with volcanic lightning. Wikimedia Commons, Spalt, O., 1995.
p.20 Creation and Its Mysteries Unveiled. Wikimedia Commons, Snider-Pellegrini, A.,1858.
p.21 The origin of continents and oceans. Wikimedia Commons, Wegener, A., 1929.
p.22 Diagram demonstrating formation of new ocean crust. Wikimedia Commons, Pelech, O., 2007.
p.23 Subdivision of the earth's lithosphere into plates. Wikimedia Commons, Unknown, 2004.
p.24 Eruption of Mount Etna. Wikimedia Commons, NASA, 2002.
p.25 James Hutton. Wikimedia Commons, Raeburn, H., before 1798.
p.26 The 1902 eruption of Mount Pelée. Wikimedia Commons, Heilprin, A., 1902.
p.27 Volcanic activity on Io. NASA Image of the Day Gallery, NASA/JPL, 1997.
p.28 Layers of volcanic tephra and pyroclastic debris. Wikimedia Commons, Brank, L., 2011.
p.29a The Lake Petworth Sunset. Tate, 2012.
p.29b Sunset. Tate, 2012.
p.30 Isopach map for 1815 CE eruption of Tambora. Wikimedia Commons, Woudloper, 2010.
p.31 Gas collection from Mt. Baker, WA. Wikimedia Commons, Chadwick, W., 1981.
p.32 Tsunami crashing through palm trees. Wikimedia Commons, Rydevik, D., 2004.
p.33 Tsunami hazard zone. Wikimedia Commons, Harriv, 2005.
p.34 Tsunami size scale. Wikimedia Commons, Vasquez, D., 2004.
p.35 Dart Tsunamicover. Wikimedia Commons, National Oceanic and Atmospheric Administration, 2012.

Chapter III
p.36 Adeche Gorge. Wikimedia Commons, Wieschendahl, G., 2004.
p.38 The hydrologic cycle as understood by Da Vinci. Moor, K., 2012.
p.39 River systems in northern France. Wikimedia Commons, Shizhao, 2005.

p.40 The water cycle. Wikimedia Commons, Saperaud, 2005.
p.41 Groundwater flow. Wikimedia Commons. KrisK, 2005.
p.42a Earth orbital eccentricity. Thomson Higher Education, Unknown, n.d.
p.42b Precession. NASA GSFC, Simmon. R., n.d.
p.42c Variation in axial obliquity. NASA GSFC, Simmon. R., n.d.
p.43a Rainfall recorded in tree rings. NASA, Hughes, 1999.
p.43b Tree rings. NASA, Grissino-Major, H.D., n.d.
p.43c Radioactive decay of carbon-14. CK-12 Earth Sciences, Rosenkrantz, K., 2010.
p.44 Oxygen isotope ratios. NASA, Jouzel et al., 1994.
p.45 Snowball Earth. SPL, Butler, C., n.d.
p.48 Mount Ararat. Fotopedia, Djajasasmita, B., 2010.
p.49a Anorthosite rock. Wikimedia Commons, Sosnowski, P., n.d.
p.49b Radar image. NOAA, Unknown, 2012.
p.50 Location of P-T Extinction on geologic time scale. Rotondi, J., 2012.
p.51 An image of Pangea. Wikimedia Commons, Dejendi, 2007.
p.52 An image of a bucky-ball. Wikimedia Commons, Hajv01, 2008.
p.53 Aquatic dead zones map. Wikimedia Commons, NASA, 2010.

Chapter IV
p.54 Fossilized Velociraptor Eggs. Fotopedia, CameliaTWU, 2009.
p.56 Photograph of a fresco of Aristotle. Wikimedia Commons, Keslon, 2005.
p.57 Schematic of the Swan-neck flask experiment. Wikimedia Commons, Carmel830, 2010.
p.58 Schematic of the Miller-Urey experiment. Wikimedia Commons, YassineMrabet, 2008.
p.59 Model of an *E. Coli* ribosome. Boston Museum of Science, Iwasa, J., n.d.
p.60 Portrait of Jean Baptiste Lamarck. Wikimedia Commons, Thevenin, C., 1802-1803.
p.61 Darwin's Galapagos finches. Wikimedia Commons, Gould, J., before 1882.
p.62 Darwin's tree of life. Wikimedia Commons, Darwin, C., 1859.
p.63 Melting of arctic ice cap. National Aeronautics and Space Administration, Viñas, M., 2012.
p.64a Anaximander. Wikimedia Commons, Unknown, 2006.
p.64b On the Origin of Species book. Wikimedia Commons, Unknown, 2012.
p.65 *Phacops rana* compound eye. Wikimedia Commons, Unknown, 2011.
p.66 Comparison of phyletic gradualism and punctuated equilibrium. Wikimedia Commons, Chavez, M., 2008.
p.67 *Archaeopteryx* Berlin specimen. Creative Commons, Chan, D., 2010.
p.68 Classification of the category of substance. McPherson, S., 2012.
p.69 *Campanula rotundifolia*. Wikimedia Commons, Lavin, M., 2003.
p.70 Portrait of Carolus Linnaeus (1707-1778). Wikimedia Commons, Scheffel, J.H., 1739.
p.71 Masiakasaurus knopfleri Fossil Partial Skeleton on Display at the Royal Ontario Museum. Wikimedia Commons, CaptMondo, 2012.
p.72 Ammonite fossil. Creative Commons, Unknown, 2012.
p.73 Fossil excavation site in Spain. Creative Commons, Mata, M., 2008.
p.74 The Tiktaalik forms a morphological bridge between the fishes and tetrapods. A firm step from water to land, Ahlberg and Clack, 2006.
p.75 Machinery like mass spectrometers can be useful in radiometric dating. Creative Commons, 2007.
p.76 A painting of Anning. Wikimedia Commons, Donne, 1856.
p.77 A sketch of a plesiosaur fossil. Wikimedia Commons, Buckland, 1918.
p.78 A plaque commemorating Anning. Wikimedia Commons, Cornelius, 2006.
p.79 An artist rendition of P. Darwin. Wikimedia Commons, Tamura, 2009.
p.80 Megalosaur footprints. Wikimedia Commons, Ballista, 2006.
p.81 Othniel C. Marsh and Edward D. Cope. Wikimedia Commons, Unknown, n.d.
p.82 Fossil fragments in mud. Wikimedia Commons, Circa24, 2001.
p.83 *Ornthomimus* fossil. Wikimedia Commons, Bergmann, S., 2004.
p.84 Elephant jaw drawing by Georges Cuvier. Creative Commons, Cuvier, G., 1796.
p.85 Glacial striations. Creative Commons, Amezcackle, 2003.
p.86 Ice age fauna of northern Spain drawing. Creative Commons, Antón, M., 2004.
p.87 Milankovitch variations. Creative Commons, Rohde, R., 2006.
p.88 Portrait of Dr. C. Owen Lovejoy. FlickrCC, Hurd, C., 2012.
p.89 Cast of Laetoli footprints. Wikimedia Commons, Evanston, T., 2012.
p.90 Skeleton of Lucy. Wikimedia Commons, Donmatas, 2011.
p.91 Ape and human evolutionary tree. Wikimedia Commons, Kübelbeck, A., 2008.

Chapter V
p.92 Machu Picchu, Peru. Fotopedia, Szeke, 2007.
p.97 A DEM of the Andes. NASA/JPL/NIMA, Unknown, 2000.
p.99 Coal. Flickr, Beall, J., 2012.
p.100 A petroleum refinery in Grangemouth, Scotland. Wikimedia Commons, Unknown, 2006.
p.101 Graph of carbon emissions. Wikimedia Commons, Thorpe, M., 2010.
p.102 Making salt (a slight return). Fotopedia, Mononen, J., 2008.
p.103 Salt mine. Fotopedia, blankdots, 2007.
p.104 The Burghley nef. Wikimedia Commons, Nguyen, M., 2012.

p.105a Halite. Wikimedia Commons, Lavinsky, R., 2010.
p.105b Ice crystal ferns. Fotopedia, photoholic1, 2008.
p.106 Assyrian battering and archers. Wikimedia Commons, Iglonghurst, 2006.
p.107 Teofrasto. Wikimedia Commons, Singinglemon, 2009.
p.108 Battle of Messines. National Library of Scotland, Brooke, J.W., 1917.
p.109a The mechanism of a scratch. Valdron, J., 2012.
p.109b Selpologne. Wikimedia Commons, Descouens, D., 2009.

Chapter VI

p.110 Northern lights. Koo, M., 2011.
p.112 Francis Bacon. Wikimedia Commons, BurgererSF, 2012.
p.113 David Hume. Wikimedia Commons, Huerlisi, 2004.
p.114 Bedform stability diagram for flows approximately one meter deep. Physical Geology & the Environment, Plummer et al., 2007.
p.117 Erotosthenes' method Geodesy for the Layman. Unknown, 2011.
p.118 Rhumb lines. Wikimedia Commons, Unknown, 2006.
p.121a Charles Lyell in 1875. Wikimedia Commons, Unknown, 1875.
p.121b Edward Sabine in 1873. Wikimedia Commons, Unknown, 1873.
p.121c John Tyndall ca.1885. Wikimedia Commons, Unknown, 1875.
p.122 Charles Darwin in 1830. Wikimedia Commons, Leakey, R. and Lewin, R., late 1830's.
p.123 The museum of creation and earth history. Wikimedia commons, Mycota, 2003.
p.124 The molecular structure of ozone. Wikimedia Commons, Mills, B., 2006.
p.126 What the ozone layer would look like if the Montreal Protocol had never been banned ODSs. Wikimedia Commons, NASA, 2009.
p.126 The catalytic destruction of ozone by CFCs. Wikimedia Commons, Sparling, B., 2003.
p.128 An aerial photograph taken in 2010. Creative Commons, Abassi, L., 2010.
p.129 A replica of Chang Heng's seismometer. Creative Commons, Unknown, 2005.
p.130 Milne's seismograph was made the standard earthquake detector in his time. Encyclopædia Britannica, Unknown, n.d.
p.131 During the Apollo 11 mission on July 21st, 1969. National Aeronautics and Space Administration, Unknown, 1969.
p.132 Babylonian maps. Wikimedia Commons, Unknown, n.d.
p.133 Turin papyrus map part. Wikimedia Commons, Zyzzy, n.d.
p.134 Claudius Ptolemaeus. Wikimedia Commons, Manuel, 2005.
p.135 Diagram illustrating the map overlay process. Pennsylvania State University, DiBiase, D., 2012.
p.138 Needles for assessing alloys. Agricola on Metals, Dibner, B., 1958.
p.139 MESSENGER X-ray spectrometer. Oxford Instruments.
p.140 Hematite. Creative Commons, Wilson, M.A., 2008.
p.141 Calibration Curve. American Chemical Society, Fortune, W.B. and Mellon M.G., 1938.
p.142a Electrolysis Cell. American Chemical Society, MacNevin, W.M. and Baker, B.B., 1952.
p.142b Titration Curve. American Chemical Society, Scott, F.A., Peekema, R.M. and Connally, R.E., 1961.

Conclusion

p.144 Icelandic Canyon. Kasper, A., 2008.