History of the Earth

Volume II: Science through the Ages

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The Tablelands in Newfoundland is an area of stony infertile soils and ultramafic rocks believed to originate from the Earth's mantle. This region provides a great Canadian historical example of plate tectonic movement and composition of the Earth's core.

Foreword

Gerard V. Middleton
Professor emeritus of Geology

Science is the Differential Calculus of the mind,
Art is the Integral Calculus; they may be
Beautiful apart, but are great only when combined.

— Sir Ronald Ross
quoted by Hugh MacDiarmid, above his poem Poetry and Science,
pp. 196-197 in Selected Poetry *(NewDirections).*

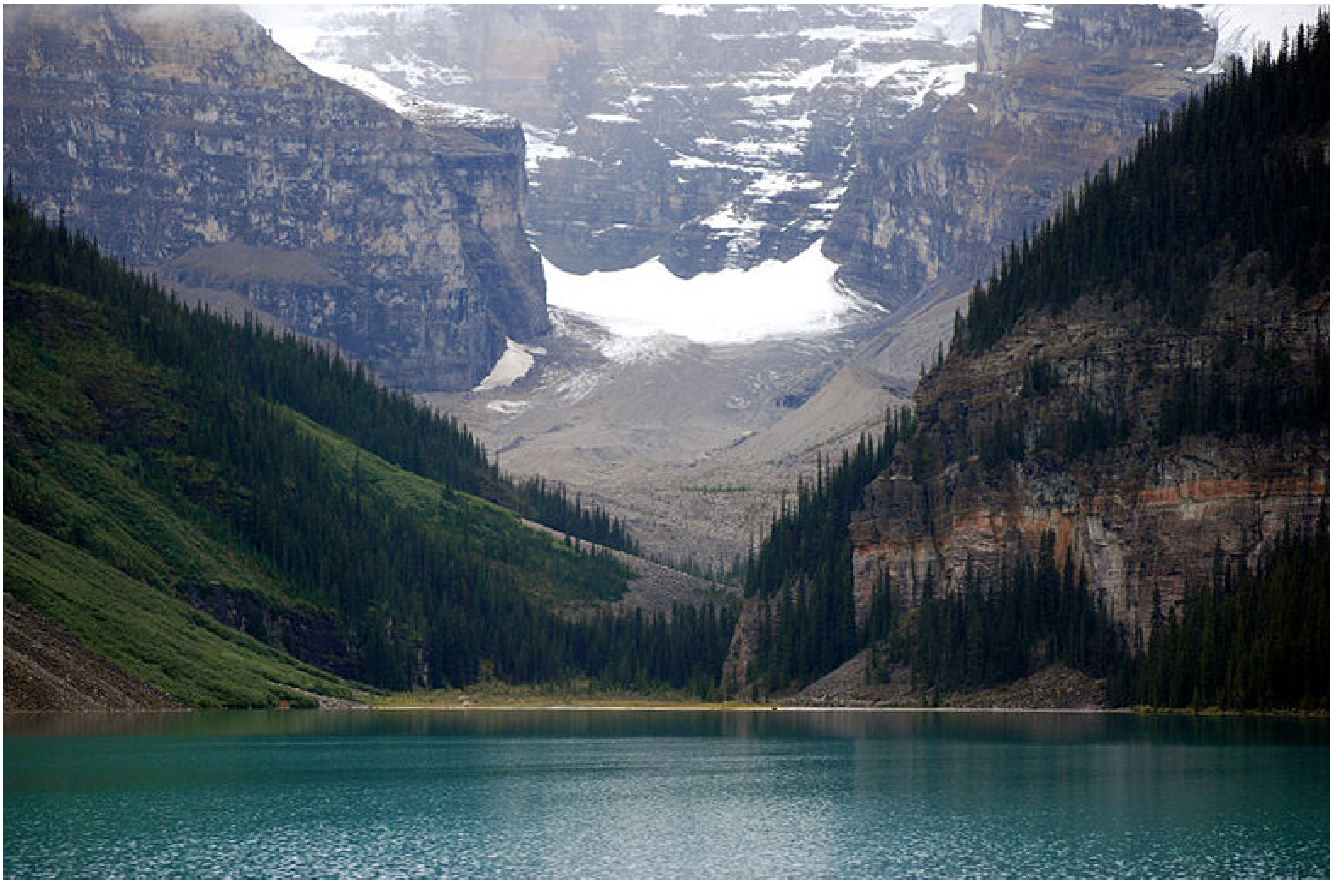
The history of geology as a science dates back at least to the end of the eighteenth century, but geology as a profession dates to the middle of the nineteenth century, when the British government began funding the Geological Survey, directed by Henry de la Beche (1835). Its establishment was preceded by that of several state surveys, and followed rapidly by that of many other national surveys, including the Geological Survey of Canada (1842). Their aim was to classify the exposed rocks stratigraphically, and to determine their value as natural resources (at that time, mainly coal, metallic ores, and building materials).

Study of the history of science can perhaps be dated back to 1837, when William Whewell published his *History of the Inductive Sciences*. Whewell himself was not a historian but a typical Victorian polymath. Born in 1794, son of a carpenter, he attended Trinity College, Cambridge, where he was awarded the Chancellor's gold medal for poetry and was Second Wrangler in 1816 (i.e., he stood second in the examinations mathematics). He served as Professor of Mineralogy from 1828 to 1832. He is remembered by geologists mainly for introducing several neologisms, including the term "uniformitarianism" to describe Lyell's philosophy of geology. In a second volume on *The Philosophy of the Inductive Sciences* (1840) he also introduced the concept of "consilience," which has recently been revived by the biologist Edward O. Wilson, as a more useful criterion for the truth of a scientific theory than the one more often cited by physical scientists, namely survival of experimental tests, which is difficult to apply to natural sciences such as geology and some aspects of biology (e.g., evolution). The professionalization of the history of science dates to the writings of George Sarton and I. Bernard Cohen, and the founding of the journal Isis in 1912.

Though many scientists are interested in the history of science, it is rarely taught in science departments, and is mentioned only briefly in most disciplinary text-books. The idea that science itself, taught from an historical perspective, should be part of a liberal university education was first strongly urged by James Bryant Conant, a noted American chemist, who served as President of Harvard from 1933 to 1953, and transformed it from a "parochial to an increasingly 'diverse' and world-class research university" (Wikipedia). For the Harvard general education program taught in the 1940s, Conant developed a series of *Case Histories in Experimental Science* (two volumes, 1957). Thomas Kuhn, a student in physics at Harvard, helped develop this program and later taught history of science there from 1948 to 1956. In 1961 he published his long paper *The Structure of Scientific Revolutions* which became the single most influential work in history and philosophy of science in the late twentieth century. Meanwhile, in England the British physicist and novelist C.P. Snow delivered his Reith Lecture *The Two Cultures*, in which he deplored the growing gap (in the U.K.) between literary intellectuals and scientists. Many scientists, like Dirac, were surprised to discover that they were not even considered to be intellectuals.

The attempt to remedy this state of affairs, and follow Harvard's example, influenced many innovative undergraduate programs in education: notable examples at McMaster being the Arts and Science Program; and since 2009, the iSci program. Though these programs involve only a small number of students, one can only hope that their influence on undergraduate education will be widely felt. Reading through the students' contributions collected in this volume one is impressed by the diversity of the topics covered, and of the literature sources on which they are based. The number of professional historians of the earth sciences is still relatively small: among those listed in the references are Peter Bowler, Joe Burchfield, James Fleming, Naomi Oreskes, Martin Rudwick, and Michael Ruse (who used to teach at University of Guelph). Others not cited, but worth well-worth looking up, are Rachel Lauden (*From Mineralogy to Geology*), David Oldroyd (*Thinking About the Earth*), James Secord (*Controversy in Victorian Geology*; *Victorian Sensation*) and Hugh Torrens. As regards periodicals, besides *Isis*, there is now the *British Journal for the History of Science* (both cover the history of the earth sciences), and *Earth Sciences History*, the only international journal devoted exclusively to the history of the earth sciences.

As well represented by the papers in this volume, most of the history of the earth sciences is still being written by scientists who are not professional historians, or by journalists or science writers (e.g., Simon Winchester, who studied geology as an undergraduate; or Alan Cutler, or Cherry Lewis, both of whom have doctorates in geology; or John Gribbin; or Stephen Baxter). If it is important that the (still existing gap) between literary intellectuals and scientists should be bridged, it is also important that a new gap should not open up between "amateur" and professional historians. Students graduating from the iSci program will be well placed to make sure this "gap" does not widen.



Lake Louise and Victoria Glacier in Banff National Park, Canada.

Geology is intimately related to almost all the physical sciences, as is history to the moral. An historian should, if possible, be at once profoundly acquainted with ethics, politics, jurisprudence, the military art, theology; in a word, with all branches of knowledge, whereby any insight into human affairs, or into the moral and intellectual nature of man, can be obtained. It would be no less desirable that a geologist should be well versed in chemistry, natural philosophy, mineralogy, zoology, comparative anatomy, botany; in short, in every science relating to organic and inorganic nature. With these accomplishments the historian and geologist would rarely fail to draw correct and philosophical conclusions from the various monuments transmitted to them of former occurrences.

— Sir Charles Lyell

Principles of Geology (1830-1833), Volume 1, 2-3.

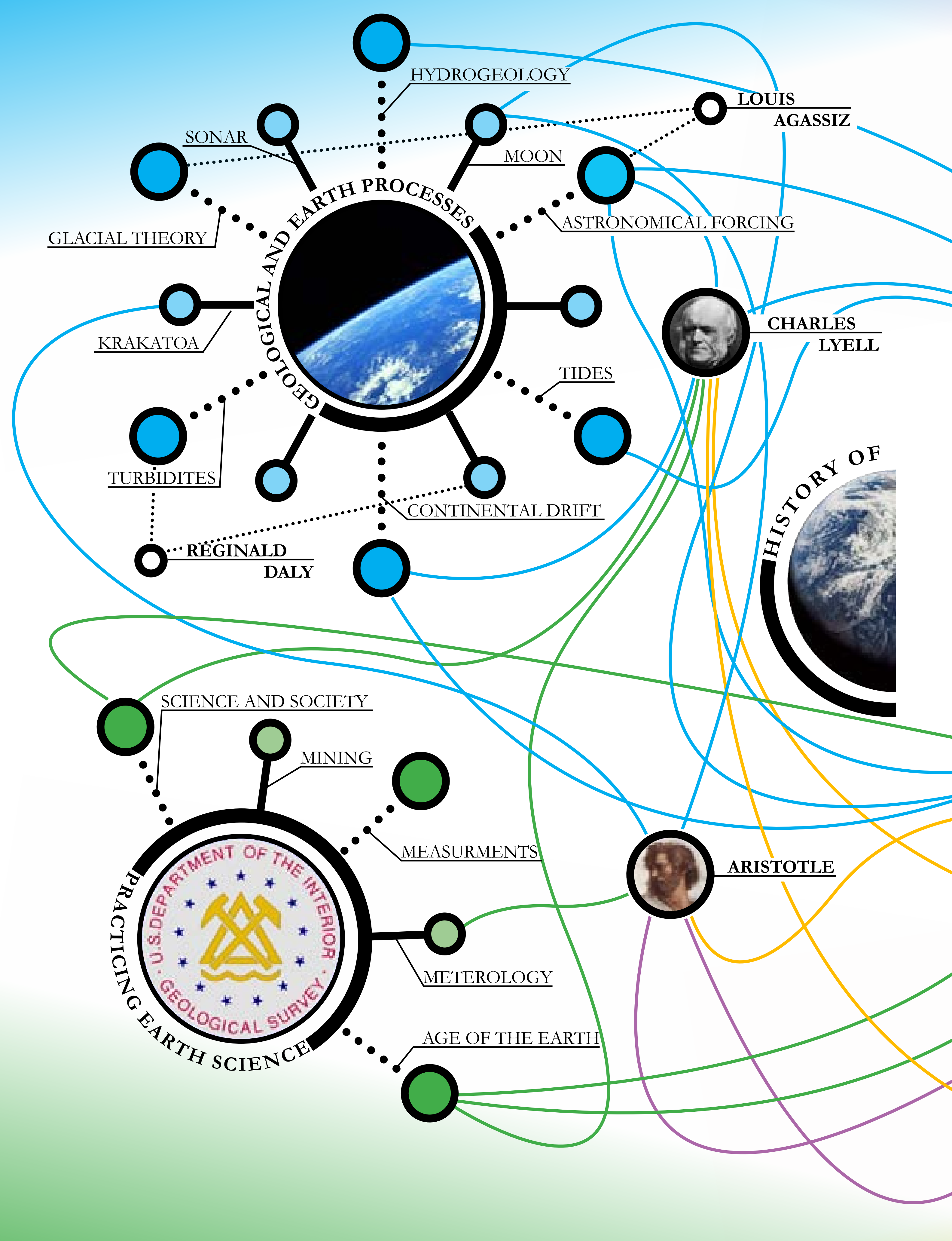
Introduction

Throughout its 4.6 billion year history, the Earth has been subjected to constant change. Our planet has seen the formation and splitting of continents, the expansion and retreat of glaciers, and the development and erosion of mountains. Similarly, the field of Earth Science has also evolved, with the formation of new disciplines and the subdivision of existing areas of study driving more recent discoveries. Innate human curiosity has led many scientists to study their surrounding environments, leading to the advancement of the field of Earth Science.

History of the Earth - Science through the Ages is divided into four chapters, each focusing on a different theme relevant to the history of the discipline of Earth Science. Within each chapter, the development of scientific ideas that apply to the Earth Sciences is explored. The four chapters found within this book focus on scientific developments related to important themes within Earth Science: geological and Earth processes, the chemical and physical properties of the Earth, the understanding of organisms found on this Earth, and the applications gained from this knowledge to human endeavours.

This book not only tells the stories of scientific discoveries and interpretations in Earth Science, but also discusses the people responsible for these findings. Each discovery was influenced by the societal, cultural and academic perspectives of its time period. As you progress through the book, you will see how ideas have changed through time, and will appreciate the benefit of scientific collaboration and the integration of ideas from different disciplines.

This book seeks to foster an appreciation for the interdisciplinary perspectives that have shaped our understanding of the Earth's history and to encourage the reader to carry this view forward into future scientific endeavours. Major strides in Earth Science are often made by scientists who combine approaches used in various disciplines including biology, physics, chemistry, and mathematics, and not by those who work solely in one field. To help the reader more fully understand the interdisciplinary aspects of Earth Science, a visual summary of concept connections is provided on the next two pages.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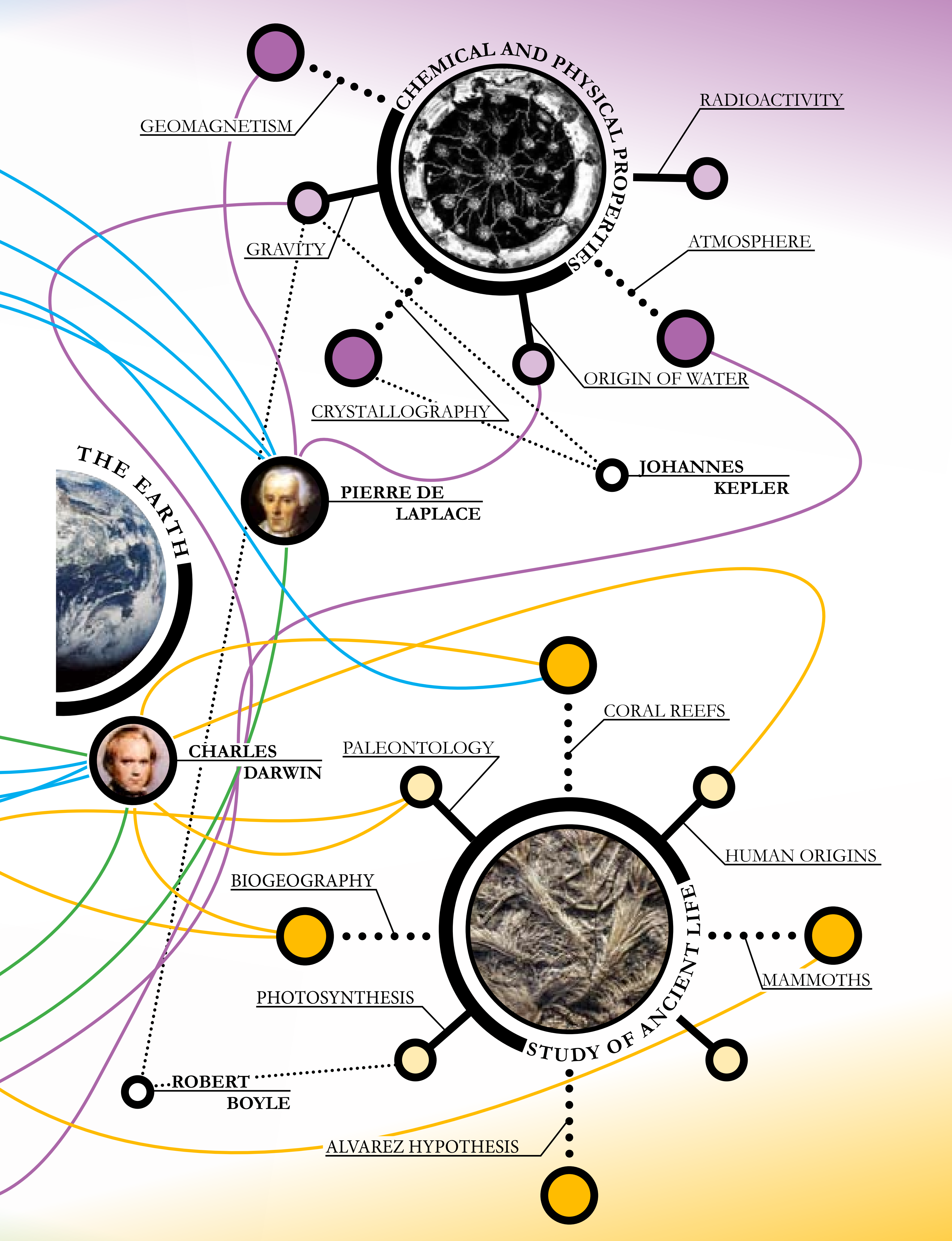
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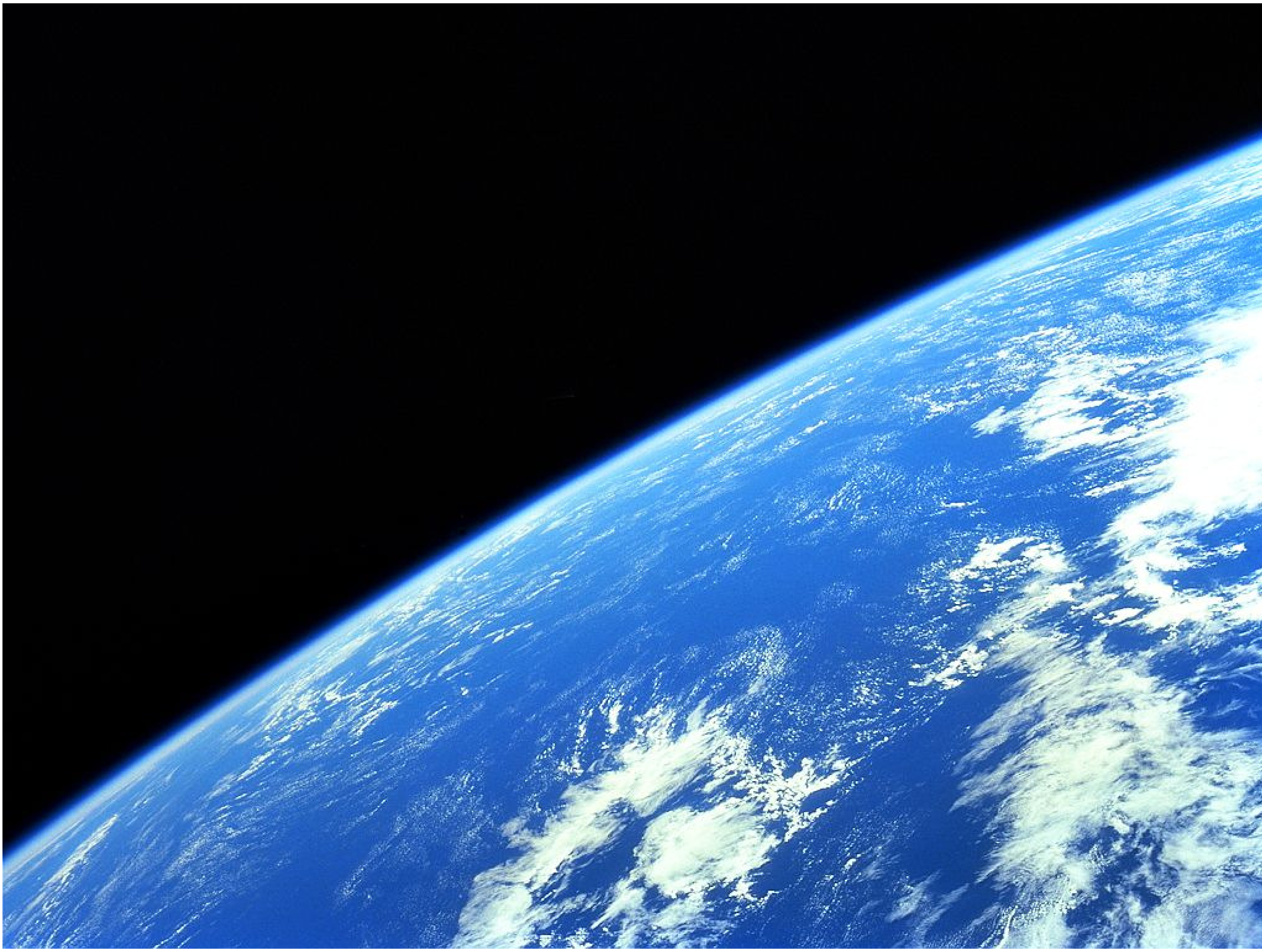


A photo of the Earth from outer space. The Earth is full of different processes that range from the movement of the oceans and atmosphere, visible in the above photo, to subterranean and subaqueous processes that aren't immediately evident.

Chapter 1: The Study of Geological and Earth Processes

Since before the Common Era, scientists have been studying the processes that govern changes on our planet. The study of geologic and Earth processes have led to more accurate ideas and a greater understanding of global conditions, such as climate, and processes, such as plate tectonics, that acted in the past as well as the present. From Darwin to Darcy, influential thinkers have proposed theories that at first were debated and questioned, but have grown to form the basis of modern interpretations.

For many years, astronomers have studied the solar system in an attempt to determine the origin of extraterrestrial bodies and their effects on our planet. The origin of the Moon, the cause of the tides, and astronomical influence on ice ages were all explored through different disciplines. Underwater processes were even more difficult to understand, as direct observations were not possible. Technological advances in SONAR recently made seafloor mapping a reality and also allowed for the observation of deep marine structures such as turbidite sequences. The realization that the oceans and continents are in fact resting on shifting plates was fundamental in explaining Earth's processes. This discovery provided a new mechanism for many disputed processes, including the formation of mountains and volcanoes. The occurrence of earthquakes could then be explained through scientific methodology rather than mythological speculation.

Throughout our history, scientists have attempted to understand the world around us, and while much progress has been made in solving Earth's mysteries, there are many more that remain unanswered. This chapter aims to provide the reader with some of the history of how and why these monumental ideas came to be.

Historical Views on the Creation of the Moon

Since the beginning of human civilization, the Moon has been an essential part of people's everyday life. Civilizations have expanded and differentiated across the globe and developed different ways of portraying our solar system. Starting from ancient myths, mankind has been able to develop and challenge hypotheses concerning the origin of the Moon and its role in the Earth's system. Additionally, modern technological advancements have enabled accumulation of new evidence to help determine the Moon's origin. It is crucial to note that multiple theories exist to explain the origin of the Moon.

Understanding the Moon in History

The Moon has been observed by many ancient civilizations across the globe. Starting with the ancient Babylonians, the Moon has been observed by historical figures in many ancient civilizations (Newton, 1970). An ancient Greek philosopher, **Aristotle**, identified both the Earth and the Moon as spheres using the basic principles of astronomy developed by **Anaxagoras** (426 BC), while Seleucus of Seleuia successfully theorized that the Moon influenced the Earth's tides (Couprie, 2011; Leconte et al., 2010). As early as 1609, Galileo Galilei identified structural characteristics of the Moon. However, along with factual information, there also existed non-factual perceptions of the Earth's satellite, viewing natural processes from religious and spiritual perspectives. Especially in the 1600s, conflicts existed between the religious and scientific communities (Hibbs, 1960; Ferngren, 2002). Religious conflict became less dominant around the mid 1600s, enabling further development of astronomy. Hypotheses concerning the creation of the Moon were no exception, and no significant contribution was made regarding the evidence-based origin until the development of the fission theory of Moon formation by **George Darwin** (who will be discussed in the following page) (Darwin, 1898). This theory eventually led to the development of other hypotheses, and enabled movements away from diversification created by mythological and religious origins of the Moon.

Binary Accretion Theory

Prior to George Darwin's contribution in the research field, the **binary accretion theory** was popular amongst the European academia in the early 1800s. The theory stated that the Earth and the Moon were formed simultaneously from the dust clouds during the early stages of development of the solar system. Due to the close proximity of the two masses, the Moon was caught in the Earth's orbit (Binder, 1986; Wilkins and Moore, 1961). Unfortunately, quantifiable data were extremely difficult to obtain using the limited technologies from the 1800s. As a result, the theory was strictly based on theoretical calculations (Huxley, 1987). The binary accretion theory was widely accepted by academia and no arguments were made to disprove the theory until technological advancements. After the space exploration and obtaining lunar rocks, the theory was immediately disputed. It was found out that the compositions of the two masses are somewhat different (Poitrasson et al., 2004). Although the Earth consists of iron and nickel **inner core**, lunar seismology experiments indicated a low quantity of iron in the Moon's core (Kuskov and Kronrod, 2002). By obtaining more information and evidence, new theories were developed.

Capture Theory

During the development of binary accretion theory, a new theory was introduced by the astrophysics community to address the issues associated with the binary accretion theory. Unlike the binary accretion theory, the **capture theory** placed a primary focus on the Earth and the Moon's structural differences, and stated that the two masses had entirely different origins (Singer, 1970). Instead of simultaneous formation with an identical formation history, the theory identified the Moon and the Earth as discrete entities from distinct part of the space. However, this theory was challenged and eventually replaced as the theory proposed capture of the Moon by the Earth's gravitational field. The probability of this phenomenon was calculated to be extremely low (Opik, 1955).

George Darwin and the Fission Theory of Moon Formation

One of the major contributions to this specific research field was provided by George Darwin (1845-1912), son of **Charles Darwin** (1809-1882), in 1898. Since childhood, George Darwin was influenced by his father's work and showed incredible passion for astronomy and mathematics. At the University of Cambridge, he studied the effects of solar and lunar **tidal forces**, and developed the **fission theory of Moon formation** (Darwin, 1898). The theory suggests fission of the natural satellite from the Earth to occur due to centrifugal force. This theory was developed by considering Newtonian mechanics and calculating the distance between the Earth and the Moon over a period of time (Singer, 1968).

George Darwin was always interested in mathematical models applied to study rotation of a fluid mass, and employed methods created by **Pierre-Simon Laplace** (1749-1827) and **William Thomson** (Lord Kelvin) (1824-1907) to study the changes in distance between the two masses (O'Connor and Robertson, 2003). The calculations he made did indicate a progressive increase in distance between the two masses, and was confirmed by the scientific community. His theory suggested that if the distance between the two masses is increasing, the masses must have originated from one single point before the fission. However, this theory was easily challenged due to three major assumptions (Stroud, 2009). First, the magnitude of initial spin of the Earth must be significantly greater than today's magnitude. Second, the atmosphere of the Earth must have covered thicker distance in the past. Third, **accretion disk** formation must occur prior to complete mass differentiation (Stroud, 2009). Although increasing distance between the two masses served as appropriate evidence, there was lack of evidence to support the three conditions (Singer 1968).

Using Darwin's calculation, there was no way of extrapolating the data to determine the initial stage of the fission process. Additionally, there was no way of measuring thickness of the atmosphere in the past. Questions concerning the magnitude of **angular momentum** associated with the initial stage of the fission also posed several problems (Stroud, 2009). The three assumptions were re-addressed by the scientific community, and lead to the development of the **giant impact hypothesis**.

Giant Impact Hypothesis

In 1946, Darwin's Fission Theory of Moon Formation was challenged by Reginald Aldworth Daly (1871-1957) from Harvard University. He hypothesized that the creation of the Moon (approximately 4.5 billion years ago) was due to collision between the Earth and another large planetary mass, instead of centrifugal force (Daly, 1946). The large planetary mass is named after a Greek deity, Theia, who gave birth to the goddess of the Moon, Selene (**Figure 1)** (Marquardt, 1981). Due to lack of evidence, this theory did not receive much attention. This idea was re-established and strengthened in 1975 by individuals including Cameron (1976), and eventually gained popularity.

Today, computer simulation is available for modeling and visualization of the collision process. According to the calculations, Theia's collision with the Earth occurred at an oblique angle of approximately 45 degrees, with velocity of 4 km/s (Canup, 2003). In the initial stage of the collision, iron core of Theia merged with the iron core of the Earth while outer layer of Theia and the Earth was ejected into the orbit around the Earth. Prior to the mass separation, the collision was associated with a rapid increase in temperature, homogenizing materials from the two planets (Canup, 2003).

Along with the computer simulation, this hypothesis was also supported by Wiechert et al. (2001) as they found identical oxygen isotopic signatures in both the Moon and the Earth's crust. However, it was possible that Theia carried the identical isotopic signatures prior to the collision. Researchers from the California Institute of Technology studied this issue, and concluded this probability was less than one percent (Pahlevan and Stevenson, 2007). Aside from the isotopic evidence, the highly anorthositic composition of the Moon's crust indicated presence of high energy activity in the past. It is important to note that if the giant impact hypothesis does hold true, the Earth's angular momentum and mass have significantly changed after the event.

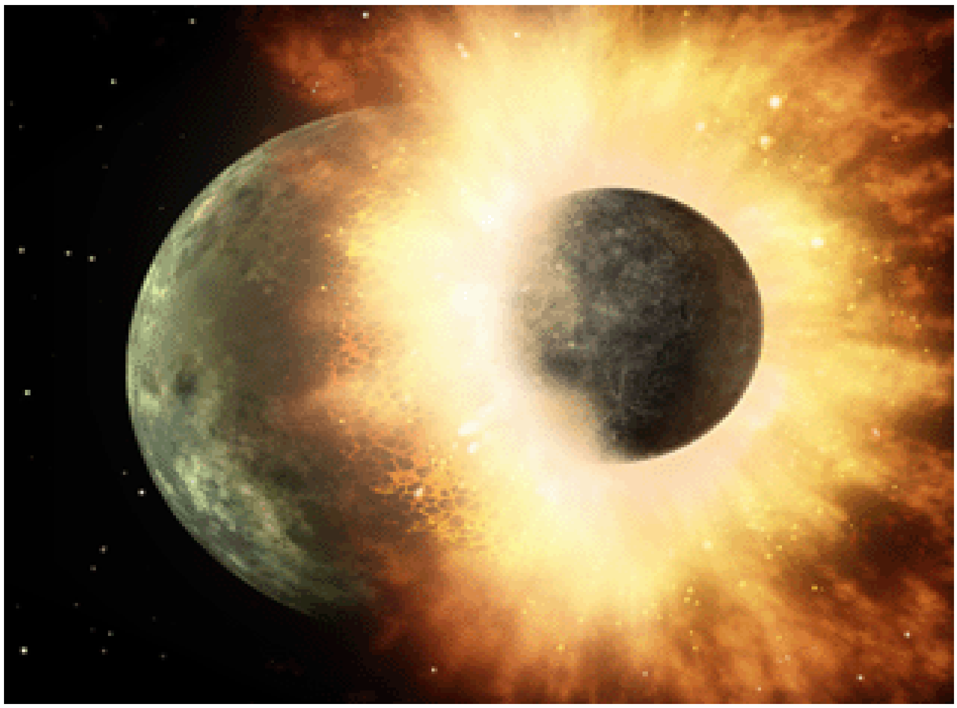


Figure 1: *An illustration of the high energy collision between Theia and the Earth. The giant impact hypothesis is adopted by many astronomers.*

Although the giant impact hypothesis is now accepted as a valid hypothesis for the origin of the Moon, there are some limitations and outstanding questions. Due to invention of more powerful analytical devices in 1990s, scientists were able to generate greater quantity of data. With large sets of data, the system becomes more complex and information may contradict one another. Collision between the two large masses generates significant heat increase, and a magma ocean was formed on the surface of each of the two masses (Abe, 1997). Although formation of the magma ocean may explain the homogenization of crustal materials, geologists were not able to find a specific basalt layer on Earth to support this idea (Jones, 1998). Additionally, the theory of the formation of the magma ocean was challenged through chemical analysis. The catastrophic heating event should have released volatile elements including hydrogen and water. However, Saal et al. (2008) used secondary ion mass spectrometry on lunar basalt to indicate incomplete depletion of the volatile elements, thus challenging the validity of the magma ocean formation in giant impact hypothesis.

Astronomers also searched for a similar collision on another planet to investigate the likelihood of the collision and moon formation. Venus became the target interest, due to its close distance to both the Earth and the Sun. Interestingly, the planet does not have a moon, although the planet went through significant number of collisions (Alemi and Stevenson, 2006). For individuals supporting the giant impact hypothesis, there exist numerous theories to explain the absence of a moon around Venus. Alemi and Stevenson hypothesized a secondary collision to knock out the pre-existing moon. Sheppard and Trujillo suggested large influence from the Sun's tidal force to disrupt Venus' orbit. (Alemi and Stevenson, 2006; Sheppard and Trujillo, 2009).

Understanding of the Moon's origin is a developing field, and new hypotheses may arise with more evidence. Although it is rather difficult to completely prove a theory or a hypothesis, modern understandings of such events will enable scientists to move forward and even analyze formations of the Earth itself.

Use of Satellites to Explore the Earth

Artificial and Natural Satellite

The Moon is a natural satellite that has been investigated by many scientists throughout history. By addressing the mystery of the Moon's origin, modern society developed greater understanding of the Earth's gravitational field and satellite capture processes. This was crucial for designing artificial satellites that orbit our planet.

Fiction Develops Into Reality

Interestingly, the historical development of artificial satellites intertwines closely with the development of theories concerning the Moon's origin. In 1869 (after the binary accretion theory), a famous fiction by Edward Everett, *The Brick Moon*, was written to describe a space station orbiting the Earth (Huxley, 1987; Moskowitz, 1974). The fiction received positive response from the public, and lead to publication of more fictional works dealing with artificial satellites. However, the satellites were only considered fictional, and no scientific contributions were made until 1903 by Konstantin Tsiolkovsky, who employed mathematics and physics to suggest the possibility of developing the fiction into reality (Kosmodemyansky, 2000). *Fission Theory of Moon Formation* by George Darwin in 1898 explored mathematical models to characterize the natural satellite, and similar principle was used to design an artificial satellite. He believed in a possibility of creating a natural satellite with more developed technologies. His publication, *Means of Reaction Devices*, consisted of rocket design and mathematical trajectories associated with creating an artificial satellite (Kosmodemyansky, 2000). Greatly inspired by Tsiolkovsky, Herman Potocnik in 1928 calculated a geostationary orbit and suggested a manned mission to the Moon. In 1945, Arthur Clarke suggested that artificial satellites had application for mass communication (Brady and Oslo, 2002). Eventually, communities across the globe realized the significance of artificial satellite development. In 1957, the first artificial satellite, *Sputnik 1*, was created by Soviet Union (Cracknell and Varotsos, 2007).

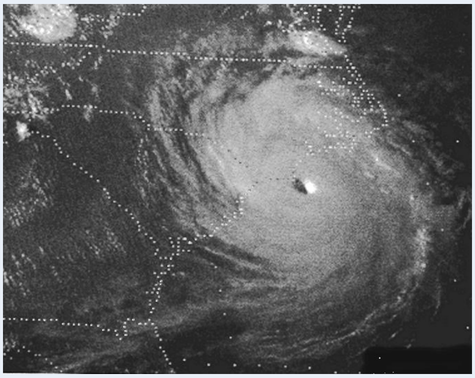


Figure 2: *Image of Hurricane Diana taken from one of the Weather Satellites. It is possible to visualize the cloud movements and hurricane formation pattern. Satellite images are commonly used for weather predictions.*

Current Status

There exist more than 1000 artificial satellites orbiting the Earth, and many of the satellites serve different functionalities while some are non-functional satellites that serve no purpose. The satellites are currently owned by many different countries, and play significant roles in today's global economy and politics. Types of satellites include: communication, navigation, and weather satellites. Artificial satellites are also used for exploring other planets (Cracknell and Varotsos, 2007).

Artificial Satellites' Contribution to Analysing the Earth's Surface

Weather satellites are frequently used to take measurements of the Earth's physical properties. Hurricanes are one of the natural phenomena that are analyzed by these satellites, and this enables the meteorologists to predict hurricane movements and to evacuate if necessary (**Figure 2**). These satellites are also able to detect pollution, snow activity, and dust clouds (TNAS, 2007). Prior to the invention of an artificial satellite, climatologists had difficulties in analyzing cloud movements. Modern weather satellites contain scanning radiometers, and are used to record thermal and infrared images. This information is used to accurately locate and characterize clouds. Additionally, the height of land and water surfaces can also be measured along with surface temperatures (Kearly and Hook, 1993). This provides critical information for geologists who study continent movements and ocean currents.

Evolution of the Theory of Continental Drift

Geologists have debated the origin of the Earth for a long time. Many have tried to develop a theory to explain how the continents and mountains came to be. The most well documented attempt was the theory of continental drift proposed by Alfred Wegener in 1912 (Oreskes, 2001). Although ultimately proven wrong, this theory paved the way for modern views of mountain formation, encapsulated within the theory of **plate tectonics**.

The Forerunners to the Theory of Continental Drift

Figure 1: *James Dwight Dana, an American geologist, born in 1811 and died in 1889 who was the founder of permanence theory*

One of the first theories describing how mountains were formed was **contraction theory** introduced by the Austrian geologist **Edward Suess** (1831-1914) in the early 19th century. His theory compared Earth to a drying apple. Initially the crust of the Earth was continuous, but as the interior shrunk, the crust broke apart. The portion that collapsed inwards became the oceans while the parts that remained on the surface became the continents (Oreskes, 2001). One perplexing observation **Leonardo Da Vinci** (1452-1519) had tried to explain in the 15th century was the occurrence of marine fossils on land. Da Vinci hypothesized that there once existed an ocean where the mountains now stood, although he provided no mechanism for how this could have occurred (UCMP, 2012a). The solution proposed by contraction theory was that, with continual cooling, continental masses would subside to form the new ocean floor and the old ocean floor would then become part of the continent (Oreskes, 2001). This continual rearrangement of continent and oceanic plates would explain Da Vinci's observation.

In 1859, **Charles Darwin** (1809-1882) published *On the Origin of Species*, theorizing that plants and animals evolved independently in different locations with different environments (Oreskes, 2001). One observation, found by multiple scientists that became controversial was that similar **fossils** could be found thousands of miles apart. This was easily explained from the creationist perspective by ascribing these findings to the work of God. From an evolutionary perspective, if species evolved independently, in response to different environments, then what would cause them to evolve to the same species? Contraction theory provided a more scientific explanation for this phenomenon than the creationist view by proposing that these species evolved when the Earth was composed of one massive supercontinent called Gondwanaland.

Suess' theory was accepted in most of Europe, but in North America a different version of contraction theory was proposed by **James Dwight Dana** (1813-1895) (**Figure 1**). Based on his own observations made during an expedition in the Pacific, he refined a hypothesis put forth by Darwin in 1843 on **oceanic subsidence** by adding geomorphic evidence for the process (Dott, 1997). Dana proposed that as the world cooled, low-temperature minerals formed the continents, and high-temperature minerals formed the ocean basins (Oreskes, 2001). Continual contractions once the Earth was solid caused deformation of the surface, which occurred mainly at the boundaries between the ocean and continents. It was this deformation that Dana hypothesized caused mountain formation. This view of continent formation later became known as **permanence theory** as it asserts that the continents and oceans were globally permanent features.

The **theory of geosynclines** was closely tied to permanence theory. The theory of geosynclines was first put forth by **James Hall** (1811-1898) between 1857 and 1859, and later refined by James Dana in 1873 (Dott, 1997). Hall was a **paleontologist** who lived in New York and was the first president of the Geological Society of America (Oreskes, 2001). Hall postulated that as sediment erodes from the continent, it accumulates in the adjacent marginal basin, subsequently causing the basin to subside. This process would continue until the weight of the pile caused the sediment to be heated and converted to rock, and then finally uplifted to form a mountain.

Dana disagreed with this view, as he believed it provided the result rather than the cause of mountain formation (Oreskes, 2001). In 1873, Dana revised the theory to provide a causal mechanism for the formation of mountains. His view was that contractive pressure caused the **continental margin** to buckle and be filled with sediment deposited through erosion (Dott, 1997). The sediments would then be compressed and deformed. The whole system would then uplift and become an addition to the continent in the form of mountains.

The next major theory to come along that would cause scientists to rethink their views on the formation of the Earth and mountains was the theory of continental drift, pioneered by Alfred Wegener.

Continental Drift

Many new scientific discoveries came along with the 20th century, casting doubt on the validity of the contraction theory. The repercussions were felt most intensely in Europe, where Suess' theory had been more widely accepted than in America (Oreskes, 2001). One of the most promising new theories proposed was by the German meteorologist, **Alfred Wegener** (1880-1930) (**Figure 2**; UCMP, 2012b). Wegener asked why "the east coast of South America fit exactly against the west coast of Africa, as if they had once been joined? The fit is even better if you look at a map of the floor of the Atlantic and compare the edges of the drop-off into the ocean basin rather than the current edges of the continents" (Schwarzbach, 1986, p.76). Because of his meteorological background, Wegener noticed that the **paleoclimate** changes on Earth could also be attributed to changed locations of the continents (Oreskes, 2001). In 1915, he published his theory of continental drift in a book titled *The Origin of Continents and Oceans*. He presented his theory as a way to connect historical geology with **isostasy**, which states that the plates are in a state of equilibrium with the mantle below because of either density variations or differences in crustal thickness between the layers.

Paleontological evidence showed that the continents were once connected; however, geological evidence showed they could not be connected in the way that was predicted by contraction theory. He proposed that the Earth's crust drifts atop a liquid core and at one point, all the continents were joined in a supercontinent he named **Pangea**, meaning 'all-earth' (**Figure 3**). The idea came to him while recuperating in a military hospital from an injury obtained fighting for the Germans during World War I (USGS, 1999a). The injury provided him with plenty of time to develop ideas that had interested him for years. Before Wegener's untimely death in 1930 at the age of 50, he would revise his theory and publish four subsequent editions (Schwarzbach, 1986).

Figure 2: *Photo of Alfred Wegener. He was the pioneer of the theory of continental drift, a theory that would later be proven wrong by the theory of plate tectonics.*

Wegener was an interdisciplinary scientist who obtained a Ph.D in astronomy but was also interested in geophysics, meteorology, and climatology (UCMP, 2012b). In addition to his contributions to the earth sciences that at the time were met with criticism, he also helped advance the field of meteorology. Wegener participated in four expeditions to Greenland for research where he ultimately met his end (Schwarzbach, 1986). Alfred Wegener passed away at the age of 50 on the journey back from providing supplies to one of the research stations in November of 1930. He was found almost seven months later in May of 1931, once winter ended.

Critics of Continental Drift

Wegener's theory of continental drift was largely debated throughout the 1920s and 1930s. One of the major challenges that he faced was the lack of support from leading geologists because they were wary of Wegener's meteorological background. (USGS, 1999a). The theory was also rejected, especially in the United States, where it was marked as 'bad science' because it did not provide a proper causal mechanism for the proposed lateral movement of the continents (Oreskes, 2001).

Despite the criticism, Wegener's theory found a supporter in American geologist, **Reginald A. Daly** (1871-1957), who suggested in the 1920's that tectonic activity could be a result of the Earth's layers (Oreskes, 2001). He proposed that if the Earth's mantle is not solid, and instead glassy, then it could possibly flow. Daly encouraged his American colleagues to pursue Wegener's theory, but few chose to.

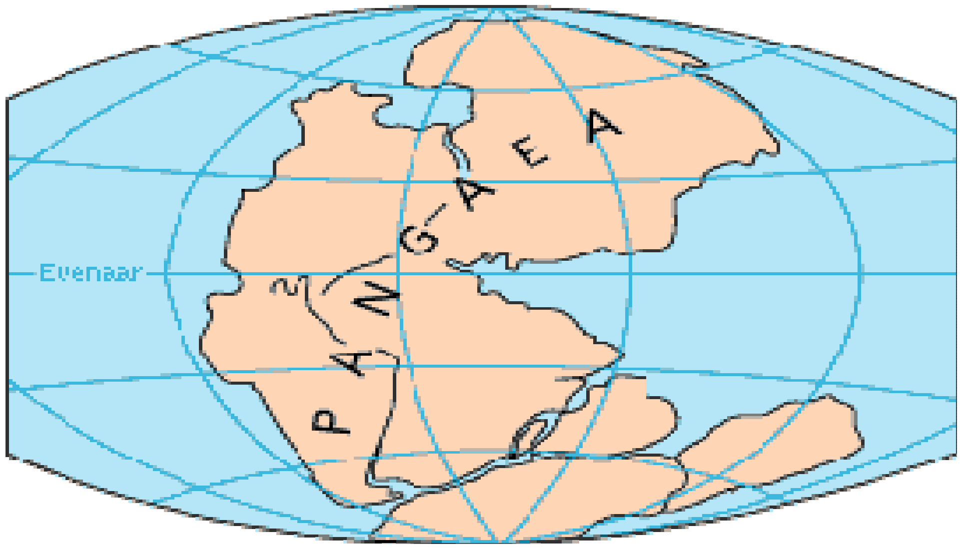


***Figure 3**: Theory of continental drift proposed that the continents were once arranged in a supercontinent called Pangea. This theory is based on the puzzle-piece fit of the continents and other findings by Alfred Wegener.*

In Europe, Daly's ideas were met with more favour. Irish geologist, **John Joly** (1857-1933), and English geophysicist, **Harold Jeffreys** (1892-1989), took up the debate on how continents moved across the Earth. Jeffreys strongly disagreed with Wegener's theory stating that the Earth is completely solid, and that the forces proposed could not possibly be strong enough to move continents. Joly, on the other hand, agreed with Wegener and believed that while the Earth may be solid now, it may not have always been that way. British geologist, **Arthur Holmes** (1890-1965), suggested that the mantle did not need to be liquid as Wegener stated, but instead needed to be only plastic. This allows it to be rigid under high strain, such as during seismic activities, and also ductile under low strain, such as during mountain formation. In 1928 Wegener proposed that it was convection currents in the mantle that acted as the driving force for continental movement (DU, 2003). However, Jeffreys held onto his beliefs even after the theory of plate tectonics was released (Oreskes, 2001).

Rejection of Continental Drift

Despite the new evidence for continental drift put forth by Holmes, many American geologists still did not support Wegener's theory (Oreskes, 2001). There were three main reasons for the Americans not to accept continental drift. First, they believed that good science was like a good government, a democracy. For it to work, multiple hypotheses were needed on a topic, and then whichever one held against the wealth of information would be considered correct. Continental drift was first proposed as a theory with supporting evidence being sought afterwards, which according to the Americans was settling on a conclusion far too quickly. Second, Wegener's theory went against the version of isostasy that the Americans accepted, which ascribed it to variations in density between the Earth's layers. Finally, Wegener's theory contradicted the legacy of **uniformitarianism**, most famously discussed by **Sir Charles Lyell** (1797-1875), which believed that in order to understand the past one should use analogues that exist in the present (UCMP, 2012c). Whether uniformitarianism was correct or not, by the early 20th century this was the common scientific approach used in America. Wegener's ideas simply viewed the present as just another moment in history, thus going against the principle of uniformitarianism (Oreskes, 2001). By 1937 when Alexander du Toit, a South African geologist, published *Our Wandering Continents*, a book looking at evidence for continental drift, the scientific consensus was against the theory. While Wegener was wrong about the mechanism of continental drift, his theory was still vital in the development of later theories. It is here that the debate ceased for two decades until new evidence was discovered leading to a new theory that is widely accepted today, based on the theory of continental drift, the theory of plate tectonics.

Measuring Plate Movement

Once the theory of plate tectonics had become globally accepted, scientists turned their attention to trying to determine the rate and direction of modern plate movement (Oreskes, 2001). Many methods are now used to measure the rate of plate movement, two of which will be discussed below.

Measuring Rate of Movement of the Sea Floor

While **Hess** was part of the US Navy in 1941, part of his job was collecting echo sounding information of the Pacific basin to improve navigation (Oreskes, 2001). This gathering of information led him to the discovery of **guyots**, submarine, inactive volcanic mountains. These were the first piece of evidence used to show that the ocean basins have not been preserved since early Earth, but instead are tectonically active like the continents. This then provides a location to measure the rate of plate movement.

It was then found that the rocks on the sea floor recorded magnetic anomalies and that these were consistent with known magnetic reversals recorded in lava flows on land (Plummer et al., 2007). Since the magnetic reversals on land had been dated, these could be used to date the reversals identified on the sea floor. By dividing how far the anomaly is presently from the ridge by the time the magnetic reversal occurred would provide one with the rate of motion for that plate, which is generally between 5 and 10 cm/year.

Measuring Plate Movement on Land

With new technological advances, the rate of plate movement can also be measured on land. Ground-based or satellite-based methods can be employed to measure plate movement (USGS, 1999b). While ground-based techniques such as using laser-electronic equipment can be used, satellite-based methods are much more useful as plate movement occurs on a global scale. The most commonly used satellite-based method is the global positioning system (GPS) however, others do exist, such as very long based inferometry (VLBI) and satellite laser ranging (SLR). The invention of GPS, originally designed for military purposes, has provided geologists with an efficient and accurate way to track the movement of plates. The GPSs used to track plate boundaries are much more accurate than the hand-held GPSs. These specialized GPSs can accurately predict locations to within distances as small as a grain of rice (IRIS, 2010). There are currently 24 satellites orbiting the Earth taking **geodetic measurements**. The GPS receiver is located on the ground and its specific location is determined by triangulation (**Figure 4**) with at least three other satellites in space. The receiver calculates the distances and angles between the satellites. With this information from three or more satellites, the receiver can accurately calculate the specific position, providing the result as a position on the surface of the Earth in terms of its latitude and longitude. By taking many measurements over a period of time, it is then possible to determine the distance travelled and subsequently the rate the plate moved. This information has been key to further understanding continent and mountain formation.

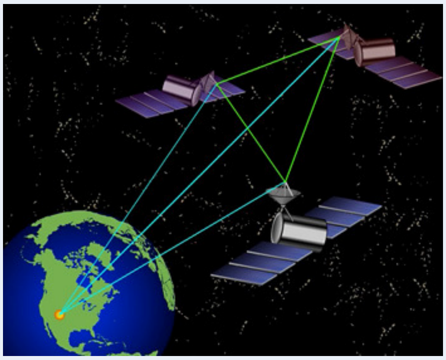


***Figure 4**: Diagram showing how a position on Earth can be determined using triangulation with three satellites.*

Krakatoa: The Eruption Heard Throughout History

On the morning of August 27, 1883, the populace of Java – that is, the natives, the Dutch colonists, and the slaves that had been brought from overseas were enjoying a serene beginning to their day of rest. For a great stretch of the coast of the islands of Java and Sumatra, the lightly-inhabited mountain-island of Krakatoa could be seen quite clearly just a few kilometres off the coast. Since May, at least one of the island's three volcanoes had been coughing lava and producing a deep rumbling, but by this Sunday in August these features were simply an interesting feature of everyday life, ominous as they were (Winchester, 2003).

Figure 1: *A lithograph of the beginning of the 1883 eruption of Krakatoa.*

It was on this day that a mountain that had been pushing at its seams for months finally broke through and exploded in one of the most violent and awe-inspiring eruptions in recorded history (**Figure 1**). A plume of gas and ash was thrust about 30km upward into the stratosphere, tons of pumice stone rained down on the surrounding areas, and waves were reported by many as being 100 feet tall near the mountain (Winchester, 2003). Due to the ash that was thrust into the stratosphere by this eruption, even countries on the other side of the world experienced unusually cold temperatures, witnessed unusual sunsets for years to come, and battled through one of the poorest growing seasons in years (Winchester, 2003).

Krakatoa had a great impact on society not simply because of the rapidly increasing population, but also because of industrialization. This meant a higher Dutch presence in the East Indies and as a result more investment in the area's welfare (Vlekke, 1945). However it was also associated with the advent of the telegraph (Winchester, 2003). Prior to this invention, if a mysterious force was darkening their skies, people on the other side of the world had nothing to do but fear for their lives and turn to religion or lore. However, now the newspapers were able to tell the story of the eruption that had happened thousands of miles away. Not only would this have boosted interest and therefore funding in geology, but it also was one of the first manifestations of the modern globalized world (Winchester, 2003). This, along with the quickening demise of the colonial system, placed Krakatoa at both a time and place of vast change.

Krakatoa, nestled amongst the temperate, bountiful islands of modern-day Indonesia was formed and then decimated by geological processes that were near-unknown to the scientists of the day. They were striving to explain this phenomenon that sent a pressure wave around the world seven times and which produced measureable water waves that travelled around the coast of Africa and as far north as the coast of France (Winchester, 2003). Great thinkers had long been making conjectures with regard to the heat they knew existed in the depths of the earth and what caused molten rock to spew forth from its home. However they still had not found the answer, and the reason for this Plinian explosion was still beyond them. Due to the fact that few historically sound observations were made regarding Krakatoa prior to the 1883 eruption, and that generalized facts about subduction zone volcanoes are pertinent to Krakatoa, the first topic of discussion will be the history of the study of volcanoes in general. This will give the framework of knowledge that Dr. Verbeek, addressed below, possessed when he analyzed the aftermath of the 1883 eruption of Krakatoa.

The Tip of the Volcano: the Long and Winding Road to Understanding our Earth's Interior

In prehistoric times, whenever eruptions occurred, all mankind could do was wonder, baffled at the events transpiring before them. In the very early times this was answered by the creation of legends and mythology. In ancient Greece and Rome, the lords of the underworld Hades (Greek) and Pluto (Roman), the gods of fire and volcanoes Hephaestus (Greek) and Vulcan (Roman), and the fiery-tongued monster Typhon that was said to have been imprisoned by Zeus under Mount Etna are all examples of attempting to explain the writhing fire below us (Winchester, 2003). More relevant to Krakatoa, it was said that the Javan god and mountain ghost Orang Alijeh, who resided in Krakatoa, exhaled fire from his nostrils when he was displeased with the goings-on of earth (Winchester, 2003).

In the classic civilizations, where science was beginning to emerge, secular explanations were emerging as well. Among the Greeks, Aristotle (see pg. 4, 106-10) and Anaxagoras (5 BCE) believed in the theory of trapped wind, which suggests that gas stored inside the earth produces much heat upon release through volcanic vents. On the other hand, the Roman Lucius Seneca (65 CE) believed that heat came from combustion of a vast storehouse of sulphur. This notion was expanded on in poetry, which included reservoirs of alum, coal and tar as the source (Winchester, 2003).

An interesting development occurred when Pliny the Elder (23-79 CE) (see pg. 54) was inspecting a cloud of gas emanating from Mount Vesuvius. While he was on the island the volcano erupted, causing him to die of asphyxiation. This gaseous and explosive flavour of eruption was henceforth given the name of a Plinian eruption, and would much later on be a model for the eruption of Krakatoa in 1883 (Winchester, 2003).

The combustion of something within the Earth continued to be an accepted idea for centuries, with fuels such as "sulphur, bitumen (i.e. asphalt), coal, salt, Nitre (vague mineral), Coaly Earth and Calcanthum or Vitriol, and such kinds of metals" being suggested in the Renaissance era (Young, 2003). Despite these strong attempts at an explanation, one man proposed an idea remarkably close to those pervading today's conclusions. In the 17th century, René Descartes suggested that the earth originated by way of gravitational attraction and gaseous condensation, placing the denser, hotter layers in the middle and the lighter, cooler layers at the top (Winchester, 2003). This idea was affirmed later on in Robert Ball's book, The Earth's Beginning (1903), in which he states that "the evidence has proved that, under the extraordinary pressure that prevails in the earth, the materials in the central portions of our globe behave with the characteristics of solids rather than of liquids. But though this applies to the deep-seated regions of our globe, it need not universally apply at the surface or within a moderate depth from the surface." However, this was not to be confirmed until much later.

Chemistry began to be used as a tool to explain Earth's heat. In the 17th and 18th centuries people believed that exothermic chemical reactions were the explanation (Winchester, 2003). After the Renaissance, naturalists generally agreed that pyrite (Figure 2) was a likely fuel for eruptions, among other fuels. Pyrite's combustibility was shown by Lémery through the mixing of its constituents: water, iron and powdered sulphur (Young, 2003). By 1807, the Geological Society of London was founded and their accepted theory was that oxidation of the newly discovered alkaline metals sodium and potassium was the probable generator of heat in the Earth (Winchester, 2003).

Figure 2: *A chunk of the rock known as pyrite. In the 17th and 18th centuries, pyrite was strongly believed to be the subterranean fuel for volcanoes.*

Another major debate that persisted through the 18th and 19th centuries was that between the Neptunists and the Plutonists. The Neptunists were led by Werner, who suggested that the oldest rocks (granite was supposedly the oldest) were formed as a chemical precipitate from a universal ocean, and clastic sediments came from the erosion and deposition of these original rocks (Williams & McBirney, 1979). He also proposed that volcanoes were anomalous curiosities caused by the subterranean combustion of coal. "The Plutonists" was a name given to a group of scientists who, led by James Hutton, disproved this theory. Among other things, the discovery that igneous intrusions are younger than the rock that they intrude showed that deposition was not as simple as granite being precipitated out of solution and then sedimentary rocks overlaying it (Williams & McBirney, 1979).

In 1825, Scrope coined the term magma, and proposed that different magma compositions could be produced by the same parent volcano, and recognized the important role of gas in the violent nature of volcanic eruptions (Williams & McBirney, 1979).

The development of thermodynamics in the mid-1800s was a big step for volcanologists, as pressure and temperature were becoming more and more important to describe the inner workings of the Earth. In 1850, German chemist Robert Bunsen did an experiment showing that melting point increases with temperature; he extrapolated these results to the high pressures and temperatures prevailing deep in the Earth (Sigurdsson, 2000). In 1878, King suggested that lakes of magma exist beneath the ground where enough of the underside of the crust has been eroded away for decompression and subsequent melting to occur (Sigurdsson, 2000).

The Inspection of the Eruption

This is the lens through which a certain Dr. Verbeek, sent by the Dutch government, looked in order to analyze the remnants of the Krakatoa explosion seven weeks after it happened. When he arrived at the scene, he described clogged pipes, steam vents and collapses of central parts of the volcano (Winchester, 2003). He was able to describe the features, but his suggestions as to a cause were limited. What he suggested as for the cause was "seawater mixing suddenly with the magma, and flashing over, turning into superheated steam, in a gigantic and uncontrollable explosion" that is these days given the name of a **phreatomagmatic explosion** (Winchester, 2003). John Judd, president of the Geological Society of London, wrote later that magma and seawater mixed to produce the explosion and pumice was created by a lowering of magma's melting point by the addition of water (Winchester, 2003). This was expanded upon by Dana (1890) who compared Krakatoa to the Tarawera eruption of 1886, which had been accompanied by the loss of waters in nearby Lake Rotomahana. He suggested that since the two eruptions had produced similar noise and seismic activity, Krakatoa's violent outburst came as a result of ingressing water as well.

Making the Right Conclusions

As late as the 1920s, notable geologists still believed that earth's internal heat was due to chemical reactions between gases. One, Sir Harold Jeffries (who also vehemently opposed continental drift because the plates were too rigid), also stated that volcanism was a phenomenon that was local and occasional, not perpetual and worldwide (Winchester, 2003).

However, there were some that had been on the right track. Going back in time to 1859, when the findings of **Alfred Russel Wallace** (see pg. 97, 100) were presented, we discover findings that would start people to thinking about plate tectonics. Wallace was an ecologist that was fascinated with the East Indies. While he was there, he noted that the islands of Bali and Lombok, naught but 15 miles apart, were distinctly different in the organisms (birds, plants and mammals) that occupied them. For example, to the west there lived the Indo-European thrushes, monkeys and deer, and to the east there were the Australian fauna of cockatoos and kangaroos. This division was consistent for a series of islands in the area, and from them he drew a line of division – the so called **Wallace Line**. He was excited by this division, but since knowledge at the time could not provide the answers for him, he suggested his own conclusions. He made the at-the-time unheard of, and therefore unfounded proposition that – somehow – something to do with movement and submergence and upheaval and spreading and earthquakes and volcanoes had caused this division (Winchester, 2003).

This was indeed a great deal of foresight into the correct answer. Foresight that would be substantiated in 1915 by Alfred Wegener's theory of continental drift, and then later on in 1965, when **John Tuzo Wilson** came up with his theory of **plate tectonics** (see pg. 8-11,16) that effectively explained volcanism as a result of **plate subduction** (Winchester, 2003). On another note, the Krakatoa eruption was a factor that destabilized the peace in the Dutch East Indies and incited their fight for autonomy – a fight similar to many others around the world (De Klerck, 1938). Krakatoa was at a turning point in history, integrally tied to important events both in the present and in the future.

The Modern-Day Analysis of Krakatoa and Other Phreatic Eruptions

The plate tectonics theory put forth by Wilson in 1965 was the key to unravelling the Krakatoa eruption. Krakatoa is part of the "Ring of Fire," the chain of volcanoes that borders the west, north and east coasts of the Pacific Ocean. The volcanism in these coastal areas is a result of the subduction of the Australian plate under various other plates as it moves northward. The subducting Australian plate is melting as it moves downward, producing magma that forms into a reservoir and rises toward the surface (**Figure 3**). The area surrounding Krakatoa has a complicated geology; it is divided by a number of faults and also acts as a sort of hinge point for the Australian plate. As Winchester describes it, as the Australian plate moves, the islands of Sumatra and Java are swinging towards each other like "a northward-closing book." Meanwhile, the Australian plate is subducting under the area of the Asian plate on which lie Sumatra and Java.

To further complicate the issue, as the Australian plate subducts, the waterlogged sediments move down into the asthenosphere with it. This water lowers the density and melting point of the basaltic oceanic crust, causing it to melt at a relatively shallow point relative to the rest of the constituent rock. This water is then boiled out of the rock, creating superheated steam under a lot of pressure that is pushing upward in an attempt to find an outlet (Winchester, 2003) (Simkin and Fiske, 1983). This steam may dissociate into hydrogen and oxygen as pressure decreases on its way up the pipe due to the constant high temperature, increasing the pressure even more (Simkin & Fiske, 1983).

Although the theories are still sketchy, these help to explain the evidence gathered from the great explosion that rocked the world in 1883.

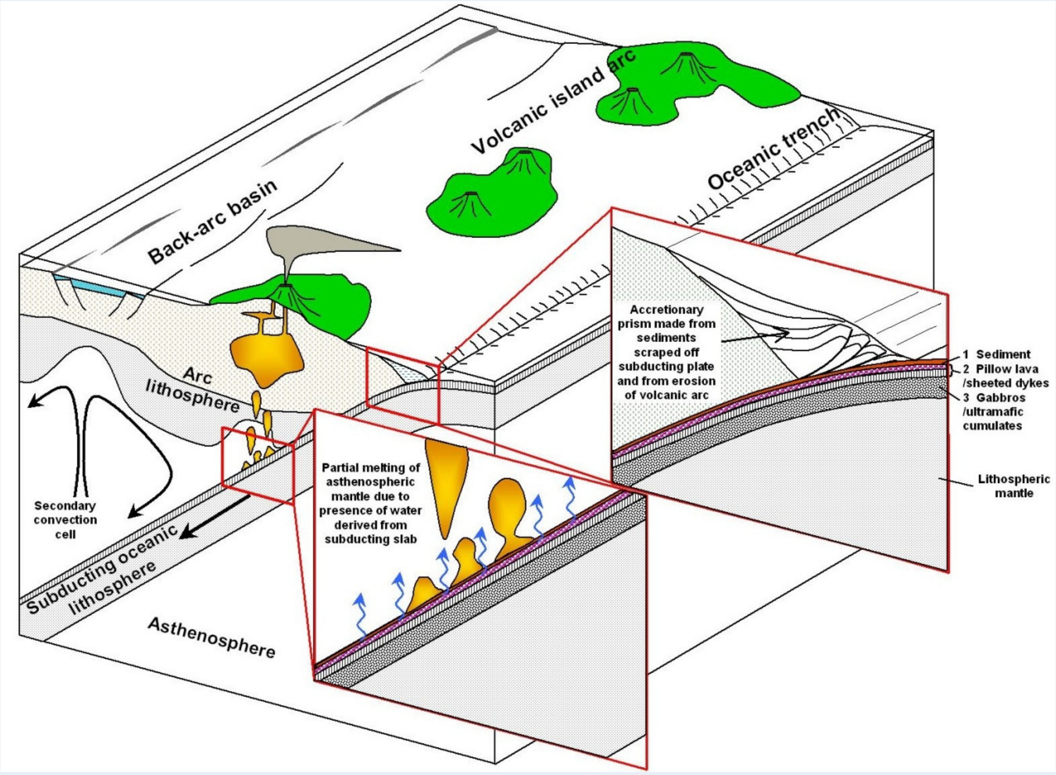


Figure 3: *A cross-section of a subduction zone similar to that which produced the Krakatoa volcano.*

The Turbidite Paradigm

Over 50 years ago, geologists believed that the deep seafloor was a tranquil environment with only **pelagic** sediment deposition (Friedman and Sanders, 1997). Today, our understanding of the deep sea is well established as a highly dynamic environment (**Figure 1**). Gravity-controlled mass-transport processes such as slides, slumps, debris flows, and turbidity currents transport sediment hundreds of kilometers downslope from the continental shelf edge (Shanmugam, 2000). During mid to late 20th century, studies on deep-sea processes focused on turbidity currents and their deposits (i.e. **turbidites**). Thus, this research paradigm evolved as the most influential factor in directing geological interpretations of deep-sea environments. However, our overall understanding of the depositional processes still remains in its infancy.

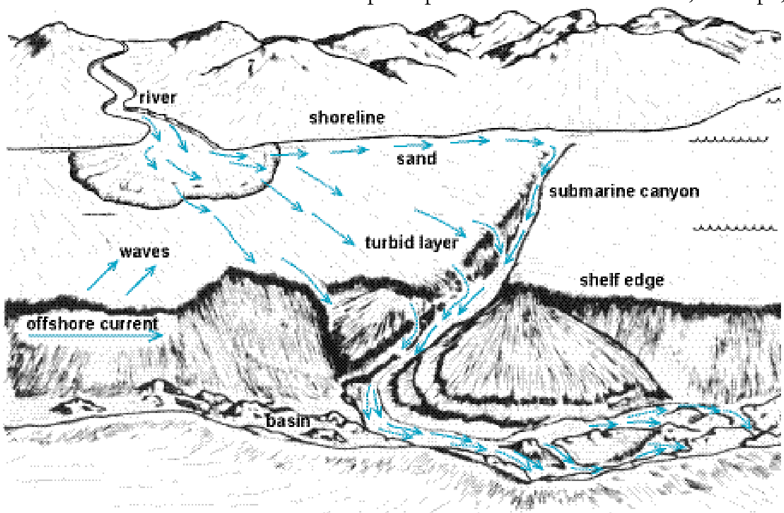


Figure 1: *Before the turbidity current and turbidite concepts were introduced in the 1950s, geologists did not think that the deep sea was a dynamic environment with complex depositional processes.*

The turbidite paradigm presents turbidity currents and turbidites as the fundamental building blocks of deep-sea depositional systems (Shanmugam, 2000). Initially, this hypothesis aroused controversy amongst geologists throughout the 1950s and 1960s. The popularity of experimental and model studies of turbidity current reached its climax in the 1970s and 1980s; however, the research interest declined to the point of abandonment in the 1990s (Shanmugam, 2000). By that point, the majority of geologists realized that there is no comprehensive **facies** model that interprets all variations of the deep-sea sedimentary systems (Shanmugam, 2000). Nevertheless, the turbidite paradigm paved the way for modern technologies and approaches in **sedimentology** (Shanmugam, 2000).

Early Interpretations

Geologists originally recognized turbidites as facies with repetitive alternating layers of sandstone and shale (Ricci-Lucchi, 2003). In 1827, **Bernard Studer**, a Swiss geologist, labelled these thick successions as 'flysch' (Studer, 1827). This led to active discussions regarding the **lithology** of 'flysch' among sedimentologists nicknamed 'flyschermen'. Throughout the past two centuries, the term 'flysch' has been used in various ways. At first, it was used to describe the **Tertiary** formations in the **Alps**, but was later redefined and broadened by Studer (1847) to include older **Cretaceous** rocks in the Eastern Alps, **Carpathians**, the **Apennines** and older mountain ranges (Mutti, Bernoulli, Ricci-Lucchi, and Tinterr, 2009).

Geologists found an important connection between the formation of turbidites, flysch, and tectonically active depositional settings. They generally accepted 'flysch' as a type of tectonically controlled deposit, which was termed a 'tectofacies' (Ricci-Lucchi, 2003). It was considered a **syn-orogenic** deposit rather than the product of a certain sedimentary environment and this origin was consistent with the **geosyncline theory** (Mutti, Bernoulli, Ricci-Lucchi, and Tinterr, 2009). **Émile Argand**, another Swiss geologist, interpreted that "flysch sedimentation marked the closing of a geosyncline" (Argand, 1920).

The term 'flysch' remained for a while before geologists accepted the turbidite paradigm in the 1950s. For instance, **Nikolai Vassoevich** (1948) suggested that oscillatory tectonic movements cause the repetitive alternating layers of sandstones and shales of 'flysch'. However, **Carlo Migliorini**, a major supporter of the turbidite paradigm, dismissed Vassoevich's idea (Kuenen and Migliorini, 1950). As new ideas of plate tectonics emerged during the 1960s and the 1970s, the geosyncline theory was abandoned. The term 'flysch' was too ambiguously defined and geologists began avoiding its use.

The Turbidity Current Concept

Prior to the development of the turbidite paradigm, several geologists suggested the existence of deep-sea currents. **Reginald Daly** (1936) advocated the origin of submarine canyons through erosion by **density currents**. The first laboratory experiments on density currents in relation to Daly's hypothesis were conducted and the results were in agreement with his speculation (Kuenen, 1937). In 1938, **Douglas Johnson** (1938) introduced the term "turbidity current" to describe sediment-laden density currents. However, the geologic community of the time was skeptical of the importance of these deep-sea sediments.

The Revolution

Graded sandstone beds of the **Miocene Marnoso-arenace Formation** in Italy were first recognized by an Italian geologist, **Roberto Signorini** (1936). However, he failed to explain the mechanism by which they were deposited. Migliorini was the first to interpret these graded beds as "sand originally deposited in shallow waters and then displaced to deep waters by turbidity density currents triggered by slope instability processes" (Migliorini, 1943). It could be argued that this finding was a historic landmark in sedimentology. However, it was not until the 1950s when Migliorini and **Philip Kuenen** produced a joint publication (Kuenen and Migliorini, 1950) that the turbidity current and turbidite concepts were accepted by the geologic community (Mutti, Bernoulli, Ricci-Lucchi, and Tinterr, 2009).

In 1948, at the 18th International Geological Congress in Great Britain, Kuenen suggested the possible occurrence of high-density turbidity currents based on his experimental work (Kuenen, 1948). Kuenen postulated that 1) turbidity currents form graded deposits and 2) turbidity currents, originating in a submarine canyon, likely starts as a slump which evolves into a turbid liquid (Kuenen, 1948). Migliorini supported these ideas and remarked that "when a high-density current ceased to move larger blocks, the finer material would pass down gentle slopes to the lowest enclosed depression and there give rise to well graded sediments" (Mutti, Bernoulli, Ricci-Lucchi, and Tinterri, 2009). The two geologists subsequently collaborated on a classic paper that describes the relationship between turbidity currents and graded bedding (Kuenen and Migliorini, 1950). Their findings provided a novel way of understanding the mechanism for the origin of deep-sea sands. The collaboration of Kuenen and Migliorini truly set the stage for the scientific revolution about to take place in which geologists could explain the origin of graded beds with turbidity currents. The impact of the turbidite paradigm was great enough to mark the rebirth of sedimentology.

The 1929 Grand Banks Earthquake

Following the publication of the 1950 seminal paper by Kuenen and Migliorini, marine geologists re-examined mysterious submarine events that had occurred in the past. A prime example is the 1929 Grand Banks Earthquake that broke 12 transatlantic telegraph cables (**Figure 2**). At this time, the cables were installed along the steep continental slope that descends southward off the edge of the Grand Banks (Natural Resources Canada, 2010). The exact time of successive cable breaks was recorded (Natural Resources Canada, 2010). Twenty years later, an interesting correlation was discovered between the cable breaks and the earthquake. Seven cables high on the continental slope, near the epicentre, were broken instantaneously during the earthquake and the remaining five snapped sequentially farther and farther downslope (Natural Resources Canada, 2010; **Figure 3**). **Bruce Heezen** and **William Ewing** (1952) postulated that a submarine landslide triggered by the earthquake, initiated high-velocity turbidity currents that successively ruptured the cables in the downslope order (Heezen and Ewing, 1952). This became the

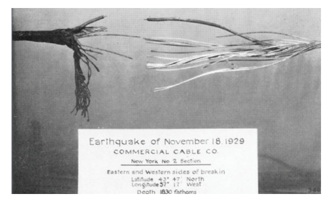
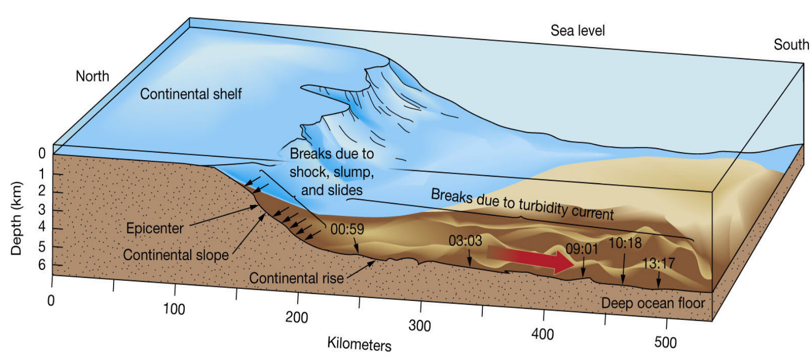


Figure 2: *Turbidity currents triggered by a submarine slump during the 1929 Grand Banks Earthquake ruptured 12 transatlantic cables.*

Figure 3: *A seafloor profile of south of the Grand Banks. The turbidity current is thought to have sequentially broken the transatlantic cables downslope. The times of each break were recorded.*



first documentation of a deep-sea turbidity current (Ricci-Lucchi, 2003).

The Turbidite Controversy

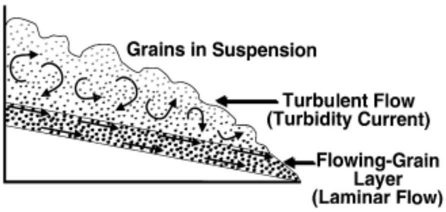


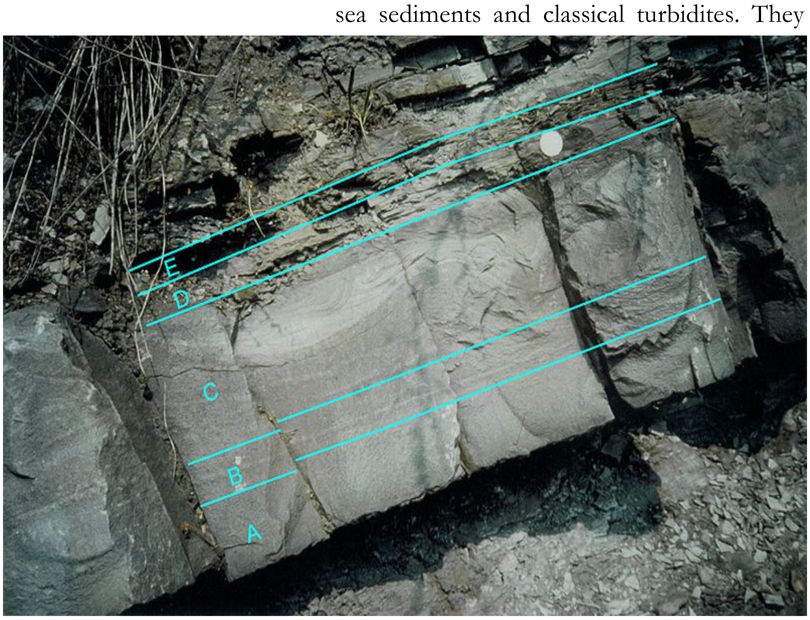
Figure 4: *The controversy over the definition of turbidity currents began when Kuenen considered the flowing-grain layers at the base of the flow to be part of the turbidity current (bottom layer). Sanders argued that only turbulent flows (upper layer) are turbidity currents.*

The recognition of the **Bouma sequence** in 1962 further supported the use of the term 'turbidite' to describe graded sandstone beds (Ricci-Lucchi, 2003). However, disagreements concerning the hydrodynamic properties of turbidity currents were also raised. **John Sanders**, a process sedimentologist, believed that the term 'turbidity current' was inadequately defined (Sanders, 1965). Sanders argued that **laminar flows** are not turbidity currents (Sanders, 1965; **Figure 4**). Furthermore, field and experimental observations at this time indicated that factors other than turbidity current (i.e. slides, slumps, debris flows, grain flows, and bottom currents) also exert significant influence on deep-sea sediment deposition (Shanmugam, 2002). Unfortunately, Sanders' concerns were overlooked by most of the geologists at the time. In fact, the conflicting definitions of the 'turbidity current' remain unresolved today (Mutti, Bernoulli, Ricci-Lucchi, and Tinterr, 2009).

Further Complications

In the 1970s, geologists began to acknowledge the complexity of facies and depositional processes associated with deep-sea sediments and classical turbidites. They recognized that the Bouma sequence (**Figure 5**) was not enough to illustrate the lithology of all turbidites or deep-sea sediment types. The origin of other types of deposits commonly seen in ancient turbidite basins also had to be considered. **Gerry Middleton** and **Monty Hampton** were mainly responsible for identifying this complication through a novel approach. They classified sediment-gravity flows based on sediment-support mechanisms into four main types: 1) debris flow (flow strength); 2) grain flow (grain-to-grain collisions); 3) fluidized flow (upward water escarpment); and 4) turbidity current (turbulence) (Middleton and Hampton, 1973).

Figure 5: *The Bouma sequence describes the lithology of five distinct sedimentary beds of a turbidite. Labelled from A (lowest) to E (uppermost), these beds fine upwards.*



During the 1970s, there was a shift from a process-based approach to an environment oriented approach in sedimentology and deep-sea research (Ricci-Lucchi, 2003). Predictive depositional models called **deep-sea fan** models were introduced by an American geologist, **William Normark** (Normark, 1970).

These predictive facies models became highly popular and instigated a number of studies of other depositional environments in the 1970s. Facies analysis in fluvial, nearshore and shallow marine sedimentary environments thrived. However, facies modeling was plagued with many problems when applied to studies of turbidites in deep-sea environments (Ricci-Lucchi, 2003). In the 1980s, geologists questioned the validity of the Bouma sequence, fan models, and the turbidite facies scheme (Shanmugam, 2000). Further research demonstrated the complexity of fan models that baffled researchers (Ricci-Lucchi, 2003). Nonetheless, these models continued to dominate deep-sea sedimentology and were utilized in the development of sequence stratigraphy (Shanmugam, 2000).

Period of Abandonment

By the 1990s, much of the interest in using fan models for deep-sea research declined. Interests for turbidites also subsided. At this point, deep-sea research associated with turbidites was almost deserted by field geologists (Ricci-Lucchi, 2003). After nearly 50 years of being a subject of major controversies in sedimentology, the turbidite paradigm reached its full circle and completed its short history.

Seismic Surveying in Oil Exploration

In the late 1980s, marine geologists began postulating the existence of petroleum in turbidite reservoirs. Soon, these deposits became the last great frontier in petroleum exploration (Slatt and Weimer, 2000). Currently, various parts of the world such as the Gulf of Mexico, California, offshore West Africa, the North Sea, and Brazil are being actively investigated for oil reservoirs in deep marine turbidite facies (Slatt and Weimer, 2000). There are currently 43 known turbidite fields worldwide and each is thought to contain more than 500 million barrels of oil equivalent (Slatt and Weimer, 2000).

The conceptual deep-sea fan models of the 1970s were plagued with limitations and were severely criticized by exploration geologists (Mutti, Bernoulli, Ricci-Lucchi, and Tinterri, 2009). However, integration of conceptual models with modern field data obtained from advanced deep-sea technologies and field studies that enhance understanding of the stratigraphic location, architecture, and the origin of the oil reservoirs have improved exploration models significantly (Slatt and Weimer, 2000).

As one of the most useful of the advanced deep-sea technologies, marine seismic surveying rapidly developed to visualize and analyze depositional systems and other geologically significant features. Two dimensional (2-D) and three dimensional (3-D) **seismic surveys** of deep-sea environments and deposits can now be conducted (**Figure 6**).

The difference between 2-D and 3-D surveys is that 2-D surveys use one seismic source and one set of receivers whereas 3-D surveys use two seismic sources and multiple sets of receivers. The seismic source towed along by a ship generates **seismic waves**. These waves travel through water and the seafloor and reflect back towards the surface when a boundary between geological formations is encountered. They are then recorded by receivers, known as geophones or hydrophones (Canadian Association of Petroleum Producers, n.d.). The recordings are then sent to the **seismograph** on the vessel to be stored and processed. Using the travel times and the velocity of the seismic waves, the pathways of the waves are reconstructed to produce an image of the subsurface (Canadian Association of Petroleum Producers, n.d.).

Most of our current understanding in **stratigraphic** architecture of the deep-sea systems is driven by oil and gas exploration. Continuous improvements in seismic resolution will eventually allow us to clearly image and better understand these complex deep-sea environments (Davies, Posamentier, Wood, and Cartwright, 2007).

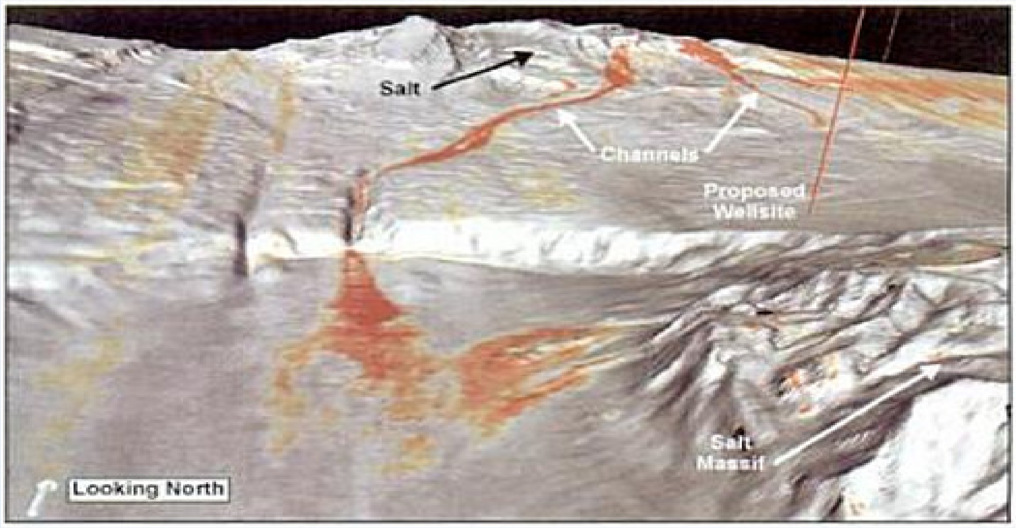


Figure 6: *A 3-D image obtained from seismic surveying the seafloor in the Gulf of Mexico. This technology allows oil companies to search for turbidite reservoirs, which are known to contain large amount of petroleum.*

The Development of Sonar Surveying

The *RMS Titanic* was at its time the largest ocean liner that had set sail in the oceans (Hawkins, 2011). The ship was outfitted with various accommodations, ranging from gymnasiums to libraries, and had a carrying capacity of 3 547 passengers. Major technological innovations of the early 1900s, such as wireless telegraph, allowed the vessel to communicate with operators on nearby ships to warn of stormy weather and oncoming icebergs. Despite these technologies, the "unsinkable" ship encountered a fatal collision with an iceberg adrift in the North Atlantic Ocean during its maiden voyage. On the early morning of April 15th, 1912, the ship sank and 1 517 passengers suffered death from drowning or hypothermia. The news of the sinking of the *RMS Titanic* was published in major newsstands throughout the world in the following days (Ainslie, 2010). Particularly, it was the printing of the story in newspapers and broadcast journalism that prompted inspiration in various inventors, such as Reginald Fessenden, to develop a method of detecting objects at a distance for accident avoidance (Ainslie, 2010). Shortly after, patent offices received methods of using underwater acoustics to monitor submerged objects. This happened prior to the outbreak of World War I (WWI), an important event for sonar development.

Figure 1: *A painting completed in 1912 by German artist Willy Stowler. It depicts the sinking of the Titanic, a popular culture icon.*

Arguably, the first successful step towards making sonar possible was the development of an underwater **transducer**. The electrodynamically driven circular plate was designed by Canadian Reginald A. Fessenden while employed by the Submarine Signal Company located in Boston, Massachusetts (D'Amico and Pittenger, 2009). After having received news of the *RMS Titanic*, Fessenden began work on his prototype in 1912, being awarded a patent for his device a year later. Testing of the device named the "Fessenden oscillator" was conducted on April 27th, 1914 (D'Amico and Pittenger, 2009). A United States (U.S) Coast Guard ship carried Fessenden and his assistant to a site off the coast of Newfoundland, Canada near floating masses of ice. The system was able to demonstrate the ability of echo ranging through detection of a distant iceberg that was located 3.2 km from the ship. After the expedition, improvements continued to be made to his invention until about 1931, at which point they were phased out by more sophisticated models.

The Fessenden oscillator was an example of passive sonar, that is, it detected marine signals without sending sound waves into the water (Ainslie, 2010). Although quite efficient in calculating distances to remote objects, the equipment was not able to determine the direction of approaching danger (Ainslie, 2010). This quickly became apparent with the onslaught of WWI and the emergence of U-boats as a naval threat. The arrival of this new "menace of the seas" required the need for active sonar devices (Ainslie, 2010). Unlike passive sonar, active sonar is able to both transmit and receive acoustic signals by emitting high (supersonic) or low frequency (infrasonic) sounds that are reflected by underwater objects (Ainslie, 2010). Based on the size, composition, and shape of the reflected waves, the signal is converted into a visual display for interpretation by the ship's crew. This discovery was imperative in determining a course of action for war boats.

World War I

The outbreak of WWI and the appearance of the submarine as an "asymmetrical threat" – a weapon of choice for the weaker naval powers – was the primary motivation for intensified research into developing advanced sonar systems. Since sound is the only transmitted energy that travels through water for an appreciable distance, further investigation in acoustic echo-ranging for countering the otherwise invisible submarines, was needed. This effort was initiated jointly by the British and French Navies in response to the sinking of several

Allied ships including the *HMS Formidable*, *Aboukir*, *Hogue*, and *Cressy* (Messimer, 2002). The German U-boat campaign rendered the British destroyers obsolete and the formation of the Allied Submarine Detection Investigation Committee (ASDIC) took place in 1915 as a result (Messimer, 2002). The greatest contributions made to the committee were from French physicist Paul Langevin, and Russian engineer Constanin Chilowsky, that worked on estimating target range and bearing.

In February 1915, Chilowsky submitted a plan to find submarines using "elastic high frequency waves by transforming the electric oscillations of high frequency, commonly used in wireless telegraph" to the French government (Messimer, 2002). His proposal was forwarded to Professor Paul Langevin, an early supporter of general relativity and an expert in **paramagnetism** (Messimer, 2002). Langevin decided Chilowsky's basic idea had merit and asked him to join a laboratory at the School of Physics and Chemistry in Paris (Messimer, 2002). The goal of the research was in developing intense pulses of high frequency sound. By April 1915, the results were promising enough that the French Navy relocated their work to Toulon to begin undersea experiments (Messimer, 2002). An audible, clear echo was detected for the first time in January 1917, a major achievement in active sonar technology.

However, the feat did not offer the required range for submarine detection. After continued experimentation, Langevin devised an improved design that utilised the **piezo-electric** properties of quartz to receive and emit sound impulses (Messimer, 2002). Between June 5th and July 8th, 1918, a working prototype was tested in Toulon (Messimer, 2002). The combined efforts of Chilowsky and Langevin were shown to be successful with results superior to any other sonar at that time used for hunting submarines. It was capable of effectively locating submerged targets between 600 - 1300 m, and coupled with the accuracy of the device, its performance surpassed that of the best hydrophones (Messimer, 2002). The development of sonar in the U.S and Britain took place following the Washington Antisubmarine Warfare research conference in 1917 (Messimer, 2002). The French representatives briefed both nations on their technologies.

World War II

During WWII, most mainland European countries, with the exception of the Soviet Union, were occupied by Nazi forces. The last remaining stronghold to Nazi resistance was the United Kingdom (UK). To ensure that the UK did not surrender required safe passage of North American ships delivering wartime supplies, such as ammunition and rations to the island nation. Termed "The Battle of the Atlantic", a struggle between opposing nations to establish dominance over these waters was enforced (Messimer, 2002). To accomplish this required the use of better sonar equipment in helping to find submarines. Both the Axis and Allied powers developed sonar systems. However, the Allied systems were superior to those of the Axis Powers (Ainslie, 2010). WWII saw far more extensive use of sonar than did WWI in locating submerged targets.

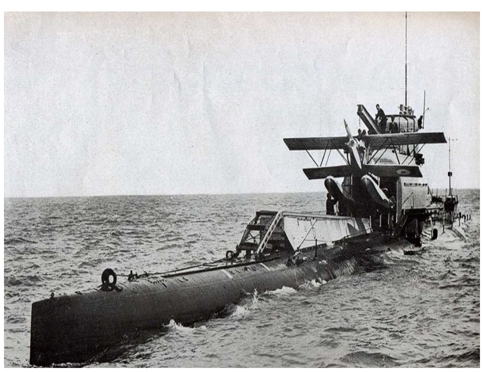


Figure 2: *An example of a Royal Navy Aircraft carrying submarine, the HMS M2, that was deployed during the Second World War.*

More specifically, the U.S Navy made large investments in their sonar technologies. They made the key discovery that the amplitude of high frequency underwater sounds became far more **attenuated** than low frequency sounds whilst passing through seawater (D'Amico and Pittenger, 2009). This led to the development of Low Frequency Active (LFA) sonar (D'Amico and Pittenger, 2009). The term 'sonar' was coined in 1942 by the director of the Underwater Sound Laboratory, F.V Ted Hunt, and stands for Sounding Navigation and Ranging (D'Amico and Pittenger, 2009). Prior to 1942, they were referred to either as hydrophones or *asdics*. The efforts in sonar development could not be attributed to any one person, as it consisted of teams of scientists working for militaries in multiple nations. Additionally, many documents, especially those of German technology, were assimilated into Soviet and U.S technologies.

Cold War

The Cold War era saw perhaps some of the greatest achievements in sonar technology. The development of scanning side sonar, a powerful form of active sonar, compensated for faster submarine speeds and was able to switch rapidly from short-range to long-range detection of an attacking submarine (D'Amico and Pittenger, 2009). In scanning sonar, the transducer forms an array of elements that are arranged in a vertical cylinder (D;Amico and Pittenger, 2009). This allows for omnidirectional transmission and reception. The disadvantage of active sonar is that, when turned on, it allows enemies to locate your position by using the emitted sound pulses the sonar sends out, whereas passive devices do not encounter these measures. Thus, in the 1970s, as submarines began to be equipped with intercontinental ballistic missiles, the research into long-range passive sensors had been accelerated. However, the development and deployment of nuclear and diesel-electric powered submarines operating on batteries changed the course of sonar development towards active sonar once more (D'Amico and Pittenger, 2009). As submarines were progressively quieter and faster, they became difficult to spot in a timely manner. Consequently, the U.S and NATO started to pursue passive acoustics alternatives, resulting in the development of LFA systems.

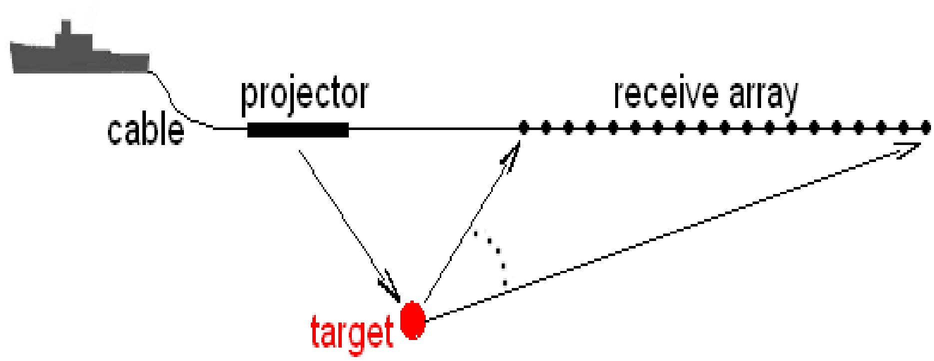


Figure 3: *An active side scanning sonar system typically used for oceanographic research. The projector transmits sound waves that are reflected by the target. The reflected signal is detected by the receive array and travels through the cable to the crew for display.*

Oceanographic Research

From the Second World War to present day, the U.S Navy has been involved in funding oceanographic research, primarily for possible military uses (MIT, 2008). This funding spurred numerous civilian technologies critical to ocean science and industries. Major institutions that received this monetary incentive include MIT and the Woods Hole Oceanographic Institution (WHOI).

An influential MIT Professor, Harold. E. Edgerton first collaborated with WHOI to assist in underwater photography in the 1930s (MIT, 2008). In 1953, Edgerton began experimenting with sonar while aiding Jacques Cousteau in taking deep ocean pictures of the Mediterranean Sea (MIT, 2008). In order to accurately focus the camera, the distance between the camera and sea bottom was needed. For this, Edgerton used sonar and from the signal observed that the sound waves could penetrate into layers of sediment. As a result, he began work on the "mud penetrator", a high-resolution sub-bottom profiler.

In 1961, an engineering student by the name of Martin Klein approached Edgerton to be his thesis supervisor (MIT, 2008). Edgerton proposed that Klein improve the signal processing of the "mud penetrator". Soon after, Klein accomplished the task and following graduation, worked in Edgerton's lab, then his company. Between 1963 - 1964, Klein was responsible for designing and installing side scan sonar systems on submersibles.

A dramatic demonstration of the search abilities of side scan sonar became apparent when, in 1967, Klein assisted a pioneer underwater archaeologist, George F. Bass, in locating a 2000- year old Roman shipwreck near southwest Turkey (MIT, 2008). This was the first ancient shipwreck discovered by remote sensing.

Bathymetry: Mapping the Sea Floor

Following the advent of sonar in response to the sinking of the *RMS Titanic* and the emergence of the submarine threat, sonar remained largely unused in determining ocean depth until about the 1960s (Garrison, 2011). It was then used by Martin Klein in 1965 in the Atlantic Ocean for bathymetric surveying. Bathymetry is the study of nautical depths of ocean and lake floors with the terrestrial equivalent being topography. Similarly, bathymetric charts plot the same information as a topographic map would, the most important feature being contours that display depths of objects.

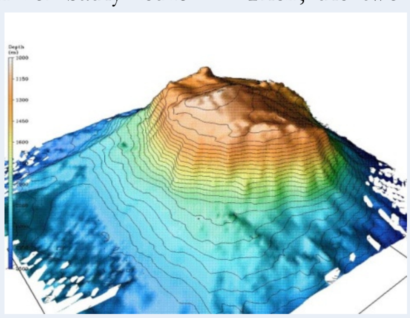


Figure 4: *A bathymetric survey of Bear Seamount, the oldest of the New England Seamount Chain located in the Atlantic Ocean.*

Bathymetric Measurements

Early measurements taken for bathymetry involved placing lead weighted ropes into the water over the ship's side (Garrison, 2011). The premeasured cable would then sink to the bottom and the resulting rope output would be counted. Often times, the lead weight would be coated in either lead or wax to collect a sample of the surface sediment (Garrison, 2011). The depth information was then transferred onto positions on a chart using celestial navigation methods, such as **astrolabes** and **quadrants** (Garrison, 2011). However, these recordings only gave single point measurements as opposed to a continuous reading. Also, wave currents and movements of the ship would move the line out of place, resulting in inaccuracies. One particular expedition, that of the *HMS Challenger*, set out to gain "soundings" – depth measurements - of the Atlantic sea floor (Garrison, 2011). Although, the method described limited the capabilities of mapping the sea floor, the *HMS Challenger* collected sufficient measurements to establish that "The bottom of the oceans it appears is as varied as the land for there are valleys, and mountains, hills and plains all across the Atlantic" (Garrison, 2011).

Later on, the introduction of wave based acoustic measurements replaced mechanical means of recording the ocean's depths and was the modern basis of oceanographic research. The system involved using the transducer, a device able to generate sound wave pulses, placed directly beneath a ship. Then, the two way travel time, that is, the time it takes for the pulse to reach the ocean floor, be reflected and return to the ship, would be recorded. After multiplying this transit time by the speed of sound in water and dividing by two, the underwater distance would be obtained. This form of measurement was the basis for subsequent echosounder systems. Early single beam echosounders used a single transducer to transmit and receive acoustic signals (Ainslie, 2010). Low frequency echosounders were subsequently developed to penetrate the sea floor, providing information about subsurface sediment layers (Garrison, 2011). To increase the accuracy and coverage of bathymetric readings, the swath bathymetric system was developed in the 1970s so that multiple swaths or points of the ocean floor were ensonified for each transmission of acoustic energy (Ainslie, 2010). The addition of motion sensors also allowed the pitch, heave, and roll of the vessel to correct soundings (Garrison, 2011). Interferometry is a technique that is used to describe the phase content of a sonar signal in order to measure the angle of wave fronts returned from the sea floor. Interferometric systems are able to measure the angle and range from a series of points located on the seabed. This produces high-resolution depth and backscatter measurements in a survey area.

Henry Darcy and the Legacy of Darcy's Law

Hydraulics is the study of fluid mechanics in the applied sciences and engineering. The word originates from the Greek word *hydraulikos*, meaning water pipe (Hoffman, 1919). Theoretical groundwork in hydraulics was established in the 16th and 17th century before Henry Darcy's time by distinguished individuals such as **Benedetto Castelli** and **Blaise Pascal** (Usher, 1929). However, Henry Darcy (1803-1858) was the first to relate hydraulic properties through, fittingly, the construction of water pipes, to geology in his formulation of Darcy's Law. This fundamental equation set the foundation for groundwater movement and paved the way for further developments in the field of hydrogeology.

Formative Years

Henry Philibert Gaspard Darcy was born in Dijon, France. Dijon was then an undeveloped town with a population of less than 30 000, compared to today's established city (**Figure 1**). At the start of the 19th century, France endured the French Revolution and was entering a period of prosperity fuelled by the Industrial Revolution (Simmons, 2008). With the support of a good education in France, Darcy successfully acquired the crucial background he needed for his future accomplishments. In 1823 at the age of 20, he was admitted into the prestigious L'École des Ponts et Chausseés in Paris, notable for its famous graduates of engineering and mathematics such as **Henri de Pitot** (1695-1771) and Augustin Louis Cauchy (1789-1857) (Simmons, 2008).

Figure 1: *Portrait of Henry Darcy in his later years from the Collection of the Bibliothéque Municipale de Dijon.*

Upon graduation, Darcy worked for Le Corps des Ponts et Chausseés, an elite fraternity of engineers that had influential status during the mid-19th century (Freeze, 1994). His first major project involved performing a preliminary feasibility study of the Dijon public water supply (Simmons, 2008). In an initial report to the town council of Dijon, he made the first crucial observation that set the basis for his future inquiries: that **aquifers** provide significant resistance to water flow (Simmons, 2008).

Prominent Years

Darcy excelled in the working field and by 1840 he had transformed Dijon from a city filled with filth into a city with one of Europe's best water supply systems, using the Rosoir Spring as the city's water source (Simmons, 2008). Darcy's rise to prominence was swift, highlighted by being awarded the prestigious Legion of Honour by King Louis Philippe in 1842. One of his most notable work as Chief Engineer for the Department of Côte d'Or was the design of the Paris-Lyon railroad that involved the construction of the 4 km long Blaizy tunnel still in use today (Simmons, 2008). Darcy oversaw the development of Dijon's water supply system and was able to make critical advancements in the field of hydrology through the design and operation of various hydraulic projects. Pressure decline due to resistance in pipe flow is one of the most important parameters when designing a water supply system. At the time, the most widely used equation for describing **head** losses on pipes was the Prony equation; however, this expression was prone to error in that friction constants fail to account for pipe roughness (Brown, 2002). Darcy improved the estimate of Prony friction coefficients together with Julian Weisbach in 1845 by making them a function of pipe diameter (Simmons, 2008). Head loss is now described with the Darcy-Weisbach equation,

$$h_L = f\frac{L}{D}\frac{V^2}{2g} \qquad (1)$$

where *f* is called the Darcy friction factor that Darcy added onto the original Prony equation to account for head loss due to friction (Simmons, 2008).

Despite the accumulation of successes, Darcy was subjected to the political turmoil that the economic depression of 1848 brought on and the replacement of the French constitutional monarchy with the Second Republic (Freeze, 1994). At age 45, he was suspended from his duties and banned from Dijon because he was considered "dangerous for the new state of things" and had too much influence on Dijon for the new government's likings (Simmons, 2008). However, his talent did not go unnoticed as he was soon called to Paris to serve as the Director of the Service of Water and Pavements under the new regime (Freeze, 1994). He had the opportunity to travel to England and Belgium to consult on their water systems, where his publication on English road construction practice earned him the promotion to Inspector General, 2nd Class, in 1850 (Brown, 2002).

Final Years

Despite regaining his previous high status within the government, Darcy's health began to deterioate. In 1855, he requested release from all assigned duties except for research (Brown, 2002). It was in his last years of dedicated research that he wrote the famous *Les Fontaines Publiques de la Ville de Dijon* (The Public Fountains of the City of Dijon) in 1856 where Darcy's Law made its first appearance (**Figure 2**) (Simmons, 2008).

Darcy also made important contributions to the development of the Pitot tube, an instrument that measures point fluid velocity by recording differences in pressure between two glass **manometer** tubes when lowered into water. The Pitot tube was first invented by French engineer Henri de Pitot (1695-1771) in 1732, but its theoretical and design weaknesses prevented it from being more than a mere scientific toy (Brown, 2003). Darcy outlined the first modern design of the Pitot tube in his last work and the improved instrument was able to provide accurate measurements of point fluid velocity. His final instrumental design is still in widespread use today (Brown, 2003).

Henry Darcy died of pneumonia at age 54. His outstanding work was recognized by the city of Dijon by renaming the square Château d'Eau, the location where waters of the Rosoir Spring enters the city, to Place Darcy (Simmons, 2008).

Les Fontaines Publiques de la Ville de Dijon

Darcy's Law is a fundamental empirical equation that describes the linear relationship between fluid flow rate *(Q)* and hydraulic potential gradient (h/L) (Freeze, 1994), seen in its modern form,

$$Q = AK\frac{h_1 - h_2}{L} \qquad (2)$$

For small distances, the hydraulic gradient, ($\Delta h/L$), can be expressed in differential form (dh/dL) with a minus sign being introduced to indicate that fluid flow is in the direction of decreasing head,

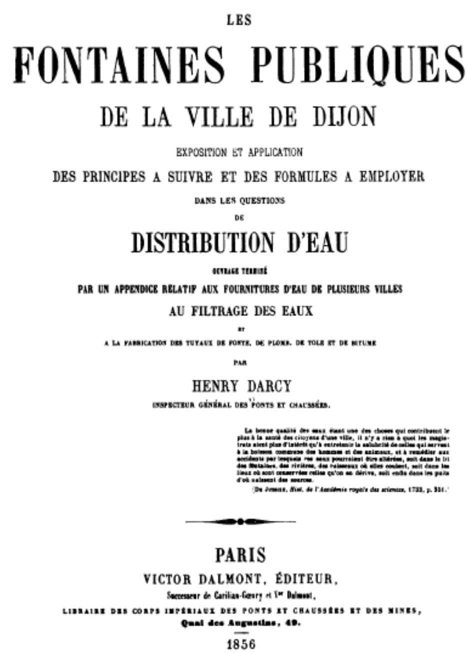
$$Q = -AK\left(\frac{dh}{dL}\right) \qquad (3)$$

Modern forms of Darcy's Law often convert discharge to velocity by dividing by the column cross-sectional area.

Darcy's Law first appeared in the 1856 *Les Fontaines* report, a publication prepared by Darcy that summarized water needs, available resources, and design of water systems for the city of Dijon (Brown 2002).

This publication is a compilation of all the designs and discoveries Darcy made in his life as Department of Côte d'Or's Chief Engineer. The development of a water-distribution system in Dijon made a significant impact on the citizens' lifestyles. At the time, European cities did not have water-supply or sewer systems (Freeze, 1994). Buildings had adjoining sewage tanks and "great dripping wagons could be seen as they lumbered through the street carting human waste out of the city" (Burchell, 1971). Rainfall often washed neglected waste into the Seine River, Paris' primary source for water (Freeze, 1994). The contamination of this water supply resulted in the death of 20 000 Parisians during the February Revolution in 1848 (Freeze, 1994). Darcy's pipe designs in Dijon went into operation in 1840 and revolutionized European water supply systems.

Starting late in 1855, Darcy conducted two sets of column experiments with the


LES
FONTAINES PUBLIQUES
DE LA VILLE DE DIJON
EXPOSITION ET APPLICATION
DES PRINCIPES A SUIVRE ET DES FORMULES A EMPLOYER
DANS LES QUESTIONS
DE
DISTRIBUTION D'EAU
OUVRAGE TERMINÉ
PAR UN APPENDICE RELATIF AUX FOURNITURES D'EAU DE PLUSIEURS VILLES
AU FILTRAGE DES EAUX
ET
A LA FABRICATION DES TUYAUX DE FONTE, DE PLOMB, DE TOLE ET DE BITUME
PAR
HENRY DARCY
INSPECTEUR GÉNÉRAL DES PONTS ET CHAUSSÉES.

PARIS
VICTOR DALMONT, ÉDITEUR,
Successeur de Carilian-Gœury et V[ve] Dalmont,
LIBRAIRE DES CORPS IMPÉRIAUX DES PONTS ET CHAUSSÉES ET DES MINES,
Quai des Augustins, 49.
1856

Figure 2: *The front page of Darcy's famous publication in 1856 that contains Darcy's Law and outlined his work as Chief Engineer in developing a water-supply system for the city of Dijon.*

assistance of engineer Charles Ritter in an unnamed hospital's courtyard (Simmons, 2008). The apparatus consisted of a vertical steel pipe 3.50 m high with an internal diameter of 0.35 m (**Figure 3**).

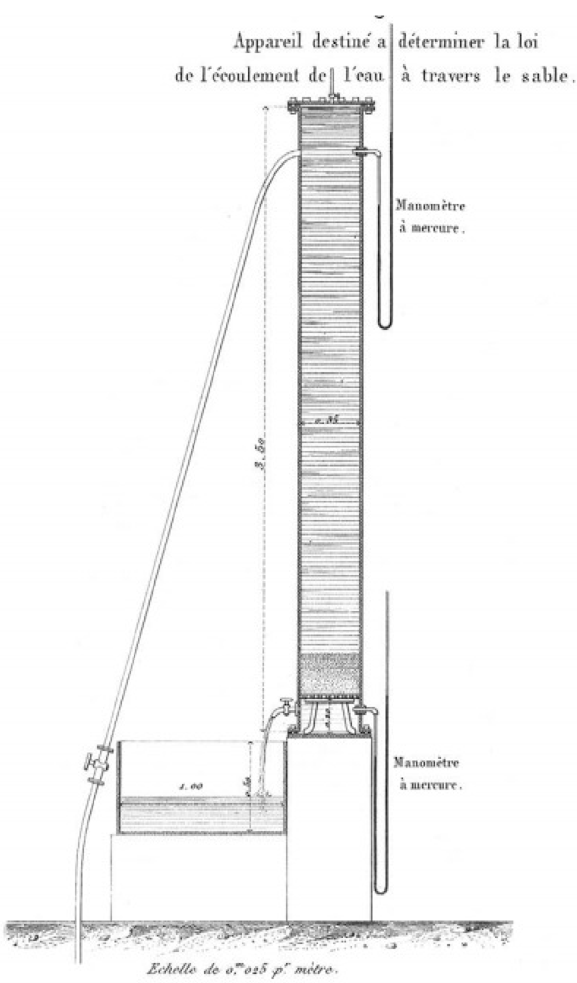


Figure 3: *Darcy's original column experimental setup for his formulation of Darcy's Law, as appeared in Les Fontaines. The inlet reservoir on the left is connected directly to the hospital house line. Water flowed from top to bottom into an outlet reservoir set above the ground where the discharge was determined by timing the fluid accumulation in the tank.*

The column was filled with siliceous sand from the Saône River and the pressure at the two column ends was measured with mercury U-tube manometers as the water supplied directly from the hospital house line was passed through (Brown, 2002). The inlet and outlet pressure was observed until there was uniform flow down the column, and then the discharge through the sand filter was noted for a certain time interval (Domenico and Schwartz, 1990). The only significant problem with the apparatus setup was the use of an unregulated water supply, as considerable oscillations are induced whenever the house line was used (Domenico and Schwartz, 1990).

Darcy's measurements showed that for fluid flow through a porous medium, the discharge is directly proportional to the head and inversely proportional to the thickness of the sand transversed (**eq 1**). This central relationship forms the theoretical and quantitative basis for applications in various scientific fields, including hydrogeology, soil science, and civil engineering.

The Legacy of Darcy's Law

The experimental work done by Darcy in describing the motion of groundwater has the most significant impact in the field of hydrogeology. The first modern aquifer analysis, in which Darcy's Law was applied, was conducted by Arsene Jules Emile Juvenal Dupuit (1804-1866) in 1863 (Simmons, 2008). Dupuit, Darcy's associate, solved the **radial flow equation** for steady flow in aquifers with the assumption that flow pattern is steady and Darcy's equation is applicable (Kitterød, 2004). Germans Adolph and Gunther Thiem also carried out pioneering studies on groundwater flow to wells using field-based methods instead of developing novel theoretical work (Simmons, 2008). Later in the 19th century, French physicist Valentin Boussinesq (1842-1929) and Austrian hydraulic engineer Philipp Forchheimer (1852-1933) discovered that Darcy's Law, under steady-state conditions and the continuity principle, yielded the well known **Laplace Equation** (see pg. 64) and that groundwater flow is surprisingly similar to heat flow (Simmons, 2008).

While Darcy focused his work on small-scale artificial pumping wells with the purpose of water filtration, M. King Hubbert (1903-1989) explored the natural flow of ground water in large geologic basins (Domenico and Schwartz, 1990). Using Darcy's Law as the theoretical background, Hubbert introduced the concept of force potential to show the difference between hydrostatic and hydrodynamic conditions (Weyer, 2011; Simmons, 2008). These significant developments in the evolution of groundwater science illustrate how Darcy's Law was employed in the post-Darcy years to coordinate the groundwork for modern quantitative hydrogeology.

The contribution Darcy made to the field of hydrogeology was the foundation for many future developments. The design of simple, yet theoretically complete, experiments allowed him to formulate his fundamental equation describing fluid flow through a porous media. In addition to Darcy's Law, Darcy played an important role in the development of pipe hydraulics, recognized through the Darcy-Weisbach pipe head loss equation, and made critical improvements to the Pitot tube. Despite a short life of only 54 years, Darcy established himself as a renowned engineer and scientist who will forever be immortalized by Darcy's Law and his scientific legacy.

Modelling Groundwater Flow and Pollution in Environmental Toxicology

Groundwater is a crucial source of fresh water for human consumption and for the ecological function of maintaining streamflow during dry periods by discharging to rivers (Natural Resources Canada, 2009). Contamination is an important concern that plagues the water industry today and pollution models are necessary to design and implement effective groundwater protection strategies.

To develop a model for subsurface contaminant transport, it is important to understand the mechanisms and processes of groundwater flow (Fried, 1975). Contaminants can come from point sources such as landfills and industrial disposal sites, or from distributed sources such as pesticide infiltrations. There is a broad range of methods employed to assess water flow, based on Darcy's Law. The hydraulic head of a region can be determined by measuring water levels in **peizometers** installed in fluvial plains (Kalbus et al., 2006). The difference in hydraulic head between individual peizometers over a horizontal length yields the hydraulic gradient (Kalbus et al., 2006). **Hydraulic conductivity** can also be calculated with a **permeameter**, an instrument with similar setup to Darcy's column experiments (Kalbus et al., 2006).

Akara Mine Contamination

Water flux measurements provide further insight into toxicological analysis by allowing the evaluation of past and future migration patterns of contaminants (Bear et al., 1992). An application highlighting the value of groundwater flow modelling can be seen in a study conducted by Putthividhya and Chotpantarat (2008), where the impact of heavy metal **leachate** from mine tailings at the Akara mine in Thailand was investigated (**Figure 4**).

The objective of the study was to examine the migration of heavy metals into natural subsurface environments by looking at soil moisture content and desorption properties of tailing samples (Putthividhya and Chotpantarat, 2008). A conceptual model was constructed and designed with boundary conditions for numerical simulations using a two-dimensional computational model, HYDRUS-2D, that simulates water movements in variably saturated media (Putthividhya and Chotpantarat, 2008). Various column experiments that determined heavy metal fluxes via Darcy's Law were performed and the results were used as input parameters in the HYDRUS-2D model (Putthividhya and Chotpantarat, 2008).

It was found that the heavy metal plume migrated predominantly through the **unsaturated zone** where the decreased water content resulted in longer contaminant life in the groundwater system due to decreased mobility (Putthividhya and Chotpantarat, 2008). Research is currently being conducted on the potential of using biological and vegetation root uptake activities as a way of removing toxic metals from groundwater, in a process called **phytoremediation** (Tangahu et al., 2011). Interest in using phytoremediation has been high during the past two decades and current studies yield promising results in using this method as a viable contaminant removal strategy.

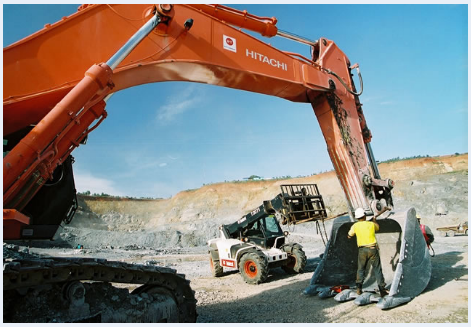


Figure 4*: A Hitachi excavator on site at the Akara gold mining site in Thailand. Simple drill and blast technology is first used to release buried rocks. Excavators and hydraulic loaders then transport the blasted mineralised rocks onto trucks to the processing plant. Waste is trucked to a waste rock dump.*

Historical Views on Tidal Change

The fluctuations of coastal ocean waters have long been observed and recorded. The word 'Tide' holds close connections with 'Zeit', 'Gezeiten', and 'Time', all early Anglo-Saxon words, inferring the knowledge of tides by North Sea coastal dwellers, fisherman, navigators, and pirates (Cartwright, 2000). The existence of such archaic terminology such as, "What Moon maketh a Full Sea?" suggests the commonplace of tidal knowledge in ancient society (Cartwright, 2000).

Figure 1: *A section of the 'Carta Marina' by Olaus Magnus depicting the maelstrom off the Northern shore of Norway.*

Ancient Greek Observations

Circa 330 BCE the ancient Greek astronomer and explorer Pytheas set out on his voyage from the West Mediterranean Sea to the British Isles (Ekman, 1993). In the British Isles, the movement of the tides is highly pronounced, and once Pytheas arrived there and spent enough time in the area he noticed the rising and falling of the sea level near the coasts twice per day. Pytheas not only observed the tides, but also speculated as to their origin. Through careful observation, Pytheas proposed that the phase of the moon controlled the amplitude of the tides, thus marking the starting point of tidal research and analysis (Ekman, 1993). Following Pytheas in terms of tidal observations was Seleukos, who in 150 BCE observed that the two daily tides of the Rea Sea had unequal amplitudes when the moon was a significant distance from the equator (Ekman, 1993). In the oldest known intact text on tidal theory "*Geographika*", written in 23 CE by the Greek Strabo, observations are recorded of the rising and falling of water in a well at the Temple of Heracleium at Gades. Curiously, the tide in the well was out of phase with the ocean tide such that high tide in the well corresponded with low tide in the ocean (Ekman, 1993). These observations describe crucial characteristics of modern day tidal theory, with Seleukos observing the **diurnal inequality**, and Strabo **earth tides** and **tidal strain**. The discoveries may have been made 2000 years ago, however it required 1600 years and the combined work of many scientists, philosophers and mathematicians to fully elucidate the origin and underlying mechanisms of the tides (Ekman, 1993).

Tidal Mechanisms

Theories of the mechanistic causation of tides began with Bede the Venerable (673-735 CE), an English monk who, at the start of the 8th century, noticed that different ports had different tidal phases, thereby discovering the phase lag of ocean tides. He speculated that the Moon 'blowed' on the water, causing ebb tide, and that the tide would flow once the moon shifted enough (Ekman, 1993). The first real attempt at a scientific explanation came in the middle of the 13th century from Arabian scientist Zakariya al-Qazwini (c. 1203-1283). He believed that the flowing tide was caused by the Sun and Moon heating the water causing it to expand. This theory, however, fails to explain why the phase of the Moon plays such an important role as opposed to the position of the Sun (Ekman, 1993). Attempting to explain the tides in terms of the Moon and Sun's influence on Earth became too tasking for scientists, and the whole theory that extraterrestrial celestial bodies played a role on the terrestrial tides became untrusted. People sought a physical explanation on Earth. A popular idea was that the great Malstrommen off the northern coast of Norway (*left*), a giant whirlpool, was the cause of the world's tides. During times of low tide, the maelstrom would 'swallow' massive amounts of seawater, and release it at times of high tide (Ekman, 1993). This was not the first time tide and maelstroms were linked, however. The great ancient Greek poet Homer writes of the mythological *Scylla* and *Charybdis* in his epic poem the *Odyssey*, where *Scylla* is a large rock on the Italian shore off the Strait of Messina, and *Charybdis* a great whirlpool on the Sicilian shore (Homer, 1889). The two sit close enough one another in the strait that they pose an unavoidable threat to sailors attempting passage. When describing *Charybdis,* Homer writes, "Under this divine Charybdis sucks in black water. For thrice in a day she sends it out, and thrice she sucks it in terribly." (Homer, 1889). In Strabo's writings, he attributes some form of rudimentary knowledge of the tides to Homer based on this passage, and rationalizes that the use of 'thrice' instead of 'twice' could have been scribe error, a generalization, or a purposeful hyperbole (Harris, 1904). Although it is now known that maelstroms do not cause the tides, it is interesting to note that there is a connection, and in fact the changing of the tides gives rise to the great maelstroms of the ocean (Ekman, 1993).

Early Scientific Explanations

The notion that the Moon and the Sun played the key role in controlling the tides returned in 1609 with German astronomer Johannes Kepler (1571-1630). In his work *Astronomia nova*, he explained that there existed some kind of attractive force between the Earth, Sun, and Moon. This was around the time that English physicist William Gilbert (1544-1603) had discovered the Earth's magnetic field, and therefore Kepler attributed the attractive force to magnetism (Ekman, 1993). Galileo Galilei (1564-1642), the famous Italian physicist and astronomer, was shocked that a man of Kepler's stature, "Became interested in the action of the Moon on the water, and in other occult phenomena, and similar childishness" (Ekman, 1993). He himself thought that the tides were a result of the rotational motion of the Earth about its axis, as well as its rotation about the Sun. Galileo's theory of tides defended the recent Copernican theory developed in 1616 that the Earth did in fact rotate (Finocchiaro, 2010). Another advocate of lunar theories was French Mathematician Rene Descartes (1596-1650). He presented an idea in 1644 that there existed a vortex encompassing the Moon and the Earth. The vortex of the Moon would exert pressure on the Earth and subsequently cause the tides (Ekman, 1993). The problem here, however, was that Descartes' theory predicted low tide when in fact there was high tide (Ekman, 1993). In 1666 English mathematician John Wallis (1616-1703) agreed with Galileo, and built upon his already existing theory. He hypothesized that the oscillation of tides resulted from a combination of Earth's rotation, Earth's motion around the Sun as well as Earth's rotation about the center of the Earth-Moon system (Ekman, 1993).

The Law of Gravitation

The solution and missing piece of the puzzle that many had alluded to, but failed to pinpoint, was the law of gravitation. English mathematician, physicist, and astronomer Isaac Newton (1642-1727) published his theory of gravitation in 1687 in his work *Philosophiae naturalis principia mathematica* (Ekman, 1993). Newton directly addresses the issue of tides in his work, stating clearly in Proposition 24, Theorem 19 that, "the flux and reflux of the sea, arise from the actions of the Sun and the Moon", and illustrated the Northern and Southern flood tides in the adjacent figure (Newton, 1729). Correctly answering this question of the origin of tides served in part as motivation for Newton to develop his now famous theory (Ekman, 1993). He carefully analyzed existing English tidal observations and data, and by comparing **spring tides** and **neap tides**, found that the gravitational tidal force supplied by the Moon is 4.5 times larger than that of the Sun (Newton, 1729). Swiss mathematician Daniel Bernoulli (1700-1782) conducted his own analysis of French tidal observations of the time, and found the Moon's force to be 2.5 times greater than the

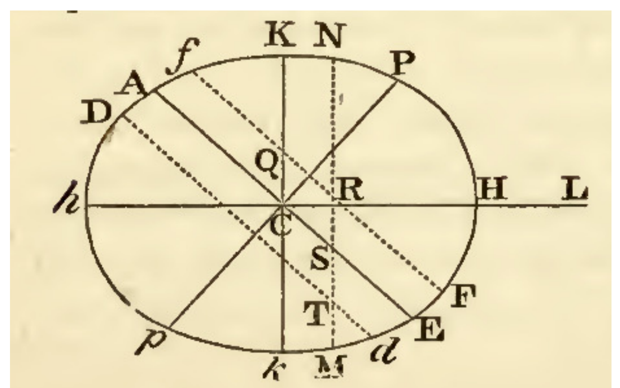


Figure 2: *Isaac Newton's depiction of a tidally deformed Earth in his work 'Principia'. The sphere illustrates the Earth, rotating about its axis Pp, with equator AE, and moon location L. Newton suggests that there are flood tides in the Northern and Southern hemispheres exactly opposite*

Sun's. Bernoulli's estimate is much closer than Newton's to the modern day accepted value of 2.2 (Ekman, 1993).

The Rise of Geophysics

Newton's theory explained so much and fit so well with tidal observations that English scientists of the 18th century figured there was no longer a need for tidal research, and largely abandoned the subject altogether (Cartwright, 2000). The French mathematician Pierre de Laplace (1749-1827) was left to pick up where Newton had left off, and succeeded in defining the dynamic response of the oceans to Newton's gravitational force field with his tidal formula in 1799 (Ekman, 1993). Laplace's equations were not solvable without the help of a computer, and with the British having lost interest due to Newton's giant leap forward, tidal theory was largely at a standstill for the next 100 years (Ekman, 1993). At this time, nearing the end of the 19th century, geophysics was becoming an increasingly popular subject of research, and many of its contemporaries saw that its problems involved large-scale properties of the oceans and the Earth (Cartwright, 2000). Of great interest in geophysics was the total rate of energy dissipation in the oceans. The problem had been commented on many years prior by German philosopher Immanuel Kant (1724-1804), who in 1754 said that friction between the ocean and Earth would act to slow the rotation of the Earth until the period of its rotation about its axis was equal to the period of the moon around the Earth (Ekman, 1993). American oceanographer and meteorologist William Ferrel (1817-1891) was to revive this idea once geophysics picked up steam in North America (Ekman, 1993). Ferrel theorized that if in fact tidal friction was causing the lengthening of the day, then there could be observed an apparent acceleration of other celestial bodies in the sky. Ferrel did eventually observe a slight acceleration, corresponding to a lengthening of the day by one second in 300 000 years (Ekman, 1993). However, it is through French astronomer Charles Delaunay (1816-1872) that tidal friction is well known, as he supposedly arrived at the same conclusion as Ferrel at about the same time (Ekman, 1993). Today, energy transfer in terms of tides is of great importance, as engineers look to harness the power of the tides to provide clean and renewable energy to homes.

Earth Tides and the End of Tidal Theory

In 1863, English physicist William Thomson (Lord Kelvin) (1824-1907) proposed that the Earth acts as an elastic solid, subject to deformation by the gravitational forces from the Moon, Sun, and other celestial bodies. He termed these deformations Earth tides, and theorized that they would act to reduce the observed amplitude of ocean tides. Thomson's student George Darwin (1845-1912), son of Charles Darwin, tested Thomson's theory, and found the ratio of the height of an ocean tide on the elastic Earth to that on a rigid Earth to be $\gamma = 0.68 \pm 0.11$ (Darwin, 1882). Showing the ratio to be significantly less than one, he thus proved the existence of Earth tides, and published the result in 1882 in *Nature* (Darwin, 1882). English geophysicist Augustus Love (1863-1940) continued applying ratio values to tidal theory and developed h and k, known as Love numbers, where h characterizes the height of deformation caused by the tidal potential, and k the additional potential caused by deformation, leading him to the relation $\gamma = 1 + h + k$ (Ekman, 1993). The first ever Love numbers originating from a realistic elastic Earth model came in 1950 from Japanese geophysicist Hitoshi Takeuchi who used three differential equations of the second order to obtain them (Ekman, 1993). The curious phenomenon seen in the wells of antiquity by Strabo were explained in 1940 by American geophysicist Chaim Leib Pekeris (1908-1993), who made the connection that a downward Earth tide would 'squeeze' ground water into the less resistant wells. This initiated research into tidal strain (Ekman, 1993).

Tidal research continues in the form of prediction of tidal events and effectively transferring tidal energy into electricity, however most, if not all of the theory surrounding tides has been worked out to date (Ekman, 1993). Although the history of tidal science ebbed and flowed with a mix of correct ideas and now-seemingly outlandish hypothesis, the scientific method has worked itself out, and we find ourselves all the more knowledgeable as a result.

Harnessing the Power of Tides

Development of Tidal Energy

Just as tidal theory has a history, so does the use of tidal fluctuations for power generation. Before tidal theory was fully understood, the basic characteristics of tides were exploited to meet human needs. Since the 12th century people living in coastal regions have utilized the periodicity of the tides to power their mills (Baker, 1991). Interestingly enough, it was the use of tidal mills that sparked English astronomer and geodesist George Airy (1801-1892) to think about the energy transfer of tides and realize that the heat produced by the mill must associate with the loss of kinetic energy somewhere in the system. Building off of Ferrel and Delaunay's theories, he hypothesized that the energy was coming from tidal friction (Ekman, 1993).

General Principle and Mechanism

Modern day tidal power uses the same principles that tidal mills did from antiquity, but with major upgrades in form and efficiency. The basic theory is to block the entrance to a bay with pronounced tidal activity with a barrier or **barrage** containing **sluices** and turbines. Water is allowed to enter the bay as the tide rises, and is then trapped by the closing of the sluices (Garrett and Cummins, 2004). As the tide ebbs, the water outside of the barrier retreats from the newly formed reservoir, leaving a gap. When a large enough gap has established (minimum of five meters), the reservoir water is released and channelled through the turbines (*right*) in the barrier. This movement of water acts to turn the turbines, thereby generating electricity (Gevorkian, 2007). The electrical energy collected comes from the conversion of the reservoir water's potential energy by the turbines.

Efficiency

In 1926 German physicist Albert Betz developed a simplified model of power retrieval from current flow for wind turbines, which is directly analogous to tidal turbines. He came to the conclusion that the maximum possible power that can be harnessed from a moving current is 59% of the currents initial energy (Garrett and Cummins, 2004). Flow through a turbine is only capable of generating power when there is a pressure difference on either side (i.e. the current slows down). By applying Bernoulli's principle to an upstream current affected by some resistance, the power term can be derived, given by,

$$P = \frac{1}{2}\rho(u_o^2 - u_1^2)$$

where ρ is the density of water, and u_0 and u_1 the speed of the current in the before and after case, respectively (Garrett and Cummins, 2004). It is evident then that no power is generated if the speed of the current before and after is the same, or if the resistance of a turbine is so high as to stop the current flow altogether. Efficiency is also maximized when the current flow is exactly orthogonal to the axis of the turbine.

Drawbacks and Conclusions

If implemented on a global scale, tidal power generation could disturb a number of coastal ecosystems and habitats, as well as compromise the commercial and recreational potential of bays. Large turbine barrages also have the capacity to cause flooding by displacing large amounts of water (Garrett and Cummins, 2004). Not only would large-scale implementation be detrimental, but also impossible, as there are only a select few bays and coastal regions in the world that can properly support tidal power and produce enough energy to warrant its use (Garrett and Cummins, 2004). Overall tidal power poses a novel, highly reliable, and renewable energy alternative, although it is best used in conjunction with other power generation techniques instead of as a stand-alone method.

Figure 3: *An example of a tidal turbine used to convert potential energy of ocean water into electricity.*

The Development and Triumph of Glacial Theory in the 19th Century

Figure 1: *Louis Agassiz in 1865. His glacial theory would start a geological debate in the second quarter of the 18th century and would eventually become widely accepted.*

Geologists today can attest to the great erosional and depositional power that glaciers possess. Glacier processes and deposits were not well understood prior to Louis Agassiz's (1807-1873) (**Figure 1)** declaration in 1837 that the glaciers found in the Alps had at one point in history covered much of the Northern Hemisphere. This statement shook the geological community for the next quarter of a century and received much criticism. Nevertheless, Agassiz continued to study glaciers and his theory was slowly accepted, triumphing over an established theory and opening a new page in geology.

Early Development

In 1787, Bernard Friederich Kuhn, a Swiss minister, viewed erratic boulders in Jura as evidence for ancient **glaciation**; this was also noted by **James Hutton** several years later (Imbrie and Imbrie, 1979). John Playfair in 1816 made observations around Neuchâtel and Pierre-a-Bot, located in eastern France, and arrived at the conclusion that a glacier had filled the Swiss plain from the Alps to the Jura and had transported the erratic boulders found alongside the mountains. Later, in 1824 Jens Esmark also saw evidence of glacier extension in Norway (Agassiz, 1837). These scientists arrived at the same conclusion: glaciers at one point in history had a greater extent than their current position. They did not publish these ideas as they knew they would cause great controversy (Wright, 1898).

Louis Agassiz's Predecessors

Louis Agassiz's original field of study was not glaciers but rather **ichnology,** especially marine fossils. His interest and research into glaciers stemmed from the influence of scientists who believed in ancient glaciation. The first person to have indirectly led to Agassiz's interest in glaciers was **Jean-Pierre Perraudin** (1767-1858) a mountaineer from the southern Swiss Alps. Having lived surrounded by glaciers, Perraudin concluded that the boulders he observed were too large to be transported by water and therefore must have been transported by glaciers that once filled the valley of Val de Bagnes (Agassiz, 1837). Another remarkable conclusion that Perraudin made was that the 'mark or scars' that were present on the rocks must have been made by glaciers. These two observations led him to conclude that more extensive Alpine glaciers must have made those features (Agassiz, 1837).

Perraudin communicated these observations in 1815 to **Jean de Charpentier** (1786-1855), who at the time ignored this theory (Imbrie and Imbrie, 1979). Perraudin subsequently shared his conclusions with Ignance Venetz, a highway and bridge engineer, who happened to be working in the area in 1818. Venetz was highly interested, though somewhat reluctant to agree with Perraudin, and started performing his own research (Agassiz, 1837). In 1829 Venetz presented to the Swiss Society of Natural Sciences his conclusion that glaciers had covered parts of Europe outside of the Alps. His presentation was received negatively and ignored by most except for Jean De Charpentier (Wright, 1898). Venetz's claim inspired De Charpentier to re-examine this theory. While conducting his own research, De Charpentier casually asked a woodcutter from Meirigen, how pieces of granite could be found around the area. The woodcutter astonished De Charpentier by saying "The Grimsel glacier transported and deposited them on both sides of the valley". De Charpentier found that the people of the Alps had come to a conclusion which many scientists would not accept (Agassiz, 1837). In 1834, he restated Venetz's ideas and was met with mockery. Agassiz, a professor of Natural History at Neuchâtel and a distinguished specialist in fossil fishes, heard De Charpentier's presentation but also initially rejected this theory (Wright, 1898).

Louis Agassiz's Declaration

During the summer of 1836, Agassiz visited De Charpentier, in Bex to study fossils in the area. He began by examining fossilized fish in the area, but after visiting the glaciers of the Diablerets in the valley of Chamonix (**Figure 2)** and the **moraines** of Rhône Valley with Venetz and De Charpentier, he quickly converted into a glacial theory advocate (Warren, 1928). Once Agassiz came home to Neuchâtel, he examined the slopes of the Jura Mountains, and concluded that in the past there was a period where glaciers covered great parts of the continent. He would coin the term '**Ice Age**' to describe this period of glaciation following the suggestion of his friend Karl Schimper (Agassiz, 1837).

Within a year of his visit to Bex, Agassiz presented the conclusions of his work in his *Discours de Neuchâtel* (Speech of Neuchâtel) on July 24, 1837 to the Swiss Society of Natural Sciences (Imbrie and Imbrie, 1979). At the time, Agassiz was the president of the society, having shown a promising future with his studies on fossils. This unexpected discourse shocked the members of the society and Agassiz was very heavily criticized by his peers who once held him in high regard (Wright, 1898). A trip to the mountains that was set the next day did very little to convince members of the society. Agassiz's theories were raw and even De Charpentier was disappointed at the rashness in which Agassiz shared his conclusions (Agassiz, 1837). Despite this, Agassiz achieved something that no scientists before had done - with his respectable status he brought forth an unprecedented idea about glaciers that would be debated within geology for years to come.

The Trials of Glacial Theory

At the time in which Agassiz was working, science breakthroughs were changing the understanding of the world; nevertheless religion still played a large part in 19th century Europe. One of the greatest challenges that Agassiz's glacial theory faced was religious opposition. At the time it was believed that Noah's flood had been the primary geomorphological agent in geology, having the support of one of the most influential text at the time, the Bible (Gordon, 1995). This '**diluvial**' view of geology explained fossils as life before the flood and the Earth's landscape a result of erosion by the flood. A direct contradiction that Agassiz proposed was that the erratic boulders deposited throughout Europe were not deposited by boulder-laded icebergs and ice rafts that had drifted during the flood, something Charles Lyell himself supported, but instead were deposited directly by glaciers (Agassiz, 1837).

For Agassiz to overcome this established diluvial theory he would need to gather further evidence. After a couple of months of research, Agassiz was once again ready to present his theory. In September of 1838, Agassiz was finally able to convince members of various scientific societies (including the Geological Society of France and the Association of German Naturalists) that erratic boulders and polished rocks were formed by glaciers (Wright, 1898).

In the summer of 1839, Agassiz continued to do more fieldwork on the mountain chain Monte Rosa and the region of the Matterhorn. By September of 1840, Agassiz finished his most influential book, *Etudes sur les glaciers* (Studies on Glaciers) (Wright, 1898). It summarized all of his research on glaciers including the knowledge that De Charpentier taught him. This publication was met with its usual degree of controversy but it also brought the displeasure of De Charpentier who was upset to see that his pupil had published work on glaciers before he had finished his own *Essai sur les glaciers* (Essay on glaciers). Agassiz's book brought attention to his Glacial Theory to American geologists as they became intrigued by Agassiz's claims and its applications to the United States (Imbrie and Imbrie, 1979).

Figure 2: *An image of Chamonix Valley, found in the Mont Blanc, France, a mountain range in the western Alps. This glaciated valley was one of many sites that Agassiz examined to establish his glacial theory.*

Outside the Alps

Agassiz was slowly gaining supporters for his theory; scientists who lived in the Alps were the fastest to sway as they could see both the glaciers and the evidence of past glaciation juxtaposed. Agassiz realized that he needed to gather evidence for his theory outside of the Alps, starting with the British Isles (Gordon, 1995). He began this mission by engaging the **Reverend William Buckland** (1784-1856) of England. Buckland was a professor of mineralogy and geology at Oxford and one of the most widely respected geologist in England. He was an avid supporter of the flood theory and Agassiz knew that Buckland's support was crucial to his Glacial Theory (Hansen, 1970). By the end of the 1830s, Buckland had been filled with doubt in diluvialism, despite biblical evidence, and was trying to formulate a better theory for the erratic boulders found in England. In the fall of 1840, Agassiz visited Buckland and after presenting his glacial theory to the British Association for the Advancement of Science in Glasgow, Buckland quickly accepted Agassiz's Glacial Theory (Hansen, 1970). These two men soon embarked on various field expeditions to observe the geological evidence for glaciation in the British Isles. In the Highlands of Scotland, they found various moraines and striated rock. At Blackford Hill, they found scratches and **grooves** on rock surfaces on what is now known as 'Agassiz Rock' (**Figure 3)**. In Scotland, he visited the terraces and mounds at the north of Loch Treig that provided evidence that in the past Scotland had been covered by glaciers. Agassiz presented his findings to the Geological Society where he was supported by Buckland and Lyell (a newly turned advocate that gave Agassiz even more support in the English geological community) (Gordon, 1995).

Figure 3: *An image of Agassiz Rock in Blackford Hill. This rock upon further examination contains striations and grooves.*

Agassiz's Retirement

With the conversion of Buckland and Lyell, Agassiz had gained two allies in the British Isles who would continue to advocate for him in Europe. Agassiz continued to work on glaciers in the Alps, studying the structure of glacier ice, **crevasses,** and the movement of glaciers. In the summer of 1844, he presented his findings to the Geological Society of France and finally all of his past opponents accepted of his theory (Wright, 1898). A year later in Geneva, he presented his findings based on three years' work on the Aar glacier to the Swiss Society of Natural Sciences; this would be his last European talk about glacial theory. In September of 1846, he parted for Boston to examine evidence for glaciation in North America and was received by John Amory Lowell, a member of Harvard University who ensured a professorship for Agassiz at Harvard (Imbrie and Imbrie, 1979). In America, he was glad to see that his glacial theory had been widely accepted in the community. He found evidence of past glaciation such as rocks with polished surfaces, erratic boulders, and scratched rocks in various parts of the Northeastern United States. Agassiz was convinced more than ever that glaciation had an effect on a global scale (Agassiz, 1837). Agassiz found a new home in an America, but by 1850s, his interest in glaciers had died down and his ichnology research was his main focus (Wright, 1898). Despite his absence, Agassiz's work would continue.

Glacial Theory's Legacy

In the span of a decade, Agassiz had created an enormous change in geological thinking, overthrowing religious convictions for scientific reasoning. His theory that glaciers covered much of the Northern Hemisphere in a past Ice Age had taken European geologists by storm and had sparked an interest in what were once thought of as static structures (Agassiz, 1837). Agassiz's theory had inspired geologists around Europe to examine glaciers, something many geologists had not done. The discovery of Greenland glaciers and the Antarctic Ice sheet in in the latter part of the century further supported Agassiz's theories of a major ice sheet covering Europe in the past (Wright 1898). This research was further propelled by Queen Victoria's prosperity and the wealth generated by the industrial revolution. Victorian geologists had the resources to explore parts of the world that were previously unmapped (Wright ,1898). By the mid-1860s, Agassiz's Glacial Theory had been widely accepted in both North America and Europe. By 1875, geologists had: completed the first survey of the world, described what the world looked like during the Ice Age, and determined the effect of glacier growth on sea levels. However most importantly they had determined that there was not just one ice age as Agassiz predicted, but many ice ages had occurred, separated by **interglacial periods** (Imbrie, and Imbrie, 1979). It was up to the next group of scientists to develop Agassiz's theory and explain the phenomenon of Ice Ages.

Glacial Striations

Agassiz's examination of 'scratches', now called **striations**, on rocks was a crucial element on his the development of glacial theory. Agassiz and the scientist in the 18th century understood that these striations were caused by rock fragments in glacier ice being dragged across bedrock during past glaciations. These subglacial erosional features have now been extensively researched.

Sublacial Erosional Features

Subglacial erosional features form beneath glacier ice, creating features of various types and scales (Glasser & Benner, 2004). These landforms include striations, **whalebacks**, **roches moutonneé, p-forms,** grooves, and valleys (Puckering, 2011). The exact processes involved in the creation of these features are highly debated and include: **glacial abrasion**, streaming of **basal ice**, erosion by deforming beds, erosion by **saturated till,** and erosion by **subglacial meltwater** (Boulton, 1972; Gjessing, 1965; Eyles, 2006). Glacial erosional landforms are studied as they allow scientists to make inferences about the subglacial conditions under which they were formed.

Striations

Striations are a type of subglacial erosional feature that are formed by glacial abrasion. They consist of lineations ranging from cm to m in length (Embleton & King, 1975). These scratches are formed by pieces of rock (clasts) entrained in the basal ice that have been removed from their source rock and are being transported within the glacier sole (Price, 1973). These rocks fragments are entrained in the ice by the refreezing of meltwater on bedrock (Embleton & King, 1975). If the ice thickness is high enough, the tensile stress between rock fragments held in the ice and the bedrock will create fractures in the rock beneath the ice. Striations have been determined to be a succession of small rock failures that, upon macroscopic observation, look linear (Boulton 1979). The length and depth of the striation will vary depending on the following conditions: the force exerted on the clast, velocity of the clast, the velocity of the debris (the greater the velocity the greater the amount of abrasion), and the concentration of debris within the ice (Benn & Evans, 2010). Gravel and boulder sized clasts will produce striations but silt and sand sized clast will produce another feature described by Agassiz, a polished rock surface (Price, 1973). Polished surfaces usually occur between striations (Benn & Evans, 2010).

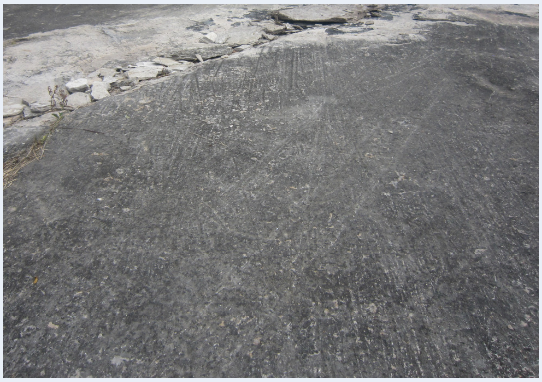


Figure 4: *The limestone bedrock on Pelee Island in Lake Erie shows good examples of glacial striations. Cross cutting striations can also be observed in this image.*

Applications

Striations can be used to infer directions of former glacial movement, very much like Agassiz predicted. In general, striations are oriented parallel to the direction of former ice flow (Virkalla, 1951). The wide and blunt ends of nail head striations can be used to give specific ice flow information as they point up-glacier (Benn & Evans, 2010). These observations are used alongside other glacial evidence such as erratic boulders to reconstruct patters of former ice movement (Embleton & King, 1975). Crossing striations were once thought to be evidence of erosion during successive glaciations, but they are now interpreted to indicate slight fluctuations in ice movement within the same glaciation period (Embleton & King, 1975).

Reconstructing former patterns of ice movement is important for resource exploration in previously glaciated terrains such as Canada. The 'scratches' that Agassiz examined and interpreted as the product of glacial erosion are now studied and researched in detail to learn more about subglacial processes and conditions. Agassiz' work on these important features helped pave the road for the field of glacial geology.

The Astronomical Theory of the Ice Ages

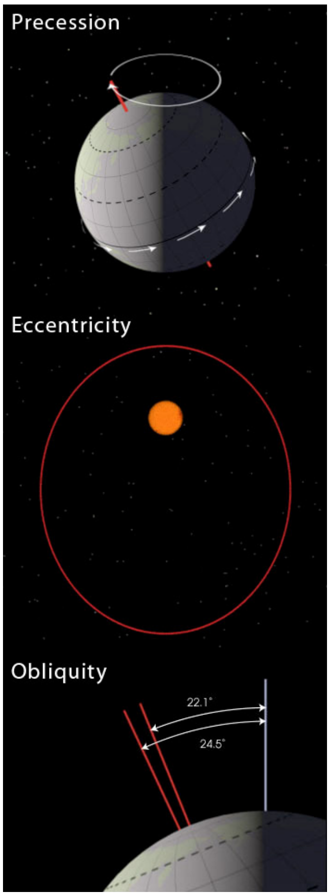


Figure 1: *Precession is the phenomenon in which the direction of tilt of the Earth's axis changes over time. This causes the location of each season to rotate around the orbit every 22 000 years. Eccentricity describes the elongation of the orbit and has a cycle of 100 000 years. Lastly, obliquity is the tilt of the Earth's axis and cycles every 40 000 years.*

After **Agassiz** (1807-1873) speculated about the existence of a previous ice age, geological surveys showed that there had actually been a succession of past glaciations (Berger, 2007). Immediately, the scientific community wanted to know why the ice ages had occurred. The astronomical theory of the ice ages was introduced in the 19th century by Joseph Adhémar and was expanded upon by James Croll and subsequently by Milutin Milankovitch. Although the idea that orbital variations could alter Earth's climate was advanced by mathematicians, scientists such as Lyell, Wegener, and Darwin also contributed knowledge from their respective disciplines (Imbrie and Imbrie, 1979). Development of the astronomical theory of the ice ages required the integration of mathematics, earth science, and biology to explain past climate changes. While scientific opinion fluctuated over time, today the theory has widespread acceptance.

Joseph Adhémar (1797–1862)

The French mathematician Joseph Adhémar was the first to propose that glaciations could be a result of celestial mechanics. Inspired by Agassiz, Adhémar published his results in his 1842 book *Revolutions of the sea* (Bard, 2004). Thanks to the work of Johannes Kepler in the 17th century, Adhémar used diagrams of Earth's orbit and the locations of the **solstices** to observe that currently winter is seven days longer in the Southern hemisphere than in the Northern hemisphere. Adhémar reasoned that the Southern hemisphere must therefore be growing colder and presented the Antarctic ice sheet as evidence (Adhémar, 1842). Having explained why the Southern hemisphere is partially glaciated, Adhémar then called upon calculations done by the Greek astronomer Hipparchus in 120 BCE to understand the periodicity of the ice ages (Imbrie and Imbrie, 1979).

Hipparchus observed that like a spinning top, the direction of Earth's axis traces a circle clockwise. This phenomenon, called **precession**, causes the position of the solstices to rotate around the ellipse every 22 000 years (NASA[a], n.d; **Figure 1**). Adhémar reasoned that when either solstice falls at the **perihelion**, one hemisphere would experience an ice age due to a longer winter. Therefore, he believed every 11 000 years, glaciation would occur at alternating poles (Adhémar, 1842).

In general, scientists were fond of the attribution of precession as a possible cause for the ice ages. However, the German naturalist **Alexander von Humboldt** (1769-1859) soon saw the flaws in Adhémar's reasoning. Humboldt's principal objection was that the Southern hemisphere is not continuously cooling (Imbrie and Imbrie, 1979). The reason the Antarctic ice sheet persists is its isolation from other continents and the lack of warm ocean currents. Other scientists also critiqued the lack of empirical support for an 11 000 year climate cycle, and based on available techniques, the implausibility of a quantitative test (Imbrie, 1982). While in its entirety, Adhémar's theory was ultimately thought to be wrong, it was an important contribution to understanding ice ages.

James Croll (1821-1890)

Born in a rural Scotland town in 1821, James Croll was not the most likely candidate to develop a theory for the cause of the ice ages (**Figure 2**). Although brilliant and a critical thinker, he stopped attending school at the age of 13 in order to support his family. In his life he worked as a millwright, a housejoiner, an innkeeper, an insurance salesman, a newspaper man, and a janitor at Andersonian College and Museum in Glasgow (Fleming, 2006). It was in this latter position that he was inspired by, and began to elaborate on Adhémar's work. Croll later wrote in his memoirs, "Little did I suspect that this was the beginning of a path so entangled that fully twenty years would elapse before I could get out of it" (Irons, 1896).

Croll recognized that Adhémar was incorrect in postulating that the length of seasons could trigger an ice age. Believing another astronomical mechanism was at work, Croll was motivated to conduct his own investigations after reading publications on celestial mechanics by Frenchmen **Pierre Simon de Laplace** (1749–1827) and **Urbain Leverrier** (1811-1877; Gribbin, 2002). Leverrier, who also discovered Neptune, developed formulas describing changes in the shape of the Earth's orbit over time. Due to the gravitational pull of moving planets, the **eccentricity** of Earth's orbit varies on a predictable 100 000 year cycle (Leverrier, 1843; **Figure 1**). It occurred to Croll that eccentricity may have been the factor that Adhémar was missing. Croll did not discount the impact of precession presented by Adhémar, but believed "eccentricity was sufficiently great to account for every extreme of climatic change" (Irons, 1896).

Croll was able to show that the intensity of **insolation** between seasons varies with eccentricity. He also suggested that extremely cold winters, when snow accumulated, were critical in triggering an ice age (Imbrie and Imbrie, 1979). Now called **ice-albedo feedback**, this concept describes how the reflection of light by snow inhibits melting and therefore allows more snow to build up (Curry and Schramm, 1995). Croll included the idea that "glacial cycles may not arise directly from cosmological causes, they may do so indirectly" in his 1864 paper, *On the physical cause of the change of climate during geological epochs.* Positive feedback loops would become very important in future modifications of the theory as well as its perception by other scientists (Irons, 1896).

Fellow Scotsman **James Geikie** (1839–1915) was the first geologist to openly support Croll's musings. Geikie stated that "the astronomical theory would appear to offer the best solution of the glacial puzzle. It accounts for all the leading facts, for the occurrence of alternating cold and warm epochs and for the peculiar character of glacial and interglacial climates. It postulates no other distribution of land and sea than now obtains; it calls for no great Earth movements the world over" (Imbrie and Imbrie, 1979). In this last sentence, Geikie is referring to the absurd theory presented by fellow geologists, **Charles Lyell** (1767–1849) and **James Dana** (1813–1895). They believed that ice ages were caused by vertical movements of the Earth's crust into colder, higher altitudes. Lyell was initially vehemently opposed to Croll's theory and wrote a 22-page letter to a colleague explaining why geographic causes had to predominate over astronomical ones (Fleming, 1998). **Charles Darwin** (1809–1882) also received a letter from his close friend Lyell, but Darwin disagreed with Lyell's view. He felt the astronomical theory provided a mechanism for speciation and that Lyell had formed "too extravagant notions" in his crust displacement theory (Imbrie and Imbrie, 1979).

By 1866, Lyell had accepted Croll's theory as a secondary cause of climate change, on the advice of colleagues. However, after surveying Niagara Falls in 1894, Dana initiated a demise in support for Croll by announcing that "the Glacial Period closed not more than 15 000 years ago, instead of the 150 000 or at the least 80 000 that the eccentricity hypothesis predicts" (Imbrie and Imbrie, 1979). By the end of the 19th century, the majority of scientific opinion was against Croll because the proposed timing of glaciations did not match the stratigraphic record and because Croll still believed that ice ages alternated between hemispheres (Fleming, 2006). Croll's theory was largely forgotten, although some scientists, such as Geikie, were convinced that modifications of Croll's views would "eventually clear up the mystery" (Imbrie and Imbrie, 1979).

Milutin Milankovitch (1879-1958)

When Croll was on his deathbed in 1890, Milutin Milankovitch was an 11 year old child in Yugoslavia (**Figure 3**). After studying at the Institute of Technology in Vienna, he worked as an engineer on concrete buildings. Supposedly, during one drunken night at a coffee house, Milankovitch simply decided that he would develop a mathematical model for Earth's past climate based on orbital variations (Milankovitch, 1952). While Adhémar and Croll had theorized about how precession and eccentricity might affect climate, both lacked the mathematical expertise to calculate the precise impact. Milankovitch was aware of other theories, but he felt that none of them had correctly incorporated all of the astronomical elements. Specifically, he noted that "the inadequacy of Croll's theory lies in the fact that the influence of the

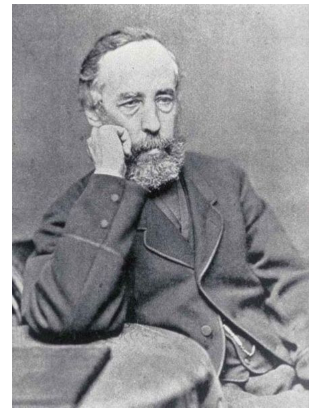
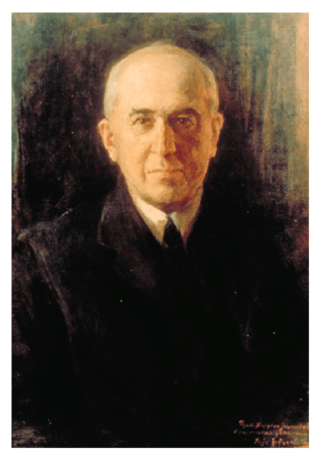


Figure 2: *James Croll (1821-18990) was not formally educated, however he made important contributions to the astronomical theory of the ice ages. He added eccentricity to the list of variables which alter insolation.*

Figure 3: *Milutin Milankovitch (1879-1958) identified obliquity as another parameter in the astronomical theory. It took him 30 years to develop a mathematically precise model.*



variability of the **obliquity** upon the insolation [was] not sufficiently taken into account" (Milankovitch, 1941; **Figure 1**).

Rather than having to refer to Hipparchus and Leverrier as Adhémar and Croll did, Milankovitch was fortunate that only seven years earlier in 1904, German mathematician Ludwig Pilgrim had published formulas for all three key cosmological properties (Berger, 1988). From these calculations, Milankovitch was able to derive the amount of insolation for each season and latitude. In the 18th century, Isaac Newton had established that irradiation depends on the distance from the sun and the angle at which the rays enter the atmosphere (Imbrie and Imbrie, 1979). While the geometrical properties could be determined from Pilgrim's results, the task became particularly daunting for Milankovitch due to the quantity of calculations that had to be done without any sort of mechanical aid (Grubi'c, 2006).

Unfortunately, due to the Balkan war and other disturbances in Europe in 1914, the publication of some of his calculations went largely unnoticed by the scientific community. Although hindered by World War I, in 1920 Milankovitch completed his computations (Imbrie and Imbrie, 1979). While many geologists ignored his work, it attracted the attention of climatologist **Vladimir Köppen** (1846-1940) and his son-in-law **Alfred Wegener** (1880–1930) (Imbrie, 1982). These two were able to help Milankovitch describe the past climate of the Earth based on solar radiation. At the suggestion of Köppen and Wegener, Milankovitch chose the summer insolation at 65 degrees North as the most important contributing factor, as a reduction in summer snowmelt would lead to ice sheet growth (Berger, 1988; **Figure 4**). This idea was opposite to Croll's belief that cold winters acted as triggers. Milankovitch's curves of summer solar radiation at 55, 60, and 65 degrees latitude were included in Köppen and Wegener's book *Climates of the geological past* in 1924 (Köppen and Wegener, 1924). The curves for the eight remaining latitudes, now called Milankovitch cycles, were included along with a comprehensive summary of his life's work in the publication of *Canon of insolation and the ice age problem* (Imbrie and Imbrie, 1979).

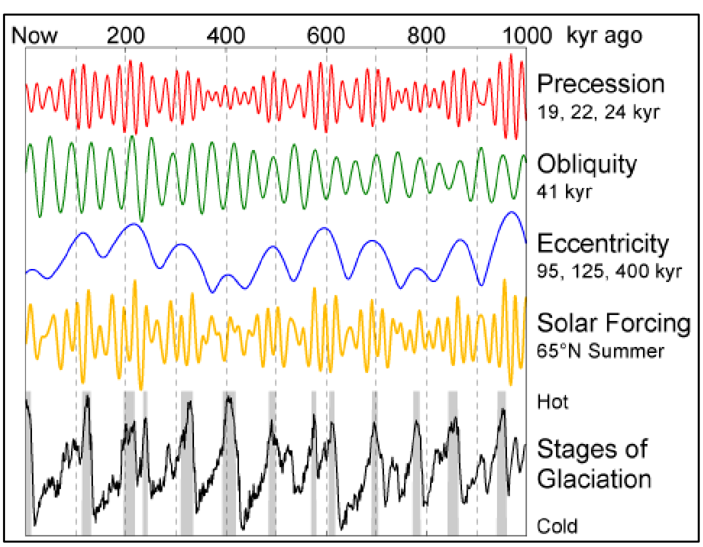


Figure 4: *Milankovitch theory states that precession, obliquity and eccentricity are responsible for causing the observed 100 000 year cycle in ice ages by varying the amount of sunlight received by the Earth at different times and locations, particularly high northern latitude summer.*

The Canon, as it is now referred to, was recognized worldwide as a great scientific achievement. Supporters of Milankovitch cycles pointed to the history of the Alpine glaciers, as documented by German geographers, as evidence for the model's validity. In their opinion, the radiation curves matched close enough to Alpine glacial history to indicate a cause for the ice ages (Imbrie and Imbrie, 1979). Across the ocean in America, those who were pro-Milankovitch linked the four North American glacial drifts to the four radiation minimums predicted by the curves. Critics of the theory rebutted that the ages of the North American drifts were not specific enough to warrant any sort of correlation and that sedimentary evidence was fragmentary (Imbrie, 1982). Proving Milankovitch's theory was therefore limited by the geological techniques available.

Despite these uncertainties, by the 1940's most scientists were supporters of the astronomical theory of the ice ages (Berger, 1988). However, a decade later opinions began to shift as a result of the development of radiocarbon dating techniques. Initially, it was not known that dates beyond 70 000 years were not reliable for carbon dating. Therefore, belief in *The Canon* was ultimately shattered when a peat layer, usually deposited in warm climates, was dated to a time when Milankovitch cycles predicted an ice age (Imbrie and Imbrie, 1979).

Despite the controversy, Milankovitch refused to defend himself on paper. Before the scientific community had even began to choose sides, he stated "I do not consider it my duty to give an elementary education to the ignorant, and I have also never tried to force others to accept my theory, with which no one could find fault" (Milankovitch, 1952). Having felt he had met his objective and completed the theory, Milankovitch retired to writing his memoirs until he died in 1958 (Imbrie and Imbrie, 1979).

Regardless of the fact that few still supported his theory at the time of his death, Milankovitch had ultimately succeeded in improving upon the ideas presented by Adhémar and Croll. The true significance of his work and the impact of the astronomical theory of the ice ages would only be realized nearly twenty years later when **climate proxies** would provide strong evidence for Milankovitch cycles (Hays et al., 1976).

Isotopic Analysis of Oxygen in Deep-Sea Cores

Milankovitch's model for orbital forcing remained relatively unchanged as geologists searched for supporting evidence (Imbrie and Imbrie, 1979). This pursuit required scientists to find climate proxies in order to compare the past climate of the Earth to that predicted by Milankovitch. One main proxy used in the seminal study by Hays et al. that ultimately resuscitated belief in the astronomical theory was isotopic analysis of oxygen in deep-sea cores (Hays et al., 1976).

Oxygen mostly exists as two **isotopes**, the lighter O^{16} and the heavier O^{18}. The ratio of these two isotopes in water is directly influenced by climate (Imbrie and Imbrie, 1979). When air moves towards the poles and cools, water with heavy oxygen will condense first due to its weight. Therefore, precipitation will have more light oxygen as air moves to higher latitudes. During ice ages, the water containing heavy oxygen will rain in the ocean at even lower latitudes, so snow deposited and trapped in ice sheets at poles will have mostly light oxygen and ocean water will be enriched in heavy oxygen (**Figure 5**). During warm periods, meltwater from ice sheets will increase the ratio of light to heavy oxygen in the oceans (NASA[b], n.d.).

The oxygen isotope ratio of past ocean water can be determined from microfossils contained within sediment layers on the ocean floor. The most common organisms studied had calcium carbonate shells that that record the ocean oxygen isotope ratio (Van Der Zwaan et al., 1999). Once a core is obtained, fossils are extracted and **mass spectrometry** is used to determine their oxygen isotope ratios. **Paleomagnetic reversals** encoded in the sediment are used to give an approximate date to each layer (Hays et al., 1976).

In recent years, it has been realized that the mechanisms involved in this climate proxy are more complex than originally thought. First, organisms exhibit a higher preference for water containing heavy oxygen as temperatures decrease. This temperature skew effect implies that the oxygen isotope ratio in shells does not translate precisely to the ratio of the water in which they were formed (Wejner et al., 2010). Scientists attempted to correct for this by looking at other chemical ratios affected by temperature (NASA[b], n.d.). Variations in pH, mixing of water, and ocean currents as a result of climate can also influence the accuracy of using oxygen isotopes as a proxy for global ice volumes. Ditchfield et al. identified that the quality of preservation of shells declines with age and burial depth so the older sediments would have less accurate records. Lastly, scientists must also consider the influence of **diagenetic** calcite incorporated after the organism died (Ditchfield et al., 2001). While isotopic analysis was important in reviving Milankovitch theory, its accuracy and complexity is still being evaluated today.

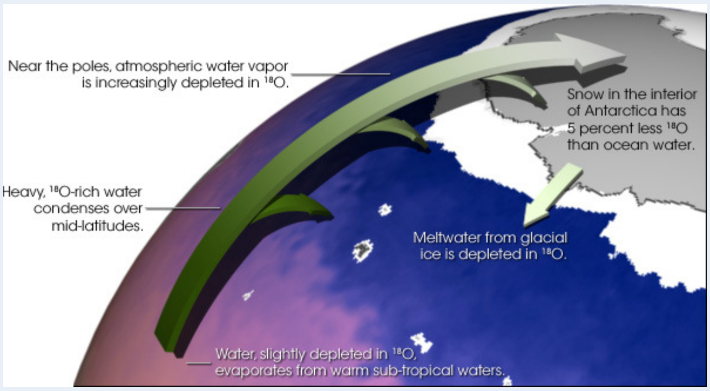
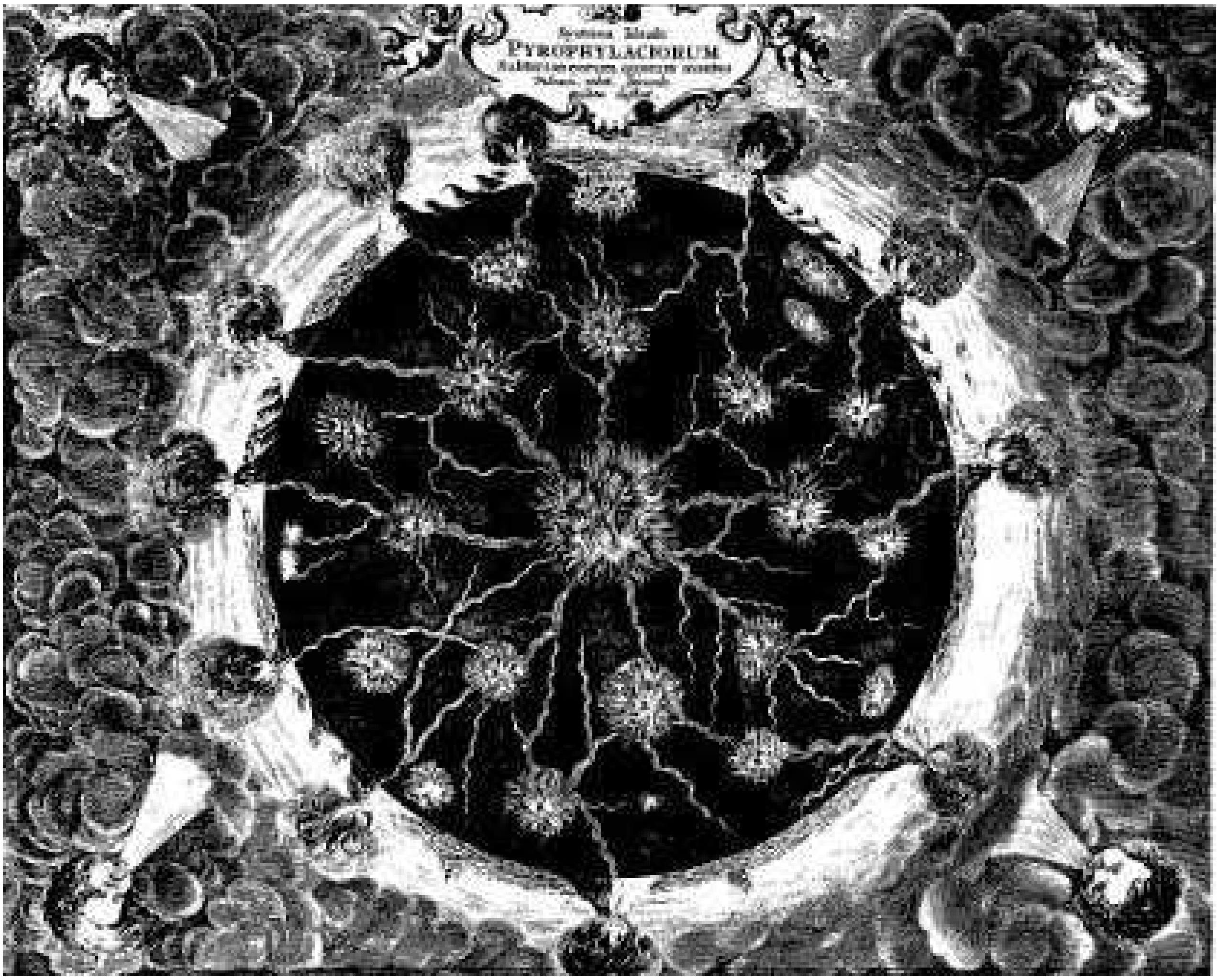


Figure 5: *This diagram shows a simplification of how evaporation and precipitation influence isotopic oxygen ratios.*



An artist's rendition of the interior of the Earth, from Athanasius Kircher's Mundus Subterraneus *(1678). Kircher used his model of the Earth to explain volcanic processes; however, similar to many of the theories discussed in this chapter, the model was revised by several scientists that followed in order to become the present day theory.*

Chapter 2: Understanding the Earth's Chemical and Physical Properties

For thousands of years, humans have questioned the physical principles behind the geological processes that shape the Earth. Through observation and the development of scientific techniques, theories were constructed to explain processes including magnetism, gravitation, the formation of our atmosphere, crystal structure, radioactivity, and the origins of water on the Earth. The initial explanations proposed for these phenomena were not always correct, and ideas often had to undergo several revisions before they became the modern theories that are used today.

The studies and theories of the scientists discussed in this chapter have helped shape our current understanding of the world around us. There is still much to learn about the chemical and physical processes that govern our universe. However, by understanding past ideas as well as the challenges and struggles involved in their development, we can continue to progress our understanding of nature.

William Gilbert: The Study of Geomagnetism throughout History

A Brief History of the Study of Magnetism

While William Gilbert is often referred to as the father of geomagnetism, the study of magnetism predates Gilbert by thousands of years. One commonly expressed myth states that magnetism was discovered by a shepherd in Ancient Greece, who was held to the ground on Mount Ida by iron nails in his shoes (Smith, 1992). As early as 300 BCE, Plato's *Ion* documents Socrates speaking about a chain of **lodestones** suspended by an attractive force (Plato & Allen, 1996).

Lodestone was the material in which magnetism was first identified, and the field was thus named because much of the supply of lodestones came from a region in Thessaly called Magnesia. Lodestone consists of the mineral **magnetite**, an iron oxide occurring as black crystals or sands that are naturally magnetic (Smith, 1992). Despite the widespread use of lodestone in compasses for navigational purposes, before Gilbert's time many people believed that magnetism was magical or spiritual in nature. Scientific explanations were purely speculative: one stated that there were miniature hooks on the surface of magnets and rings on the surface of iron, while another explanation held that particles were released on the surface of the magnet, creating a vacuum that drew iron in (Bozorth, 1947).

Figure 1: *Portrait of William Gilbert. This image is the cover of Gilbert's main works, De Magnete.*

Many of the earliest applications for the magnet had to do with its supposed spiritual properties. One myth claimed that carrying a magnet made its bearer invincible, while another claimed that a man could use magnets to verify his wife's chastity (Smith, 1992). The first documented use of the magnet in the compass came from the Chinese mathematician Shen Kuo (1031-1095) in 1088 CE (Buschow, 2006). The compass then appears in Europe approximately 300 years later (Bozorth, 1947). Some scholars claim Marco Polo (1254-1324) brought back the compass from Asia, including Gilbert, who states (although without a source), "*knowledge of the mariner's compass appears to have been brought into Italy by the Venetian Paolo who about the year 1260 learned that art of the compass in China*" (Gilbert, 1600).

From the 13th century onwards, many European scientists attempted to explain the mysterious force of magnetism. One of the major developments came from St. Thomas Aquinas (1225-1274), an Italian philosopher and theologian. Aquinas discovered that the magnetic force decreases with distance, and that magnetism can be induced by rubbing a material with lodestone (Thomas et al., 2003). In 1269, Peter Peregrinus wrote *Epistola de magnete*, in which he developed the idea of magnetic poles, and proposed a perpetual motion machine driven by the magnetic force. Gilbert spoke highly of both Aquinas and Peregrinus, and in his main works, *De Magnete*, he both refutes and further develops many of their ideas (Bozorth, 1947).

Prior to Gilbert, most scholars followed the Aristotelian philosophy and scholastic method in their studies. This philosophy was primarily theoretical, employing reason in order to understand the natural world and deduction to construct physical laws. Gilbert is often credited for developing the empirical method that is widely used today in the study of science (Zilsel, 1941).

William Gilbert's Life (1544-1603)

William Gilbert (**Figure 1**) was born in 1544, the son of Jerome Gilbert, a recorder in Colchester, England. He completed his studies in medicine in 1569 at St. John's College in Cambridge, and then moved to London to practice medicine (Roller, 1959). A successful physician, Gilbert was elected a fellow of the Royal College of Physicians in 1573, and in 1600, he was elected President of the College. In 1601, Gilbert was appointed royal physician to Elizabeth I (1533-1603). He maintained this position until Elizabeth's death in 1603, and continued as royal physician to James I until his own death by the plague just a few months later (Roller, 1959).

Gilbert established a laboratory within the College, in which he performed many of his experiments on the magnetic properties of lodestone. Gilbert is most well-known for his works *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure* (On the Magnet and Magnetic Bodies, and on That Great Magnet the Earth), published in 1600. *De Magnete* consists of 115 chapters arranged into six books, with a preface written by Edward Wright (1561-1615), the mathematician famous for Mercator's projection (Zilsel et al*.,* 2003).

An Overview of *De Magnete*

The main aspect of *De Magnete* that distinguishes it from other scientific works of its time is its focus on the scientific method. *De Magnete* is written in the form of a modern scientific paper; it discusses historical development in the study of magnetism, details Gilbert's experiments with a clear statement of his methods, discusses experimental results and their implications in a broader perspective, and concludes by introducing further questions to be explored (King, 1959).

In 1600, when *De Magnete* was published, it was still illegal for a British naval helmsman to have garlic on his breath, due to the belief that garlic could remove the magnetic properties of the lodestone in a compass (Turner, 2011). In *De Magnete*, Gilbert tested and disproved this and many other common myths about the properties of magnets. He also discounted techniques in medicine using magnets to cure various ailments (Gilbert 1600). However, Gilbert still supposed that the properties of magnetism were in some way controlled by the soul of the object. He writes in *De Magnete,* "*The magnetick force is animate, or imitates life; and in many things surpasses human life*"(Gilbert 1600).

In *De Magnete*, Gilbert discussed and differentiated between electric and magnetic forces. He proposed that the electric force is mediated by the "humid" material making up the crust of the Earth, and that the magnetic force is mediated by the "dry" material in the crust (de Heathcote, 1967). Gilbert suggested that the humid material is what constitutes amber, the material in which the force of static electric attraction was first discovered. By burning humid materials, it removes their moisture, thus explaining why amber does not conduct electricity when roasted. Gilbert proposed that it is the electric attraction between moisture-containing elements that coheres the components of the Earth's **crust**, and magnetic attraction that causes the rotation of the earth about an axis through the poles (Gilbert, 1600). In common with scientists of his time, Gilbert believed that an action between two objects could not be mediated except by contact. He thus proposed that something must be sent between two interacting bodies. In *De Magnete*, Gilbert described the actual force as "a breath…proceeding from a body which had been compacted; …the body that is reached is united with the attracting body" (Gilbert, 1600). He correctly identifies this force as emanating perpendicular to the surface of the magnet.

Gilbert had little idea how lodestone could become magnetized. He did perceive, however, that the magnetic properties of iron could be modified by smelting, and proposed that by hammering iron with an anvil while at an extremely hot temperature one could induce magnetism. It is now known that above a certain temperature, termed the **Curie temperature**, one can modify the magnetic properties of a mineral; however, magnetism is induced by alignment in an external magnetic field (for example, the Earth's magnetic field) as the object cools (Mills, 2011).

Gilbert also proposed that lightning could be responsible for the magnetization of lodestone. He noticed that a piece of lodestone positioned on the top of a church for a long period of time became magnetized, and hypothesized that it may have been struck by lightning (Gilbert, 1600). In doing so, Gilbert, although unknowingly, made one of the first connections between the forces of electricity and magnetism, which would later be discovered to be inherently connected (Duffin, 1965).

Many of Gilbert's experiments were done with his *terrella* ("little earth"), a small spherical lodestone. By moving a compass needle over the *terrella,* Gilbert tested many of his theories of geomagnetism. He demonstrated some of these experiments in

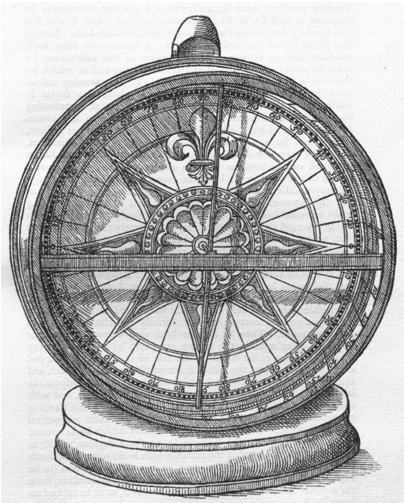


Figure 2, above: *Dip circle for measuring magnetic dip, invented by William Gilbert. Gilbert proposed that this instrument could be used for determining latitudes at sea.*

front of Queen Elizabeth I and the royal court (Stern, 2002). Gilbert identified that the Earth operated as a giant magnet, and hypothesized that this was due to the lodestone in the Earth's interior. This was in contrast with beliefs at the time that the compass needle was attracted by the North Star, or a giant magnetic island at the North Pole (Gilbert, 1600). Gilbert stated that magnetism was the soul of the Earth, which he referred to as its "magnetic vigour." He wrote in *De Magnete,* "*A magnetick vigour exists then in the earth just as in the terrella*." (Gilbert, 1600) Gilbert stated that because the *terrella* underwent rotation when aligned with poles through its axis, the Earth's daily rotation could be explained by its magnetic properties.

With his *terrella,* Gilbert successfully demonstrated **magnetic dip**, the deviation of the magnetic needle from horizontal near the poles. Magnetic dip, which was first identified in 1581 by Robert Norman (1560-1585), occurs due to the alignment of the magnetic needle with the Earth's magnetic field. Gilbert also recommended an instrument to measure dip angle (**Figure 2**) Gilbert thoroughly described the operation of his instrument, termed a dip circle, in *De Magnete*, and proposed its use for determining latitudes at sea (Gilbert, 1600).

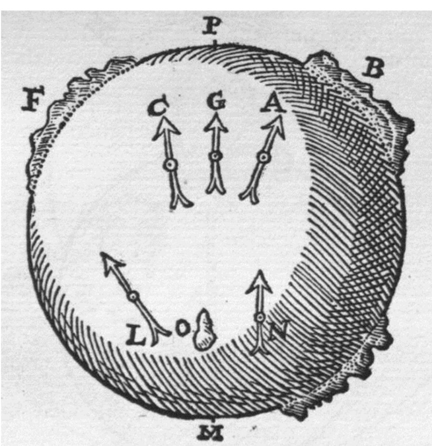


Figure 3, above: *Magnetic declination demonstrated on the terrella. By representing continents with impurities on the surface of the sphere, Gilbert was able to demonstrate his theory magnetic declination. He showed that the compass needle would point towards areas of greater continental mass.*

In *De Magnete*, Gilbert also discussed **magnetic declination**, the variation in true north from magnetic north (**Figure 3**). He noticed that variation occurred in the direction of continental masses, and hypothesized that declination happened as a result of attraction towards the "dry" material making up the continental crust (Gilbert, 1600). By making a large gash representing the Atlantic Ocean on the surface of his *terrella,* Gilbert was able to show magnetic declination experimentally. Although Gilbert correctly identified magnetic declination, he incorrectly stated that the Earth's magnetic field was unvarying (Gilbert, 1600). In 1634, the English mathematician Henry Gellibrand discovered that the magnetic field of the Earth is constantly changing, and that magnetic declination cannot be accounted for by the position of the continents (Gellibrand, 1635).

In the final book of *De Magnete,* Gilbert related stellar and terrestrial motion to magnetism. He considered his theories on magnetism in support of Copernican theory, which stated that the universe was heliocentric rather than geocentric. Gilbert calculated the solar velocities that would be required for a geocentric universe and found them to be highly unrealistic. He proposed that solar and lunar orbits occurred due to magnetic attraction between the Earth and the sun and the Earth and the moon, respectively (Gilbert, 1600). He made these statements in a dangerous environment however; in the same year that *De Magnete* was published, the Italian astronomer Giordano Bruno (1548-1600) was burned at the stake for supporting Copernican theory (Gatti, 2002). While Britain was less scientifically restrictive than Italy at the time, Book 6 was removed from many copies of *De Magnete* (Malin & Barraclough, 2000).

William Gilbert's Impact

Until the 18th century, *De Magnete* was considered to be the major reference for electricity and magnetism. Both the Gilberd School in Colchester and the unit of magnetomotive potential, the Gilbert, are named in William Gilbert's honour. Gilbert's theories for magnetism were employed by Kepler in developing his famous laws of planetary motion, and his development of the Copernican theory was furthered by Galileo, who is credited for substantiating the heliocentric universe through astronomical observations (McMullin & Carli, 1968). However, another equally essential contribution from Gilbert was his development of the scientific method. Following *De Magnete*, the famous works *Principia* by Isaac Newton (1642-1727), *Astronomia Nova* by Johannes Kepler (1571-1630), and *Sidereus Nuncius* by Galileo Galilei (1564-1642) were published, each employing Gilbert's empirical method (Tiner, 2006). Scientific papers today continue to follow Gilbert's method, nearly half a millenium after his death.

Rare earth magnets

The permanent iron magnets studied by William Gilbert more than 400 years ago are still employed in compasses, some electric motors, and radio components, due to their prevalence and relatively low cost. However, **electromagnets** have now replaced permanent magnets for most applications requiring stronger magnetic fields that can be easily altered (Coey, 1995). In electromagnets, discovered by Oersted in 1820, electric current passes through a wire (usually in the shape of coil) generating a magnetic field that is proportional to the current in the wire (Bozorth, 1947). Conversely, rare earth magnets are permanent magnets that are composed of **lanthanide** (rare earth) **elements** (**Figure 4**), which are able to produce strong magnetic fields due to their high **magnetocrystalline anisotropy** and **coercivity** (Coey, 1995).

The magnetic anisotropy of a rock describes its susceptibility to magnetization along a particular direction. It is dependent on the susceptibilities of the mineral types contained in the rock, as well as their structure and alignment (Tarling & Hrouda, 1993). Specifically, magnetocrystalline anisotropy, the important property for rare-earth magnets, refers to the preferential arrangement of the magnetic moments along the direction of the crystal axis (Skomski & Sellmyer, 2009). The coercivity of a rock is the strength of the reverse magnetic field which is required to demagnetize it. Highly coercive magnets are referred to as "hard", while magnets with low coercivity are termed "soft" (de Lacheisserie et al., 2005).

The high magnetocrystalline anisotropy and coercivity of rare earth magnets comes from the deeply nested 4f electrons of the lanthanide elements (Skomski & Sellmyer,, 2009). Normally, anisotropy is reduced by interactions between orbital electrons and the electric fields of neighbouring atoms. However, the 4f electrons are well shielded from interactions with external electrons, allowing their **magnetic moments** to have a greater effect on the anisotropy of the material. The magnetic moments of these electrons are enhanced by their high speeds as they travel in highly localized orbits near the dense lanthanide nuclei (Skomski & Sellmyer, 2009).

Figure 4: *Samples of lanthanide elements commonly used in rare earth magnets (clockwise from centre: praseodymium, cerium, lanthanum, neodymium, samarium, and gadolinium). While rare earth elements are relatively abundant, increased demand in recent years has reduced global supplies.*

A more practical measurement of the strength of a magnet is the **energy product**, a measure of the density of energy stored in a magnet. Rare earth magnets have energy products up to ten times greater than those of permanent iron magnets (Coey, 1995). Another important property, the Curie temperature, describes the temperature at which a material loses its magnetic properties. In modern devices that operate at high temperatures, a high Curie temperature is essential for magnetic components. Rare earth elements have Curie temperatures below room temperature; therefore, the addition of **transition elements** with higher Curie temperatures is required (Coey, 1995).

Following the development of the ability to magnetize steel over 1000 years ago, the strength of magnets has increased substantially due to the addition of alloys of iron, cobalt, aluminum and nickel to permanent magnets (Coey, 1995). In 1960, Strnat and Hoffer found high magnetic anisotropy in an alloy of samarium and cobalt (Sm-Co) (Strnat, 1967), and shortly after this discovery, Philips produced the first Sm-Co rare earth magnets (Cullity & Graham, 2009). In the 1970s, a reduction in global cobalt supplies prompted the development of rare earth magnets consisting of neodymium-iron (Nd-Fe) alloys. Neodymium and iron are the the most abundant and have the largest energy products of the lanthanide elements and transition elements, respectively (Coey 1995). However, as no known binary Nd-Fe compounds exist, Boron is added to these compounds, making up the family of Nd-Fe-B rare earth magnets. These magnets now comprise more than 98% of rare-earth magnets used worldwide (Minowa, 2008).

Despite their name, rare earth elements are relatively plentiful in the crust, with abundances similar to those of zinc or lead (Coey, 1995). Currently, rare earth magnets are used in applications requiring high performance magnets, including computer hard drives, hybrid vehicles, wind turbines and magnetic resonance imaging (MRI) (Fastenau & van Loenen, 1996).

Newton and Gravity

Young Newton

Late 1942, early Christmas Day, Isaac Newton was born in the small manor of Woolsthorpe just south of Grantham. As a young child Newton attended two day schools and Grantham School in Lincolnshire, where he was described as a "sober, silent, thinking lad" by a seventeenth-century writer (Rattansi, 1974; Westfall, 1993). Newton's creativity and precocious behaviour set him apart from his fellow classmates.

Figure 1: *A popular depiction of Sir Isaac Newton in his adulthood.*

As the eldest son, Newton's widowed mother expected him to manage the property and upkeep the farm. Pulling Newton out of grammar school early, Hannah Newton gave her son humble duties pertaining to a farmer (Rattansi, 1974; De Morgan, 1914). On market day, Newton was sent into Grantham to sell farm produce and provide for his family. It was not long before Newton acquired a trusted assistant to sell the produce for him as he hid away reading volumes of old books until the servant reappeared. Henry Stokes, Newton's schoolmaster, noticed his blossoming ingenuity and "never ceased remonstrating to his mother what a loss it was to the world, as well as a vain attempt, to bury so extraordinary talent in rustic business" (Feingold, 2004, p.3). Not long after, Isaac Newton was sent back to Grantham School where he was relieved of his humble duties and, instead, prepared for higher education in the hands of Stokes (Feingold, 2004).

Arrival at Cambridge

At eighteen and a half years of age, Newton was two years older than his contemporaries and well set in his ways (Rattansi, 1974). The intellectual sophistication and cosmopolitanism that Cambridge embraced in the early 1660s was far from the rusticity and classicalism present in the Lincolnshire countryside. Newton entered Cambridge as a subsizar, a placement reserved for poor students who served their social betters in exchange for accommodations and tuition (Westfall, 1993; Feingold, 2004). Despite this, Newton was fairly wealthy and had the potential to become an affluent member among his Trinity undergraduates. However, Hannah Newton was willing to sacrifice money for status and, for Newton, this status held some enticing aspects. More specifically, Newton was understood to be the subsizar of Humphrey Babington, a family friend, who would relieve Newton from the humble chores affiliated with being a subsizar and allow him to easily interact with wealthier undergraduates (Westfall, 1993; Feingold, 2004).

Before Newton arrived at Cambridge, English Universities drastically revamped their curricula such that all undergraduate students, irrespective of their social background, followed a similar course of studies (Feingold, 2004). The new, altered curriculum took an integrated approach in informing students of various disciplines with a portion catered to each individual's course of study. The ultimate goal was to produce a "general scholar" with the ability to specialize in the discipline of choice (Feingold, 2004). Undergraduate students were each assigned a tutor that guided their progress. Even at the undergraduate level, the tutor was nothing more than a supervisor who ensured the acquisition of higher-level skills (Feingold, 2004). Newton was assigned Isaac Barrow, Lucasian Professor of Mathematics at the time, as his tutor (Feingold, 2004; De Morgan, 1914; Westfall, 1974). It was noted by William Stukely, an early biographer as well as friend, that had Newton "'not take a byass favor of mathematical studys from him, at least he confirmed it thereby. And indeed he made such advances that he soon outstripped his tutor, tho' so considerable a man'" (Feingold, 2004, p.7). Stukely recalls Barrow admitting that he knew a bit of mathematics, but "reckoned himself a child in comparison to his pupil Newton" (Feingold, 2004, p.7). Barrow played a crucial role in the development of his mathematical creativity (Westfall, 1993).

For the first two and half years at Cambridge, Newton was exposed to scholastic philosophy like all other undergraduates. While taking courses that dealt with logic he was introduced to *Organon* ("On Logic") by Aristotle and *Logicae artis compendium* ("An Epitome of the Art of Logic") by Robert Sanderson. Newton's exposure to scholastic philosophy would continue until early 1664 when a newer science, that questioned Aristotelian philosophy, appeared in his notebook. It was *Physiological Epicuro-Gassendo-Charletoniana: Or a Fabrick of Science Natural, upon the Hypothesis of Atoms* by Walter Charleton that was responsible for his exposure to ancient atomic theories as well as works written by **René Descartes** and Boyle (Feingold, 2004; De Morgan, 1914). He began to explore topics such as meteorology, optics, and matter theory. It was not long before Newton put aside his traditional note-taking methods and began to experiment as an alternative means of challenging the theories (Feingold, 2004).

His first experiments dealt with physically altering the shape of his own eyes to achieve observable effects (De Morgan, 1914). Newton's enthusiasm and excitement from the range of colours produced caused him to proceed with experimentation and insert a bodkin "as neare to the backside of my eye as I could" underneath his eye just above the bone (Feingold, 2004;p11). Newton would continue to perform experiments on himself to such an extreme that he temporarily lost vision in his right eye for starring at the sun. Further expanding Newton's interests in cosmology, was a comet, originally mistaken for another object, that he witnessed several times near the end of 1664. It was at this time that Newton picked up a work by Thomas Street and read the theories of **Johannes Kepler** (Feingold, 2004; De Morgan 1914).

Distasteful Theories

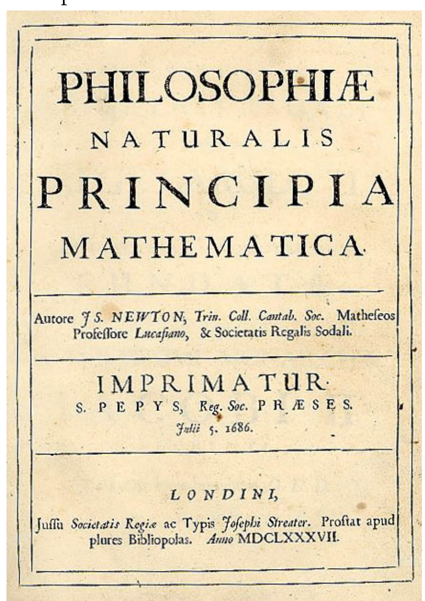
In the late seventeenth century, René Descartes's physics was the prevailing doctrine. Descartes's doctrine stirred up much controversy in the existence of vacuums and mechanical laws that govern motion, and ultimately how these interpretations contributed to his theory of gravity (Snow, 1926). Atom theorists would ask Descartes, "if there is no vacuum, and all space is full of matter, how is motion possible?" (Snow, 1926, p.51). Descartes responded with his theory of impact motion, such that all motion is the result of immediate contact. Even more dispute arose when Leibniz, a prominent mathematician and theist, who supported Descartes's position by stating that matter must occupy all space, "why would God cease the opportunity to create?" (Snow, 1926, p.48). Descartes, with Leibniz's support, believed that matter was infinitely divisible and did not hold finite value, thus all diversity of matter depends on motion (Snow, 1926).

Samuel Clarke took great sensation to Descartes's theories, along with many other atomists at the time including Gassendi, who was heavily influenced by Galileo's belief in the indivisibility of atomic particles. Alongside Clarke and Gassendi was Boyle, who held similar views and simultaneously argued against Descartes's philosophy. Among these three atomists, Gassendi and Boyle grounded the intellectual atmosphere for the formation of Newton's **Epicurean** theories (Snow, 1926). However, Gassendi and Boyle merely constructed an atmosphere, for Newton's theories were furnished by Kepler and Galileo. Kepler, alongside his laws of planetary motion, stated that a body cannot pass from rest to motion by itself. Galileo filled in the gaps by declaring that a body cannot change its state of motion or pass from motion to rest (Snow, 1926). Together, Kepler and Galileo's conceptions would constitute the Newtonian law of inertia,

Figure 2: *A sketch of Kepler in his adulthood.*

where it was accepted because Newton was the first to express it in the form of a general law (Snow, 1926).

Herein, it has been demonstrated that some of Newton's theories were borrowed from his predecessors. It is also important to note, and it is not an understatement to say, that the Gassendist revival of atomism, along with Gassendi's disputes involving Descartes, played a major role in the development of Newton's theories (Snow, 1926). The new **Copernican system** demanded a new doctrine to better serve an understanding of the celestial mechanics. Descartes's physics and astronomy, which built off of his theories regarding mechanical laws and motion, apparently addressed this new system; however, his physics was highly opposed by Newton. Newton was greatly stimulated by Descartes's irritating doctrine to derive his own conceptions from Gassendi's filter of Epicureanism (Snow, 1926). Newton owes thanks to Barrow for introducing him to Cartesian geometry because he would ultimately recognize contradictions between Descartes's fundamental principles and observations (Snow, 1926).



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Figure 3: *Newton's publication on mathematics and philosophy, incorporating his theory of gravity.*

Two Brilliant Years

While Newton's interests in the new science were expanding, much of his success was attributable to his mathematical capabilities. During his first two and a half years at Cambridge Newton made rapid progress in mathematics, owing thanks to his older mentor, Barrow, for allowing access to his personal collection of books. Coincidentally, Newton's course of education nearly paralleled that of Barrow's, which made Barrow an ideal person to answer any questions Newton had (Feingold, 2004). Newton claimed, in later years, that he stumbled upon mathematics. Newton said he purchased a book at the Sturbridge Fair, 1663, that sparked his confounding interest in trigonometry. Newton went on to read *Elements* by Euclid and *La Geometrie* ("Geometry") by René Descartes (De Morgan, 1914; Feingold, 2004). Apart from the literature, Newton claimed that the Lucasian lectures delivered by Barrow may have aided his commencement into calculus: "Dr. Barrow then read his Lectures about motion and that might [have] put me upon taking these things into consideration" (Feingold, 2004, p.12).

This mathematics would later prove crucial in the writing of *Principia*, in which Newton inserted his theories regarding gravity twenty-five years later (De Morgan, 1914). Newton's realization of universal gravitation started in June, 1665, when he left Cambridge for the Lincolnshire countryside because of the recent Plague outbreak. At first, Newton dedicated several months to mathematics where he investigated **infinitesimal calculus**. Following this in the year of 1666, Newton claimed he had his initial insight on the theory of universal gravitation (Westfall, 1974; Feingold, 2004; De Morgan, 1914):

"I began to think of gravity extending to the orb of the moon and (having found out how to estimate the force with which [a] globe revolving within a sphere presses the surface of the sphere) from Keplers rule of the periodical times of the Planets being in a sesquialterate proportion of their distances from the center of their Orbs, I deduced that the forces which keep the Planets in their Orbs must [be] reciprocally as the squares of their distances from the centers about which they revolve: and thereby compared the force requisite to keep the moon in her Orb with the force of gravity at the surface of the earth, and found them answer pretty nearly. All this was in the plague years of 1665-1666. For in those days I was in the prime of my age for invention and minded Mathematicks and Philosophy more than at any time since." (Feingold, 2004, p14)

Newton's strong mathematical background gave his theory of gravity an edge over previous theories suggested by Descartes and Leibniz. Newton laid down rules in mathematical physics that previous metaphysical hypotheses lacked and concluded that gravity is not dependant on matter to facilitate motion, gravity is the motion caused by an "immaterial" principle (Snow, 1926). It took Newton nearly two decades of wrestling with mathematics before publishing his work in *Principia*. It was here that he characterised the force of gravity between two bodies to be directly proportional to the product of the masses and inversely proportional to the distance between them squared (Knight, 2007; Nahin 2009). Following the publication of *Principia* in 1686, Newton was accused of plagiarism because he refused to mention Robert Hooke, the Curator of Experiments for the Royal Society of London, for co-founding the inverse square law. However, Hooke did nothing but propose the theory. All of the marvelous mathematics incorporated in Newton's *Principia* were his own doing (Feingold, 2004; Nahin, 2009).

Gravity Surveying

As described by Newton, the force of gravity between two bodies is directly proportional to the product of the masses and inversely proportional to the distance between them squared, assuming each body has uniform density (Knight, 2007). A body with variable density will have a non-homogeneous gravitational attraction varying from point to point (Knight, 2007). Modern day instruments are capable of measuring the acceleration due to gravity on the earth's surface. Gravity surveying utilizes method of analyzing variations in the gravitational pull on the Earth's surface to determine the density of subsurface rocks and other valuable information about the subsurface geology (Smith 2001).

Figure 5: *A modern day gravimeter used for gravity surveying.*

Gravitational surveying is based on the presence of bodies within the Earth's crust that are responsible for producing **gravity anomalies** (Marjoribanks, 1997). Analysis of these anomalies with an instrument called a **gravimeter** can provide information about the depth, dimensions and density of these bodies (Marjoribanks, 1997). This can be used as an aid exploration for valuable ore bodies. For example, the **Hishikari Epithermal gold deposit** of Japan was located from analysis of gravimetric data (Izawa et al., 1990).

In order to provide usable data several corrections need to be made to the raw gravity data to compensate for several naturally occurring effects. Some of these include latitude, where a correction must be made to account for differences in the shape of the **geoid**; **elevation**, where the height above sea-level is taken into account; and tidal, where the change in tides are accounted for by measuring relative to a base point throughout the survey. Other variations are caused by atmospheric pressure and **gravimeter drift** (Virtanen et al 2006).

It is necessary to make these corrections to avoid confusion in determining the subsurface geology. Precisely identifying the subsurface geology is of importance to several geological and economic applications. Gravity surveying has become a key factor in mineral and petroleum exploration, volcanology, and tectonic studies. It is beneficial to employ these data corrections to effectively serve these geologic and economic objectives (Seigel, 1994).

The Structure of the Atmosphere

Earth's atmosphere has been the subject of fascination and study for thousands of years, as ancient cultures continuously tried to understand and give reason to its vast size and incredible complexity. In ancient near east mythology, the sky was understood to be the median between the heavens and the Earth, a physical barrier that held back the heavenly waters (Walton, 2006). Aristotle, an ancient Greek philosopher, tried to characterize the composition of the atmosphere, naming the substance that makes up the outer atmosphere **Aether**, which was a divine substance suitable for the living conditions of Gods (Wildberg, 1988). Although these ideas were thought provoking and suitable for the needs of ancient populations, it wasn't until 1648 that scientists from around the world began to discover the true structure of Earth's atmosphere. Hundreds of independent discoveries and inventions led to the current model of the atmosphere, but three of these historical discoveries were truly groundbreaking and enabled further research and understanding.

Figure 1: *Aristotle was one of the first philosophers to consider and explore the composition of the atmosphere.*

First Step towards Discovery

Until 1648, very little was known about the variations of temperature and pressure within the atmosphere. This changed drastically when **Florin Périer** was able to show that as altitude increased, atmospheric pressure decreased (Houston, 1998). Périer used two **Torricellian barometers**, leaving one with a monk (a trusted individual) at the base of Puy de Dôme, a local mountain, and carrying the other one up the mountain with a group of townspeople (Houston, 1998). As they moved up the mountain, the height of the mercury in the barometer increased, indicating lower pressure. When they returned to the bottom, the monk truthfully told them that he observed no such change in mercury height (Houston, 1998). Périer deduced that the change in pressure must have been caused by the only changing variable between the two barometers, the changing elevation. This discovery was the first to indicate that the atmosphere is not necessarily constant throughout, and laid the basis for further research and experimentation into exactly how the atmosphere varies.

The Initial Division

The second finding that contributed substantially towards understanding the structure of the atmosphere was completed in 1901, when it was first discovered that the atmosphere did not change uniformly with elevation, but that it was composed of at least two distinct layers. **Léon Teisserence de Bort** is the scientist credited with both first using rubber balloons to record atmospheric pressure and temperature, and with developing self-recording instruments that were light enough to be lifted by such balloons (Zimmerman, 1909). Léon attached self-recording barometers and thermometers to weather balloons, then released the balloons into the atmosphere where they would rise until they popped, and then fall to the ground (Teisserence de Bort, 1902). As this was before the invention of GPS units, Léon Teisserence de Bort solved the issue of tracking down the fallen balloons by attaching a hand written letter to each balloon asking whoever found it to return it for a small prize (Teisserence de Bort, 1902). Although this seems like a primitive method, Léon was able to achieve a retrieval rate of 94%, with any losses attributed to balloons falling into nearby bodies of water (Teisserence de Bort, 1902). Using these methods, Léon found that temperature decreased constantly as the balloon ascended until it reached an altitude of 11 km, at which point it continued to rise, but did so isothermally (Zimmerman, 1909). This puzzled Teisserance, and initially he was sure that the results were due to some form of error (potentially due to the instruments malfunctioning under cold conditions), or because of an increase in solar radiation counteracting the decrease in pressure. He meticulously altered the thermometers to improve performance in cold temperatures and ran the experiment overnight to reduce the effect of solar radiation, but still received the same result (Zimmerman, 1909). Thus, Léon Teisserance de Bort concluded that there must be two distinct layers in the atmosphere. He named the first layer, stretching from the ground to the 11 km barrier, the **troposphere**, and the second layer, consisting of all of the area outside the troposphere, the **stratosphere** (Zimmerman, 1909). This discovery was the first definitive classification of the structure and organization of the Earth's atmosphere, and became a key stage in the creation of a more complex model of the Earth's atmosphere.

The Ionosphere

A third discovery concerning the make-up of the Earth's atmosphere came to light in 1924, due to the findings of four independent scientists, culminating nearly 30 years of work. In the late 19th century, **Guglielmo Marconi** began experimenting with electromagnetic waves to send and receive signals. By 1901, Marconi was able to successfully send these 'radio' signals distances of up to 18 miles, and felt that with the proper equipment he could do what was deemed impossible at the time: transmit a signal wirelessly across the Atlantic Ocean (Belrose, 1995). At the time, other physicists were extremely sceptical that this kind of transmission could be completed due to the curvature of the Earth, but on December 12, 1901, Marconi successfully set up a base in England that was able to receive a Morse code message from Newfoundland, Canada (Belrose, 1995). Marconi was unable to explain how the signal could navigate the curvature of the Earth, and as such came under a great deal of pressure from his peers who insisted that he had fabricated his results (Belrose, 1995). The mystery behind the trans-Atlantic transmission remained unsolved until 1902, when two researchers independently came up with the same solution. Oliver Heaviside and Edwin Kennelly proposed that there is a portion of the atmosphere that is made up of ionized particles, which acts to reflect electromagnetic waves back towards Earth, rather than allowing them to pass through into outer space (Nahin, 2002). This model explained that the radio signal sent from Newfoundland travelled out and up over the Atlantic Ocean, where it struck the upper atmosphere and rebounded down towards England, where it was identified by the receiver (Nahin, 2002). The explanation had good merit, and was widely accepted by the scientific community, but both Heaviside and Kennelly did not have the technology available to them to prove that such an ionized zone existed. In 1924 however, Edward Appleton developed the **ionosonde**, which was able to definitively show the existence of the ionosphere (Clark, 1971). The **ionosonde** was used to shoot a broad frequency spectrum of radio waves up into the atmosphere, and then record when the device received each particular wave after they were deflected off the ionosphere (Clark, 1971). The difference in time it took waves of different frequencies to return

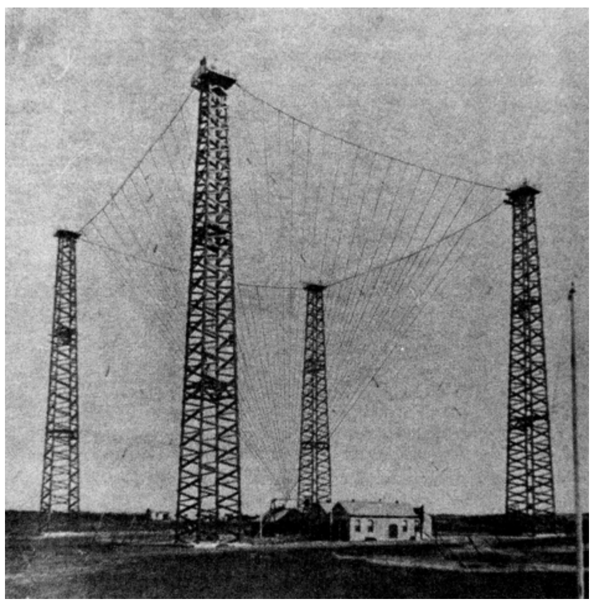


Figure 2: *The Marconi radio receptor station, located in Cornwall England. The four towers were used to hold a web of wires that could receive a wide range of radio signals.*

demonstrated that there was indeed a thick layer of the atmosphere that was capable of reflecting radio waves back towards the Earth, and that such a layer began at roughly the stratosphere and extended into outer space.

Recent Discovery and Implications

The innovation of ballistic rockets in the 1940s that were able to take precise temperature and pressure measurements in the upper atmosphere has enabled research on the structure of the atmosphere to be continued. The ionosphere proposed by Heaviside and Kennely has been subdivided into several smaller layers, each of which has the ionized properties identified in 1902. The first ionized layer, and third overall layer, of Earth's atmosphere has been called the **mesosphere**, and is identified as the layer following the stratosphere (the isothermal layer) in which the temperature once again decreases with increasing altitude (Tasa, 2006). The fourth layer of the Earth's atmosphere has been labelled the **thermosphere**, and is identified by the rapid increase in temperature with increasing altitude throughout the layer (Tasa, 2006). The final layer in the classification of the Earth's modern atmospheric structure is the **exosphere**, which forms the outer limit of the Earth's atmosphere and is largely devoid of matter (Tasa, 2006).

Although it took over 300 years and the work of hundreds of renowned scientists, understanding the structure of the atmosphere has proven to be more than just a challenging scientific endeavour. This understanding has allowed scientists to design a space station that could successfully orbit the Earth within the thermosphere, has enabled the prediction of weather systems such as hurricanes and strong thunderstorms, and has assisted with investigation of the ozone layer (which lies in the stratosphere) and identification of what can be done to stop the deterioration of this natural radiation shield. The long process of discovering the structure of the Earth's atmosphere is a testament to what can be accomplished through scientific collaboration, and may serve as a template for future scientific discovery.

Figure 3: *The outer atmosphere of the Earth. As elevation increases, the decreasing density of the atmosphere is shown by the gradual darkening of the blue colour.*

The Ozone Layer: Discovery, Destruction, and Recovery

Ozone is a molecule, made up of three oxygen atoms, which has the ability to absorb and dissipate ultra violet (UV) light (Plummer, 2003). The **ozone layer**, which lies in the lower region of the stratosphere, is defined as the area within the atmosphere that has the highest concentration of ozone, and as such acts as a physical barrier against incident UV light. The ozone layer was first discovered by Charles Fabry and Henri Buisson in 1912, but didn't garner much attention until 1985, when it first began to show signs of weakening (Mulligan, 1998).

Ozone Depletion

UV light is a known carcinogen. In 1985 when an article in Nature indicated a 10% per decade decrease in atmospheric ozone levels, and thus a significant weakening of the only shield protecting life from UV radiation, the scientific community began to frantically search for the cause of the depletion (Farman, 1985). Scientists looked back to a study proposed in 1974 that showed how chlorofluorocarbons, or CFCs, could destroy ozone in the presence of UV light (Molina, 1974). Based on this information, and the identification of CFCs in the atmosphere, the scientific community concluded that CFC's were the root cause of the weakening ozone layer. At that time, a worldwide effort was launched to reduce the amount of CFCs produced and consumed by humans. The **Montreal Protocol** was drafted and signed in 1987 as an international treaty to stop the production of all CFCs in an effort to protect, and eventually rehabilitate, the depleted ozone layer (UNEP, 2000). A total of 196 countries signed the protocol, which resulted in the elimination of the most active CFCs in 1996, and the elimination of the less active CFCs in 2010 (UNEP, 2000). When the Montreal Protocol was originally signed, it came with the goal of restoring the ozone layer to its previous form by 2050, and while a perfect reconstruction is no longer expected, the restoration of ozone in the atmosphere is well underway (**Figure 4**).

Ozone Recovery

The first piece of evidence that suggested that the Montreal protocol was having its desired effect on the ozone layer came in 1999; when it was first found that the concentration of harmful CFCs in the atmosphere was beginning to decrease (Butler, 1999). Additionally, in 2000, it was found that, "the rate of ozone destruction 35-45 km above the Earth [had] roughly halved," since the Montreal protocol was signed into effect (Newchurch, 2003 18). Although this rapid turnaround in ozone depletion clearly represents a step in the right direction and has garnered the Montreal Protocol considerable acclaim, the extensive damage previously done to the ozone layer serves as a warning. Future scientific exploration of the atmosphere will enable a deeper understanding of the Earth and its processes, decreasing the probability of a future catastrophic event.

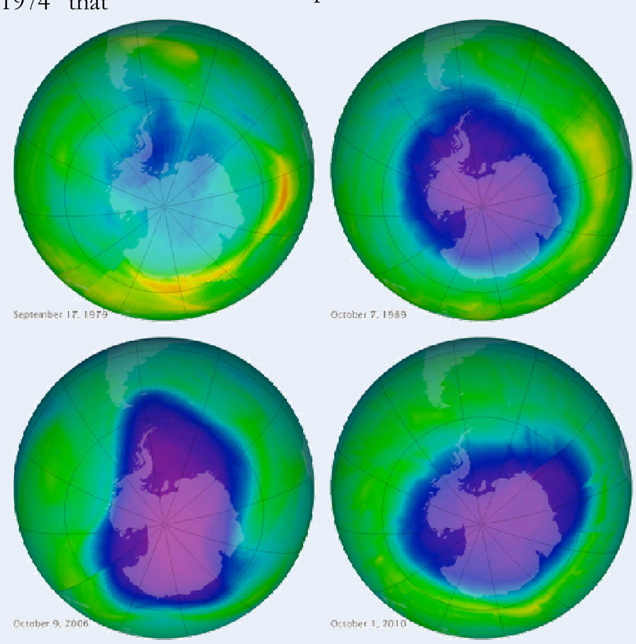


***Figure 4:** False colour image showing the depletion and recovery of the ozone layer above Antarctica.*

The Origins of Modern Crystallography

Pliny the Elder (23-79 CE) described an aniministic notion of crystals, claiming that they could give birth to young (Burke 1966). This indirectly influenced the Renaissance theory of panpsychism, the concept that minerals possess life.

Nicolaus Steno (1638-1686) wrote a treatise on matter in 1669, in which he outlined his theory that crystals grew when particles from an external fluid were added to an existing body, although he did not know what started the original crystal growth (Burke, 1966). The translation of his treatise into English lead to the discrediting of panpsychism.

Johannes Kepler (1571-1630) also contributed to the early study of crystallography, by explaining the shape of a snowflake using the packing of spherical particles in space (Burke, 1966). This mathematical treatment explained cubic, tetrahedral, hexagonal and octahedral crystals. The work of Steno and Kepler marked the first time that crystals were investigated in a scientific manner (Berry in Whittaker, 1981). Carl Linnaeus (1707-1778) also created a classification system for minerals. Although incorrect, his work influenced the mineral classification systems of two other men: Romé d'Isle and René-Just Haüy (Burke, 1966).

Romé d'Isle (1736-1790)

The first major contributor to what is now recognized as the modern study of crystallography was Romé d'Isle (Burke, 1966). He was a well-educated Frenchman who spent much of his life studying and writing about crystals. He is credited with the **Law of Constant Angles**, which was actually discovered by his student **Arnould Carangeot** (1742-1806) (Touret, 2004). The law, which was first recognized by Steno in quartz, states that in a crystal only the angles between the adjacent faces are constant. He recognized that crystals have characteristic idealized angles that can be used for identification (Burke, 1966). This has not been previously recognized because crystal growth is variable, growth may occur more rapidly in a certain direction, creating a **distorted habit** (Touret, 2004). This was the first time the internal structure of a crystal was related to its external form.

In 1783, d'Isle published a book (**Figure 1**) containing hundreds of drawings and descriptions of minerals (Touret, 2004). He defined a crystal as a type of mineral that displayed a geometrical figure (Burke, 1966). d'Isle also divided crystals into four classes

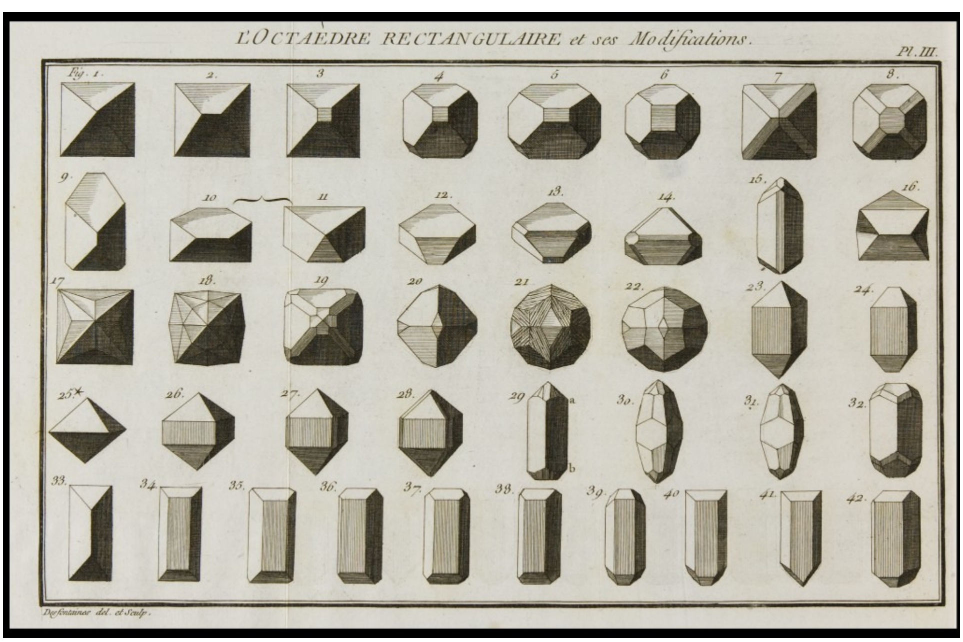


Figure 1: *An illustration from Romé d'Isle's book Crystallographie, published in 1783. d'Isle introduced the classification of crystals based on their internal angles and the use of crystal models in the study of crystal structures. Each mineral illustrated in the book was available as a terracotta model.*

based on their chemical properties: saline, stony or rocky, sulfurous or arsenious, and metallic crystals.

d'Isle introduced two methods that changed the study of crystallography. His student, Carangeot, invented the **application goniometer** (Touret, 2004). This tool allowed both the accurate measurement of angles in crystals, and the classification of minerals based on their internal angles (Burke, 1966). Additionally, in order to increase the sales of his book, he offered each purchaser a collection of 448 terracotta models (**Figure 2**), one for each of the minerals described in his book. This established the use of **crystal models** as an important part of descriptive mineralogy.

Figure 2, left: *A terracotta crystal model, designed by Romé d'Isle. The model measures approximately 1 cm thick and 3 cm long. René-Just Haüy also produced crystal models, although his were carved from pearwood.*

Romé d'Isle was the first to suggest that crystals are made up of particles that are arranged in a regularly repeating pattern, a concept that is still the basis of modern crystallography (Dent Glasser, 1977). However, the event that had the greatest influence on the establishment of crystallography as a modern science occurred entirely as the result of an accident on the part of René-Just Haüy (Kunz, 1918).

René-Just Haüy: Early Life

René-Just Haüy was born the son of a weaver in Saint-Just, France on February 28th, 1743 (Black, 1918). Although his family was poor, his intelligence and musical talent took him to Paris, where he became a chorister (Kunz, 1918). From there he received a scholarship to study physics and ancient languages at the college of Navarre (Black, 1918). He transferred to the college of Cardinal Lemoine where he met Charles François L'Homond (1727-1794), who informally taught him botany. During this time period, Haüy was also ordained a priest (Burke, 1966).

As a result of his interest in botany, Haüy frequently visited the *Jardin du Roi*, in Paris (Kuntz, 1918). On one of his visits, he attended a lecture on mineralogy given by **Louis-Jean-Marie Daubenton** (1716-1799). Haüy's knowledge of physics and botany allowed him to quickly understand the general principles of mineralogy; it is claimed that he preferred this subject to both physics and botany (Black, 1918).

Haüy and Crystallography

Haüy began to study and collect minerals (Kunz, 1918). He developed his own ideas about crystals which he shared with Daubenton, who in turn shared them with **Pierre Simon Laplace** (1749-1827). Laplace encouraged Haüy to present his findings to the French **Academy of Science**. Haüy made two presentations in 1781 and was offered membership in the exclusive Academy of Science in 1783 as an associate in botany (Burke, 1966). He published his first crystallography paper *Essai d'une théorie sur la structure des crystaux* in 1784 (Black, 1918). When the Academy of Science was dissolved during the French Revolution, Haüy became a teacher at *L'Ecole des Mines* (Burke, 1966). Here he was the curator of the mineralogical collection, which allowed him to continue studying minerals (Kunz, 1918). Haüy used his connections developed during his time as a member of the Academy of Science to survive the French Revolution, despite the fact that he refused to accept the limitations imposed on Catholic priests (Burke, 1966).

***Figure 3, below*:** *A calcite crystal. From the examination of the broken fragments of a calcite crystal, René-Just Haüy recognized that they all had the same rhomboidal shape. He realized that crystals were built up from smaller, identical structures to give the external shape.*

In 1794 Haüy was examining the mineral collection of his friend M. De France du Croisset (Black, 1918). He accidentally dropped a **calcite** specimen (**Figure 3**), but upon examination of the fragments, Haüy recognized that each of the broken fragments had a similar rhomboidal shape (Touret, 2004). He continued to break apart the fragments, and each smaller piece also had a rhomboidal shape (Gratacap, 1918). He determined that the entire calcite crystal was made up of a repeating pattern of rhomboid nuclei (Kunz, 1918). Haüy assumed that this was a property of all crystals and developed a theory of crystal structure in which crystals are constructed by stacking together small identical unit cells to give the overall crystal form (Moses, 1918). Haüy called this the 'Law of Equal Numbers', and it is the basis of the modern **Law of Rational Intercepts.** This refined d'Isle's original Law of Symmetry by limiting the number of possible crystal forms.

Traité de Minéralogie

Using this idea in combination with his research into the current understanding of mineralogy at the time, Haüy published a four volume book ***Traité de Minéralogie*** in 1801 (Gratacap, 1918). The book described over 700 mineral species, each accompanied by a drawing of its ideal crystal shape (Touret, 2004). Haüy outlined a classification system for minerals, emphasising the importance of distinguishing minerals based upon the internal crystal geometry (Burke, 1966). He describes the '*molécule intégrante'* (integral molecule), the building block of all crystalized matter (Touret, 2004). Haüy demonstrated the success of his classification system by reclassifying several minerals. The results of his reclassifications were confirmed by chemical analysis (Gratacap, 1918).

However, his work was not without criticism. Romé d'Isle called him a crystal smasher and refused to accept his theories (Touret, 2004). In 1773, Torbern Bergman (1735-1784) had published a description of the dodecahedral structure of garnet built from rhombic subunits (Burke, 1966). Ev1en though Haüy denied that he was influenced by Bergman's work, modern scholars feel that it is impossible for him to have not been aware of it. Despite the controversy, *Traité de Minéralogie* instantly became a popular basic text and was used worldwide in the study of mineralogy (Touret, 2004).

Figure 4*: An 1812 engraving of René-Just Haüy by Johann Anton Riedel. Haüy is shown holding a calcite crystal and an application goniometer. Haüy discovered his Law of Rational Intercepts after dropping a calcite specimen and observing the fragments. The application goniometer was used to measure angles in crystal and was an important tool for crystallographers during Haüy's lifetime. For his contibutions to the early study of crystallography, Haüy is often titled "The Father of Modern Crystallography).*

Like Romé d'Isle, Haüy constructed crystal models, although his were carved from pear wood (Touret, 2004). The sale of these models financed his research. These models were in great demand, for both teaching as well as for collectors. The models are still considered to be valuable in the study of crystallography (Saeijs, 2004).

Haüy's Influence

In his lifetime (**Figure 4**), Haüy published over 100 papers about crystallography, as well as several books of physics (Burke, 1966). He exerted considerable influence; he was the member of over twenty scientific societies, as well as a founding member of the ***Institut National des Sciences et des Arts*****,** which replaced the former Academy of Science. He was also a favourite of **Napoléon**, who appointed him an honorary canon of the cathedral of Notre Dame and to the Legion of Honour (Tourent, 2004). In his later life, however, he would not accept new developments in crystallography, especially those put forth by German scientists, nor would he listen to any criticisms of his theories (Buke, 1966). Haüy died on June 3rd, 1822, as the result of a fall (Black, 1918). During Haüy's lifetime the study of crystallography was primarily conducted in France, however after his death the study was taken up by the Germans (Burke, 1966).

The work of Haüy is recognized as raising the study of crystallography to the rank of a science (Whitlock, 1918). Even though his work was described as mineralogy during his lifetime, Haüy's studies were more closely related to the modern field of crystallography, as he studied minerals through the examination of crystal forms, rather than through chemical analysis (Saeijs, 2004). His work introduced the fundamentals of modern crystallography including the concept of integral molecules, his Law of Rational Intercepts and his identification of crystal forms (Wherry, 1918). Haüy is considered to be the father of modern crystallography, as his ideas, especially the relationship between a crystal's internal structure and its external form, still heavily influence modern crystallographers (Adams, 1918).

X-ray Crystallography

X-rays are a high-energy form of electromagnetic radiation useful for crystallographic studies, as their wavelength is on the same order as the distance between atoms (about one angstrom or 10^{-10} metres; Dent Glasser, 1977). In 1912 Max von Laue and Paul Peter Ewald noticed that irradiating a crystal with X-rays produced an interference pattern, as the atoms of a crystal are arranged in a regularly repeating pattern (Berry, in Whittaker, 1981). Crystallographers produce X-rays by accelerating electrons through a high voltage. The electrons strike atoms in a target which emit an X-ray photon (Whittaker, 1981).

A **crystal lattice** is a regularly repeating three-dimensional arrangement of atoms with an associated three-dimensional pattern of electron density (Dent Glasser, 1977). X-rays are shone on a crystal, and scatter when they hit electrons (Whittaker, 1981). The repeating structure of the crystal influences the direction in which the scattering occurs. The scattered electrons interfere, producing a **diffraction pattern** (Dent Glasser, 1977). The diffraction pattern produced depends on the arrangement of atoms in the crystal lattice; the amount of constructive interference changes as the distance between atoms changes.

A crystal can be imagined as stacked parallel lattice planes, each separated by distance *d* (Dent Glasser, 1977). Each lattice plane is like a mirror, as when struck with electrons, the angles of incidence and refraction (θ), are equal (Whittaker, 1981). Each lattice plane produces reflected waves that interfere constructively only if they are in phase, if the waves reflected from each plane are separated by a whole number of wavelengths (Dent Glasser, 1977). This occurs if the wavelength (λ) satisfies the Bragg Equation: $n\lambda=2d\sin\theta$, where *n* is an integer as shown in **Figure 5** (Whittaker, 1981).

The repeating pattern of a crystal lattice means that an electron at a certain position in one **unit cell** diffracts constructively with those in a different unit cell only when they are separated by the distance that satisfies the Bragg Equation (Dent Glasser, 1977). At the same time, destructive interference is also occurring between reflected waves that are not in phase, producing a diffraction pattern. Using the Bragg Equation the spacing between lattice planes can be determined by using monochromatic X-rays (as λ is constant) and varying θ (Whittaker, 1981). The shape of the diffraction pattern is dependent on the size and shape of a unit cell in a crystal lattice and the intensity depends on the distribution of electron density within the unit cell (Dent Glasser, 1977). Diffraction patterns are recorded on photographic film. Crystallographers can use the information obtained from a diffraction pattern to determine features of the crystal structure including bond lengths and the position of atoms within the crystal lattice, which give information about the structure of the crystal.

Prior to the use of X-ray diffraction, scientists were only able to predict the arrangement of crystal structures mathematically (Burke, 1966). The discovery of X-ray diffraction shifted the study of crystallography from the external form of crystals to their internal structure.

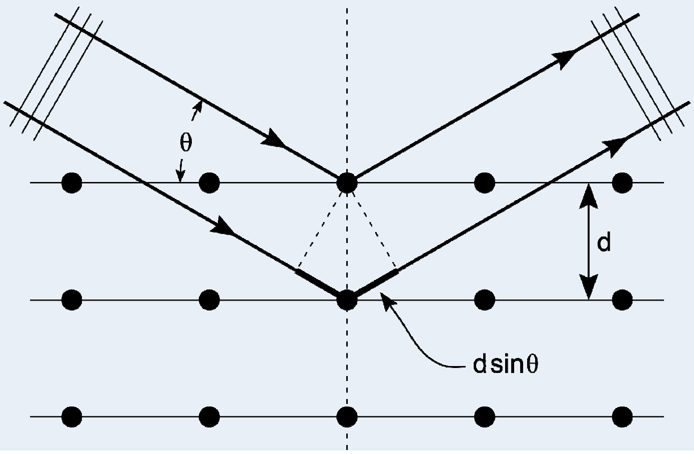


Figure 5: *An illustration of Bragg's Law. Atoms and their associated electron densities are arranged regularly in a crystal lattice. The lattice planes are all separated by a constant distance d. An incoming beam of X-rays strikes the electrons at an angle θ, and is reflected at the same angle. Constructive interference occurs only if the reflected waves are in phase, which occurs if they satisfy the relation known as Bragg's Law: nλ=2dsinθ. Other reflected waves, not separated by this ideal distance interfere destructively, producing a diffraction pattern that crystallographers can use to determine the structure of a crystal.*

Marie Skłodowska-Curie: The Development of Radioactivity

Figure 1: *Photo of Marie Curie posing for her Nobel Prize in physics in 1903. She received the prize along with Henri Becquerel and her husband Pierre Curie in 1903 for their work in studying radioactivity (Fröman, 1996).*

Marie Skłodowska-Curie (born as Marya Skłodowska) (1867-1934) was a Polish-born scientist widely known for her work in developing the field of **radioactivity** (Reid, 1974). To appreciate the motivations behind her discoveries that resulted in her becoming the first woman Nobel Laureate (**Figure 1**) and the first to win in two sciences (Physics in 1903 and Chemistry in 1911), one must examine her early life (Fröman, 1996).

Marie was born into a poor family at a time when Russia occupied Poland. At a very early age, her father, a professor of physics, taught Marie and her siblings science and Polish, despite the Russian government's oppression of the Polish language and the teaching of women (Goldsmith, 2005). The lessons that Marie's father instilled in her, both in science and in following her beliefs, would resonate throughout the rest of her life.

After struggling with money, Marie was able to move to Paris at the age of 24, where she would complete her undergraduate degree and spend the majority of her life (Curie, 1937). There she met her husband, a physicist named Pierre Curie. Their relationship at first was purely a mutual understanding of each other's passion for science, which was sufficient for Marie to accept Pierre's marriage proposal in 1895 (Curie, 1937). Pierre and Marie worked as a team in order to make their revolutionary discoveries, which also strengthened their personal relationship.

Scientific thought in the late 1800s

The years before the Curies made their discoveries were exciting times for physicists and chemists alike. In 1895, **Wilhelm Röntgen** discovered x-ray radiation, which sparked a huge public and scientific interest (Goldsmith, 2005). Less than a year later, Röntgen's work led **Henri Becquerel** to become the first scientist to observe a new type of radiation emitted from uranium, which were later called 'Becquerel rays' (Fröman, 1996). However, Becquerel did not pursue his studies into Becquerel Rays, believing that there was little to expand upon. Not many scientists of the time followed Becquerel's work because the amount of rays emitted were thought to be too small to be measured comprehensively (Reid, 1974). However, this did not prevent Marie and Pierre Curie from performing their studies in the subject.

At the time, **Dalton's atomic theory** proposed by John Dalton in the early 1800s, was widely accepted, and the existence of subatomic particles were unknown (Goldsmith, 2005). The atomic model had been unchallenged scientifically since it was first proposed by the Greek philosopher Democritus in the 4th century BCE (Bertrand, 2004). In 1897, around the time when Curie was making her major discoveries, J.J. Thompson performed experiments that disputed the atomic model and proposed a new subatomic particle – the electron (then known as a corpuscle) (Reid, 1974). The work that would soon follow from the Curies, **Ernest Rutherford**, Becquerel, and others would provide evidence that would challenge the atomic model and revolutionize the study of chemistry and particle physics.

The Curies

In the late 1890s, Marie Curie, with the encouragement of Pierre, decided to continue the study of Becquerel rays emitted by uranium by analyzing the uranium in **pitchblende ore**. It was in these studies that she first measured the 'radioactivity' of a substance using an **electrometer** designed by her husband (Goldsmith, 2005). The tools used by scientists were not comparable to the technology used today, which limited the discoveries that could be made. In fact, electricity itself was a relatively new phenomenon being integrated into society towards the late 1800s. The electrometer functioned (though the method was not completely understood at the time) by having the radioactive substance **ionize** air and cause electron flow. This current was then used to create a magnetic field that caused a mirror to swing (Goldsmith, 2005). This allowed Marie to measure minute currents induced by shining a light on the mirror, and determining its deflection. The tools that Marie used in her discoveries were designed by her husband and were considered state-of-the-art at the time – yet were made using discarded plywood and a hand vacuum pump (Goldsmith, 2005). In addition, the laboratory they worked in was described by a German chemist Wilhelm Ostwald as "a cross between a stable and a potato cellar" (Reid, 1974).

Equipped with Pierre's electrometer, Marie was able to compare the radioactivity of various pitchblende samples. However, the work was arduous, requiring both concentration and skill (Curie, 1937). Amongst preparing her samples to be studied, during data collection she was required to simultaneously measure the deflection of the mirror, and determine the length of time over which the deflection occurred (Goldsmith, 2005). Marie discovered that the radioactivity within a sample of pitchblende (**Figure 2**) was greater than the amount expected from the uranium contained within it. This led her to believe that another element existed that was more radioactive than uranium (Fröman, 1996).

After measuring the radioactivity of all other known elements at the time, Marie concluded that she had discovered an entirely new element. In the summer of 1898, Marie, with the help of a chemist named Gustave Bémont, was able to isolate a compound that contained an element 150 times more radioactive than uranium, which she called polonium after her native country (Draganić, 1993). However, in her haste to publish her data before others made the same discovery, Marie had not completely isolated the element to allow for a full **spectral line**, which cast some doubt to the validity of her discovery (Goldsmith, 2005). In the same year, Marie also discovered a compound containing an element that was seemingly 900 times more radioactive than uranium (later found to be even greater), which she and her husband called radium. She was able to produce unique spectral lines from radium, demonstrating its existence. In addition to her work in discovering new elements, Marie performed research into general properties of Becquerel rays, such as the fact that they were unaffected by temperature and pressure. Marie published her findings in papers, which are noteworthy for two reasons: they demonstrated that radioactivity 1) could be used to isolate new elements and 2) was an intrinsic atomic phenomena (Reid, 1974). Both radium and the idea of radioactivity being an intrinsic property would play an important role in the development nuclear physics in the years after Marie published her work, but radioactivity itself would not be fully understood until the advent of quantum mechanics nearly 30 years later (Fröman, 1996; Goldsmith, 2005).

***Figure 2**: Pitchblende ore (Uranite), a mineral ore mainly composed of uranium oxide but also containing thorium, polonium, and radium. Marie Curie performed a majority of her experiments using this mineral (Jedrzei, 2008).*

After her discoveries in 1898, Marie proceeded in the long, laborious task of isolating pure radium and polonium to determine their atomic weights and demonstrate that they were indeed new elements (Fröman, 1996). Five years later, Marie isolated 10 grams of pure radium chloride, and accurately placed radium on the periodic table, which allowed her to complete her doctoral thesis (Durance, 1986).

Scientific Struggles & Competition

Throughout their entire scientific careers, the Curies often found themselves in a race with other scientists to publish their results. There were several instances where scientists have published, only to discover that a similar paper had been published only months before (Curie, 1937). Marie herself was pre-empted in publishing the identification of thorium as a radioactive element by the German chemist, Carl Schmidt. This stimulated Marie Curie to quickly publish her discoveries of polonium and radium before she was completely confident of the results. This had consequences, as in 1903, Willy Marckwald, a German scientist challenged her identification of polonium as an element, and himself claimed to have discovered a new radioactive element during his studies into Marie's work (Reid, 1974). However, Marie was able to later demonstrate indisputably that polonium did exist through isolating it, and that Marckwald's element was indeed polonium (Reid, 1974).

To publish material quickly, scientists in France often presented their papers to the **Academy of Science**, where scientists would regularly meet. However, this required membership in the society, a privilege that was denied to Marie as a woman (Goldsmith, 2005). Much of the early work of the Curies were presented to the society by Henri Becquerel who, among several other scientists, continued his own studies into radioactivity after the Curies had renewed interest in the field. Rutherford was another well-known scientist who significantly advanced the understanding radioactivity and nuclear physics. In his early work (circa 1899), Rutherford was able to classify the three types of radiation emitted (alpha, beta, and gamma) (Durance, 1986).

Figure 3: *A collection of the various radium products made available after Marie Curie's discovery in 1898. The harmful effects of radium were unknown at the time. Nevertheless, most of the products contained minute quantities of radium because it was costly to isolate (Reid, 1974; Travus, 2009).*

After the Curies had discovered radium and a method of measuring radioactivity, many chemists and physicists in the early 1900s were focused on adopting the observations into known theory. There were two major opposing theories accounting for the source of the radiation (Goldsmith, 2005). Pierre Curie proposed that the radioactivity was a result of a perturbation of a field in the area surrounding the atom (Durance, 1986). Contrarily, Ernest Rutherford proposed that the radioactivity resulted from the breakdown of the atom itself (Goldsmith, 2005). The issue was settled when Rutherford and his colleague, Fredrick Soddy, were able to show that the radium atoms decayed into other atoms, eventually turning into lead. This '**transmutation**', a phenomenon once attempted by the alchemists in the Middle Ages, was unheard of at the time, and contradicted the belief that atoms were indivisible (Reid, 1974). Rutherford and Soddy also noted that this transmutation occurred with a relatively consistent half-life that varied between radioactive elements (Durance, 1986). Although the Curies did not develop the model for radioactive decay, it is certain that Marie provided the purified form of radium that was required to make this discovery.

The work that the Curies performed had begun a chain of events into a field that may have been ignored for years. For this reason, they, along with Henri Becquerel, were awarded the Nobel Prize in Physics in 1903 for the discovery of radioactivity (Fröman, 1996). Marie was not originally included in the nomination, likely because she was a woman, but was added after Pierre refused to be nominated without her (Goldsmith 2005). However, she did receive her own Nobel Prize in Chemistry in 1911 for the discovery and isolation of radium.

Societal Effects

When the Curies discovered radium, chemists and physicists became excited about how this new discovery would allow exploration of atomic properties. Society, however, had different concerns with the new element. The public had begun using radium in beauty cream, toothpaste, inhalers, and fertilizer (**Figure 3**). Becquerel and Pierre had both noted that radium was capable of damaging one's skin (Reid, 1974). Very quickly, radium was discovered to have medicinal uses, and eventually was found to remove cancerous tumours (Goldsmith, 2005). This application of radioactive elements is still in practice today in cancer therapy (e.g. in brachytherapy).

In addition to the beneficial applications of radioactivity, scientists were acutely aware of the huge amount of energy stored within radioactive elements. Both Pierre and Rutherford wrote about the damage possible from releasing the energy stored within radium (Goldsmith, 2005). Marie Curie's future research, even after her husband passed away in 1906, focused on promoting peaceful applications of radioactivity. Despite such efforts, radioactive elements did eventually become used in nuclear weapons (Goldsmith, 2005).These damaging effects resulted in a steady decline in the health of Marie, ultimately leading to her death to leukemia in 1934. (Reid, 1974).

Marie Curie's Legacy

Marie Curie's life demonstrated a wholehearted focus on science. Many scholars have noted that radium and polonium were like children to her. Even her death due to leukemia resulted from her work with radioactive substances (Fröman, 1996). However, in addition to science, Marie Curie raised her children to strive for excellence. She has been noted by scholars to having made sure they received a proper education despite being women, and ensured that they lived a healthy lifestyle with physical activity (Goldsmith, 2005). She even took her eldest daughter, Irène, to become the partner she lost when Pierre died (Curie, 1937). Irène subsequently became the second woman to receive a Nobel Prize (Fröman, 1996).

Marie Curie faced poor living conditions, as well as prejudice from being a woman and a member of an ethnic minority, yet this did not detract from her determination to succeed in her research. She set an example, not only for women, but also for all scientists that hard work and perseverance even in unsatisfactory conditions can result in great accomplishments.

Radiometric Dating

The results of Marie Curie's early research into radioactivity continue to be applicable in modern earth science. Based on Marie's work, Rutherford was able to deduce that radioactive elements had relatively stable half-lives. In addition, because of Marie Curie's work, scientists know that the half-life is unaffected by temperature, pressure, and other external conditions (Durance, 1986). This allows radioactive elements to be excellent indicators of the age of as substance, called radiometric dating. Radiometric dating is a foundational technique used in the earth sciences to age rocks, fossils, and other material, providing an accurate description of the timing of geological events.

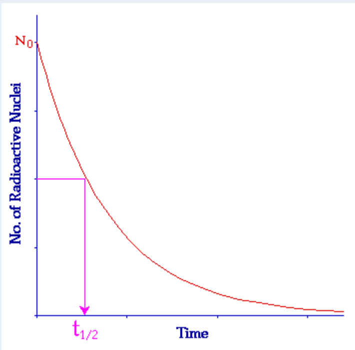


Figure 4: *Graphical representation of nuclear decay of an element. Each element has its own half-life, resulting in either a steeper or gentler slope. The half-life $t_{1/2}$ indicates the time when exactly half of the nuclei have decayed (Kieran, 2006).*

Radiometric dating involves the use of the steady half-life of **radioisotopes**, isotopes of an element that are unstable. Radioactive substances are inherently unstable, and their nuclei decay, releasing waves of energy either in the form of protons (alpha decay) or electrons (beta decay) (Draganić, 1993). Although the instant when a particle will decay is unknown, the rate of decay of a collection of radioactive atoms of the same element will decay at a rate proportional to the amount of the material available (**Figure 4**). This results in a simple differential equation, which can be solved to give

$$N(t) = N_0 e^{-rt}.$$

Where N_o is the initial amount of the radioactive element, *N(t)* is the amount of the element at a certain time later, and *r* is a constant representing the rate of decay which is inversely proportional to the half-life. By measuring the ratio between the parent radioisotope concentration and the concentration of decayed daughter product, and knowing the half-life one can determine the age of a substance using the equation above (Durance, 1986).

Radiometric dating can often provide geologists the absolute age of a material. Using the absolute ages, geologists are able to reconstruct a timeline that outlining the past major geologic events.

Carbon Dating

Different radioisotopes are capable of dating materials of different ages. Carbon-14 is one of the most accurate methods of dating geologically recent samples and has been used since the 1960s when it was first developed as a dating tool. Carbon-14 has a half-life of 5 730 years, and is able to date specimens within the last 50 000 years (Draganić, 1993). Carbon-14 initially forms in the upper atmosphere as cosmic radiation triggers the ejection of protons from nitrogen atoms. Studies have shown that cosmic radiation has produced a relatively steady supply of carbon-14 over the past 100 000 years (Draganić, 1993). The carbon-14 generated in the atmosphere is ingested by organisms in the biosphere and begins to decay upon death of the organism. The carbon-14 content of preserved organic material (e.g. fossil wood, shells, and bone) can be determined with the use of mass-spectrometers to determine the ratio of carbon-14 to carbon-12 (Draganić, 1993). Radiometric dating, such as carbon dating, has allowed scientists and historians to reconstruct and provide an accurate timeline for relatively recent geologic events. It is evident that Marie Curie's work continues to be a foundation for modern discoveries.

The Origin of Water on Earth

Introduction

Water is an essential part of life; nothing can survive without its existence. This was recognized in Ancient times by the Greeks and the Egyptians who believed that everything was created from water. Water was the only substance of which they knew that could exist in all three phases: gas, liquid and solid. They also perceived water as surrounding the Earth because it came up from the ground and down from the sky.

The importance of water was passed down from the Ancient civilizations; however, it was not until much later in time that the origin of water was investigated.

The sun and planets formed 4.55 billion years ago from the protosolar nebula, seen in **Figure 1**. The **protosolar nebula** was a rotating disk of gas and grains largely made of molecules of hydrogen and helium. The disk had an homogenous isotopic composition from its center to it edge. The isotopic composition of water on Earth is different from that of the primitive Sun, which raises the question of where the Earth's water came from (Robert, 2001).

The first person to try and solve the origin of the Solar System was **Laplace** (1749-1827) in 1796 (Delsemme, 1991).

However, due to the lack of appropriate investigational technologies, there were not many theories proposed for the origin of water for many years. It was not until around the 1900s that the origin of water on the Earth started to be explored in great detail.

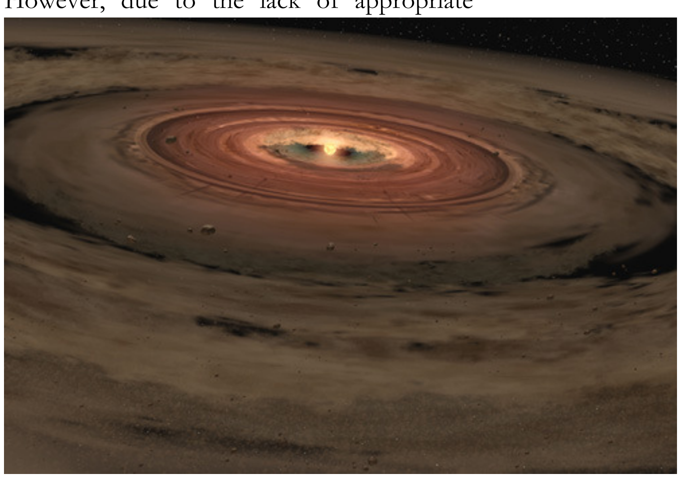


Figure 1: *This figure is a representation of a protosolar nebula. The Sun is in the middle and the disk of dust containing gas and grains is surrounding it.*

The Late-Veneer Scenario

The primary hypothesis for most of the early to middle 1900s was that water came from the bombardment of comets on the Earth, late into its formation (Harder, 2002). This is known as the **late-veneer scenario.** This hypothesis states that the source of the water on Earth was from the outer solar system and was carried to Earth by comets that collided soon after its formation (Morbidelli et al., 2000). The outer solar system regions included comets from the Uranus-Neptune region and from the **Kuiper Belt** (Morbidelli et al., 2000).

This theory was widely accepted for many years because of the limited information available on the topic. It was not questioned until the mid 1980s, when three comets passed close enough to the Earth for spectral analyses of the chemical composition to be preformed. The names of the comets were Halley, Kyakutake and Hale-Bopp, which passed by the Earth in 1986, 1996 and 1997, respectively. These analyses were the first to ever examine the hydrogen in water on bodies from a remote region and they revealed a crucial difference between the water found on Earth and the water in the comets (Harder, 2002).

Commonly on Earth, hydrogen atoms contain a nucleus made up of one proton. The less common form of hydrogen, called **deuterium**, contains both a proton and neutron in the nucleus. Deuterium behaves chemically like hydrogen, however, when it is used to form water or other compounds, the molecules are significantly heavier (Harder, 2002). There is one deuterium isotope for every 7,000 hydrogen atoms on Earth, which is known as the **Deuterium/Hydrogen ratio** (D/H ratio). The D/H ratio found in the comets that passed by Earth was twice that of Earth's D/H ratio (Harder, 2002).

Geologist **Francois Robert**, from the Museum of Natural History in Paris, showed in 2000 through the uneven D/H ratio above, that cometary bombardment (**Figure 2**) could account for no more than 10% of the Earth's water supply (Harder, 2002). This low contribution of comet water may also result from the fact is that as comets move towards the Sun, water vapour sublimates, therefore the contribution of cometary water to terrestrial oceans should be small (Robert, 2001).

Carbonaceous Chondrites

Shortly after this discovery in 2000, **Leonid Ozernoy** (1939-2002), who worked at both Harvard and Boston universities, suggested that asteroid-size **planetismals** which contain less deuterium could have contributed to the late veneer of water on Earth. Ozernoy hypothesised **carbonaceous chondrites,** which have a lower D/H ratio than comets, hit the Earth at high numbers and could have delivered a significant amount of Earth's water (Harder, 2002). Carbonaceous chondrites came from the asteroid belt or the Jupiter-Saturn region where the D/R ratio is lower and much more similar to Earth's than those of asteroids found in the Uranus-Neptune region or Kuiper Belt (Morbidelli et al., 2000). An interesting fact about carbonaceous meteorites is that they are the most primitive objects of the solar system available for laboratory study (Robert, 2001).

Figure 2: An artist's representation of asteroids and meteorites bombarding the Earth during the final stages of its formation.

Before this theory could be developed further, **Tobias Owen**, from the University of Hawaii, later that same year examined the ratio of xenon to krypton in the Earth's atmosphere and found that it was significantly different from the ratio found in typical carbonaceous chondrites today. The ratio of argon-to-water was also examined and similar results. In addition to these dissimilar compositions, the isotope profiles of nitrogen and oxygen measured from meteorites and Earth add to the argument against carbonaceous chondrites providing much of the wet veneer (Harder, 2002).

The Wet-Accretion Hypothesis

Another hypothesis to account for the origin of Earth's water, known as the wet-**accretion** hypothesis, was developed by Michael Drake (1946 - 2011), from the University of Arizona early in 2002. The wet-accretion hypothesis states that Earth developed from silicate rocks that trapped water as ice and **coalesced** with other objects around it. This suggests that the band of solar nebula from which Earth formed was much cooler than first thought in order for the ice to condense and become bound to the silicates (Harder, 2002).

Both the late-veneer and the wet-accretion models were widely accepted hypotheses in their time, however, **Allesandro Morbidelli** (1966 - present) of the Observatory of the Cote d'zur in France, had doubts that the planet evolved only from material found in a tight band a specific distance from the sun. He created simulations which hypothesised that water and volatiles were brought from the outer solar system into the inner solar system. He emphasized that this occurred during the formation of the planets rather than late in planetary development. If the water was to have come from small meteorites and asteroids near the end of the planet's development, the same celestial rain would have also bombarded Mercury, Venus and Mars. From what is known, these planets do not have the same water properties as the Earth therefore this cannot be the case (Harder, 2002).

There is a high degree of oxidation of the Earth's mantle which suggests that a small amount of water was already present during the early phases of Earth's formation. The D/H ratio in the present-day mantle is close to that of the water in the ocean. If most of the Earth's water has been delivered by hydrated carbonaceous asteroids, roughly 10x more than the mass of the entire asteroid belt would be needed. The most plausible reservoir of water in the primordial solar system which can deliver large enough amounts of water with low D/H ratio would be the existence of massive **planetary embryos** in the asteroid belt (Morbidelli et al., 2000).

A Changing D/H Ratio

A paper released in 2007 by **Hidenori Genda** (1975 - present) and **Masahiro Ikoma** suggested another hypothesis that, if correct, would have a large impact on all other previous hypotheses (Genda and Ikoma, 2007).

Due to the D/H ratio measured in Earth's water, it has been hypothesized that carbonaceous chondrites contribute the most to the Earth's water supply, while comets contribute no more than 10%. Genda and Ikoma recognized that this was only true if the D/H ratio on Earth has remained unchanged for the past 4.5 Gyr (Genda and Ikoma, 2007).

By modeling the changes in D/H ratio on Earth through multiple simulations, it was found to increase for multiple reasons (Genda and Ikoma, 2007).

First, it was assumed that the early Earth had a hydrogen rich atmosphere due to the nebular gas which remained until the terrestrial planets were completed (Genda and Ikoma, 2007).

The model suggests that when the atmosphere is hot enough to turn all of the water into vapour form, the gasphase reaction for deuterium exchange causes water to gain more deuterium. When the atmosphere cools down the water vapour falls to create an ocean. After the ocean is formed, deuterium is exchanged between the ocean and the hydrogen rich atmosphere. Because of the relatively small levels of hydrogen that are currently present in the atmosphere, it can be concluded that a large amount was lost through atmospheric escape which results in deuterium enrichment in the atmosphere (**Figure 3**; Genda and Ikoma, 2007).

The cooling of the atmosphere relative to the timescale for the reaction of D/H ratio is much slower. This means that, during cooling, the D/H ratio of water vapour always reaches equilibrium. Therefore the liquid water that formed at a certain temperature would have the equilibrium value of the D/H ratio of water vapour at that temperature. "Deuterium exchange between the liquid water and the hydrogen gas would also occur through circulation of water in the atmosphere-ocean system during and after the ocean formation" (pg. 45, Genda and Ikoma, 2007).

Figure 3: *Water being evaporated into the atmosphere and then being poured back into the ocean. This process increases the D/H ratio.*

Conclusion

As technology develops, the theories of the origin of water continue to change and become more complex. Through collaboration of these theories and ideas, possible theories can be ruled out or expanded upon in order to make them as accurate as possible. By learning more about how water originated on the Earth, the formation of other planets can be more clearly understood along with how life could be present on other planets.

Current Theories on the Origin of Water on Earth

Today, the origin of water on Earth continues to be a perplexing question and is a large area of investigation. In 2010, Professor **Nora de Leeuw** and her international team where able to develop a new theory to account for the source of terrestrial water on the Earth. The hypothesis suggests that water was not a latecomer to the Earth, but was present from the very beginning at its birth (de Leeuw et al., 2010).

Through computational research, Nora de Leeuw and her team were able to model the adhesion properties of water to a mineral commonly found in the interstellar dust clouds with computer simulations. Their results showed that this adhesion proved to be strong enough to provide a viable origin of terrestrial water for Earth (de Leeuw et al., 2010).

Background Information

During the formation of a solar system, dust clouds have been observed to collect around young solar objects. These clouds are called interstellar dust clouds and consist of Mg-rich olivine and other refractory minerals (**Figure 4**; de Leeuw et al., 2010).

Figure 4: The mineral olivine can be found broken up into tiny pieces in interstellar dust clouds and helps to store water.

The minerals are able to have low impact velocities which create low-density, irregular shaped fractal structures (de Leeuw et al. 2010). These properties allow water vapour and atomic hydrogen to be present in the dust and gas around the Earth, causing gas-solid interactions (de Leeuw et al., 2010).

Computer Simulation

The molecular-level calculations produced by the computer simulation, designed by de Leeuw and colleagues, showed not only that it was "viable for water to become absorbed at the surface of dust particles in the interstellar medium where planets form", but also that the adhesion of water to the dust grains was strong enough to survive the harsh conditions of the interstellar dust clouds where planets form. The water was then trapped and incorporated into the Earth during accretion.

Additional simulations showed that the interstellar dust grains contained fractal surfaces that were appropriate for the strong retention of water under the extreme temperature and pressure conditions prevalent in the accretion disk during planetary formation. As the planet coalesced through the dust, the pressure and temperature increased significantly enough to detach the water from the grains, depositing it on Earth (de Leeuw et al., 2010).

Implications

The implications of this discovery are quite large. As Nora de Leeuw et al. (2010) note:

"The origin of water on our planet is not only of interest for our understanding of the evolution of our own planet and life thereon, but even more so for the increasing exploration of other planets within our solar system and the discovery of potential planetary systems in other galaxies." (Pg. 8923)

Research continues to be done on this topic with the hopes of one day discovering the secrets behind not just the formation of the Earth and its origin of water, but the solar system as a whole.

Fossilized specimens, such as these beautifully preserved crinoids from the Jurassic period, are a valuable tool in the study of ancient life.

Chapter 3: The Study of Ancient Life

The planet Earth is host to a wide variety of life, ranging from microscopic bacterium to whales weighing hundreds of tons. Given the sheer number of species present, the discovery of each has not been a feasible task, creating many obstacles for the modern study of life. Similarly, the study of ancient life is faced with problems concerning the rich history of life that existed on our planet before our time. Not only have an incredible number of different species existed over the course of the Earth's history, but evidence of this past life is rarely preserved and subject to a wide range of interpretations. As a result, the study of ancient life is problematic, but also very rewarding. The information that is gained from the study of ancient life gives us valuable insight into the history of the Earth while aiding us in the study of life today.

Moving from the discovery of photosynthesis to historical perspectives in the study of biogeography, this chapter covers a range of topics pertaining to the study of ancient life. The benefits of learning about the history of a scientific topic are two-fold as it places our current understanding of the topic in a historical context while increasing our awareness of the difficulties associated with the subject and how they are mitigated. As such, it is beneficial to learn about past endeavors relating to the study of ancient life before attempting to do so ourselves.

In order for the human race to move forward effectively, we must first have a solid understanding of what has come before us. The sections outlined within this chapter will lay the foundations for how the life we see today came to be, as well as the historic and modern approaches that have been used to facilitate its study.

From Priestly to de Saussure: Discovering Photosynthesis

Eighteenth-Century England

Mid-eighteenth-century England was a place with a large degree of political and religious unrest and radical social movements (Olsen, 1999). With a distinct hierarchy, the middle class had begun to lead several protests resulting in new legislations and change (Olsen, 1999). Furthermore, although religious pluralism had been legalized since the 17th century, there was a strong union with the state and the church as seen by the Blasphemy Act, which had made denial of the Trinity punishable by imprisonment (McEnery, 2005). It was also at this time that the **Industrial Revolution** had begun to take root, beginning with the textile industry, which was the first to become mechanized (Olsen, 1999).

Joseph Priestly: Early Life

Figure 1: *A depiction of Joseph Priestly, a British scientist, in his adulthood, as a, dissenting clergyman and teacher.*

Joseph Priestly (**Figure 1**), often credited as a forefather in understanding photosynthesis, was born in Yorkshire, England in 1733 (Harvey, 2010). His father was a cloth dresser and, when his wife Mary Swift passed away in 1739, was obligated to give up one of his six young children. Joseph Priestly, the oldest of the siblings, was only seven at the time of his mother's death (Harvey, 2010). His aunt, Sarah Kneighly, with no children of her own, offered to take him under her care (Wilkinson, 2004). By 1742, she had arranged for all his schooling, and according to Priestly, “From this time she was truly a parent to me till her death in 1764” (Lindsay, 1970). Soon after Priestly’s addition to the family, Kneighly’s husband passed away, leaving a considerable fortune behind (Boyer, 1964). In the words of Priestly about his aunt, “By this truly pious and excellent woman, who knew no other use of wealth, or talents of any kind, than to good, and who never spared herself of this purpose, I was sent to several schools in the neighbourhood” (Boyer, 1964). In his memoir, Priestly further accounts the high quality of the schools he was sent to and how he was soon proficient in math, Latin, Hebrew, Chaldee, Syriac, and Arabic (Lindsay, 1970).

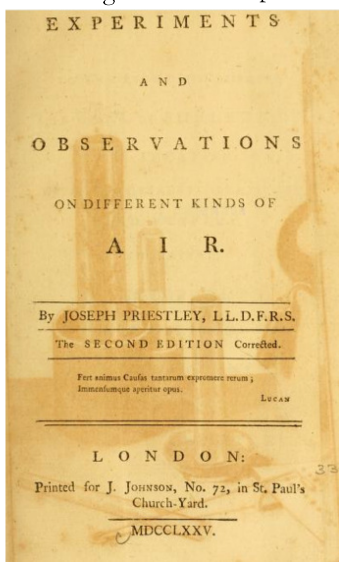
Priestly was, however, often ill and suffered a severe attack of tuberculosis in childhood. Often restricted from physical activity as a result of his ailments, he became an avid scholar at an early age. Encouraged by his religious family, Priestly entered Daventry School of Northamptonshire to train as a Nonconformist clergyman when he turned 19. Despite the high academic standing of the school, Priestly greatly supplemented his lessons with further studying on his own. At age 22, he became an assistant minister to a Presbyterian congregation; however, his stammer, single marital status and his views - which were becoming quite unorthodox - eventually led to his removal (Wilkinson, 2004).

In search of further opportunities, Priestly moved to Cheshire three years later, where he started a day school teaching students. It was here that Priestly was able to actively entertain his interests in science, and was soon providing his pupils with air pumps and electrostatic generators to teach them as well. He soon became recognized as a great teacher, and after being offered positions at other schools in England, was conferred an LL.D degree by Edinburgh University for his accomplishments (Wilkinson, 2004).

Over the next few years Priestly cultivated his interest in science, and following 1768, spent at least one month a year in London to debate scientific and political theories with leaders in the fields (Wilkinson, 2004). Among his many celebrated contributions to photosynthesis and chemistry, Priestly also had other accomplishments that are often overlooked, including the identification of graphite as an electrical conductor, the discovery that India rubber can be used to erase pencil marks and several renowned publications on electricity (Wilkinson, 2004). Following 1770, he began to focus his experiments on charcoal with adherence to the phlogiston school of thought, marking the start of his years of advancements in photosynthesis and chemistry (Lindsay, 1970).

Phlogiston Theory

Phlogiston Theory first emerged in early 1667 by German scientist **Johann Joachim Becher** who was attempting to explain the processes of combustion and the rusting of metal (Conant, 1950). This theory proposed the existence of an element called 'phlogiston' in materials that burn that is liberated upon combustion (Harvey Gibson, 1914). Joachim Becher lived his last years in London, England where he wrote his three major publications on alchemy (Conant, 1950). Although largely ignored throughout the seventeenth century, this theory began to regain popularity during the time of Joseph Priestly in the mid-eighteenth century (Wilkinson, 2004).



EXPERIMENTS

AND

OBSERVATIONS

ON DIFFERENT KINDS OF

AIR.

By JOSEPH PRIESTLEY, LL.D.F.R.S.

The SECOND EDITION Corrected.

Fert animus Causas tantarum expromere rerum;
Immensumque aperitur opus.
LUCAN

LONDON:

Printed for J. Johnson, No. 72, in St. Paul's Church-Yard.

MDCCLXXV.

Figure 2: *Priestly's original publication "Experiments and Observations on Different Kinds of Air" in which he outlines his discoveries of oxygen and other gases.*

Priestly and Photosynthesis

In 1771, Priestly first observed that plants had the ability to re-establish 'injured' or 'depleted' air. His experiment involved placing a small green branch of mint in a container with a burning candle. He witnessed that the presence of the mint kept the candle alive for longer than it stayed lit in the jar by itself. However, when he replaced the mint with a mouse he found that the candle stayed lit for a briefer time than usual (Asimov, 1989).

From this he concluded: '...the injury which is continually done to the atmosphere by the respiration of such a large number of animals ... is, in part at least, repaired by the vegetable creation' (Partington, 1989). In accordance with phlogiston theory, Priestly supported the idea that plants continuously remove the hypothesized element 'phlogiston' from the atmosphere, which was critical for the basic understanding of photosynthesis (Harvey Gibson, 1914).

In later years, Priestly went on to isolate and identify oxygen and several other gases including nitrous oxide, nitrous dioxide, ammonia and hydrogen chloride, and outlined his discoveries in his book *Experiments and Observations on Different Kinds of Air* (**Figure 2)** (Schofield, 2004). Although his work was significant for further progress in the field of chemistry, Priestly refused to abandon phlogiston theory until his death (Schofield, 2004). This stubbornness can be exemplified by the words of the French naturalist George Cuvier who called him 'the father of modern chemistry [who] never acknowledged his daughter' in his eulogy of Priestley (Schofield, 2004).

The Role of Light in Photosynthesis

Jan Ingenhousz, born three years before Priestly in Breda, the Netherlands, greatly drew on, and added to Priestley's theories on photosynthesis. Both scientists were driven by a deeply religious attitude and throughout his research, Ingenhousz expressed a firm belief that "balance in nature is the best expression of the harmony created by its author". It was common practice in the eighteenth century for European scholars to travel between European capitals frequently to gather information from a breadth of resources and collaborate with other scientists. After several years of travelling, Dutch-born Ingenhousz settled in London England in 1779, where his contributions to photosynthesis ensued (Magiels, 2010).

Unlike Priestly, Ingenhousz studied medicine; thus, his research was greatly motivated by problems in health (Beatty *et al*, 2005). In an attempt to determine if plants had the ability to cure illnesses, he performed many tests, at the end of which he concluded that the green parts of plants cleaned the air when placed in strong light (Beatty *et al*, 2005). He did this independently of Priestly but delayed the publication of his results (Lindsay, 1970). Priestly was given a work of Ingenhousz documenting his similar research, and he sincerely communicated a response clarifying that he had not had any intent of taking merit from Ingenhousz, and had discovered this regeneration of air independently as well (Lindsay, 1970). A few years after this exchange Ingenhousz added to Priestley's theory of photosynthesis and demonstrated that plants need light to 'dephlogistate' the air, and further, that the green part of plants is necessary for this ability (Rabinowitch, 1946). With the identification of the major components of photosynthesis, other constituents of the reaction needed to be identified and were done so by Nicolas Theodore de Saussure.

Water as a Reactant

Nicolas Theodore de Saussure, born in 1767 in Geneva, Switzerland, but French in origin, was the oldest son of the geologist **Horace-Bénédict de Saussure.** Horace-Bénédict was one of the first successful alpine travelers and made various advancements in geology and meteorology during his trips (**Figure 3**). He studied rocks, mountain chains, water bodies, glaciers, and the atmosphere with equipment that he had carefully designed himself; and his work was so diligent that it remains largely undisputed even 300 years later (Hart, 1930).

Figure 3: *Copperplate engraving by Christian von Mechel in 1787 depicting H.B. de Saussure's descents in one of his expeditions.*

As he disapproved of the education methods in public schools, his eldest son, Nicolas Theodore was educated at home. Later in life however, Nicolas was placed in l'Academie de Genève where he developed an interest in the natural sciences, later becoming his father's assistant (Hart, 1930).

While assisting his father in a number of experiments and expeditions, he learned to isolate and weigh atmospheric gases and in a famous climbing expedition of Monte Rosa in July 1789, they performed several experiments on the weight of the air. Their findings substantiated the observations of Mariotte, another researcher at the time, who developed his own version of **Boyle's law** in relation to gas behaviour (Houghton Mifflin Company, 2003).

In the same year, Nicolas began to pursue his interests in chemistry and plant physiology. Following the Mt. Rosa expedition, he began gathering numerous observations of the mineral nutrition of plants and published his work in 1797 (Hart, 1930). As a result of his accomplishments, Saussure was offered a position in plant physiology at the Geneva Academy (Hart, 1930). However, with an upcoming revolution threatening Switzerland with a French intervention, Nicolas left for England returning only in 1802 to be named honorary professor of mineralogy and geology instead (Steinberg, 1996). Dissatisfied with this title, he requested a leave of absence a few days later and although he held the title until 1835, he never gave a course at the Academy (Hart, 1930).

With his expertise and accuracy in measuring gases, Nicholas supplied a plant, isolated in a jar, with carbon dioxide and water and carefully determined the amount used up along with how much weight the plant gained. He found that the plant was gaining mass from both the carbon dioxide and the water, demonstrating that both played a role in the plant's survival. In 1804, he published a book on plant nutrition, *Recherches Chimiques sur la Vegetation* in which he outlines his experiments and also includes a detailed analysis of gases (Asimov, 1989).

With further experiments to substantiate his views, he states in this book that "plants appropriate the elements hydrogen and oxygen from water, and in doing so cause it to lose its liquid state, but this assimilation is not very pronounced unless carbon be appropriated at the same time" (Harvey Gibson, 1914).

He had in fact completed the basic outline for the reaction of photosynthesis, which is now understood to be:

$$6CO2 + 6\ H2O + \text{light} \rightarrow [CH2O] + 6\ O2$$

Although his works were greatly recognized during his time, the implications of his findings could only truly be appreciated and understood following his death in 1845 (Hart, 1930).

Although Priestly, Ingenhousz and de Saussure, had diverse backgrounds and perspectives ranging from medicine to geology, all three greatly contributed to the current understanding of photosynthesis. It is due to their contributions that scientists were later able to piece together the fundamental reactions of photosynthesis and cellular respiration. By understanding that bacteria were oxidizing water to produce oxygen scientists were able to look for clues such as a build up of oxygen in the Earth's Atmosphere to potentially indicate the emergence of photosynthetic life.

Evidence for Primordial Life

The first evidence of life on earth dates back 3.8 billion years ago to an atmosphere scarce in oxygen but abundant in sulfur and carbon dioxide (Des Marais, 2000). This environment, detrimental for **aerobic** life forms but ideal for **photoautotrophs**, is thought to have facilitated the proliferation of **primordial** life (Freeman, 2008). From the developments made by Priestly and de Saussure, it is now known that these organisms had the ability to free oxygen from water as an energy source. With a virtually unlimited source of oxygen from Earth's large bodies of water, life forms were able to generate chemical energy at an unparalleled rate, in turn, radically raising the atmospheric oxygen levels.

As the extensive metamorphic alteration of sedimentary rocks dating back to these early times limits the presence of microfossils, a change in terrestrial oxygen levels can be used to indicate the presence of photosynthetic life (Dismukes et al. 2001).

Banded Iron Formations

It is hypothesized that Proterozoic rocks exposed to the Earth's surface had high levels of iron that were released as ions from weathering . With limited diatomic oxygen gas available to bond with the released iron ions, they would be released into neighboring bodies of water. It is hypothesized that when the first photosynthetic organisms began to proliferate, the extra oxygen would bind with iron to form precipitates of iron oxide Fe_3O_4 or **magnetite**. This precipitate would then sink to the sea floor creating a band of iron rich sediments. However, consumption of the iron ions would eventually reduce their ability to neutralize the oxygen being produced. This would in turn lead to a buildup of toxic oxygen in the oceans resulting in the large-scale extinction of the life responsible for the oxygen production. Such extinction would be followed by a period of **silica** deposits (iron-poor sediment) on the sea floor until the microbial populations were able to re-establish themselves to continue the cycle (Koehler et al, 2010).

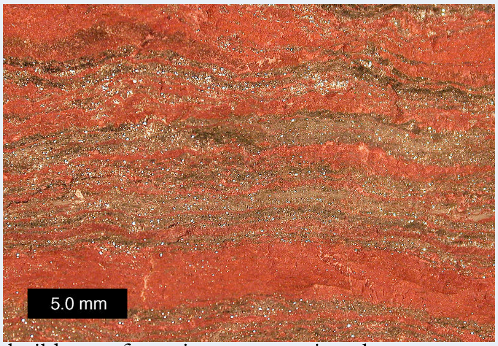


Figure 4: *This figure depicts a Banded Iron Formation specimen from Upper Michigan. When microbe populations are high, the oxygen they produce binds with iron ions to create a layer of iron-oxide sediments (Fe rich layer). On the other hand, when microbial levels are low, there is no binding of oxygen and iron, resulting in a period of silica rich deposits as seen in between the red layers.*

These cyclical variations in available oxygen may have resulted in **banded iron formations** (BIFs) (**Figure 4**) which are sedimentary rocks composed of thin, alternating layers of iron-rich material and silica (Hohmann-Marriott and Blankenship, 2011).

BIFs are broadly classified based on their tectonic setting, shape and size as either **Superior** or **Algoma** type. Although there are likely several mechanisms linked to the formation of BIFs, geologists are able to distinguish between these based on their classification as Superior or Algoma type. Algoma-type BIFs are characterized by sequences of volcanic rock and are thought to be associated with volcanic activity. In contrast, Superior-types are composed of other sedimentary units and are associated with oxygenation. They date back to three billion years ago (from the Archean to the Proterozoic time periods) and their deposition is thought to have occurred in shallow marine conditions under transgressing sea. Very common in Western Australia, these may provide a glimpse of Earths first photosynthetic life forms (Gornitz, 2009).

Charles Darwin: The Theory of Coral Reef Formation

Charles Robert Darwin (**Figure 1**) was an English **naturalist** best known for his contributions to the study of evolution and natural selection (Ruse, 2009). The story of his investigations of the structure and distribution of coral reefs is often overshadowed by his great accomplishments on the theory of evolution by natural selection. Before becoming acquainted with natural sciences, Darwin initially followed in the footsteps of his grandfather and father and began training in the field of medicine before a number of life changes that led him to the observations of geological phenomena that rivalled the theories on coral reef formation suggested by **Charles Lyell** (Ruse, 2009; Barlow, 1958).

Figure 1: *Charles Darwin was a renowned naturalist who laid the foundation for a number of scientific theories. This is a water colour painting of Darwin during his early years.*

The Development of a Naturalist

Darwin was born in 1809 at his family home in Shrewsbury, England (Barlow, 1958). He was the fifth of six children born to the physician, Robert Darwin, and Susannah Darwin, née Wedgwood (Ruse, 2009). In his early years, he preferred collecting and observing plants, minerals and animals rather than focussing on the simple geometry and readings he was taught in class (Barlow, 1958). As a result of his disinterest, Darwin performed poorly in school and was sent, by his father, to Edinburgh University at an earlier age than usual to complete medical studies. However, his interest in nature was much greater than his interest in medicine and soon his studies were neglected and passed over for marine invertebrates and natural sciences (Barlow, 1958).

Hearing the news of Darwin's dislike for medicine, his father, much to his displeasure, suggested a career as a clergyman (Ruse, 2009). Reluctantly agreeing to this, Darwin renewed his knowledge of classical literature and entered Cambridge University, where he became well connected to **John Stevens Henslow**, a botany professor, and **Adam Sedgwick**, a geology professor (Barlow, 1958). Darwin's interest in natural science and geology flourished in this new environment and over the three years Darwin spent at Cambridge University (1828-1831), his skills as a naturalist developed along with his interest in geology. After coming back from a trip with Professor Sedgwick, Darwin found a letter from Henslow that started him on a journey that would change many principle ideas on geology and the theory of evolution (Barlow, 1958).

The letter contained information regarding **Captain Fitz-Roy**'s desire to give up part of his cabin to any naturalist wishing to volunteer on the voyage of the *Beagle* (Barlow, 1958). At first, Darwin was eager to accept the offer but was discouraged by his father who believed that no man with common sense would agree to such an endeavour (Barlow, 1958). His uncle aided Darwin in convincing his father that it was wise to accept this offer. With the kind approval of his father, Darwin began the preparations for his trip (Barlow, 1958). After leading a life fraught with many career changes and disinterest, Darwin's life as a naturalist was finally beginning to fall into place, starting with his famous voyage on the *HMS Beagle.*

Voyage of the *Beagle*

The *HMS Beagle* was commissioned for an expedition to chart the coastline of South America (Fitz-Roy, 1839). This voyage lasted five years and began on December 27th, 1831, travelling across the Pacific and Atlantic Oceans (**Figure 2**). The mission of the *Beagle* was to survey and chart the coasts but Darwin spent his time deeply enthralled by geology and collected specimens on land wherever he could (Barlow, 1958). This was the journey where Charles Darwin made observations that would later cement his reputation as a biologist. However, he spent many of the early years on the voyage focused on geological investigations (Ruse, 2009).

Despite being taught by Professor Sedgwick, a leading **catastrophist**, Darwin was a strong believer in **uniformitarianism** (Ruse, 2009). This prompted Darwin to take Charles Lyell's *Principles of Geology* on the voyage and the first two volumes quickly became the foundation for many of his geological theories (Ruse, 2009). During the first few years of the voyage, Darwin spent his time excavating fossils and collecting specimens (Barlow, 1958). But as the expedition came to a close and upon their arrival in the Pacific Ocean other scientific opportunities were realized, including the investigation of coral reefs (Fitz-Roy, 1839).

The formation of coral reefs was the subject of lively scientific debate in the 1830s (Ruse, 2009). This debate triggered the commision of the *HMS Beagle* to conduct detailed geological surveys of **atolls** to investigate how coral reefs were formed (Fitz-Roy, 1839). For this purpose, Fitz-Roy chose to land upon the Keeling Islands in the Indian Ocean where the entire crew set to work collecting information (Fitz-Roy, 1839).

At this point, the observational skills of Darwin significantly complemented the objectives of the *Beagle's* commission (Ruse, 2009). He had learnt a great deal from the second volume of Lyell's *Principles* regarding coral reef formation and was greatly interested in observing the described phenomena and aiding in the survey (Ruse, 2009). Through Darwin's early interest in marine invertebrates and geology, he became an excellent source of information regarding possible coral reef formation theories and helped greatly with the geological survey (Barlow, 1958).

Differing Theories of Coral Reef Formation

Earlier in the expedition, Darwin had already drafted his coral reef theory that identified different classes of reefs. Current knowledge shows that coral reefs are underwater structures made from calcium carbonate secreted by coral, often taking the form of a reef when large colonies form together (Stanford University, 2012). There are three types of coral reefs: **fringing reefs**, **barrier reefs**, and atolls. A fringing reef is usually attached to the coast or shoreline (Stanford University, 2012). Barrier reefs often grow along the outer edges of the continental shelf and are separated from the shoreline (Stanford University, 2012). Atolls form by coral reef growth around an island (often volcanic) is encircled by a reef rim and are surrounded by the deep ocean (Woodroffe et al., 1999). The reef rim of an atoll is often made up of many coral islands that either partially or completely surround the central island (Woodroffe et al., 1999).

Lyell's second volume of *Principles of Geology* had a chapter dedicated to theories on the formation of atoll reefs. In the Pacific and Indian Oceans between the latitudes 30° north and south of the equator, many atolls, fringing and barrier reefs can be found (Lyell, 1832). Lyell suggested that these developed around the rims of extinct volcanoes that just break the surface of the sea (Lyell, 1832). However, this theory only accounted for the possible formation of atolls and did not make possible connections to fringing and barrier reefs. Despite Darwin's great esteem for Lyell, he disagreed with this assessment of the formation of atolls (Ruse, 2009).

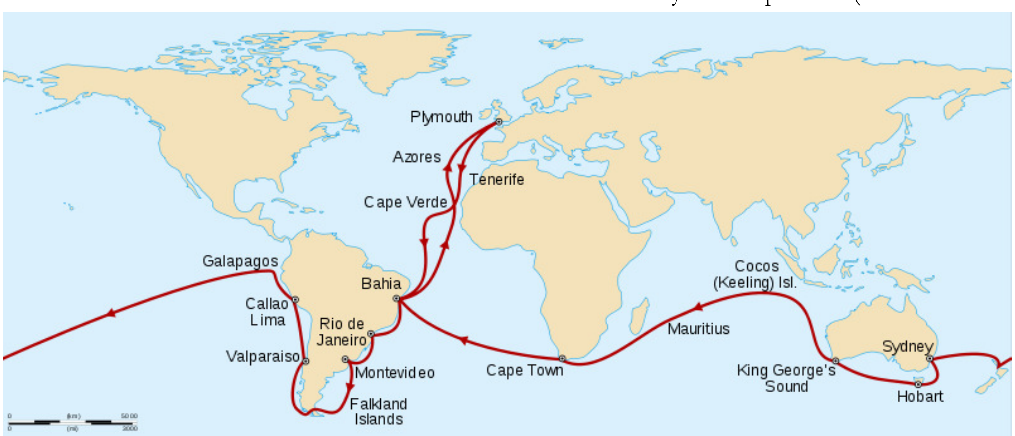


Figure 2: *The HMS Beagle was commissioned for a five year surveying mission along the South American Coast. The path that the HMS Beagle followed is indicated by the red line.*

While reading Lyell's theory, Darwin believed that it was improbable that the atolls began as extinct volcanoes. Having many volcanoes at the right heights for proper coral growth was improbable (Darwin, 1842). Instead, Darwin proposed a new theory for the formation of atolls. His new theory was based on his observations of coral growth in specific marine environments (Barlow, 1958).

Darwin's theory begins with a fringing reef being formed around an extinct volcanic island and subsequent **subsidence** as the ocean floor moves downward (Darwin, 1842). As subsidence continues, the distance from the shoreline to the reef increases and forms a protected lagoon. The reef system at this point has grown larger and has transformed into a barrier reef (Darwin, 1842). As the subsidence progresses, the island eventually sinks below the sea while the barrier reef continues to grow. This process lasts millions of years and results in an atoll that encircles a lagoon (**Figure 3**; Darwin, 1842).

When Darwin returned to England after his five year voyage on the *Beagle*, he sought out Charles Lyell and described his explanation for the formation of atolls (Barlow, 1958). Lyell encouraged him greatly as these findings and other observations from the expedition supported his concept of uniformitarianism (Barlow, 1958). Coral reefs may be geological structures but are created from slow, gradual processes and the growth of many tiny creatures over vast periods of time (Darwin, 1842). This information was considered as providing support with Lyell's theory of uniformitarianism and allowed the relationship between Darwin and Lyell to flourish despite opposing opinions (Darwin, 1842). After the five year voyage on the *HMS Beagle*, which marked him as a celebrity in many scientific circles, Darwin began to pursue interests other than geology (Barlow, 1958). Combining his exceptional observational and reasoning skills, Darwin was able to follow up his many geological publications with papers on plants, speciation and natural selection (Barlow, 1958).

Lasting Impact and Future Endeavours

Darwin's life after the *Beagle* voyage was characterized by the release of multiple publications (such as his *Origins of Species*), his marriage, and prominence in the scientific community until his death in 1882 (Ruse, 2009). Darwin left an impact on the scientific world and laid the foundation for future developments. As a person, his life may have ended, but from the viewpoint of science, his contributions were simply the beginning of ideas we would be advancing for generations to come.

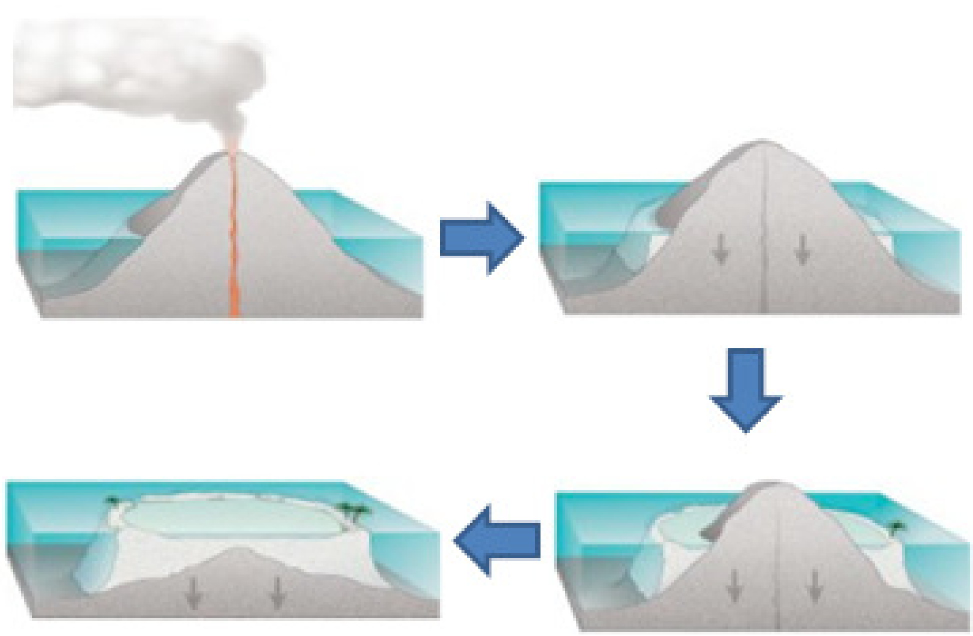


Figure 3: *Charles Darwin theorized that atolls were formed in a four step process. A volcanic island becomes inactive. Once it becomes inactive, the land subsides, forming a fringing reef. Over time, subsidence continues and the fringing reef is converted into a barrier reef with a lagoon forming. In the last step, the island is fully submerged underwater, leaving a lagoon and an atoll.*

Satellite Imaging of Current Threats to Coral Reefs

Coral reefs are fragile ecosystems that require specific water conditions for growth. Many threats plague the growth and survival of these habitats, and it has been noted that three-quarters of the world's coral reefs are deteriorating (Hoegh-Guldbery et al., 2007; Mumby et al., 2001). Coral reef loss affects not only the organisms living within its shelter but also the fishing industry, coastline protection, and tourism (Hoegh-Guldbery et al., 2007). Projects are now being initiated to identify coral reefs at risk and to evaluate the effectiveness of current protection programs. Observational data from these ecosystems are of great importance as changes in coral cover and colour over time are good indicators of its health (Mumby et al., 2001).

Imaging by Remote Sensing

Despite the need to monitor coral reefs, the current level of mapping intensity is not sufficient to identify globally significant changes. This has prompted the development and application of new technologies and methods to examine these changes (Mumby et al., 2001). A successful method of regional scale monitoring of reefs that is currently used is remote sensing. In this situation, energy is emitted from the satellite or aircraft. The radiation that is reflected from the target is detected by a sensor and the time delay between sending and returning is what characterizes the location and height of the target (Mumby et al., 2001). This is the current method being employed by the Millenium Coral Reef Project.

The Millenium Coral Reef project is a joint venture by the National Aeronautics Space Administration (NASA), international agencies, universities and other organizations to provide a comprehensive resource database on coral reef and adjacent land areas. NASA satellite images of coral reefs were compiled from 1999 to 2003 (Figure 4). Maps derived from the satellite images were made publicly available in 2005 (NASA, 2004). These maps and images were invaluable to those working on the protection and study of coral reefs. Researchers can use the images to locate reefs in relation to coastal marine ecosystems and identify areas of coral stress. The maps provide natural resource managers with data for habitat protection projects and can be used to check for temporal changes in coral cover. However, current resolution of sensors limit the determination of changing coral colour (Yamano and Tamura, 2004).

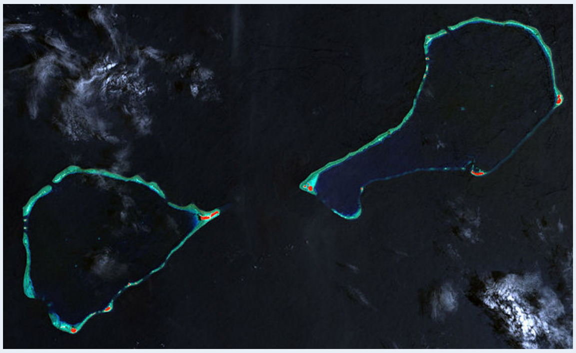


Figure 4: The Millennium Coral Reef Project produced 1 490 coral reef images for mapping. Shown in the image are the Hall atoll islands in the Federated State of Micronesia taken by the Landstat 7 satellite.

Coral bleaching is a major environmental issue identified in coral reefs. A large number of coral bleaching events have been recorded since the 1870s and these are often attributed to the rising temperature of sea water (Glynn, 1993). If bleaching is severe or prolonged, individual polyps or whole colonies of coral may die. The U.S. National Oceanic and Atmospheric Administration (NOAA) have begun to use infrared satellite data to pinpoint areas around the world where corals are at risk from bleaching. These infrared data show the amount of heat that radiates from the ocean surface (NOAA, 2011) and allow the creation of maps of sea surface temperatures. Coral reef researchers, climate scientists and natural resource managers are able to use these data to develop plans to protect at risk areas (NOAA, 2011).

The development of remote sensing has greatly impacted the protection and study of coral reefs. With these new data, many protection projects can be implemented to impede the further deterioration of the reefs.

The Alvarez Hypothesis: The Theory That Shook the World

During the **Mesozoic era**, the world was populated primarily by dinosaurs. However, around 65 million years ago, the most recent of the five great extinctions occurred, leading to the loss of roughly half of the genera present at the time. This extinction is known as the K-Pg extinction, marking the boundary between the **Cretaceous** (K) and **Paleogene** (Pg) periods. For many years there was debate as to what caused this extinction, with proposed theories including climate change, flooding, **bolide impact**, **magnetic reversal**, or a nearby **supernova** (Alvarez et al., 1980). However, none of these hypotheses were supported by convincing evidence until 1980, when a father and son team of **Luis** and **Walter Alvarez**, together with **Frank Asaro** and **Helen Michel**, were able to put forth the hypothesis that an asteroid impact triggered the extinction event and substantiate it with physical evidence.

Figure 1: *A map of Italy showing the location of Gubbio where Walter Alvarez was studying magnetic reversals in the early 1970s.*

In 1969, it was proposed that the impact of a large asteroid with the Earth could have caused the late Cretaceous extinction, however this idea was widely ignored by the scientific community at the time (Alvarez et al., 1984). In 1971, it was suggested that the explosion of a supernova sufficiently close to the Earth could have caused the K-Pg extinction (Russel and Tucker, 1971). However, there was little evidence presented to support this idea, and the theory was later disproved by the Alvarez team in 1980 (Alvarez et al., 1980).

In the early 1970s, Walter Alvarez, a professor of geology, was studying magnetic reversals recorded in limestones exposed near Gubbio, Italy (**Figure 1**). While working, he noticed a 1 cm thick band of clay separating the Cretaceous limestone from the Paleogene limestone above (Wohl, 2007). The clay layer could clearly be seen to coincide with the K-Pg extinction event, as below it in the limestone a large quantity of **foraminifera** were present; however no fossils of these marine organisms were seen above the clay layer (**Figure 2**). This suggested that the clay layer was from the same time as the extinction of the foraminifera, known to be at the boundary between the K and Pg periods (Alvarez, 1987). The limestone below the clay layer was rich in variety of fossils, with some large enough to see with the naked eye. However, above the layer, the only fossils present required magnification to be seen, again implying that the clay layer had been deposited at the same time as a reduction in ecological diversity (Wohl, 2007).

The limestone layers were mixed with small amounts of clay; however, the distinctive clay layer contained no traces of limestone. Intrigued by this discovery, Walter Alvarez cut out a section of rock that contained all three layers and showed it to his father, Nobel Prize winning physicist Luis Alvarez. To determine the time period over which the clay had been deposited, the father and son team decided to test for iridium levels in the clay (Wohl, 2007).

Platinum-group elements such as osmium and iridium are found in relatively low concentrations on the Earth's surface; however, as **meteoroids** burn up in the atmosphere, they deposit a fine dust of these elements at a fairly constant rate across the globe. Since the iridium was expected to be at levels lower than one part per billion, someone familiar with specialized nuclear chemistry detection equipment was required. To aid in the dating of the layer, Luis Alvarez contacted nuclear chemist Frank Asaro, who was later assisted by Helen Michel (Wohl, 2007).

What they found was very surprising. The levels of iridium in the clay layer were significantly higher than in the overlying and underlying limestone (Alvarez et al., 1980). At the base of the clay layer, iridium levels were found to be 30 times greater than normal, and gradually declined back to the normal level upwards in the layer (Alvarez, 1987). The unusually high level of iridium either suggested that the clay had been deposited over a long period of time or that the clay had been deposited during a time of abnormally high iridium concentration. Since it was unlikely that the clay had been deposited over a long period of time due to the absence of limestone, it was decided by the team that iridium levels had been very high at the time of deposition and gradually declined over time (Wohl, 2007).

Figure 2: *The iridium-rich clay layer in Gubbio, Italy studied by the Alvarez team. Luis Alvarez can be seen on the left of the image; Walter Alvarez is on the right.*

To determine whether the iridium-rich clay layer was simply a local Italian phenomenon, the group tested a band of clay in Denmark, which was the same geological age, but had been deposited in shallower water. The iridium levels in the Danish clay were over 150 times the level found in the rock below the clay. Similar results were soon found in over 100 sites worldwide (Wohl, 2007). The group then investigated the possibility that the iridium was of terrestrial origin and had formed by mass precipitation out of oceanic water while the clay was being deposited. They finally agreed that the most probable explanation of the high iridium levels was from a bolide impact, as bolides have iridium levels 10 000 times greater than those found in the crust of the Earth (Alvarez, 1987).

Upon examining the clay further, the Alvarez team found additional evidence to suggest that the deposition of the clay was associated with a large bolide impact. They found high levels of soot, which indicated that a large amount of vegetation had burned, as well as small glassy **spherules**, formed when molten rock thrown from the impact site cooled while travelling through the air (Wohl, 2007). They also found shocked quartz crystals with crisscrossing fracture planes, known to be seen at meteor impact sites, and microscopic diamonds and other minerals that are formed under high heat and pressure levels (Alvarez, 1987; Wohl, 2007). The team also tested the clay layer for similarity in chemical composition worldwide. They found that the clay layer had the same chemical signature in all locations, and was different from the clay constituents of the limestone above and below the iridium-rich K-Pg boundary clay (Alvarez et al., 1980).

The next step in forming their theory was for the Alvarez team to estimate the size of the asteroid that impacted the Earth. Using data from the eruption of the Indonesian volcano Krakatoa, which was the largest studied terrestrial explosion at the time, the team was able to estimate the amount of dust required to enter the atmosphere to inhibit photosynthesis. The team determined that the asteroid was about 10 km in diameter (Alvarez et al., 1980). An impact of this size was not unimaginable, as it was estimated that an object of 10 km or larger impacted the Earth about once every 100 million years (Shoemaker et al., 1988). Impact of a bolide this size would have produced a crater about 200 km in diameter. At the time of the publication of the asteroid impact theory in 1980, three impact craters greater than 100 km in diameter were known, however none were the correct age (Alvarez et al., 1980). Many years later, the most likely impact site was determined to be Chicxulub Crater, found on the Yucatan Peninsula in Mexico (Schulte et al., 2010).

The Aftermath of the Impact

When the asteroid hit Earth, it was travelling at a speed of between 30 and 60 km/s and upon impact, released energy equivalent to 100 million megatons of TNT. The asteroid sent a shockwave through the Earth in all directions, vaporizing, melting or pulverizing matter; the asteroid itself was instantly vaporized. An amount of rock equal to between 20 and 100 times the mass of the asteroid was ejected into the air, leaving a massive crater that may have been as deep as 40 km. The centre of the crater rebounded **elastically**, creating a peak that was briefly taller than Mount Everest before it collapsed back into the crater (Wohl, 2007). The impact caused earthquakes greater than magnitude 11, shelf collapse around the Yucatan Peninsula, and tsunamis that came crashing down onto coastal areas (**Figure 3**; Schulte et al., 2010). In the area near to the impact site these tsunamis were up to 1 km high (Wohl, 2007).

Figure 3: *An artist's interpretation of the moment of impact of the asteroid with the Earth approximately 65 million years ago*

The ejected material was propelled away from the impact site at speeds of several kilometres per second, leading to the spherules seen in the K-Pg boundary layer. Ejected material caught in the impact plume reached speeds greater than escape velocity; when they rained back down through the atmosphere the heat generated led to a global pulse of thermal radiation on the ground level. Although not strong enough to ignite woody plants, it did significantly disrupt ecosystems (Schulte et al., 2010). The ejected material from the impact was distributed globally, blocking out incoming solar radiation for a period of several years (Schulte et al., 2010; Alvarez et al., 1980).

At the impact site, an enormous fireball of vaporized rock rose into the air, and nitrogen gas in the atmosphere and sulfur compounds from the rocks were oxidized by the fire, leading to a rain of nitric and sulfuric acids which fell over 10 % of the surface of the Earth (Alvarez, 1987). The carbonate released from rocks thrown into the air led to massive amounts of carbon dioxide entering the atmosphere, which, after the period of cold darkness ended, led to overwarming of the atmosphere known as **the greenhouse effect** (Wohl, 2007).

On a biological level, the dust thrown into the atmosphere blocked out the sun for a period of several years, stopping photosynthesis. This would disrupt food chains at all levels. In the ocean, microscopic floating plants such as algae were nearly all killed, leading to extinction of larger marine animals such as **ammonites**, **belemnites,** and marine reptiles which depended on the photosynthetic floating plants. On land, plants either died or ceased growth during the period of darkness (Alvarez et al., 1980). Vast forest communities were eradicated within a period of months (Schulte, 2010). If a plant survived the period of darkness, it may have been able to grow again through spores, seeds, or residual root systems. However, herbivores dependent on the plants and the carnivores dependent on the herbivores became largely extinct. No land vertebrates over 25 kg were able to survive the impact. Many smaller vertebrates were able to survive and may have done so by feeding on insects and decaying plant matter (Alvarez et al., 1980). The land animals that survived were those that were small, with lower energy requirements, and were either able to eat dead and decaying biological matter or hibernate through the long dark winter (Wohl, 2007). In aquatic environments, some benthic species became extinct, while others did not. The species that survived were those that were able to feed on decaying biological matter that had settled on the marine floor (Alvarez et al., 1980).

The Alvarez team postulated that if the impact had caused the extinction of the dinosaurs, then no dinosaur fossils would exist above the clay layer. They found this hypothesis to be true, as well as finding no decrease in fossil density leading up to the clay layer, indicating that the dinosaur population had not been declining before the impact (Alvarez, 1987). Overall, the findings in the fossil record strongly supported the hypothesis that the K-Pg extinction was caused by a bolide impact (Alvarez et al., 1984).

Based on what was found both in the fossil and geological records, the Alvarez team was able to strongly support the hypothesis that asteroid impact caused the K-Pg extinction event that killed the dinosaurs and countless other species 65 million years ago (Alvarez et al., 1980).

Finding a Crater

After the Alvarez team published their hypothesis that impact of a large extraterrestrial body caused the Cretaceous-Paleogene extinction, the next step was to find the location of the crater (Alvarez et al., 1980). In 1991, it was proposed that a large, round geological structure near Chicxulub, Mexico was an impact crater. However, the group that suggested this was a crater was unable to definitively date the crater (Hildebrand et al., 1991). Later on, through the use of modern geophysical techniques it was determined that the crater was of appropriate age, leading to the consensus that the Chicxulub crater is the most likely site of the impact which caused the K-Pg extinction (Schulte et al., 2010).

The crater is located on the Yucatan Peninsula of Mexico, half on land and half underwater in the Gulf of Mexico (**Figure 4**; Urrutia-Fucugauchi et al., 2008). The structure was originally determined to be a crater by analyzing magnetic and gravity field anomalies in the area (Hildebrand et al., 1991). The gravity anomalies showed a pattern of concentric anomalies, indicative of an impact crater (Urrutia-Fucugauchi et al., 2008). The crater itself is between 180 and 200 km in diameter, matching the expected size of a crater associated with the impact of an asteroid approximately 10 km in diameter (Schulte et al., 2010).

The rock around the Chicxulub crater exhibits impact-related **slumping** and **liquefaction**, which is consistent with the impact of a large bolide. However, to assess the likelihood of this crater being the site of the impact that caused the K-Pg extinction, both ejecta patterns and age must be correct and consistent with the K-Pg boundary (Schulte et al., 2010).

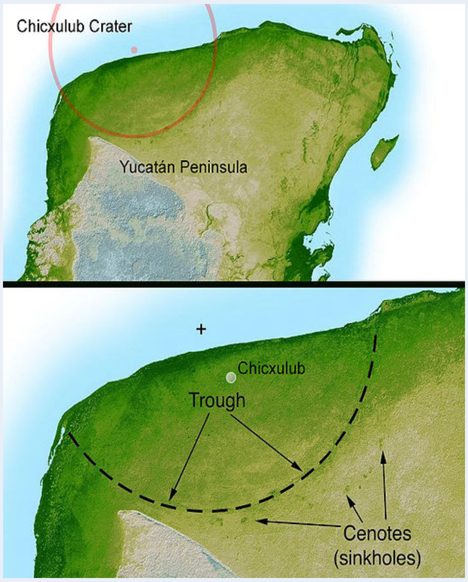


Figure 4: *The location of the Chicxulub crater. The cenotes, or sinkholes, around the perimeter of the crater are characteristic of an asteroid impact.*

The ejecta deposits found nearly worldwide coinciding with the K-Pg impact are classified into one of four groups. The first class of impact deposits is found within 500 km of the Chicxulub crater, and includes an impact-breccia sequence over 100 m thick, and a layer of ejecta-rich deposits that ranges from 1 m to over 80 m thick. From 500 km to 1000 km from the impact site, the K-Pg boundary consists of a layer of spherule-rich clastic beds, characteristic of sediment transport by tsunamis or gravity flows, both of which would be associated with the impact of an asteroid. The third class of impact deposit is found from 1000 to 5000 km away and is characterized by a 2 to 10 cm thick layer spherule layer topped by a 2 to 5 mm thick iridium-rich clay layer. The final class of ejecta-associated deposit is found greater than 5000 km away and consists of the iridium-rich clay layer which was studied by the Alvarez team in 1980 (Schulte et al., 2010).

The crater is dated as being about 65 million years old through geochronologic data, which is consistent with the K-Pg impact event. The interface between the iridium-rich clay layer and the limestone above is the official boundary marking the base of the Paleogene period. In combination, the presence of the nearby rock exhibiting features associated with a massive impact, the pattern of ejecta having Chicxulub crater at its centre, and the crater being the correct age provides physical evidence that strongly suggests that the Chicxulub crater is the location of the impact site of the asteroid which led to the ejecta deposits found at the K-Pg boundary. Since the impact coincides with the K-Pg extinction event, it is very likely that the impact of the asteroid at the Chicxulub crater led to the Cretaceous-Paleogene extinction (Schulte et al., 2010).

The First Gentle Giants: A History of Woolly Mammoth Discoveries

Long before the excavation of the first **woolly mammoth**, Siberian natives were already familiar with the ancient giants from the **Pleistocene Epoch**. To them, the beasts were thought to be underworldly creatures which, upon reaching the surface, froze to death from the harsh Siberian climate (Fisher et al., 2011). Siberian folklore is littered with stories about how Noah could not fit the mammoths on his ark before the Flood, and since the soaked soil could not bear the weight of the animals, they began sinking into the ground, where they are found today (Tolmachoff, 1929). European scientists only learned of these primitive discoveries upon Russia's conquest of Siberia, and at that point began the search across the globe that would last centuries and continue even to this day: the discovery of woolly mammoth fossils.

Figure 1: *Woolly mammoth skeleton from the Brno Museum in Anthropos seen above.*

Theories Regarding the Mammoth's Origins

The size and shape of these woolly mammoths truly confounded the scientific community, and scientists debated for decades about the creature's origins. Recovered **fossil** specimens clearly resembled those of tropical modern elephants (**Figure 1**). For this reason, many theories were developed to explain how a potentially tropical organism (resembling the present-day elephant) was found in a harsh climate like the Siberian tundra. Many theories proposed the **Noachian Deluge** as the mode of transportation of the beasts, with floodwaters carrying the 'tropical' mammoth bodies north, where they were later buried under snow and sediment (Tolmachoff, 1929). Accreditation was given to this 'floater' theory when the famous geologist **Charles Lyell** (1797-1875) agreed that these were animals from warmer climates that were carried northward by the major Asian rivers (Guthrie, 1990). Others believed that the Flood forced the animals to move north to habitats they were not well adapted to, and the species perished because of this migration (Tolmachoff, 1929). In 1825, **Georges Cuvier** (1769-1832) played a key role by showing the scientific community, through the comparison of mammoth jaw fossils with those of the Indian elephant, that they were not in fact the same species. Furthermore, the presence of fur on excavated specimens confirmed that the animals were likely well adapted to the cold climates where the animals were found (Tolmachoff, 1929).

Still, many people could not believe that such an animal could survive in Arctic conditions. New theories were developed that suggested that they lived in central to southern Siberia, and remnants and carcasses flowed through Siberian rivers such as the Ob or the Yenisei to reach the northern locations where the specimens were found. Cuvier again contested this notion, later supported by polar explorer Mathias von Hedenström (1780-1845) in 1830, claiming that there would be no way that the fossils could have survived long distance fluvial transportation and still remain intact, or at least without showing significant signs of detrition (Tolmachoff, 1929). Furthermore, if the mammoths' natural habitat was in the south, one would expect to find a larger number of 8fossils there, yet the opposite /is seen to be true (Tolmachoff, 1929). However, the efforts of Cuvier and others did not convince much of the scientific community, who still believed that Noah's flood had played a role in the transportation of these creatures. In an attempt to reconcile the scientists from both sides, Henry Hoyle Howorth (1842-1923) suggested in 1887 that mammoths lived in a very warm climate in the north, and after the biblical flood, were buried in the silt and sediment as the water receded, which later froze as the temperature fell (Guthrie, 1990).

Although these controversial debates did not reach a resounding consensus, they were able to raise awareness of the need to search for more specimens. Expeditions carried out by the Russian Academy of Sciences and the American Museum of Natural History were able to confirm that mammoths had lived in the area where they were found, and that there were not significant climate changes, and instead mammoths were well adapted to the cold environment (Guthrie, 1990).

Although the first fossils were localized to northern Siberia, preserved mammoth specimens have been found in the surficial sediments of western Europe, northern and eastern Asia, Alaska, Yukon, and many islands in the Bering Sea (Oard, 2000). Frozen mammoth carcasses are often found eroding from riverbanks along the shores of the Arctic Ocean (Oard, 2000). Occasionally sections of **permafrost** that emerge in the warmer summer weathers are exposed and transported to the cliff foot by **mudflows**. Bone fragments are often found on the shorelines of oceans and large rivers, or shallow coastal bars (Schirrmeister et al., 2002). **Figure 2** shows the chronological discoveries of woolly mammoth specimens throughout northern Siberia.

Beginning the Search for Woolly Mammoths

Fossil ivory was a major export of Siberia long before the first excavation of a woolly mammoth carcass. Ivory hunters would discover the locations of frozen carcasses, and physically mark them as their possession, so they could come for years removing small pieces of ivory from the ice (Tolmachoff, 1929). While fossil ivory was found throughout Russia, it was not until 1582, when Yermak Timofeyevich conquered Siberia, that it became a regular commodity, and subsequently raised awareness among the scientific community (Tolmachoff, 1929).

In 1720, political and scientific advocate Vasiliy Tatischev (1686-1750) urged Tsar Peter I (1672-1725) to begin the search for a complete mammoth carcass. Daniel Messerschmidt (1685-1735) was sent four years later and returned with moderate success: the bones and skull of a woolly mammoth specimen from the Indigirka River, in Northern Yakutia (Mol et al., 2003). The first discovery of a woolly mammoth in Siberia brought more attention to Russian scientists, and a decree was issued that any mammoth bones found must be delivered to the Kunstkamera, the first scientific museum in Russia (Tolmachoff, 1929). To promote the discovery of more mammoths, the Russian Academy of Sciences offered monetary incentives funded by the Russian government for word of any skeletons and carcasses found in the field (Tolmachoff, 1929). Not only was this effective in garnering numerous explorers to begin the search for more woolly mammoth specimens, but the Academy believed they would have support from the natives who lived in the harsher northern climates, as they were also offered the reward. However, this was far from true for two reasons. First, the natives were superstitious and believed that bad luck would be brought upon those who excavated the animals (Tolmachoff, 1929). Furthermore, the natives did not believe that the promised 300 rubles was enough to compensate for the troubles they had in the past with government officials. An example of this attitude was in 1857, when natives discovered a carcass of a mammoth

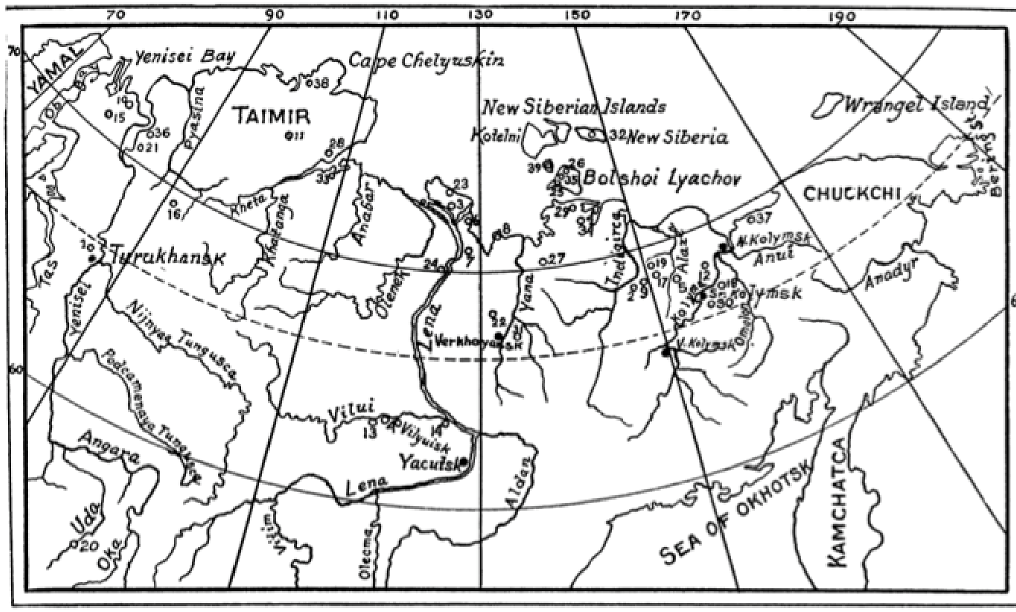


Figure 2: *Map of northern Siberia, showing the first 39 frozen carcass discoveries in chronological order. Note how almost every specimen was located near a body of water. (Numbers 4, 13, 20, 22, and 31 were not woolly mammoth discoveries).*

at Lena River, yet decided against reporting the find to the Academy, and went even so far as saying the carcass was carried away with the river when the authorities questioned them about the find. It would be another 25 years before the carcass was discovered and finally delivered to the Academy of Science (Tolmachoff, 1929).

Landmark Mammoth Discoveries

Although Messerschmidt successfully found mammoth bones in 1724, the first full mammoth carcass was not excavated until 1799 (Schirrmeister et al., 2002). Dubbed Adam's Mammoth, it was found in the thawing permafrost deposits of the Bykovsky Peninsula in Siberia. In 1843, Alexander Theodor von Middendorff found the first mammoth in the Taimyr Peninsula of Siberia (Mol et al*.,* 2003). In 1901, one of the best mammoth carcasses was found along the River Berezovka, with preserved skin, internal tissues, and a tongue (Guthrie, 1990). There were even traces of what the mammoth was eating at the time of its death, including flowers which were determined to be buttercups (Guthrie, 1990). Excitement from the Berezovka discovery somewhat waned when further discoveries, though numerous, were not as extraordinary. No find up until that point had offered as much information about the physical features of the woolly mammoth as the Berezovka Mammoth, and there would not be a better find for over 70 years.

Figure 3: *Baby Lyuba, seen above, was recovered from the Yuribei River in 2007, and is considered one of the best-preserved woolly mammoths ever found.*

In 1977, the first baby mammoth was discovered in the USSR. Named Dima, the mammoth was found in the Kirgiliakh River, and had little decomposition and signs of scavenging (Guthrie, 1990). Scientists were able to estimate the age of the specimen as 7 or 8 months old (though some say as little as 4 months), and found plant detritus, minerals, silts, clays, and insect parts in his partly destroyed gastrointestinal tract (Guthrie, 1990). Dental structure and tooth eruption patterns were difficult to determine, however scientists used elephants as analogues to estimate how the processes proceeds in mammoths (Guthrie, 1990). Interestingly, Dima did not have any fat on his body; he was emaciated at the time of his death (Guthrie 1990). Because the carcass was so well preserved, they believed that Dima most likely died in autumn.

The most recent significant mammoth discovery was in 2007, when the Nenets, local reindeer herders, found a well-preserved mammoth calf on a **point-bar** off of Yuribei River. Named Lyuba, after the wife of the herder that reported her, she is considered the best-preserved mammoth ever found (Fisher et al., 2011). Her age was estimated to be one month using counts of postnatal daily growth increments in dentin, and isotope analysis from her teeth suggested that she was born in the spring (van Geel et al., 2011). The specimen was found to have a great amount of preserved subcutaneous fat, suggesting that the calf was well nourished (van Geel et al., 2011). The fat deposits were found to be brown fat, necessary for maintaining core body temperature by warming venous blood (Fisher et al., 2011). Lyuba's thoracic cavity had samples of her lungs and her heart. Botanical microfossils and macroremains from her small and large intestines are now being analyzed to reconstruct both the paleoenvironment and the diet of the mammoth.

The Future of Mammoth Discoveries

Mammoth excavations have progressed in the magnitude of their discovery over the past two centuries. Looking back to the first discovery in 1724, the scientific community knew so little about the beasts that roamed the land thousands of years ago. Yet with each discovery, and as scientific techniques were refined, we moved closer and closer to truly understanding the lives of these animals. With the recent discovery of baby Lyuba, one particular scientific development is even closer to becoming a reality: mammoth cloning. There are still more mammoths to uncover, and now it is up to us, with a strong feeling of curiosity, to keep searching for more mammoths frozen in time, waiting to be discovered.

Determining Mammoth Behaviours and their Paleoenvironments

Each mammoth discovery in the past offered more information about the physical features of the animal, and scientists interpreted these findings to learn about the environment in which woolly mammoths lived. However, it was only in the last half century that scientists began using trace substances found with the specimens for further chemical analysis. With **carbon dating** techniques, researchers were able to use bones and soft tissue to date woolly mammoth samples (Kuzmin and Orlova, 2004). Other materials found with the mammoth carcass can now be used to help scientists to reconstruct the **paleoenvironments** and behaviours of these giant creatures.

One of the best ways to determine an animal's diet, and the surrounding vegetation of the region in which it lived, is through analysis of intestinal tract samples. The 2007 discovery of the baby mammoth Lyuba was an outstanding discovery in part for this reason. While offering a wealth of organ samples for analysis, Lyuba had a fully intact intestinal tract with numerous pollen and bacterial specimens to interpret. Poaceae and Cyperacaeae pollen samples found in Lyuba's intenstine indicated that she died in a relatively open landscape (van Geel et al., 2011). Algae meant that there might have been a source of open water nearby, and arboreal taxa pollen suggest trees such as *Pinus, Picea, Betule,* and *Alnus* were part of the local vegetation. However, with aeolian transport, pollen samples cannot be entirely accurate in their depiction of the environment the mammoth lived.

Intestinal information alone only gives part of the picture. Given Lyuba's minimal tooth development, she most likely would not be able to fully masticate the vegetation anywhere to the degree that was found in her intestine. This suggests the possibility that the animal practiced **coprophagy** (the digestion of another's feces for nutrition), a practice seen in modern elephants to build up intestinal bacteria for digestion. Digested food found in baby mammoth samples has indicated that mammoths most likely practiced coprophagy at a young age (van Geel et al., 2011).

Intestinal tract composition has offered a plethora of information in past samples and will likely to continue being the main method scientists through which scientists can begin to assess the paleoenvironmental conditions. Even so, there are other ways that scientists have assessed mammoth behaviour. Analogous to migration behaviour in elephants, researchers are able to assess migratory pathways of mammoths using strontium ratios ($^{87}Sr/^{86}Sr$) in their tooth enamel. The ratio measured in the animal is indicative of the plant material they ate, which likewise can relate to the strontium levels in the soil that results from bedrock weathering and atmospheric deposition (Hoppe et al., 1999). In this way, scientists can reconstruct the bedrock age, bedrock composition, and atmospheric input in the environments in which the mammoths lived and ate (Hoppe et al., 1999).

Figure 4: *Artist's rendition of woolly mammoths in their Pleistocene paleoenvironments.*

A very recent technique used to investigate mammoths involves reconstructing the mammoth genome in order to assess the environmental challenges they may have faced based on their genetic make-up. We can infer the significance of reconstructed ancient gene products by recreating them in the genomes of modern day organisms. One study was able to successfully assess an amino acid substitution seen in mammoth haemoglobin which conferred reduced heat loss, therefore allowing them to adapt to life in high-latitude environments (Campbell et al., 2010).

Techniques for determining mammoth behaviour and their ancient environments in which they lived are constantly developing, offering more information about how interacted with their environments. We may never be certain as to how they truly lived, but each technique brings us closer to understanding these ancient creatures.

Historical Views on Human Origins: from Darwin to the Early Fossil Evidence

For centuries humans have long pondered their origins leading to a variety of proposed explanations for the creation of the human race. In one of the Greek mythology tales about human creation, it is told that Prometheus shaped men out of earth and water, and then gave them fire (Atsma, 2000). The Iroquois believed that the humans originated from the Sky People who lived up in the floating island when an impregnated woman accidentally fell down while peering down through a hole (Murtagh, n.d.). The Old Testament tells a story of man named Adam who was created by God out of dust and a woman from his rib (Genesis 2:7-22, King James Version). It is evident is that people wanted an explanation for the origin of humanity.

The Theory of Evolution

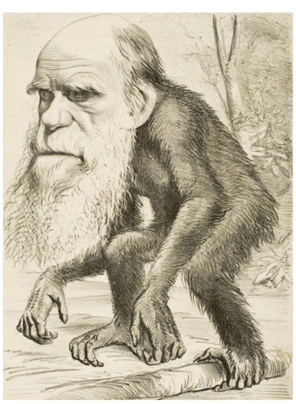


Figure 1: *Caricature of Charles Darwin as an ape published in The Hornet magazine, 1871*

In 1859, **Charles Darwin** wrote the controversial book entitled, *The Origin of Species by the means of natural selection or the preservation of favoured races in the struggle for life*, in short, *The Origin of Species.* At the time of its publication, the conservative forces backed by the Church were against the theory. This is unsurprising since the idea of 'natural' hierarchy established in the society was being threatened (Bowler, 2003). In his book, Darwin suggested an idea of evolution that was in strict opposition with the ideas that the Church and society held about a hierarchical order of organisms. In the Church's classification system for example, there was an existing assumption that all organisms were created by a rational being. Darwin states that all life forms we see today are a result of variation within a population and selection by nature of favoured varieties (Darwin, 1876). Darwin was aware of the logical implication of his theory – that humans are also a product of natural processes. However, in *The Origin of Species*, he intentionally avoids this subject on evolution of humans in an attempt to lessen the controversy caused by the book and simply stated that, "Light will be thrown on the origin of man" (Darwin, 1876).

In *The Origin of Species*, Darwin dedicated chapter six to the "Difficulties of the Theory", he immediately noted that the perceived "absence or rarity of transitional varieties" is a difficulty for the theory. Darwin asks, "…why do we not find them [transitional forms] embedded in countless numbers in the crust of the earth?" He answers this by suggesting that the fossil records are incomplete in comparison to the large collection that should be available in the crust. In chapter 10, "On the Imperfection of the Geological Record", this idea is expanded upon by examining various reasons such as, lapse of time and poor collection of samples (Darwin, 1876).

As expected, his book was met with many scientific objections as well as religious ones. There were many factors that ultimately made Darwin's book a source of debate. Those in a higher socioeconomic standing tended to oppose the theory whereas those who were less well-off tended to support it (Bowler 2003). The theory was more than merely a scientific idea, it had significance religiously and therefore socially; it threatened the established rules of the society. Nevertheless, the theory would never have survived if it had not been successful in debates among the scientific community. Inevitably, even the purely scientific debates had larger implications; there was no good distinction between debates about science, the religion, and the society at large.

In 1871, Darwin wrote his second book, *The Descent of Man, and Selection in Relation to Sex*, which details the application of his theory to the human evolution. Different aspects of the evolution of man are discussed such as the various evidences and **sexual selection**. Futhermore, Darwin noted great similarities between the modern humans and the apes and hypothesized that our ancestors likely originated from Africa (Darwin, 1882). He was the first to suggest a monogenesis of humans from Africa, which became known as the **recent African origin** hypothesis

(William et al., 2009).

Moreover, a great portion of the book is dedicated to the ideas of sexual selection to explain elaborate and beautiful traits that seemingly had no contribution to the "struggle for survival". To many opponents of evolution, this was an evidence for divine creation. Why would animals such as the peacock develop tails so colourful through evolution? Darwin elegantly explained this observation through sexual selection in which mate choices of the sexes and competition within a sex force a selection in favour of the trait (Darwin, 1882). Darwin also applied sexual selection to humans to explain sex differences.

Piltdown Man

From the time the theory of evolution was published, the race was on to find the missing links of human evolution. In December of 1912, newspapers ran headlines that the missing link in the human evolution was found (Bartlett, 2011). The *Manchester Guardian* ran the first one that read, "The Earliest Man?: Remarkable Discovery in Sussex. A Skull Millions of Years Old" (Russell, 2003). On that same day, the Geological Society in London had an unveiling of skull fragments that was attributed as the earliest known Englishman, found in Piltdown, Sussex (Bartlett, 2011). Officially, it was named *Eoanthropus dawsoni*, after Charles Dawson, credited as the discoverer of the first skull fragments (Russell, 2003). Often, it is referred to as the Piltdown man. However, scientists were puzzled and Piltdown Man was challenged as more and more evidence, such as the **Java man** and **Peking man**, suggested that hominid evolution resulted in the large brain size rather slowly which was inconsistent with the path suggested by Piltdown man (Weiner, 1980).

In 1953, more than 40 years after the big headlines first showed up, Piltdown Man was fully exposed as a forgery by means of advanced dating technologies, examination of the filing of teeth, and the artificial colouring (Weiner et al., 1953). The skull portion was identified as a modern human from the medieval age and the teeth were from a chimpanzee (Weiner, 1980).

The culprit of this forgery remains unidentified and it seems the case will go unsolved. Charles Dawson is often blamed for the hoax due to several reasons. He was originally a solicitor and he did archaeological work in his spare time. His many discoveries gave him a well-respected position in the community. He was elected a member of Geological Society in 1885 and then a fellow of the Society of Antiquaries London in 1895. He increased his fame significantly with the discovery of *E. dawsoni*, the Piltdown Man. Dawson made many discoveries previous to the Piltdown Man that were also deemed as fakes. At the very least, 33 of his discoveries were fakes, among these the teeth of *Plagiaulax dawsoni*, a hybrid of reptile and mammal (Russell, 2003). The most plausible and simplest solution to the mystery seems to be Dawson himself; he was the discoverer, he had the motive and the skills to fake it.

One of the most famous suspects accused is Sir Arthur Conan Doyle, the author of the famous Sherlock Holmes series. He was a neighbour to Dawson and lived only about 12 km from the site of discovery in Piltdown (Winslow and Meyer, 1983). In fact, he visited the site in 1912, after the initial discovery was made (Winslow and Meyer, 1983). One of the main reasons that Sir Arther is accused is due to his novels, and the seeming clues he gives in them. One of his characters, Tarp Henry, from "*The Lost World*", says, "If you are clever and you know your business you can fake a bone as easily as you can a photograph" (Doyle, 1912) Sir Arhur also had the access and perhaps the means to forge the fossils. Over the years, many theories and accusations arose and we may never know the real culprit with certainty.

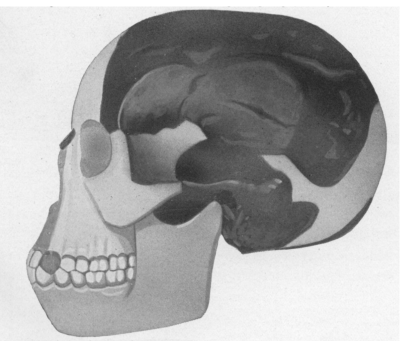


Figure 2: *Reconstruction of the skull of the Piltdown Man (left) from the pieces that were found (shown in dark). This reconstruction was published in a book, The Outline of Science, 1922. It was remarked in the book, that, "…there was a remarkable combination of ape-like and human characters."*

Tree of Human Evolution

Despite one of the greatest hoaxes in the history of scientific discoveries, genuine fossils were found constantly over the years which all contributed to the evolutionary tree of the hominids and modern humans, *Homo sapiens*. One of the very first fossils to shed some light on the descent of humans was discovered in 1891 by **Eugene Dubois**. He was deeply interested in the ideas of evolution. Born on 1858, he received a medical degree at the age of 26 and then taught anatomy at the University of Amsterdam. As his interest in evolution grew, he quit his job at the university after working less than a year. Dubois moved away to islands of Sumatra (now Indonesia) with his wife and baby daughter in search of the missing link in human evolution in 1887 (Shipman, 2002; Larsen, 2008).

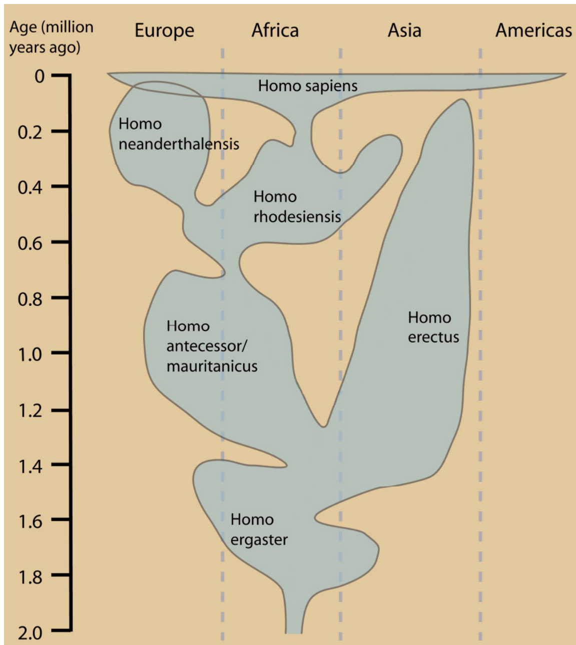


Figure 3: *One recently suggested temporal and spatial distribution of human evolution. Other interpretations disagree in the speciation and localization of the species.*

Dubois wanted to search southern Asia for the missing link due to Ernst Haeckel's argument of Asian rather than African descent of humans. This argument noted the similarities of humans to the orangutan found in Asia. While working for the Dutch military as a physician, he looked for fossils in his free time, spending his own money. After convincing the Dutch colonial government to let him search for fossils full-time, Dubois looked for fossils on the island of Sumatra with two civil engineers and 50 convicts but he did not find anything. He grew tired, sick and depressed at this point. However, Dubois refused to return to Holland empty handed, so he convinced the government to let him search on the island of Java, assuring them that he would find fossils there. After being granted permission to go there, he finally found the Java man in the pits of Trinil, the now extinct species of hominid that lived about 1.8 to 1.3 million years ago (Shipman, 2002; Larsen, 2008). Java man is classified as *Homo erectus*. Although there is still disagreement about the classification of *H. Erectus*, one hypothesis suggests that it is the direct ancestors of *H. Sapiens* whereas another hypothesis suggests that it is a separate species that branched off from our lineage (Larsen, 2008).

Subsequently, numerous discoveries were made, including fossils of *Homo habilis*, the earlier species that lived about 2.5 to 1.0 million years ago (Larsen, 2008). It was suggested that *H. habilis* is the direct ancestor of *H. erectus*, but Spoor et al. (2007) suggested that they coexisted and share a common ancestor. Using the fossil records found by numerous people, the evolutionary tree of the hominids and modern human is constructed. This is done by examining the anatomical differences between species, so there is much disagreement on the interpretation and classification of the fossil evidence.

Impact of Darwin and Dubois

To this date, there is no consensus in the scientific community about the exact line of descent for modern humans. However, we have come a very long way from the first publication by Darwin. It is now accepted by the scientific community that evolution is the main driving force that governs the biological beings. Further, ancestry of the humans is relatively well established although there is more than one hypothesis on the phylogeny and the origin. Seeing humans as a product of evolution has impacted many different fields. For example, Darwinian medicine examines the human health by considering the evolutionary forces relevant to human health (Nesse, 2001).

Furthermore, there is now some agreement in that scientific progress does not necessarily have to negate previously established religious ideas. Through the separation of scientific ideas from religious ones and metaphorical interpretations of scriptures, religion and science can arguably coexist. The church has evolved alongside science to accommodate a view that is now mainstream; just as species may coevolve, so has science and religion.

Use of DNA Evidence in the Investigation of Human Origins

Paleogenetics opens new avenues to determine the lineage of species by looking at differences at the genetic level. The number of generations between two individuals can now be estimated by looking at non-combinatory regions of DNA such as the Y-chromosome or the **mitochondrial DNA** (mtDNA; Hammer, 1995; Torroni et al., 1994). Other chromosomal DNA can be analyzed for the shared genes and to determine how they evolved over time. When polymerase chain reaction was first developed, it opened doors to the analysis of Antediluvian DNA (aDNA), and numerous papers that claimed to have sequenced genetic materials from as far back as 80 million years ago were published (Woodward et al., 1994). Further analysis of their data revealed they were human Y-chromosome (Zischler et al., 1995). However, it is now generally accepted that the maximum upper limit to which genetic material can survive in ideal conditions is around one million years (Svante et al., 2004). Therefore, paleogenetics can only shed light on relatively recent events.

Earliest Ancestor of Modern Humans

One instance in which paleogenetics has been helpful is in the investigation of the most recent common ancestor (MRCA) of humans. The time to the MRCA can be estimated by using the amount of matching portions of the genetic material, the known mutation rate at the given loci, and Bayesian statistics (Walsh, 2001). From the Y-chromosomal evidences, the Y-chromosomal Adam or the patrilineal MRCA of modern humans was traced back to about 142 000 years ago (Cruciani, 2011). From the mtDNA evidences, the Mitochondrial Eve or the matrilineal MRCA has been traced back to about 200 000 years ago (Soares et al., 2009). Therefore, the MRCA of modern humans must have lived more recently than either of the two ancestors, Adam and Eve.

Neanderthal Man

Examining nuclear DNA may have shed light on one of our cloesest relatives, *Homo neanderthalensis*. There is ambiguity in what the lineage of Neanderthals is, whether they are a separate species that share a common ancestor, or a subspecies of modern humans. The main question therefore is whether or not modern humans interbred with the Neanderthals and had viable offspring. Noonan et al. (2006) had first success in sequencing DNA from the bones of Neanderthals which suggested that they did not mate with modern humans and diverged from our species around 370 000 years ago. However, more recent genetic analysis of the Neanderthal genome shows evidence that they did interbreed with the modern humans (Green et al., 2010). There are certainly limitations to what genetic analysis can achieve due to the degradation of genetic material over time; nevertheless, it is a tool that is very helpful in investigating details of events that happened relatively recently.

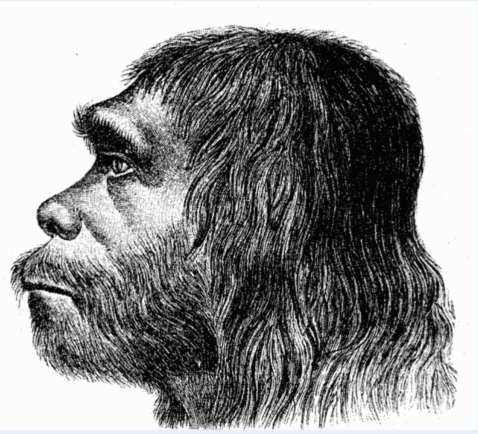


Figure 4: *The first reconstruction of the Neanderthal Man (left). New genetic evidence suggests that modern humans interbred with Neanderthals (Green et al., 2010)*

Georges Cuvier: The Emergence of Paleontology as a Scientific Discipline

The human race has accurately recorded very little of the Earth's history. In total, this history is a tumultuous occurrence composed of a series of long and complex events that span millions of years (**Figure 1**; Scott, 2008). With this in mind, how are we to construct an accurate timeline concerning the convoluted history of our planet? Although we can infer much of what has happened in the past by observing the present state of nature, we need more information in order to establish concrete details. Although incomplete, and subject to a wide range of interpretations in the past, fossils trapped in rock provide one of the most effective methods for reconstructing the history of the earth. The study of these fossils, the record they produce, and the subsequent information they provide regarding past life is called **paleontology** (Tattersall, 2010).

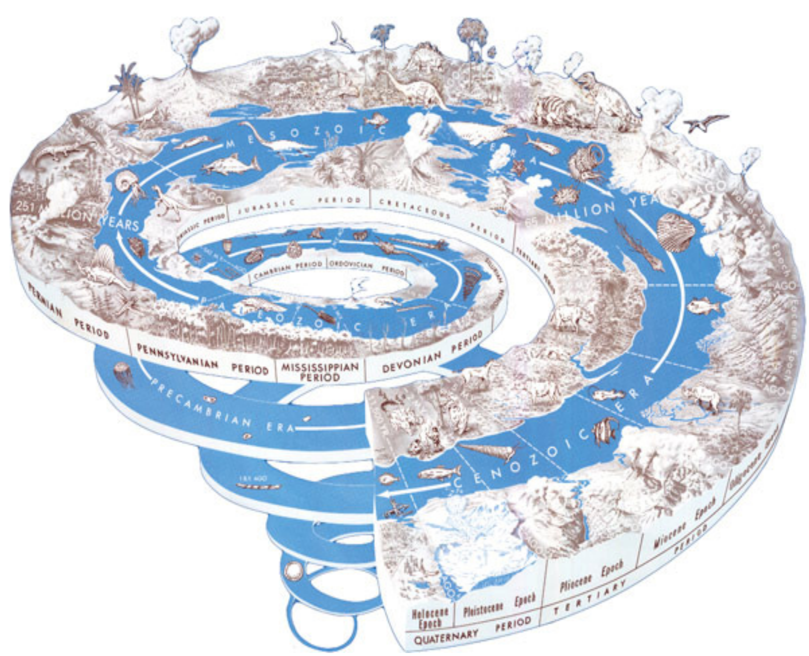


Figure 1: *The history of the Earth is vast, and spans much more than 6000-year recorded history of human civilization, the origin of homo sapiens 200,000 years ago, or even the appearance of hard-shelled organisms 543 million years ago. For this reason the fossil record is invaluable as an indicator of past environmental conditions.*

An 'Historical' Science

Paleontology is an established scientific field, however the principles of paleontology differ from those of most traditional scientific disciplines. Science generally seeks to understand the cause of natural events through the use of testable hypotheses. In doing so, an increasingly accurate depicition of nature is developed by introducing novel ideas and dismissing false ones. The result of this process is the provisional, not absolute, nature of scientific knowledge – what we think we know is always changing (Tattersall, 2010). This also means that the scope of science is limited by the hypotheses we ask and whether they can be answered through experimentation. It is here where the deliniation of paleontology from other diciplines begins, as paleontologists cannot observe prehistoric 'experiments' performed by nature. Instead, paleontologists must analyze the results of these 'experiments' preserved in the fossil record in an attempt to correctly replicate the process and conditions that originally producd them (Tattersall, 2010).

The Origins of Paleontology

The study of fossils was not always an accepted scientific discipline. In fact, the field of paleontology was not established until the 19th century. Before this time, there were many misconceptions throughout the world regarding the nature of fossils. Ancient Greek philosophers such as Aristotle (384-322 BCE) believed that living things arose from "seeds of life" (e.g rocks and mud) and that fossils were the failure of this process. During the Middle Ages (c. 500-1450 CE), fossils were regarded as works of the devil, creations made by God, or simply as a result of *vis plastica* (the moulding of rocks). The value of fossils was unrecognized even during the **Scientific Revolution** that swept Europe at the end of the **Renaissance** (c. 1400-1600) and throughout the **Age of Enlightenment** (c. 1650-1800), as it was assumed fossils were the remains of those that died during **Noah's Flood** (Rudwick, 1985; Bowler 1993).

Not until the late 18th and early 19th century were fossils widely accepted to be the remains of past life on earth. The fossil record itself, as well as its relationship to the concept of **superposition** posited by

Nicolaus Steno (1638-1686) in 1664 began to be more closely analyzed, leading to the establishment of vertebrate paleontology and fossil-based **stratigraphy**. One of the driving forces behind both of these movements was **Georges Cuvier**, the French naturalist now recognized as the father of paleontology.

The Early Life of Georges Cuvier

Georges Cuvier (**Figure 2**) was born in 1769 to a modest bourgeois family living in the town of Montbéliard. At the time, Montbéliard was a part of a French-speaking Protestant community belonging to the Duchy of Württemberg (Appel, 1987). Upon his arrival in Paris as a young scholar, the location and religious affiliation of his birthplace made him an outsider amongst his peers in two respects; he was not a Frenchman by birth (Montbéliard was eventually annexed by France in 1793 during the **French Revolution**) and the predominant culture in France at the time was Catholic. However, along with the obstacles Cuvier faced due to his origins, he had several advantages over his contemporaries.

Cuvier's family had a great respect for education because of their social class, and quickly recognized the brilliance Cuvier demonstrated as a boy. As a result, Cuvier excelled scholastically, and was accepted to the main institute for higher education in Württemberg as a teenager, the Karlsschule in Stuttgart, located in present-day Germany (Rudwick, 1997). During this time, Cuvier was educated formally in **natural history**, but was also encouraged to teach himself a great deal about1 Linnaean naturalism and basic anatomical concepts. Due to the proximity of the Karlsschule to Germany, Cuvier also quickly became fluent in German, giving him an advantage over other French scholars of the time (Appel 1987; Rudwick, 1997).

Upon graduating from the Karlsschule in 1788, Cuvier took employment as a private tutor for an aristocratic family in Normandy. This allowed Cuvier to escape the brunt of the French Revolution, which he initially supported. However, Cuvier quickly found the senseless violence and radicalism of the revolution increasingly distasteful, blaming 'unbridled ideas' as the root cause. This notion greatly shaped Cuvier's personal beliefs throughout the rest of his life, especially his fear of generalization in the sciences and his desire for overall order stability (Rudwick, 1997; Appel 1987). Normandy also allowed Cuvier to continue his studies, leading him to the realization that natural history needed to expand. As a result, Cuvier began teaching himself comparative anatomy, dissecting birds, fish, and several species of invertebrates while taking detailed measurements and anatomical sketches (Appel 1987).

At a very young age, and with little formal training, Cuvier was quickly becoming a very talented and experienced naturalist. The 'hobby' he had made of natural history was quickly becoming a vocation, and so Cuvier set his sights on obtaining an academic position in Paris (Appel, 1987).

In Pursuit of Paris

As Cuvier wanted to start a career in Paris, he began contacting the predominant naturalists of his age (Rudwick, 1997). At the same time however, a chance meeting with Henri-Alexandre Tessier (1741-1837) opened the exact opportunity he needed. Tessier, a member of the ***Académie des Sciences***, was hiding in Normandy in order to flee **the Terror**, and was recognized by Cuvier at a local meeting. The surprising talent of the young and unknown Cuvier impressed Tessier so much so that he wrote to the chair of zoology at the ***Muséum d'Histoire Naturelle***, Étienne Geoffroy Saint-Hilaire (1772-1844). Hearing of Cuvier, Geoffroy was very eager to work with him, but also politically naïve. Against the advice of many colleagues who saw Cuvier as a potential rival for Geoffroy – something that would prove to be true in later years – Cuvier was invited to become a member of the *Muséum*. Cuvier was well aware of the resistance that met him upon his arrival in Paris, and took note of the friendship Geffroy showed him (Appel, 1987).

Geoffroy quickly helped Cuvier establish himself during the months following his arrival in Paris, and once Cuvier was secure in his role at the *Muséum*, the two began working collaboratively on several projects involving the classification of mammals, two-horned rhinoceros, elephants, the natural affinities of the tarsier, and the natural history of orangutans (Appel, 1987).

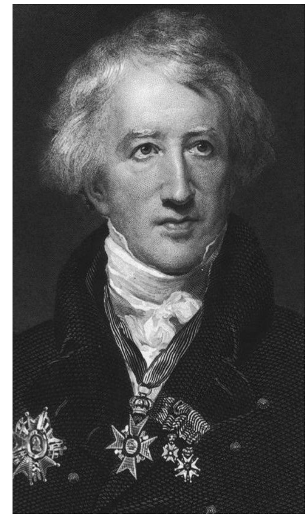


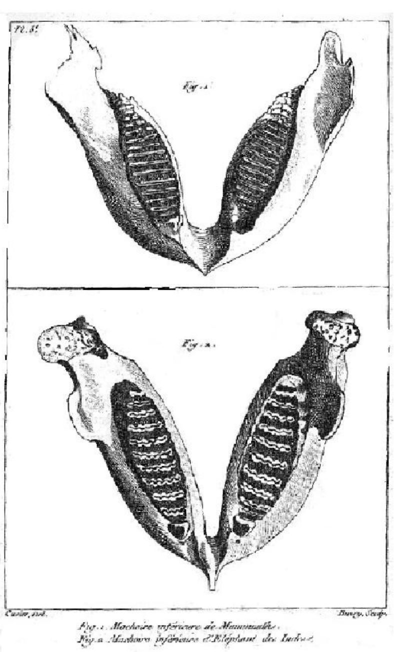
Figure 2: *Georges Cuvier (1769-1832), although largely self-taught, was a driving force in the establishment of comparative physiology and paleontology as legitimate scientific disciplines. Although an outsider in the scientific ranks of Paris, the high level of skill Cuvier demonstrated allowed him to obtain a prominent position amongst his peers very quickly. Although he is often remembered today for his anti-evolutionary attitude and theories regarding catastrophism, it would be unwise to forget the brilliance demonstrated by Cuvier in his own time.*

The Establishment of Natural History

The collaborative period between Cuvier and Geoffroy tells an interesting story, as the two would eventually become the most celebrated of rivals. Initially however, both had the same goal – to give natural history the same prestige in science as chemistry and physics (Rudwick, 1997). Natural History, compared to many of the other scientific disciplines of the time, had a poor reputation, as the science appeared to consist of no more than collecting and naming. In an attempt to give natural history a more philosophical basis, Cuvier and Geoffroy co-authored a series of five memoirs that not only provided the details of classification and description, but also dealt with the establishment of firm scientific principles (Appel, 1987).

Even at this point in time, the scientific thought of Cuvier and Geoffroy began to diverge. Throughout their memoirs, Cuvier stressed the importance of classification systems that relied on substantial principles, not just convenience like Linnaean taxonomy. Cuvier believed that organisms were functional wholes, with each individual component being essential; if there was any change in one part of the organism it would decrease functionality. As such, Cuvier thought animals should be classified into four fundamentally distinct branches based on their physiological similarities. These groups were Vertebrata, Articulata, Mollusca, and Radiata. Being distinct, these groups could not be bridged by evolution, as Cuvier saw the similarities between organisms as a result of common functions, not common ancestors. These beliefs greatly fueled Cuvier's rejection of organic evolution, and eventually lead to his great debate with Geoffroy in his later life (UCMP, 2006; Appel, 1987).

Figure 3: *Using the remains of living elephants and the fossils of Woolly Mammoths, Cuvier was able to prove that the two were different species, and that the Woolly Mammoth was now extinct. The proof for this came from the comparative analysis of both sets of bones, for example the lower jaw. An Indian elephant jaw (bottom) is shaped differently enough compared to a mammoth jaw (top) that it can be accurately said they are from different species.*



Extinction as Fact, Evolution as Fiction, and Catastrophism

One of Cuvier's most crucial and long lasting contributions to the scientific world came about in 1796, shortly after his collaborative period with Geoffroy. Although most scientists accepted fossils as the remains of dead organisms at that time, very few credited the notion that fossils were from extinct species. Instead, it was thought that fossils indicated where present day animals had lived in the past during more temperate climates (UCMP, 2006; Appel, 1987). Cuvier, using his knowledge of comparative physiology sought to clarify this issue, and in doing changed the study of fossils irrevocably. By taking the bones of present day African and Indian elephants and comparing them to fossils of European **Woolly Mammoths**, Cuvier illustrated the each was an entirely different species (**Figure 3**; Rudwick, 1997; UCMP, 2006; Bowler, 1993). Cuvier then went on to publish the results of several other studies, in which he documented a number of animals that were no longer found on Earth (e.g. the giant ground sloth, the Irish Elk, and the American Mastodon). In doing so, he definitively proved that certain species had become extinct during the course of Earth's history, and that evidence of this existed in the fossil record. This event marked the true birth of paleontology as scientists throughout the world began looking and comparing fossils much more closely (Bowler, 1993; UCMP, 2006).

The establishment of extinction as fact, although incredible, raised its own set of problems. At this point in time, **Charles Darwin** (1809-1882 CE) had not yet published the *Origin of Species*, and although some scientists believed in the transformation of one species to another, Cuvier along with many others did not. The idea of transformation did not fit with his belief of the integrated whole of an organism, as he held that by changing a single organismal component, the functionality of the whole would be impaired (UCMP, 2006). As well, while studying the fossil record in the rocks of the Paris basin with Alexandre Broongiart (1770-1847 CE), Cuvier felt he found more evidence capable of dismissing the idea of organic evolution. Cuvier and Broongiart determined that fossils where capable of precisely identifying different sequences (or strata) of rock, each representing a separate geologic time. This marked the birth of fossil stratigraphy, however, more importantly for Cuvier it confirmed his own beliefs as no transition fossils indicative of organic transformation were discovered (Bowler, 1993).

Cuvier's discoveries in the Paris basin also lead him to propose a version of catastrophism in an attempt to explain the large-scale extinctions seen in the fossil record circa 1812. Cuvier believed that a series of 'revolutions' had occurred during the Earth's history, causing mass extinctions in some areas of the world (UCMP, 2006; Bowler, 1993). Cuvier refrained from ever associating his 'revolutions' with biblical catastrophes, as it was his aim to remain distant from superstitious geology. Unfortunately for Cuvier, both his adamant opposition to the early theories of evolution, and his belief in catastrophism were wrong. Today, although he is remembered for both of these mistakes, he is also considered one of the most brilliant minds of his time, and the man responsible for shaping the study of ancient life as we know it (Smith, 1993).

Modern Paleontological Techniques: Determining the Colour of Fossilized Feathers

Although Cuvier pioneered the use of the fossil record to determine the details of past paleontological events, specific details surrounding fossilized organisms remained a mystery. As the field of paleontology progressed, the physiological comparison of fossilized remains to present day analogues allowed for the formation of realistic hypotheses regarding the shape and form of prehistoric creatures. In contrast, the finer details of prehistoric life, for example the colouring of ancient organisms, remained unknown and as such were subject to a high degree of artistic interpretation. However, with the advent of novel paleontological techniques, this trend is beginning to change (Callaway, 2008).

Researchers have recently discovered that it is possible to identify the hues of ancient remains, in particular fossilized feathers, by analyzing nanoparticles persevered in the fossil of an *Anchiornis huxleyi* specimen (**Figure 4**). These nanoparticles, previously thought to be fossilized bacteria, have since been recognised as melanosomes, a type of cell that stores pigments such as melanin (Li et al., 2010). Melanin is a highly resistant pigment produced by many animals for a variety of purposes ranging from simple display, to ultraviolet protection, and even to predator avoidance (Vinther et al., 2010). The resistant nature of melanin is in part what has allowed researchers to rely on it for determining the colour of fossilized feathers, as most other pigments degrade during the fossilization process. As melanin does not break down, the size, shape, density, and distribution of melanosomes within a fossil can be examined in order to determine the true colouring (Vinther et al., 2010).

In order to examine the properties of melanosomes on a microscopic level, **scanning electron microscopy** (SEM) is employed. SEM produces a 3D image by bouncing an electron beam off of a sample and then detecting and observing the subsequent interactions. By using this technique on both fossilized feather structures and modern birds for comparative purposes, it has been determined that narrow, long melanosomes are indicative of black and grey colouring while short, wide melanosomes are associated with red and brown hues (Vinther *et al.*, 2010).

This novel paleontological technique can provide a great deal of infromation that, until now, palaeontologists had no way of determining. Through the determination of colour in prehistoric organisms scientists can begin to observe whether prehistoric organisms exhibited sexual dimorphism and defensive behaviours in relation to their colouring, opening yet another door of study in the ever growing field of paleontology.

Figure 4: *An updated artists rendition of* A. huxleyi *using the data obtained by the comparative SEM analysis of fossilized remains and modern feathers.*

Through Space and Time: the History of Biogeography

The year was 1858 when the naturalists Alfred Russel Wallace and Charles Darwin presented their paradigm-shifting theory of evolution by natural selection to the Linnaean society (Lomolino et al., 2010). The importance of this theory is encapsulated by the noted biologist Theodosius Dobzhansky's famous quip that "nothing makes sense except in the light of evolution" (Lomolino et al., 2010). One field of study that both informed and profited from the theory of evolution was the synthetic science of biogeography. This field explores the relationship between the geographical distribution of organisms on the Earth's surface and previous geological events. While the study of biogeography was made more sophisticated in the light of evolution, it had a rich history even before the advent of the theory of evolution.

***Figure 1**: The docking site of Noah's ark was previously thought to be the point from which all animals migrated to their permanent locations.*

Noah's Ark

Prior to the 18th century, the question of how the present day distribution of species came to be was easily answered. As stated by the **book of Genesis**, all animals migrated to their current locations from the point at which Noah docked his ark (**Figure 1**; Browne, 1983). However, a challenge to this literal interpretation of the Bible soon arrived. During the 18th century, a large number of expeditions left Europe to explore distant and exotic locales. Most ships typically employed a naturalist to discover and collect samples from these remote places (Lomolino et al., 2010). The volume of these samples and specimens brought back to Europe was overwhelming. It soon became difficult to reconcile the idea of Noah's ark with the sheer abundance of the species brought back from these distant lands (Lomolino et al., 2010).

One scholar who applied himself to this problem was Carolus Linnaeus (1707-1778). A deeply religious man, Linnaeus believed that the study of the patterns of the natural world was a way to understand God (Browne, 1983). Linnaeus found it prudent to organize and catalogue the number of unknown species brought back by these explorers. The result was the creation of his famous system of classification, binomial nomenclature, which is still currently in use (Browne, 1983). In response to the problem with the literal interpretation of Noah's ark as presented in the Book of Genesis, he introduced his revised version of this story. In Linnaeus' revision, the concept of the biblical **Deluge** (or great flood) was preserved. However, instead of being placed on the ark, all species would have instead been placed on a Paradisical mountain (Browne, 1983). This mountain would be able to accommodate all these species by virtue of possessing all of the different environments required. After the flood subsided, these species would then migrate from this mountain to their permanent home where they would stay unaltered and immutable for the rest of time (Browne, 1983). This idea of a mountain as a microcosm of the world was a tangible one for Linnaeus, as he knew of the occurrence of mountains with deserts at their base but with snow at their peaks. In particular, Linnaeus suggested Mt. Ararat in Armenia to be this biblical Paradisical mountain (Briggs and Humphries, 2004). The strength in Linnaeus' revision was that it suggested a biblical interpretation that was still reconcilable with his personal experience.

A Different Point of Origin

Linnaeus' hypothesis was not without its detractors. In 1761, Georges-Louis Leclerc, Comte de Buffon (1707-1788) stated two problems with it. With his naturalism and secularism, Buffon was very much a product of the prevailing cultural movement of the time, **the Age of Enlightenment** (Lomolino et al., 2010). Firstly, he had noted that areas with very similar environments at different parts of the Earth were hosts to very dissimilar sets of organisms (Lomolino et al., 2010). This first point would later become known as Buffon's Law (Briggs and

Humphries, 2004). Second, he noted that in order for some species to reach their permanent homes, they would have to navigate through areas with environments that they were not equipped to deal with Briggs and Humphries, 2004). To circumvent these two problems, Buffon suggested an alternate point of origin from which all species were to have migrated. This point was to be in northwestern Europe (Lomolino et al., 2010). According to Buffon, this area was warm and hospitable while being inhabited by these species but later cooled allowing many species to migrate southward. As this migration occurred, the characteristics of the animals changed or "degraded" as per Buffon's terminology (Lomolino et al., 2010). At this point, the New World and Old World were both united (Briggs, 1995). However, when these two regions eventually disconnected from one another, the species further underwent "degeneration" because of this isolation (Briggs, 1995). Buffon's hypothesis was therefore extremely important for the development of the discipline of biogeography as it expressed the idea of both the Earth and its inhabitants changing (Lomolino et al., 2010).

Phytogeography

Arising from Buffon's work, there was a marked development in the biogeography of plants, or phytogeography in the late 18th and early 19th centuries. As a naturalist on Captain James Cook's ship *HMS Resolution*, Johann Forster (1729-1798), a Prussian naturalist, first determined that Buffon's Law applied not just to animals, but to plants as well (Lomolino et al., 2010). Forster also made several observations important to the development of biogeography. One such observation is that plant diversity progressively decreases when moving from the equator to the Earth's poles (Lieberman, 2000). It was observations such as this that inspired Forster's friend Alexander von Humboldt (1769-1859) to write his seminal work *Essay on the Geography of Plants* in 1805 (Lomolino et al., 2010). Influenced by the Age of Enlightenment's overarching theme of rationalism and naturalism, von Humboldt integrated geology, biogeography and ecology to great effect by producing both a detailed description and an illustration of variations in plant distribution on the surface of the Earth (Lomolino et al., 2010). Augustin de Candolle (1778-1841), a good friend of von Humboldt, who had provided him with data on plant geography in the Alps, also made important contributions to the field of phytogeography in his own right (Lomolino et al., 2010). De Candolle's work *Essai Élémentaire de Géographie Botanique* was exceedingly important because it introduced the distinction between the small scale 'stations' which were influenced by climatic factors such as temperature and light and the large scale 'habituations' which were indicative of historical patterns (de Candolle, 1820). Recognition of these scale-dependent patterns by de Candolle was very important for the future development of ideas in biogeography (Lomolino et al., 2010).

Lyell and Uniformitarianism

During this time, it was thought that all geologic structures on the Earth were caused by catastrophes such as the great Deluge described in the Bible. This theory known as **catastrophism** both informed and influenced the developing field of biogeography (Lomolino et al., 2010). However, there were some geologists who believed that geologic changes occurred gradually rather than suddenly (as endorsed by catastrophism). Because of the gradual change that characterized this theory, it was thought that the Earth had to be much older than the few thousand years it was thought to be under catastrophism (Lomolino et al., 2010). The English geologist Charles Lyell (1797-1875) popularized this theory, known as **uniformitarianism**, in his book *Principles of Geology*. This work was extremely important for the development of biogeographical thought as it placed an emphasis on the relationship between geological processes and the distributions of organisms (Lomolino et al., 2010). In addition, the theory of uniformitarianism was extremely important for the development of Darwin and Wallace's theory of evolution that in turn became an idea fundamental to the field of biogeography.

Wallace and Darwin

The contributions of Charles Darwin (1809-1882) and Alfred Russel Wallace (1823-1913) are invaluable to the field of biogeography. Born in Shrewsbury, England, the son of a well-to-do physician, Darwin (see **Figure 2a**) developed a keen interest in nature as a child (Browne, 1983). As per his father's wishes, the young Charles Darwin first studied medicine at Edinburgh University. After neglecting his studies in favour of his hobbies in the natural sciences, his father, annoyed, sent him to Cambridge University to become a clergyman (Browne, 1983). At Cambridge, Darwin honed his skills as a naturalist and after graduating with his degree in theology was itching to travel. He was soon taken on as the gentleman companion and naturalist aboard the HMS *Beagle (*Lomolino et al., 2010). Lasting from 1831-1836, and passing through distant locales including the Galapagos Islands, Madagascar and Australia, Darwin's time aboard the *Beagle* allowed him to make the observations necessary for the formulation of his theory of evolution (Lomolino et al., 2010). On his return home, Darwin did not publish his new theory until 1858 (Browne, 1983).

Wallace's childhood contrasts greatly with that of Darwin. Born in Usk, Wales, Wallace (see **Figure 2b**) grew up poor (Browne, 1983). He attended the local grammar school until the age of 14 when financial difficulties made it impossible for him to continue. Despite this, he was an avid reader, reading a wide range of material (Browne, 1983). After leaving school he worked as a surveyor and then as a schoolteacher.

It was during his time in the latter job that he starting reading books by naturalists such as von Humboldt and Darwin which instilled in him a keen interest in travel. This therefore led him to make two voyages as a ship naturalist. The first voyage lasted from 1848 to 1852 and explored places in South America while the second voyage lasted from 1854-1862 and explored locations in Indonesia and Malaysia (Lomolino et al., 2010). Like Darwin, it was his observations on the geographic distribution of species on this second expedition that led to the formulation of Wallace's theory of evolution (Lomolino et al., 2010).

In 1858, after returning to England, Wallace sent a manuscript outlining his theory of evolution to Darwin for his opinion. In doing this, he unknowingly forced Darwin to publish the manuscript he had prepared several years before (Lomolino et al., 2010). The result was that both men presented a joint paper to the Linnaean Society. The following year Darwin published his book *On the Origin of Species by Means of Natural Selection* to both great acclaim and great controversy. In the following years, the theory of evolution by natural selection would become the foundation on which biogeographical research was based. However, while Darwin did do extremely important work for biogeography, the topic did not captivate his interest to the same extent it did Wallace (Briggs and Humphries, 2004). The latter naturalist engaged himself thoroughly in the subject eventually developing many principles and concepts of biogeography still in use today (Briggs and Humphries, 2004). The work of both Wallace and Darwin therefore form the foundation of the modern field of biogeography.

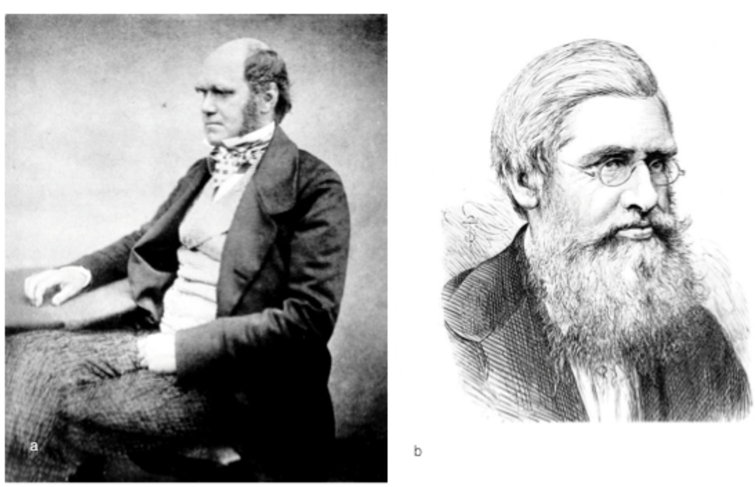


Figure 2: *Charles Darwin (left) (**a**) and Alfred Russel Wallace (right) (**b**) are celebrated naturalists who both did pioneering work in the field of biogeography.*

The Use of GIS in Modern Biogeography

Spatial mapping has been an integral part of the field of biogeography since Alexander von Humboldt published his detailed illustration showing the variations in plant distribution over the surface of the Earth in his seminal 1805 work, *Essay on the Geography of Plants* (Lomolino et al., 2010). In the 19th century, following the publication of this work, biogeographers, used climatic parameters such as temperature (typically by using lines called isotherms which connect values of equal temperatures) (Luoto and Heikkinen, 2003). Today, the availability of modern software and hardware has led to an increase in the study of biogeographical patterns worldwide through the use of geographic information system or **GIS** (Luoto and Heikkinen, 2003). GIS is a system that allows the user to store, process, analyse, interpret, and display geographical data (Millington, Valsh and Osborne, 2001). This geographical data can be displayed in a variety of different scales and across space and time (Millington, Valsh and Osborne, 2001). As the field of biogeography concerns itsgelf with the study of species distributions through space and time, it has profited from the adoption of GIS (Luoto and Heikkinen, 2003).

GIS in conservation biogeography

One sub-discipline of biogeography that has used GIS to some effect is conservation biogeography (Sanchez-Cordero, Munguia and Peterson, 2004). As biodiversity is decreasing at an alarming rate because of human-induced factors such as habitat loss, it is important to formulate predictive models that may help mitigate any future decreases.

In order to generate these predicative models, data recording the collection location information of the species being studied is first needed. This data can come from **remote-sensing** images, museum-specimen information, field-measurements, and a number of other sources (Millington, Valsh and Osborne, 2001). From this data, the **ecological niches** of the species being studied are then modelled. Ecological niche modelling can help generate more accurate and less biased data. This data is finally projected onto a distribution map (Sanchez-Cordero, Munguia and Peterson, 2004). Distribution maps can aid in the prediction of species decline and in the selection of high-priority conservation areas. These recommended high-priority conservation areas can also be contrasted with actual protected areas to see if resources are being allocated in the most effective manner (Sanchez-Cordero, Munguia and Peterson, 2004). In addition to conservation biogeography, GIS can also be used in the study of factors such as climate change or invasive species that may have a great impact on the distribution of organisms (**Figure 3**; Lomolino et al., 2010).

Figure 3: *GIS can be used in the study of invasive species such as the brown tree snake in Guam.*

Limitations of GIS in biogeography

Despite the many advantages of GIS, it also has its limitations in biogeographical research. One large issue is related to the multiple number of scales (organizational, temporal and spatial) that a data set can be studied under. As a result, the researcher may impose on the data, upon observation, a different scale than it is actually operating under (Sanchez-Cordero, Munguia and Peterson, 2004). This can lead to a poor fit between the projected and the actual distributions (Sanchez-Cordero, Munguia and Peterson, 2004). However, despite this shortcoming, GIS is a very powerful tool that has the potential to produce a great deal of insight into the distribution of organisms through both space and time.

The official seal of the United States Geological Survey (USGS). The USGS is a major scientific community in the Earth sciences. The organization has several important publications, and employs over 8000 scientists.

Chapter 4: Practicing Earth Science

Earth science, like all sciences, is ultimately a human invention – rather than rigid and infallible, it is a continuously changing and evolving construct. Indeed, the only constant in science is that of a scientific community devoted to its advancement and continuation.

In examining the Earth science community, particularly in academia, we look specifically at four of its characteristics: its origins, the driving forces behind its formation, its self-dynamics, and finally its interactions with the broader society in which it exists.

The origin of a scientific community lies in a common interest regarding a certain area of science, and the systematic documentation of discoveries in that area. This chapter explores the origins of scientific communities and the influence of individuals such as Aristotle. Aristotle recorded his ideas, and as a result other scientists were able to build on his ideas and establish a community. In Earth science, the development of a scientific community is often driven by necessity. Chapter Four uses the example of the development of measurements as a field being driven by a need for standardization. Next, this chapter examines the dynamics of scientific communities, and analyzes how preconceptions and authority within academia can profoundly impact its development through a presentation of the controversy of the Earth's age amongst the Earth science community in the Victorian era. The dynamics between a scientific organization and the society in which it exists is also examined here. The life of Vladimir Obruchev, a geologist living in revolutionary Russia is profiled and the impacts of social upheaval on the practice of science are examined. Finally, the California gold rush will be analyzed as an "anti-model", exploring why a scientific community was never established in that environment and how this impacted the fate of the gold rush.

Today, there is a vibrant and diverse Earth science community around the world. This chapter aims to give the reader some insight into the history and nature of that community in order to provide a new appreciation for advances in Earth science and the community of scientists responsible for those advances.

The History of Measurements and Measuring Devices

Throughout history, societies have relied upon accurate measurement. Whether it be accurate masses for trade, or accurate lengths for construction, the need for measurement and consequently measuring devices has been around for thousands of years. The connection between historical measurements and Earth science is that no Earth science could have taken place without these measuring devices or their modern equivalents. The very idea of mapping the locations of major landmarks and cities with respect to one another has brought about the creation of detailed maps, advanced **geographical information systems** (GIS) and **global positioning system** (GPS) technology. Standardizing units of length has allowed Earth scientists to classify various parameters such as grain size or bed thickness, which give insight to the sedimentary depositional environments. The development of balance scales and mass measurements was mainly for economic and trade purposes, but without the ability to determine absolute mass of a sample, the classifications (and more importantly the distinctions) of numerous rock types or minerals would not be possible. This chapter will discuss the earliest developments in measurement systems and their first applications in science. While they may not be directly related to Earth science it is important to keep in mind that the development of these concepts and technologies was a crucial step in the development of all the scientific disciplines.

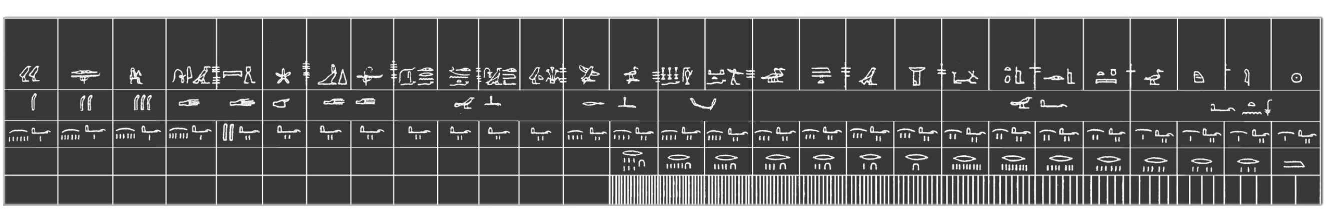
Length Measurements

Length measurements in early civilization had always relied on various body parts to be used as the measuring device. This variability in length due to the variation of body part sizes among the population posed a problem for which there is only one solution: standardization. The earliest recorded standard unit of length is the Egyptian cubit seen below (**Figure 1**). The standard cubit was divided into six palms, and one palm was further divided into four fingers. There was also a royal **cubit**, which measured seven palms. The standard and royal cubit measure roughly 46 cm and 52cm respectively. This standard unit has been preserved in the form of cubit rods accompanying the tombs several important figures such as Maya, the treasurer of **Pharaoh Tutankhamun** (Clagett, 1999). These cubit rods were used in the construction of the pyramids where accurate length measurements were a necessity (Clagett, 1999).

The Greeks developed their own standard units of length and accompanying standard rods for their own measurement purposes. Their smallest length was the daktylos, or finger, which measures 1.9 cm. The next unit of length was the pous, or foot, which measures 30.4 cm. They also had definitions of longer distances called the stadion which was defined as 600 podes (the plural of pous) and finally the milion which was equal to six stades (the plural of stadion). This system of measures was also based on the human body, from pace lengths to finger widths. The scientific community would not have any more precise definitions until the advent of the metric system (Smith and Anthon, 1851).

It is important to note that while the definitions of the units themselves are based on inaccurate measures, standardizing rods were made throughout history and used to ensure that one foot represented roughly the same length to carpenters or architects with different sized feet or hands.

__Figure 1:__ This royal cubit rod, which is seven palms in length, can be found at the Egyptian Museum in Turin.



Numerous units of length have been added to the list of length measurements throughout history. The yard is thought to have originated from the Anglo-saxon "gyrd" which was the length of a sash worn about the waist. It was later formally defined by King Henry I as the distance from the tip of his nose, to his outstretched thumb. The furlong is the distance a team of oxen can plow without resting (later formally defined as 40 rods, or 220 yards). This definition came about from the change in agriculture practices because of the heavier plow. Because this heavy plow was difficult to turn, it became common to plow single long furrows rather than numerous short furrows. When allotting land, surveyors would use acres, which were defined as a furlong long and a chain wide. The chain was formally defined by Edmund Garter as a crude but accurate surveying tool. One chain is equal to 66 ft or roughly 20.11 m; it was also subdivided into 100 links, yet another unit of length.

During the French revolution, a new standard of units was developed based not on variable body parts, but on physical properties of the Earth. From these definitions of a standard unit of mass length and time, all other units could be defined. The original definition of the metre was one ten millionth of the distance along the meridian passing through Paris from the equator to the North Pole. This new definition allowed for an international standard which every country except the United States, Liberia, and Myanmar has adopted as their official standard of measures. It should be noted however that the US military, medicine, and scientific community do use the SI units.

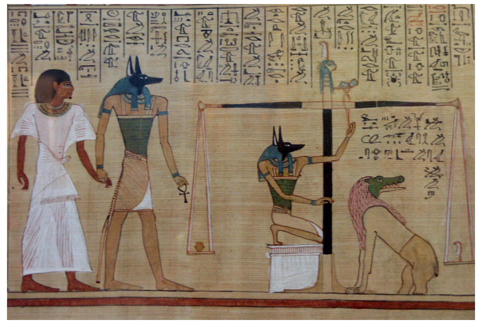


Figure 2: *A page from the book of the dead of Hunefer. The Egyptian god Anubis leads Hunefer to the judgement area. Here Anubis is also shown weighting Hunefer's heart. This is clear evidence that Egyptians used the balance scale (Lenka Peacock, 2007).*

Mass Measurements

The motivation for early mass measurement is obvious: trade and commerce. Merchants needed to ensure that a specific unit of mass was consistent in order for trade to be fair. The earliest evidence of standardization is the weights (**Figure 3**) excavated in the Indus Valley region, which is around modern day Pakistan. Close to one hundred weights were found, each was an integer multiple or fraction of a common unit, which is 13.63 grams (Petruso, 1981). The accuracy with which these stones were carved and the fact that this standard unit is observed in weights spanning a period of five hundred years and covering a massive geographical area indicates that the Harappan (inhabitants of the Indus Valley) culture had a strong basis in trade and commerce (Petruso, 1981). The high accuracy of the calibration of these weights is only capable through the use of balanced scales. Another facet of this culture gleaned from the discovery of the weights is the knowledge of decimal and binary base systems. The weights were each factors of two and factors of ten times larger and smaller. Such early evidence for base ten and binary numerical systems is astounding (Petruso, 1981).

Egyptian masses of similar (but not the same) weight were also found, as were depictions of the use of a balance scale in the famous Book of the Dead (**Figure 2**) which was found buried with the deceased in many tombs (Taylor, 2010). The Egyptians also used much larger balance scales in order to distribute shipments of grain rather than just the small scale use for spices or metals seen in the Indus Valley (Petruso, 1981).

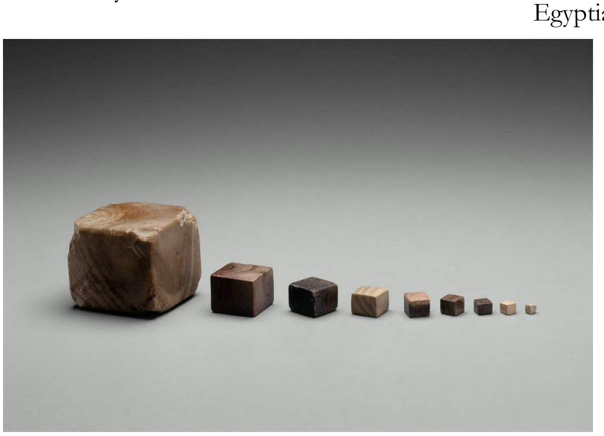


Figure 3: *This set of weights excavated from ruins of the Indus Valley Civilization (modern day Pakistan). These weights have been dated between 2600 and 1900 BCE, the mature era of the Harappan culture. (Museum of Fine Arts, 2010)*

Angular Measurements

The development of Greek mathematics was the origin of truly accurate and well catalogued astronomical observations, however there were highly accurate measurements made prior to Greek Civilization. Prior to the invention of the telescope, the maximum angular resolution of naked-eye observations is on the order of magnitude of a **minute of arc** (Rawlins, 1985). The Egyptians were well aware of angles, and indicated angle by fraction of a circle. For example 20° has the Egyptian equivalent in their notation of H/9 or one ninth of a half circle. It is believed that the concept of spherical Earth was known based on the following observations (Rawlins, 1985). It is well known that the Pyramids of Giza are oriented to the cardinal points to within the order of magnitude of a single minute of arc (Rossi, 2003). It was also speculated that the Pyramid of Giza's proximity to the 30°N latitude line was intentional. The Egyptians likely achieved this through observation of the polestar's maximum and minimum angles of elevation during the summer and winter solstices. The average of the two angles gives the observer's latitude, which they strove to locate at an angle of H/6. However, the pyramids are too far from the true 30°N latitude, even for naked-eye measurements. In Rawlins' discussion on early observational error he attributes the error to diffraction of light through the atmosphere. His calculations of the error yield almost exactly the location of the Pyramids (1985). He also lists the temple in Amarna, the temple of Karnak in Thebes, and the temple on Biga Island at latitudes corresponding to a circle divided into 13, 14, and 15 parts respectively after compensating for diffraction error. These highly influential locations could have been placed so close to such round angles due to chance, but more likely the astronomers of Ancient Egypt were well aware of the Earth's spherical shape (Rawlins, 1985).

We now move into Ancient Greek civilization, where the first laws of angles were formalized by Pythagoras. The Greeks' most common belief was in a spherical Earth. It was in this era that the first large scale astronomical and geographical observations were made. Eratosthenes (**Figure 4**) made a famous calculation of the circumference of the Earth using simple trigonometry and a few observations. First he noticed that the sun was directly overhead the city of **Syene** at noon on the summer solstice. He then observed the ratio of shadow length to **gnomon** height at noon on the solstice in **Alexandria**. From that ratio he cleverly calculated the angle of the sun to be approximately 1/50th of a circle. He then paced out the distance from Syene to Alexandria and found it to be roughly 5 000 stades and so estimated the circumference of the Earth to be 250 000 stades, a very close approximation considering the technology available at the time (Goldstein, 1984).

Figure 4: *Portrait of Eratosthenes. He coined the term geography and was the inventor of the discipline. He was also the first to invent a system of latitude and longitude.*

Another incredible scientific effort in the field of large scale angular measurements was the massive compilation of geographical and astronomical data in Ptolemy's Almagest and his Geographical Directory. In these tomes there were contained latitude and longitude coordinates as well as other significant observations such as gnomon shadow ratio at noon on summer solstice, for numerous cities and landmarks. The purpose of these texts was for the practice of astrology; however it is the only surviving volume of such completeness. There are glaring errors in Ptolemy's works; however Rawlins showed that these errors were due to poor math rather than imprecise measurement (1985). His main mistake was conversion from latitude to length of the longest day (a significant measurement at the time) and then back to latitude. Rawlin's calculations show conclusively that Ancient Greek astronomers calculated angles very precisely using the astrolabe (**Figure 5**) and other tools available at the time.

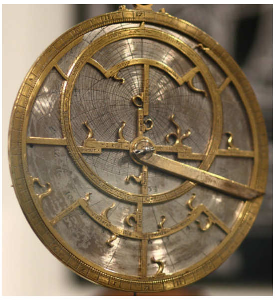


Figure 5: *Astrolabe of Jean Fusoris circa 1400 AD on display at the Harvard Science Center. This tool was used to calculate* ***angle of elevation*** *and predict positions of the sun, moon, and starts. It was also an accurate timepiece.*

Time Measurements

The oldest time measuring device is the sundial, a tall thin object is placed in the center of the dial and the shadow cast by this object traces a line on the face of the dial indicating time of day. Of course this measurement is not always practical because it may be cloudy and it is unusable during the night. On top of these limitations its accuracy is on the order of a few minutes. An ingenious solution to this problem was the invention of the water clock; a large container which has a restricted flow of water, bearing marks indicating the time passed at the current water level on its sides. Water clocks of Ancient Egyptian origin have variable hour lengths based on the month of the year. The Egyptian hour is defined as one twelfth of the time from sunrise to sunset during the day and one twelfth the time from sunset to sunrise at night. Because the length of the day is variable over the seasons (shorter in winter, longer in summer) the clock's definition of one hour varies as well. The earliest description of the water clock was in the tomb of the court official Amenemhet who described himself as the inventor (Donadoni, 1990). The water clock and later the hour-glass were refined over the years, but accuracy of one second was not achieved until the late 17th century with the invention of the **second pendulum** clock.

The Definitions of the SI Units

The Second

The second was originally defined as one sixtieth of a minute, which was defined as one sixtieth of an hour, which was defined as one twenty-fourth of one day, which is the time it takes the Earth to complete one full revolution. However, early 20th century astronomical observations revealed that the mean day length was increasing, leading to the requirements of a standardized unit of time that remains fixed. The invention of the atomic clock solved this problem and the modern day definition of one second is 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium atom. This definition is directly taken from the International Bureau of Weights and Measures which is the governing body of the SI units.

The Metre

The modern metre remained as one ten millionth the distance between the equator and the North Pole measured along the meridian passing through Paris for some time; unfortunately the original standard bar was slightly larger than the true definition of a metre at the time because there was a miscalculation concerning the flattening of the Earth. The metre was then redefined in 1889 as the distance between two marks on a metal alloy bar composed of 90% platinum and 10% iridium measured at the melting point of ice. This standard bar was replicated and sent to the countries participating in the conversion to SI units. The metre remained defined this way until 1960 when it was defined as 1 650 763.73 wavelengths of the orange-red emission line of the krypton-86 atom in a vacuum (Marion and Hornyak, 1982). Once the atomic clock had been invented, it was proposed that the metre be redefined yet again against a time standard, because time could be measured much more accurately than length. The latest, and present, definition of one metre is the length traveled by a photon in a vacuum in the time interval of 1/299 792 458th of a second.

The Kilogram

The first definition of the kilogram was the mass of water at maximum density occupying a cube of side length one tenth of a meter. This definition was replaced in 1889 by the mass of the International Prototype Kilogram (IPK). The IPK is a perfect cylinder composed of 90% platinum and 10% iridium measuring 39.17 mm in height and diameter. This definition still stands and the six sister IPKs can be found in IBWM. This standard is currently used to measure against the international copies distributed to the nations using the SI system.

Lord Kelvin and the Age of the Earth Controversy

The theory of **uniformitarianism** did not gain significant support from the scientific community until it was popularized by Sir **Charles Lyell** (1797-1875) in his *Principles of Geology* (1830-1833). By 1850, it had become an accepted theory of geology in England and extinguished much of the support for the opposing theory of **catastrophism**. An interesting contrast is that while catastrophism relied on largely unlimited banks of force to account for the formation of the Earth over a short, Biblical time span, uniformitarianism relied on an indefinitely large, and potentially infinite amount of time and weak, non-cataclysmic forces. **Charles Darwin** (1809-1882) was greatly influenced by Lyell, hence his theory of evolution also relied on the vastness of time to account for the processes of natural selection (Wyse Jackson, 2006).

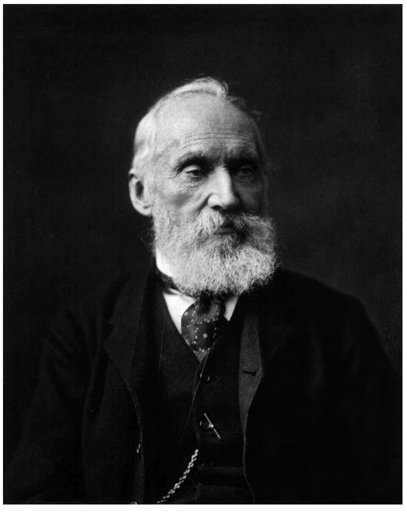


***Figure 1**: William Thompson (1824-1907), known more commonly by his later title of Lord Kelvin, was a Victorian era mathematical engineer who posited an age for the Earth in the 1860s.*

Thus when internationally acclaimed mathematical physicist Lord Kelvin (1824-1907) announced that his calculations showed the Earth to be at most 100 million years old (**Figure 1**), the claim was not without backlash throughout the **Victorian** science scene.

The events following Lord Kelvin's announcement serve as a case study of Victorian era interaction between scientific disciplines and also demonstrate how preconceptions - be they religious, scientific, or constructs of authority - can provoke research and steer scientific thought (Burchfield, 1975).

The Authority of Lord Kelvin

Geology in the Victorian era was a quintessential example of a popular science, attracting amateurs and the attention of scientists from other fields. William Thompson - referred to by his later title of Lord Kelvin for consistency in this piece - was one such amateur, shifting his focus to geochronology following a period of extensive work in **thermodynamics** (Burchfield, 1975).

While historians of science generally perceive Kelvin as a secondary figure in the Victorian scientific landscape, one who had spread himself too thin and failed to accomplish an insightful synthesis, his contemporaries ranked him alongside Newton and proclaimed him as the most prominent physicist of the generation. These differing views on Lord Kelvin's contributions reflect a change in the societal value placed on scientific methodology. Additionally, Lord Kelvin was a man of great authority and wealth. Consequently, this authority secured an attentive audience for his calculations of the Earth's age and demanded his opinion be seriously considered in any attempt at geochronology (Burchfield, 1975).

Modeling the Cooling Earth

According to Kelvin, the uniformitarian premise of an infinitely old Earth moulded by unchanging geological forces was in direct violation of the second law of thermodynamics, as it entailed the existence of a perpetual motion machine. His paper *On the Secular Cooling of Earth* was an attack on the premise of infinite Earth age and an attempt to correct what he perceived as a terrible oversight in geology, the denial of physical laws (Kelvin, 1891-1894).

In his model Kelvin posited that an initial molten state of the Earth was feasible as an extension of the **nebular hypothesis** developed by **Kant** and **Laplace** some years earlier, and assumed the Earth had become solid throughout relatively early in its history. He then used the well-known Fourier differential equation for thermal **conduction** through a solid, using measured constants for rock conductivity and a thermal gradient value of 1^{o}F per 50 feet (as this gradient was known to vary, he considered the value to be a fair mean). He arrived at a time value of 98 million years from the initial cooling of the Earth to the development of the modern-day gradient; allowing for errors in constants, he settled for 100-400 million years for the age of the Earth. In a separate calculation, he also arrived at 500 million years for the age of the Sun assuming **gravitational**

contraction as its only source of energy (Kelvin, 1891-1894; Tung, 2007).

As the temperature gradient of the Earth had varied with time Kelvin also asserted that in the past, weather and erosion had been more violent. The whole of the argument was a direct assault on the steady-state Earth theory as proposed by uniformitarianism and it also imposed a temporal limit for both geologic processes and evolution by natural selection (Wyse Jackson, 2006; Tung, 2007).

It is perhaps worth noting that Kelvin's published piece was remarkably congenial with Victorian scientific thought and physics. The nebular hypothesis was widely accepted as a valid **cosmogonal** theory and the teleological arguments within the piece fit contemporary thought and strengthened his argument. The piece carried an aura of precision, strengthened by Lord Kelvin's acclaimed mathematical prowess (Burchfield, 1975).

It is also important to note that the mathematics used were outside the scope of the majority of contemporary geologists and biologists. Nevertheless, even contemporary physicists, who could follow the paper, accepted his conclusions and thereby added to the argument's influence (Burchfield, 1975).

Evolutionist Compromise

It is suspected that the timing of Kelvin's renewed interest in geochronology closely tied in to the 1859 publication of Darwin's *Origin of Species*. While Kelvin took no issue with the concept of evolution, he did not accept natural selection on the basis that it left no room for order and intelligent design within creation - elements which he felt made the cause-effect laws of nature possible. Additionally, Kelvin felt that the finite age of the Earth was in itself a testament of design in nature as it left less time for evolution to take place (Thompson, 1910; Burchfield, 1975).

Darwin certainly felt the pressure of Kelvin's time limit and his inability to cope with Kelvin's mathematics forced him into an awkward retreat. The fifth edition of *Origin* was marked with Darwin's discomfort as he tried to speed up the rate of the process of evolution and compromise with Kelvin's results. Unconvinced of the validity of the calculations and unsure of how natural selection could handle the reduced age of the Sun and Earth, he suggested the violent environment of the Earth's past as proposed by Kelvin may have sped up evolutionary processes. Although neither he nor his supporters could supply an adequate rebuttal, Darwin made a last attempt in *Origins* to stand his ground by calling into question the abilities of science to estimate the planet's age (Burchfield, 1975).

Following Kelvin's 1868 address "On Geologic Time" before the Geologic Society of Glasgow, (spurred by Lyell's refusal to change his theory's demands for time), it was especially appropriate that **Thomas H. Huxley**, English biologist and president of the Geological Society of London, respond. Huxley was known to be a formidable public speaker and powerful figure in the Victorian science sphere; his relentless defense of natural selection (culminating with the famous Wilberforce debate nine years earlier) had earned him the nickname "Darwin's bulldog" and it was time again to defend another theory under siege (Powell, 2001). Only the result this time would be quite different. Huxley's 1869 rebuttal displayed his characteristic elegance, but failed to grasp and fully counter Kelvin's age of the Earth calculation. Although in retrospect Huxley's strongest argument was in questioning the validity of Kelvin's assumptions (knowing well that countering his mathematics was hopeless), his contemporaries failed to capitalize on it. He did however argue for the deflection of onus from the evolutionists who could postulate a faster rate of evolution, and stated that biological time is a subset of geological time. He also championed for a new and improved uniformitarianism in which processes both like and unlike the present ones could be accounted for (Thompson, 1910).

Although Kelvin responded to this rebuttal, he likely failed to realize that Huxley's argument was built on compromise, and was little more than an organized retreat (Burchfield, 1975).

Impact on Geology

Only the most astute reviewers of Kelvin's newly published piece observed that the laws of thermodynamics have added an element of directionalism into geological history, as had Darwin's evolutionary theory years before. Both theories required flux in the Earth's surface that the steady-state Earth hypothesis would not allow, and thus uniformitarian theory sank under the weight of evidence from the two disciplines. Geologists had failed to understand the consequences of the thermodynamic laws, opening themselves for Kelvin's intrusion and attack on Lyell, a man whose reputation in geology was equal to Kelvin's own in physics (Burchfield, 1975).

Lyell's proposed explanation for steady-state geology had originally been attributed to the existence of an electrochemical cycle inside the Earth's core, one that would perfectly conserve energy and drive geologic processes at a steady rate. Unable to refute Kelvin's physics, Lyell's 1866-68 and later editions of *Principles of Geology* showed desperation as Lyell himself identified his cyclic energy system as a perpetual motion machine, finally proposing that the mechanism allowing for the steady-state is divine intervention (Burchfield, 1975; Lyell, 1970).

Up until the 1860s, most attempts at geologic dating had used relative dating methods and there was little research into absolute geochronology. Geologists were initially interested in Kelvin's views on the interior structure of the earth more so than his dating attempt. However, although the initial response was slow, by the time of the Huxley debate geology was already in a state of flux (Powell, 2001; Burchfield, 1975).

The two most notable trends in geology became the 19th century zeal for quantification and the suppression of Earth age estimates unlike Kelvin's. While geology prior to Kelvin had more or less relied on qualitative descriptions of processes and structures, the 19th century served to fulfill the geologists' desire to shape geology into a quantitative and serious natural science. To this end, the Victorian age was met with an explosion of new and interdisciplinary techniques of measurement and analysis (Burchfield, 1975).

Secondly, Kelvin's results became a benchmark for scientists to verify their own absolute age calculations against. Kelvin's authority further entrenched his final numerical results to the extent that his underlying assumptions were largely forgotten. Consequently, an entire generation of geologists would grow up and come to terms with his restrictions. As geologists based their calculations on the results of Kelvin or by proxy, on the results of other geologists who cited him, a body of evidence supporting the 100 million year Earth grew without critique despite conflicting assumptions between scientists and the often questionable mathematics employed. An example of the latter can be found in the 1878 paper of geologist Samuel Haughton (1821-1897), who in his calculation of the age of the Earth used an unjustified number of significant figures and dropped his final result by an entire order of magnitude from 1.35 billion to 135 million. His mathematical background makes this an unlikely accident, and both the data manipulation and its disregard by his peers are typical of this period in history (Burchfield, 1975).

Later Years

In later years Kelvin would regularly return and amend his calculations, further restricting his estimate of earthly time. His statements became increasingly dogmatic and his final claim in 1897 predicted the age as 20-40 million years (Burchfield, 1975).

Geologists yielded at first, but the new estimates caused increasing discomfort. Geologist Archibald Geikie (1835-1924) acknowledged the debt geology held to Lord Kelvin for overthrowing the steady-state theory of the Earth, but both he and biologist Sir Edward Poulton publicly expressed denial of the new figures and disapproval of the physicist's high-handedness. They argued that while both the biologists and geologists made concessions and modified their theories to the compressed temporal scale proposed by Kelvin, physicists continued to disregard the mass of geological and biological evidence supporting an older age of the Earth (Burchfield, 1975; England, Molnar & Richter 2007). Kelvin's grip on Victorian geology was slipping, ironically because the decades of measurement he had inspired had led to the growth of the field into a quantitative and confident science.

The discovery of radioactivity by Becquerel in 1896 would come to overthrow Kelvin's theory, as the constant release of heat by radioactive salts had not been accounted for in his model (neither was the molten inner Earth, the modern understanding as to why his results were flawed; England et al., 2007; Lewis & Knell, 2001).

Historians of science agree that Lord Kelvin's work made a great impact in reforming geological thought, but disagree in their overall assessments. Some argue Kelvin stimulated an exchange of ideas between physics and geology, which was to the benefit of both disciplines and resulted in an era of new interdisciplinary and quantitative geologic methods. Others point out that Kelvin's overly harsh critique of the uniformitarian demands for time discredited Lyell and pushed geologists too hard into misleading speculations (Burchfield, 1975).

Radiometric Dating of Meteorites

Lord Kelvin's impact on geology persisted into the first two decades of the 20th century and slowed the acceptance of **radiometric dating** (see pg. 61), which posited absolute age values for samples which were far greater than Kelvin's entrenched value of 100 million years. The unwillingness to abandon a productive theory because of new physics was reminiscent of the Victorian era controversy, but the validity of the radiometric dating technique became widely apparent due to growing evidence of its precision (Burchfield, 1975).

Figure 2: The Canyon Diablo iron meteorite was used by Clair C. Patterson (1922-1995) to determine the first of the modern age estimates for the Earth.

Modern research now estimates the age of the Earth to be 4.54 Ga with an error margin of 1%. This is not the measured age of any terrestrial rock, as there are no known Earth samples from the time of initial crust formation that have been preserved from metamorphism, weathering, and other mechanisms that disrupt the closed isotope system necessary for accurate radiometric dating. The oldest Earth rocks found range from only 3.5 to 3.96 Ga old; evidence supporting a greater age for the Earth comes from meteorite dating (Geyh and Schleicher, 1990; Dalrymple, 1991).

The validity of this method stems from an understanding of lead isotope system evolution in the Earth, as described by the **Holmes-Houtermans model**. Extensive evidence suggests that meteorites and the Earth can be treated as stemming from a common U-Pb reservoir, likely because the solid bodies of the Solar system formed at around the same time. The uranium-lead composition of a primordial, uncompromised lead source is analyzed and the length of time necessary for its composition to change into that of a younger sample is calculated. The addition of the younger sample's absolute age to the result yields an age for the Earth. Graphically, this produces an **isochron** for which samples from the same lead source system will fall on its line (Dalrymple, 1991).

Clair C. Patterson (1922-1995) was the first scientist to successfully use this method in 1953 to date the Canyon Diablo iron meteorite (**Figure 2**) and calculate ages of 4.51 and 4.55 Ga using two different 'young' compositions respectively: recent oceanic sediment and a manganese nodule. The presently accepted value of 4.54±1% Ga stems from the results of Fouad Tera, who used the congruency point of four ancient lead ores to determine the age that best represents that of the source, with a lower degree of error (Lewis & Knell 2001).

Future research in meteorite dating will likely involve the search for additional ancient lead reservoirs that could reduce the uncertainty of the calculation (Dalrymple, 1991).

Aristotle: The History of Meteorology

Changes in weather and atmospheric conditions have been of interest to humans since their origin. In the past, natural climate change has resulted in droughts, floods, and famine, severely impacting the ability of humans to survive and prosper. As a result, there is great value in understanding atmospheric processes and using this information to forecast and prepare for future weather conditions. It is known that several Greek philosophers, such as Plato and Hippocrates thought about and documented some of their theories concerning weather (Taub, 2003). However, it was not until approximately 340 BCE, when Aristotle wrote his treatise Meteorologica that the science of meteorology was established (Milham, 1918).

The Life of Aristotle

Aristotle was born in 384 BCE in northern Greece (Waggoner, 1996). At the age of 17, he relocated to Athens in order to study philosophy in Plato's Academy (Figure 1). Aristotle studied under Plato for a number of years, but did not always agree with his philosophies (Shields, 2008). Following Plato's death in 346 BCE, he travelled to Assos in Asia Minor (present-day Turkey) and other nearby islands. Here he continued developing his own philosophies for a number of years (Waggoner , 1996). In 335 BCE, Aristotle returned to Athens and established a school, which he named the Lyceum (after the god Apollo Lykeios) (Shields, 2008). While at the Lyceum, Aristotle and his students discussed and wrote about a variety of topics including mathematics, astronomy, biology, politics and ethics (Waggoner, 1996). He used his treatises to teach his more advanced students about his philosophies, and is believed to have written over 150 of these works. Unfortunately, only 30 of Aristotle's treatises survive to this day, and it has been difficult to

Figure 1: *Raphael's interpretation of Plato (left) and Aristotle (right) at Plato's Academy (1509).*

determine whether all of the works were written by Aristotle himself, or by students at the Lyceum (Shields, 2008).

Aristotle's Meteorologica

One of the 30 surviving treatises is Aristotle's *Meteorologica*, which was the first known treatise devoted to the subject of meteorology (Shaw, 1919). It is for this reason that Aristotle is often cited as the father of meteorology, as he described it and established it as a separate science (Buchan, 1867). However, Aristotle's interpretation of the science encompassed many more topics than what is now considered to be meteorology. For instance, the stars, comets, the Milky Way and the composition of matter were all discussed within the four parts of *Meteorologica* (Milham, 1918).

The first part of Meteorologica briefly discussed the four elements, along with different celestial bodies, comets, clouds, dew, frost, hail and the formation of rivers (Shaw, 1919). Aristotle described dew and frost as appearing when vapour cools and descends to the earth. He hypothesized that "when the vapour is frozen before it has condensed to water again it is hoar-frost; and this appears in winter and is commoner in cold places. It is dew when the vapour has condensed into water and the heat is not so great as to dry up the moisture that has been raised nor the cold sufficient (owing to the warmth of the climate or season) for the vapour itself to freeze" (Aristotle, 340 BCE). The second part of Aristotle's Meteorologica discussed earthquakes, rain, variations in weather, the North and South Poles, in addition to winds. For example, Aristotle classified and named different winds, all travelling in different directions (Figure 2). The third part of Meteorologica concerned thunder, lightning and rainbows, while the fourth part elaborated more on the four elements. In this fourth section, Aristotle described these elements as being moist, dry, hot or cold, and either moving away from the centre of the universe or towards it

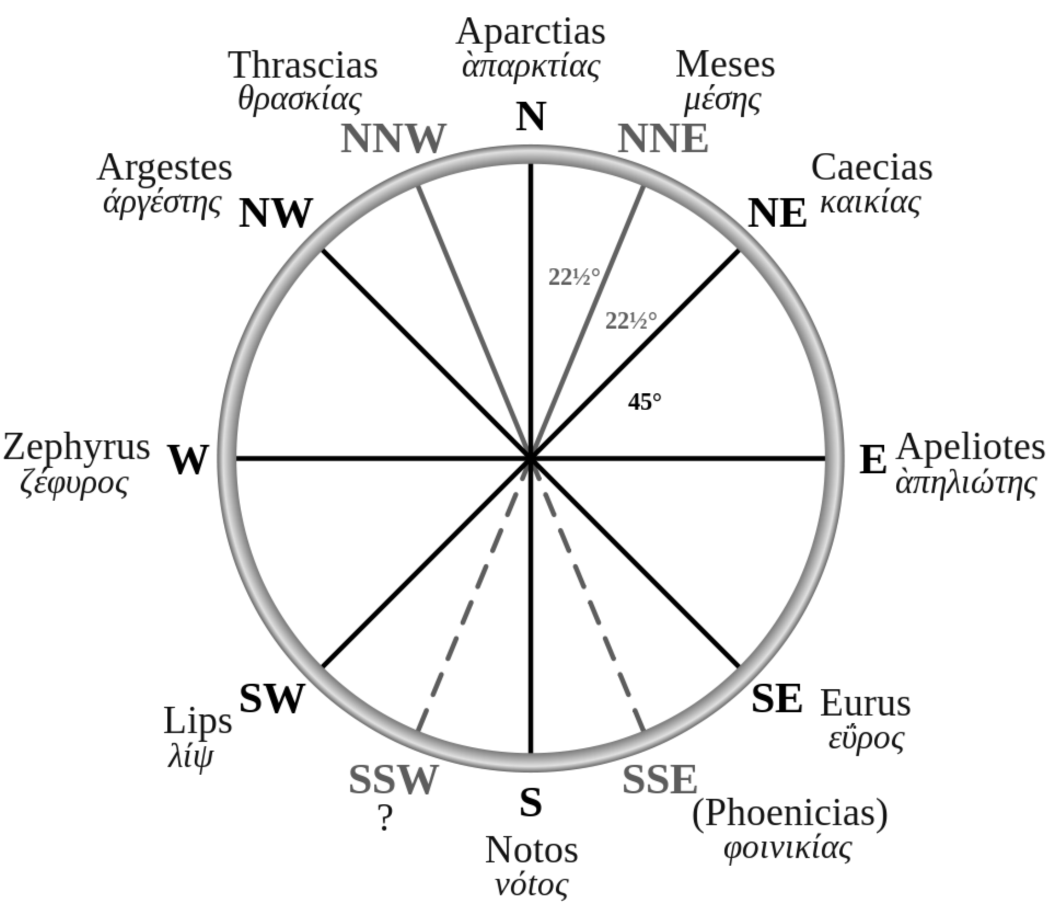


Figure 2: *The directions and names of the different winds classified by Aristotle.*

(Taub, 2003). He believed that all substances were made up of the four elements, including the atmosphere, which was composed of dry air and water (Shaw, 1919). He also hypothesized that these elements made up two exhalations, one of which was dry, hot, and smoky, while the other was a moist vapour (Martin, 2006). According to Aristotle, these two exhalations and the elements were the cause of all the phenomena discussed in the four parts of his work (Shaw, 1919).

Challenges Facing Aristotle

Although some of the theories put forth by Aristotle were not correct, other ideas in *Meteorologica* were quite accurate and profound. For example, his early description of the water cycle sounds quite modern. Aristotle said that "The same parts of the earth are not always moist or dry, but they change according as rivers come into existence and dry up. And so the relation of land to sea changes too and a place does not always remain land or sea throughout all time, but where there was dry land there comes to be sea, and where there is now sea, there one day comes to be dry land. But we must suppose these changes to follow some order and cycle" (Aristotle, 340 BCE).

Aristotle himself (**Figure 3**) recognized that much more work needed to be done in the field of meteorology in order to explain all of the phenomena he observed. He admitted that while some of the topics discussed seemed relatively simple to understand, others were puzzling, complex and challenging to explain (Taub, 2003). In *Meteorologica,* Aristotle often discussed his theories about how certain phenomena occurred, but was not always able to explain the 'final cause' of said phenomena. He hypothesized that rain occurred due to the sun, with water evaporating and condensing, but refrained from trying to determine the overall purpose, or final cause of rain (Taub, 2003). This did not mean that he did not think that these processes had an ultimate cause. Rather, it has been suggested that he believed the purpose of these meteorological phenomena could only be understood by studying and relating them to the other natural sciences (Taub, 2003). Other philosophers who would eventually write about meteorology, such as Lucretius also noted that they found it difficult to explain the causes or purpose of certain processes, and instead provided multiple possible explanations (Martin, 2006). A potential reason for these difficulties is the fact that at the time *Meteorologica* was written, Aristotle could only rely on information gathered from historians, poets, his peers and his own observations (Shaw, 1919). Aristotle used reason and logic to develop his theories, as he did not have access to tools or instruments that could accurately measure any meteorological processes.

Despite some limitations, Aristotle's treatise played a significant role in the development of meteorology as he attempted to explain the occurrences of meteorological phenomena in a way that had not been done before. Some even claim that following *Meteorologica*, no significant progress was made in the study of meteorology for thousands of years. For instance, Gustav Hellmann, a noted meteorologist and historian of meteorology said that "the

Figure 3: *Lysippus' sculpture of Aristotle (330 BCE).*

system established by Aristotle remained for nearly 2000 years the standard text-book of our science…All text-books of meteorology issued on the continent till the end of the seventeenth century are exclusively based on Aristotle" (1908). When meteorological instruments, such as the **thermometer** and **barometer** were invented, a greater interest in meteorology emerged. With accurate ways of measuring atmospheric conditions, significant strides were made in the science until it became the modern form of meteorology that is studied today

Modern Techniques in Meteorology

Due to great advances in the science of meteorology, weather forecasting has become more accurate, and checking the local forecast is a part of daily life for a significant portion of the population. The prediction of future atmospheric conditions is not only useful on a day-to-day basis, but is also important in agriculture and for alerting the public of severe weather conditions, such as high winds, floods, and tornado warnings. Today, future weather conditions can be predicted in a variety of ways.

The simplest form of weather forecasting is the Persistence Method. This method is based on the principle that weather conditions in the near future will be similar to the present conditions. This method is only accurate if weather features are relatively stable (Schoof, 2010). In addition, the Trends Method can be used to predict the weather. This involves analyzing pressure measurements, precipitation, and the movement of cold and warm **fronts** across the Earth. If these systems move in one direction and at a constant speed, this method can accurately forecast the weather in a certain region (Ahrens, 2007). Meteorologists can also use Climatology to predict future conditions. In this method, historical data are used to predict future changes. The conditions that were observed on a given day of the year throughout time are used to provide a long-term average (Ahrens, 2007). The Analogue Method can also be utilized, in which similar weather features that were observed on a day in the past are used to predict the conditions in the present (Alter, 1994).

Finally, Numerical Weather Prediction can help to predict future weather conditions. In this technique, air-pressure differences, solar radiation, the rotation of the Earth, precipitation, temperature readings and many other factors are observed and measured by tools such as satellites (**Figure 4**) and weather stations. These data are entered into a supercomputer, which uses a complex mathematical model to produce the weather forecast (Ahrens, 2007). The data are collected at points throughout the entire globe and are accessible to every country through the **World Meteorological Organization** (Ahrens, 2007). Although gaps in the data exist in locations where meteorological data are not collected, and the mathematical model can have a significant amount of error, the Numerical Weather Prediction method is often said to be the best known model for generating weather forecasts (Schoof, 2010).

Figure 4: *A weather satellite, which is used to measure meteorological data.*

Although no model is perfect and weather forecasts can often be inaccurate, they are an integral part of the lives of the general population, and have been an important factor in warning and protecting citizens from abnormal weather conditions throughout history.

Vladimir Obruchev: Science in Touch with Society

The name Vladimir Obruchev today probably holds little meaning for the majority of readers. Obruchev was never broadly recognized outside of Russia. Yet the life and work of this extraordinary scientist – one of Russia's earliest writers of science fiction – is a case study in how, historically, scientists have attempted to engage the public in their work and promote interest in science amongst others.

Biography

Vladimir Afanasevich Obruchev (**Figure 1**) was born on October 10th, 1863 in Klepenino, a small Russian village near the town of Rzhev, in Tver Province. Obruchev's father was an officer of the **Tsarist** military, and as a result the Obruchev family traveled extensively across Russia in Obruchev's youth. After completing high school in Vilnius (in what is now present-day Lithuania), Obruchev went to study geology at the prestigious St. Petersburg Mining Institute, from which he graduated in 1881 (French, 1963).

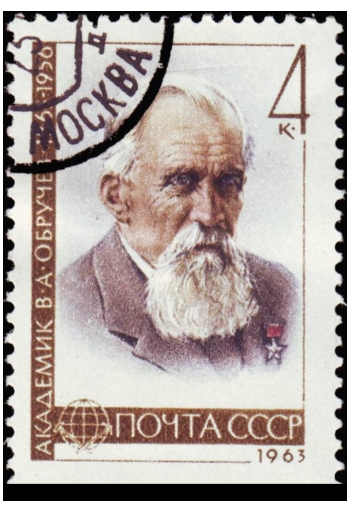


***Figure 1**: Picture of an elderly Vladimir Obruchev on the cover of a 1963 Soviet postage stamp.*

The mid-19th century was an exciting period for naturalists. Charles Lyell's ideas regarding gradualism and uniformitarianism had established a solid basis for the study of ancient geological formations (Lyell, 1830-33), while another Charles, Darwin, had electrified the European scientific community with his publication of On the Origin of Species (1859) (Desmond and Moore, 1994). This was the climate in which the young Obruchev grew up, and it instilled within him a passion for the study of geology. Obruchev became particularly interested in Siberia, Mongolia, and the northeastern region of China, which consisted of mostly desert that had, up to that point in time, never been explored. Vladimir Obruchev would change this (Tikhomirov and Voskresenskaya, 1963).

In Obruchev's early career as a geologist, he was an avid adventurer and explorer. In 1886, Obruchev undertook his first professional expedition, acting as a geologist with the Trans-Caspian Railway, which at that time was under construction in Krasnovodsk (in what is now Turkmenistan). During the expedition, Obruchev was deemed by his superiors as having great potential as a scientist and was soon appointed, in 1888, as the first official geologist in Siberia. He was only 24 years old at the time (French, 1963).

Over the next three decades, Obruchev conducted extensive geological surveys of Siberia and northern China, mapping out an area exceeding 100 000 square kilometers. 1917 found Obruchev busy surveying the Donbass region in the Ukraine on behalf of the newly formed Bolshevik government, a position he was soon forced to surrender due to a 1918 uprising of Don Cossacks in the area. From 1918 onwards, Obruchev held a variety of teaching positions at universities across Siberia and European Russia, being elected in 1929 to the prominent post of Director of the Geological Institute of the Soviet Academy of Sciences, a position he would hold until his death on June 9th, 1956 (French, 1963).

Scientific Career

Vladimir Obruchev led an extraordinary scientific career that saw the publication of thousands of essays, and his rise as the most prominent and influential geologist of his time in Russia. Obruchev would win numerous awards for his research, including five Orders of Lenin, the highest civilian honour available in the USSR, bringing him much public acclaim (French, 1963). Given Obruchev's extraordinary volume of work, it is impossible to give a comprehensive overview of Obruchev's research here. Instead, this section will focus on Obruchev's work on **loess** (**Figure 2**), and simply take a glance at his other important contributions.

Although Obruchev published on many areas within geology, his work on the origin of loess remains the most celebrated. Loess is a sedimentary structure formed by the deposition of small grains composed of clay, sand, and silt cemented together by calcium carbonate. It is known for being extremely fertile and resistant to erosion. This makes loess perfect for farming, and indeed loess deposits in China and the United States underlie many major farming regions (Heller and Michael, 1995).

Obruchev first became fascinated with loess during his first expedition to China in 1892, where he encountered extensive loess deposits what is now Shenzhen Province. At that time, there was controversy over whether loess formed as a result of Aeolian (wind) transport or by the **weathering** of existing sedimentary structures. Obruchev argued that it was impossible for loess to be formed through weathering. His reasoning was that when loess is exposed to water (thought to be the agent responsible for such weathering), characteristic deformations would form in the material. These deformations are not found in the majority of loess deposits, suggesting that the origin of the majority of loess is indeed Aeolian in nature (Obruchev, 1945). His writings on loess (and other topics) were noted for their lack of jargon, and their deliberate emphasis on being understandable to a broad audience.

Today, Obruchev's contributions are considered fundamental to those who study loess formations (Heller and Michael, 1963). There has been a recent resurgence in interest in loess amongst the geological community with the discovery of paleosols and magnetization in loess. Paleosols are "fossilized" soil deposits formed when a period of humid climate results in the increased erosion of exposed loess deposits. The discovery of these ancient soils forms an important line of evidence for climate changes in the Earth's history (Barbara and Thompson, 1991). Loess is also able to preserve a record of the Earth's magnetic polarity, an ability granted by particles of magnetite embedded in the loess. Obruchev's findings and meticulous records of loess formations in China and Russia are undoubtedly instrumental in assisting the present-day geologists studying loess (Heller and Michael, 1995).

Obruchev also published widely on a variety of topics within the geology of Russia and Siberia, popularizing these topics in European Russian society. He was the first to conduct a geologic survey of Siberia. Obruchev's compiled writings on Siberia, published in a large three-volume work entitled *The Geology of Siberia* (1936), which was widely used as a textbook in schools (French, 1963).

Obruchev's work was also considered to be of great importance by the Tsarist regime and, later, the Bolsheviks. He carried out missions prospecting unexplored Siberian territories for valuable minerals and natural resources, identifying areas suitable for the establishment of new settlements (Tikhomirov and Voskresenskaya, 1963). These efforts came at a time when the Soviet

***Figure 2**: Loess deposits near Hunyuan in China's Shansi Province.*

government was implementing the creation of new collective farms and concentration camps in Siberia. The authorities depended on Obruchev's studies to establish where new settlements could be constructed. Obruchev's surveys would ultimately prove to be invaluable to the Soviet government in 1941, when it was forced to relocate much of its industry east into Siberia in the face of Operation Barbarossa, the German invasion of the Soviet Union in World War II.

Obruchev the Writer

Although he was primarily a scientist, Vladimir Obruchev's claim to fame came mainly from his writing. Throughout his life, Obruchev was perpetually concerned with promoting interest in geology amongst the public and especially amongst the youth. To this end, Obruchev was responsible for establishing the first geological museum in Siberia, the Irktusk Natural History Museum, which stands to this day. He also established many Young Geologists' Clubs across the Soviet Union and, as a professor later in life, inspired many of his students to pursue careers in geology (French, 1963).

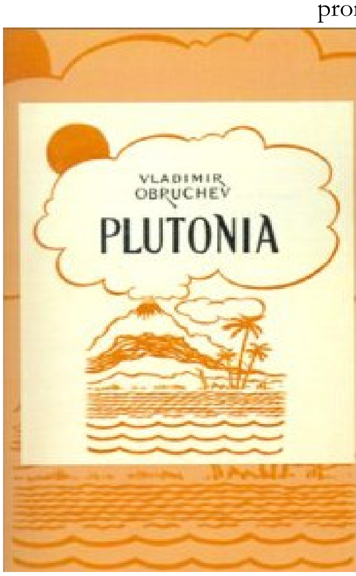


***Figure 3**: Cover of an English-language translation of Plutonia. Published in 2001 by Fredonia Books.*

By the mid-19th century, the Industrial Revolution had made printed books widely affordable to the public, and in a further effort to excite the public about the wonders of geology, Obruchev took to writing science fiction novels with geological themes, becoming one of Russia's first science fiction writers. He was inspired by Jules Verne's A Journey to the Center of the Earth (1864) and, upon deeming Verne's novel too unscientific, became determined to write his own novel that could reach out to the public and arouse their interests in geology (French, 1963). The result was Plutonia (1915), a "hollow-Earth" type novel that followed the adventures of four Russian scientists as travel through a hole leading to the insides of a fictitious hollowed-out cavern within the Earth (Figure 3). Obruchev uses this plot device to educate readers about ancient forms of life, which the four scientists discover, alive and flourishing, in the Earth's interior (Obruchev, 1915). Although by literary standards the characters of Plutonia are dry and pedantic, the realism that Obruchev was able to inject into the novel from his own knowledge and experiences made it a hit in Russia and abroad. By taking advantage of the latest technology and engaging the public's imagination, Obruchev was able to find an effective venue to establish a means of communication between the geological community and society at large.

Russian Society in Obruchev's Time

Russia in Obruchev's time was a country in the midst of a tumultuous revolution. Imperial Russia, though politically a force to be reckoned in Europe, was technologically and scientifically backwards. As a result, the Russian regime was pushed to the breaking point by the outbreak of World War I, opening the way for the communist Bolshevik party to take power by coup in the **October Revolution** in 1917 (Reed, 1919).

Obruchev had likely been a liberal, along with the majority of his colleagues in the Russian scientific community (Graham, 1990). In *Plutonia*, published prior to 1917, one of the protagonists, frustrated by the lack of scientific and technological progress in Imperial Russia, proclaims: "If the day ever comes that there's a change in the government we might be able to do things on a much bigger scale" (Obruchev 1915, p. 35), referring the popular conception amongst Russian scientists at that time that the government was impeding the march of scientific progress.

Records of Obruchev's political affiliation after the October Revolution are scarce, but he was politically reliable enough for the Soviet government to appoint him as a director of the Soviet Academy of Sciences in 1929 (French, 1963). Thanks to the rigidly hierarchical nature of the Soviet scientific community, this appointment allowed Obruchev to essentially take control the development of geology within the Soviet Union (Krementsov, 2006).

Obruchev's writing must have particularly impressed the Soviet leadership, which at the time was promoting "**socialist realism**" in every form of art created in the Soviet Union. Socialist realism demanded a "realistic" portrayal of life in art that would reflect the struggles of the working class (James, 1973). Obruchev's *Plutonia* (and his other works of fiction) matched this description perfectly, eschewing frivolous descriptions of characters and plot in favour of a rigidly accurate portrayal of the science. This may, in part, explain why Obruchev's works remained popular in the Soviet Union, as the Bolsheviks showed no reservations about banning works (and authors) it found ideologically objectionable (James, 1973).

Conclusion

The life of Vladimir Obruchev serves as a case study in how scientists have historically established lines of communication between the scientific community and the public. Obruchev was a scientist who was determined to promote interest in science amongst the public. He was able to effectively utilize books as a newly-publically affording means of communication to disseminate his work. At the same time, Obruchev was also a product of the society of Russia at that time, being particularly poised to rise to prominence within the Soviet society in which he found himself.

Earth Science in Modern Popular Culture

The scientific community has come a long way in learning how to engage the public in science since the time of Vladimir Obruchev. Today, vast improvements in both the science of geology and the available methods of communication have greatly altered the challenge of educating the public about Earth science (Leidner and Jarvenpaa, 1995).

Advances in the means of interpreting and visualizing geographic phenomena (e.g. sonar, satellite imaging) have given rise to far more visually appealing representations of landforms, geological processes, and other aspects of geology. Simultaneously, improved access to communications technology has allowed more people worldwide find the means to access educational material on geology. These factors have resulted in a public that is arguably more knowledgeable about the Earth than that of one century prior (Meinwald and Hildebrand, 2010).

However, with the explosion of available knowledge about geology, the problem today has become to separate fact from fiction in the public`s mind regarding geology. This has actually been made more difficult with the increase in freely-available information that may or may not be accurate (Burbules and Callister, 2000). There is no lack of geology in popular culture today, and the portrayal of geology therein is often less than scientifically satisfactory. Hollywood in particular has spread misinformation regarding the science of geology by releasing a number of films, including *The Core* (2003) and *Armageddon* (1998) that blend together fact and fiction, the lines of which an audience not savvy to geology might not be able to find.

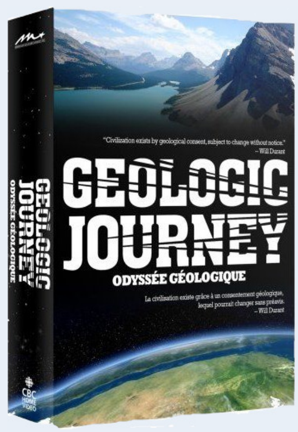


***Figure 4**: Box cover of Geologic Journey (2007).*

The solution to this problem is the same one that Obruchev found, decades ago, when he was puzzling over the problem of how to get the public interested in geology in the first place. That solution is to have geologists and other scientists take action on disseminating geology into the popular culture, as Obruchev did with the publication of *Plutonia* and his other works of science fiction. Fortunately, this is being done.

Today, it takes more than just publishing a novel for scientists to bring accurate geological information to the public's eye. The advent of video and similar forms of mass communication means that scientists have had to go to greater lengths to capture the public's attention. An example of how the geological community has succeeded in doing so is the CBC documentary *Geologic Journey* (2007) (**Figure 4**), where solid scientific facts about geology are presented in an interesting and engaging fashion.

The History of Mining – A Case Study: The California Gold Rush

Perhaps one of the most notorious and influential mining phenomena in the entire history of mining is the California gold rush. The California gold rush began on January 24th, 1848. Extensive prospecting and mining completely exhausted the gold in the area by 1855. Within the seven year time span, gold worth tens of billions of dollars by today's standards was recovered. (Paul, 1971)

The California gold rush is known not only for its massive economic repercussions, but also for the unique social, cultural, and judicial circumstances involved. In addition, relatively few important mining techniques (some of which are still used in modern times) were developed. With respect to the history of earth science, it is the relative lack of scientific progression which is most notable. The competitive nature of finding gold combined with the lack of expertise and an academic community lead to surprisingly few developments. (Stillson, 2006)

The Beginnings

The gold rush began when **James Marshall** (1810-1885) accidentally found gold in the American River on January 24th, 1848 (**Figure 1**). James Marshall was an employee of **John Sutter** (1803-1880), the operator of a lumber mill near the site of the original discovery. The two men tried to keep the discovery of the gold a secret. Their motive for secrecy was not to privately mine the gold for their sole profit as one may assume. In fact, they were dismayed when they determined the metal they found to be gold, because they thought it would ruin their plans for the development of an agricultural empire. (Paul, 1971)

***Figure 1**: Sutter's Mill was on the American River near the location where Marshall discovered the gold that initiated the California gold rush. John Sutter owned Sutter's Mill and Marshall was an employee. Due to the mining activities, Sutter's Mill was eventually trespassed upon and vandalized. Both Sutter and Marshall were financially ruined, and died in poverty. (Vance, R.H., 1850)*

Despite their best efforts, news of the gold deposits soon began to spread. Within a year of Marshall's discovery, tens of thousands of gold-seekers had arrived in California from all over the globe (Stillson, 2006). One of the most drastic examples of the population boom in the area is San Francisco, which exploded from a population of about 1,000 in 1848 to 25 000 in 1850(Stillson, 2006) (**Figure 2**).

Interestingly, as they had feared, both Marshall and Sutter were financially devastated by the extensive mining activity. The vast majority of Sutter's employees had abandoned work in favour of prospecting, and squatters decimated his agricultural investments, stealing crops and cattle. (Paul, 1971)

The Currency of Information

Credible information and expertise was very difficult to find during the California gold rush. Hundreds of thousands of people flocked to California in the years of the gold rush, but few had any experience in mining gold. Those who did have experience were not inclined to share. In addition, there was very little literature on the subject, particularly with regional relevance. Because of the discrepancies in knowledge (and in some cases luck), few miners made vast profits, and most left with little more than they had arrived with. (Stillson, 2006)

Any guidebooks or maps that did exist, especially at the beginning of the gold rush, were simply modified versions of other documents. For example, several publishing companies altered existing trail maps to show the approximate region where one could find gold. This seemed sufficient to amateurs, but proved to be entirely insufficient once in the field. As a result, it was very difficult for the inexperienced to succeed.

***Figure 2**: San Francisco had a major population boom, growing from only 1000 inhabitants in 1848 to over 25 000 in 1850. This is an image of San Francisco in 1850 or 1851. Notice all of the ships on the horizon. Many ships were simply abandoned once they reached California. As demand for expansion grew, they were used as residences, shops, and even a jail (Unknown, 1891).*

Many of the people who came to California to try to be miners and prospectors ended up working for larger companies with experienced leaders. This lead to drastic economic inequality amongst miners, who were often exasperated by the lack of legal regulations and enforcements at the time (this was largely due to California being a new state, previously a part of Mexico; Paul, 1971).

The lack of expertise and accurate information available to prospectors and miners, in combination with a highly competitive environment, prevented the formation of a scientific community. For this reason there were far fewer scientific advances than expected during the gold rush, considering the economic benefits associated with its development (Stillson, 2006).

Mass Prospecting

The main factor affecting who arrived at the gold rush first, was proximity. At this time, there was no easy way to travel to California, and the trip was often dangerous. Ship wrecks and disease (such as cholera) were not uncommon (Paul, 1971).

As such, the first wave of gold-seekers to arrive at the site consisted of California residents. Most of these miners traveled with their families, and relocated permanently close to their mining sites. Another interesting aspect to the activities of the early miners is that the entire family (including women and children) was often recruited to prospect. This allowed the retrieval of as much gold as possible when it was still abundant and easily accessible. (Stillson, 2006)

The next major influx of population during the gold rush was the arrival of several thousand Oregon residents, who travelled via the **Siskiyou Trail**. Within the first year of the original discovery by Marshall and Sutter, people arrived from as far as Chile, both by ship and overland. All of the aforementioned arrivals are known as the 'forty-eighters' because they arrived in 1848.

The most notable immigration to California happened in 1849, and these people were referred to as '**forty-niners'**. It is estimated that almost 100 000 people (approximately half of which were American) relocated to California in 1849 alone (Gregory, 1980). By this time, news of the gold rush had spread across the globe and people from as far away as Australia and Germany traveled to California (Stillson, 2006).

In the early years of mining, gold was found concentrated in the streams and rivers and could be mined using crude and simple methods. In the first five years of the gold rush, it is estimated that 12 million ounces of gold were recovered, worth greater than US$16 billion at December 2010 values (State of California, 2010).

Once most of the easily accessible surface gold was removed, more advanced and techniques for extraction were developed, refined, and implemented (see Mining Techniques section). These techniques recovered approximately 11 million ounces of gold (US$15 billion, December 2010 value) (State of California, 2010).

Mining Techniques and Environmental Impacts

As mentioned above several different mining techniques were used to extract gold during the California gold rush.

In the early years of the gold rush, simple methods which required little or no machinery were used. The most simple of these methods was **panning** which involved the use of a sieve instrument to gather material from the bottom of a river or stream, and the separation of the heavier gold from lighter minerals using water (Gregory, 1980).

As gold became scarce in the river beds, more advanced techniques were developed and implemented (Oakland Museum of California, 2003). The most notable of these later techniques is **hydraulicking** (**Figure 3**). Hydraulicking is the process of using high pressure water jets to dislodge gold-hosting material (mostly gravel) from river banks, cliffs and other exposures (Oakland Museum of California, 2003). The process was engineered by Edward Matteson, an experienced miner from Connecticut.

There were two motivations leading to the development of Matteson's hydraulic mining technique. First, he knew that there was much more gold in the mountains than in the rubble found along the stream beds. Second, he reasoned that the amount of gold found was proportional to the amount of gravel processed. Hydraulicking was his solution, as it could dislodge massive amounts of material from mountain slopes (Paul, 1971). Although Matteson was the first to use hydraulicking, it was impossible to keep the process a secret from the rest of the mining community because of the amount of noise involved. As such, hydraulicking quickly became the main mining technique used in the gold rush (Oakland Museum of California, 2003).

Hydraulicking was used extensively for many years through-out the world wherever large scale mining was taking place. However, the ramifications of the process quickly became apparent. In California, the most devastating effects were on the riparian zone (the transitional area between aquatic and terrestrial environments) and on local agriculture. Hydraulic mining consumes such vast quantities of water that it has the potential to disrupt the entire watershed. Once hydraulicking is complete, the polluted water then flows down stream leading to mass flooding (Oakland Museum of California, 2003). For these reasons, hydraulicking is used to a lesser extent today.

Hydraulicking was one of the only technical advancements made during the California gold rush. This is likely due to the competitive nature of gold mining, and the lack of education and expertise of the miners (Stillson, 2006).

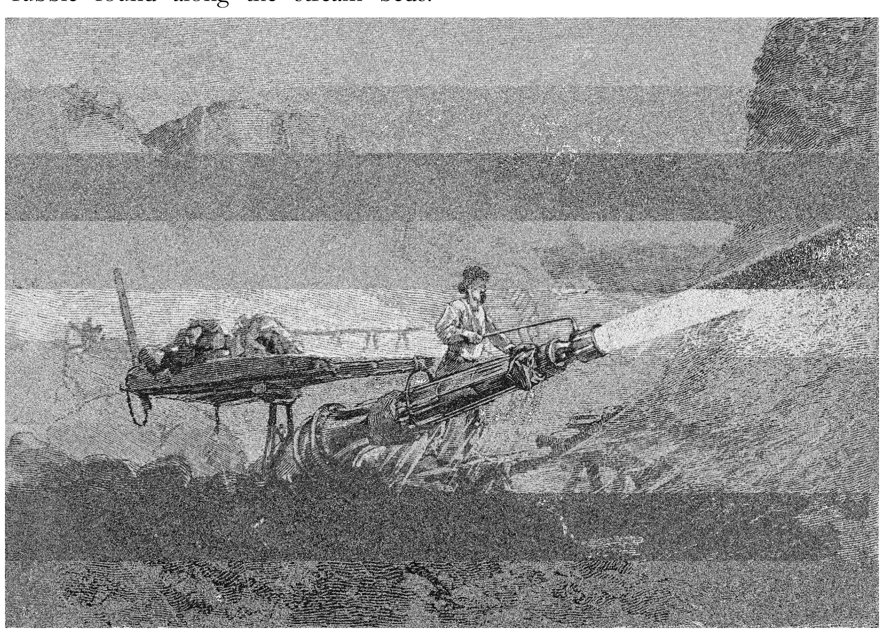


***Figure 3**: Hydraulicking was arguably the most important technological advancement made during the California gold rush. This technique alone recovered an estimated 11 million ounces of gold during the gold rush. Although hydraulicking was extensively used and extremely effective, it has unacceptable environmental impacts, which has lead to its decreased popularity. During the later days of the California gold rush, there was a law suit against a large scale mining company from the agricultural community downstream. The suit was settled in favour of the agricultural community (Sandham, 1883).*

The Alberta Oil Sands: Black is the New Gold

The **Athabasca Oil Sands**, commonly referred to as the Alberta Oil Sands, is one of the largest reserves of oil and gas in the world (**Figure 4**). This is extremely important to the Canadian economy, as crude oil prices are rising sharply. With an approximate 180 billion barrels of oil in the Athabasca Oil Sands, it is a reservoir potentially far more lucrative than the prosperous and infamous California gold stock (Oil and Gas Survey, 2011).

The Athabasca Oil Sands form an unconventional reservoir, as most of the oil is trapped in sandstone and is very difficult to access due to its high viscosity (Net Resources International, 2011). Historically, the reservoir was considered too expensive and environmentally damaging to develop. However, with the rise in global oil and gas prices, and new techniques to limit environmental damage, the Alberta Oil Sands are being actively mined (Kunzig, 2009).

Mining Techniques and Scientific Advancement

Initially, the most common technique used to extract the oil sands was **open-pit mining** (Government of Alberta, 2012). Open-pit mining consists of the removal of sediment containing the sticky oil which is then extracted. This method of mining is considered inefficient and extremely environmentally damaging as all vegetation is removed in the areas of the pits, and massive holes remain when the process is finished (Kunzig, 2009). More modern techniques use ***in situ*** methods, which allow extraction of the oil without the removal of the host sediment (Government of Alberta, 2012). There are several *in situ* techniques, all of which use hot air or more commonly water to stimulate oil flow to drilled wells. The heat in the injected air or water lowers the viscosity of the oil, which allows migration up to the wells (Net Resources International, 2011). These methods are more environmentally friendly than open-pit extraction, but there are still environmental issues to consider. The most important issue is the massive quantities of water required for oil extraction. This is a major issue for several reasons. First, the water must be retrieved, potentially depriving down-stream areas. Second, the water must be heated, requiring large amounts of energy. Third, the used water is polluted and must be either recycled or uncontaminated, a very difficult process (Kunzig, 2009).

Current mining techniques continue to be improved, and new techniques are being developed rapidly (Government of Alberta, 2012). In this way, development in the Athabasca Oil Sands differs from the California gold rush. Not only will scientists contribute toward the development of more effective and efficient extraction techniques, but also to the understanding of the origin of the oil sands in order to predict the location of similar reserves elsewhere. This interest is already stimulating vigorous scientific research into the geological and environmental history of the region.

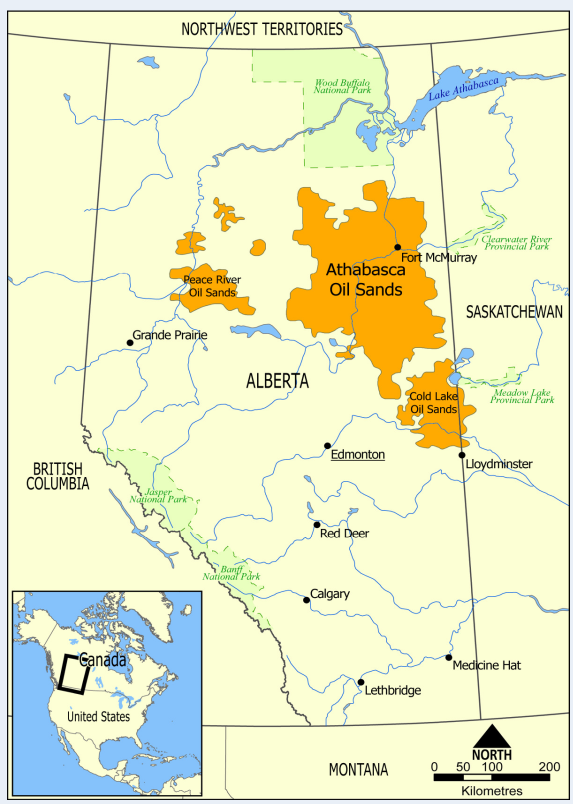


***Figure 4**: The Athabasca Oil Sands are located in Alberta, Canada, near Fort McMurray. They are the largest hydrocarbon reservoir in Canada, and make Canada the second largest oil hosting country in the world. With increasing oil prices, the value of this reservoir alone far exceeds the value of all the gold from the California gold rush. (Einstein, 2006).*

A 1630 world map by Hendrik Hondius from his atlas Atlantis Majoris Appendix. *This was the first widely available map and is notable for showing Australia.*

Conclusion

Although taken for granted today, we are only now beginning to understand the Earth and its various processes because of a long chain of often small, yet significant scientific discoveries. Throughout history, notable Earth scientists have challenged accepted theories and broken through preconceived notions to find the truths behind the origin and development of our planet and how it continues to change. *History of the Earth - Science through the Ages* tells the stories of the scientists who made these discoveries, and the earth processes that shape our planet and life as we know it. It contains four chapters, each of which outlines a unique area of scientific discovery.

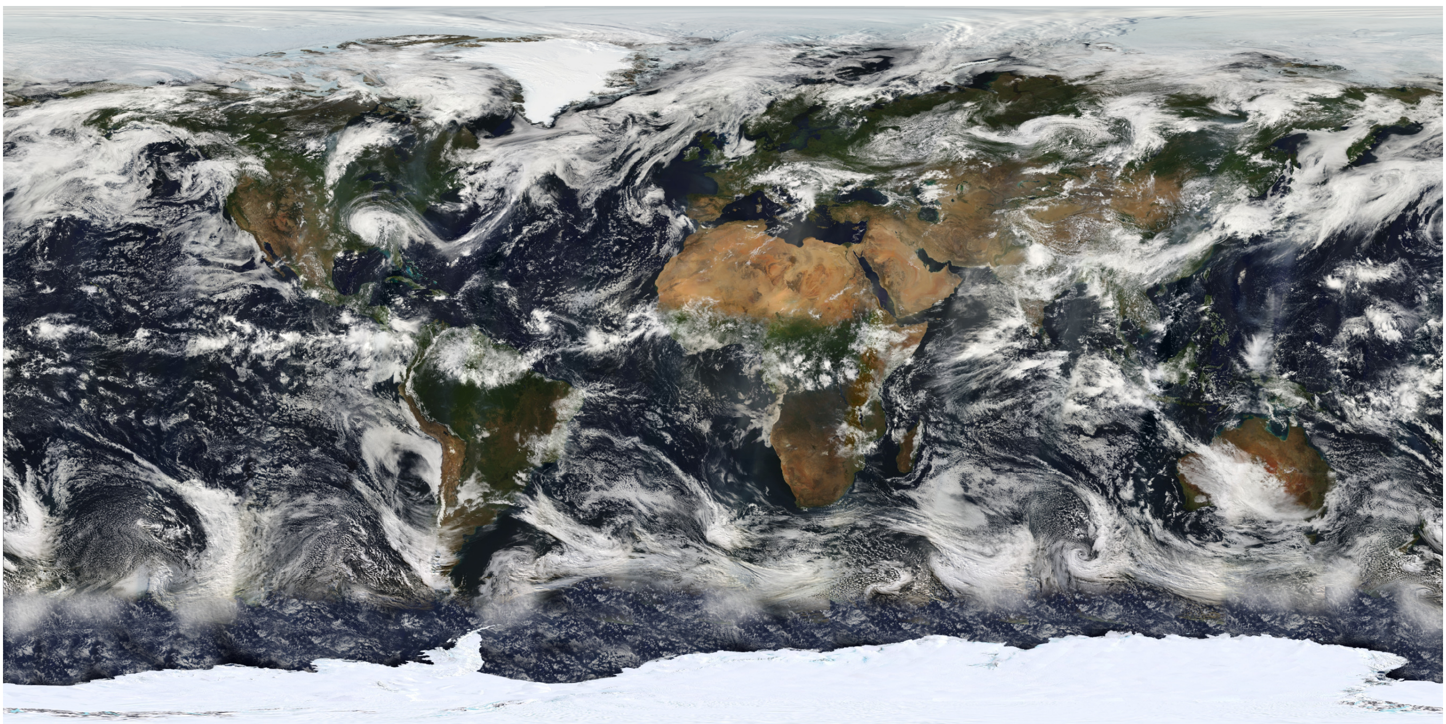
Chapter 1: The Study of Geological and Earth Processes gives the reader an introduction to several significant concepts in the discipline of Earth Science. From the creation of the moon to its effect on the world's tides, this chapter explores the processes that shape our world. It follows the development of ideas starting in ancient times to the late 20th century, emphasizing how our understanding of geological and earth processes continues to be an evolving field of study, paralleling the constant movement of plate tectonics and creation of volcanoes, such as Krakatoa. The influence of the people whose curiosity drove the understanding of these processes has had a lasting impact on our lives; for example the exploration for and protection of potable water sources is possible due to the work of Henry Darcy. Development in our understanding of Ice Ages is a prime example of how historical scientific inquiries started in the 1800s and progressed into the 1970s. As human technology advances, so does our exploration of the Earth, making possible the studies of sonar surveying and the development of the turbidite paradigm in the latter half of the 20th century. This chapter serves as not only an introduction to geological and earth processes but also to the value of human curiosity to the discipline of Earth Science.

Chapter 2: Understanding the Chemical and Physical Properties of the Earth details the exploration of the properties of the Earth from Ancient Greece to the present day. The sections within emphasize the importance of both human ingenuity and the scientific method in the discovery of new phenomena. The scientists described in this chapter discovered many of the fundamental laws of chemistry and physics. Notable events include experiments in geomagnetism by William Gilbert, description of the gravitational force by Sir Isaac Newton, classification of crystals by René-Just Haüy, and the discovery of radioactivity by Marie Curie. Scientists have also answered big questions about the Earth, by developing an understanding of the composition of the atmosphere and contributing to the ongoing debate about the origins of water on Earth. The people and events written about in this chapter made large strides in the disciplines of physics and chemistry, leading to a significant effect on the study of Earth Science and demonstrating its interdisciplinary nature.

Chapter 3: The Study of Ancient Life explores the use of Earth Science to study various topics in the Life Sciences. Many of the scientists discussed in this chapter were instrumental in the development of various fields in the natural sciences including evolutionary biology and paleontology. This chapter surveys the history behind the discovery and development of several concepts in the study of ancient life. Emphasis is placed on the challenges inherent in this field of study including the difficulties in the interpretation of specimens. Concepts presented include the discovery of photosynthesis by Nicholas de Saussure, Charles Darwin's theory of coral reef formation, and the K-Pg extinction as detailed by Walter and Luis Alvarez. Also discussed are George Cuvier and his legacy as exemplified by the paleontological study of woolly mammoths and human origins as well as historical perspectives in the field of biogeography. While the cases outlined are related specifically to the study of ancient life, they can also serve to elucidate the study of life today.

Chapter 4: Practicing Earth Science explores the various methods through which scientists have studied the Earth and its properties. One important theme in this culminating chapter, and which can be identified throughout the book, is the idea of a scientific community that is devoted to furthering knowledge in the field of Earth Science, and to finding ways to apply this knowledge. The various factors responsible for motivating scientific discoveries differ through time, as do the cultural and social make-up of the scientific community. This final chapter overviews the origins of the scientific community, the forces driving its formation, as well as its dynamics and interactions with society. The development of measuring techniques was motivated by a need for standardization across scientific studies and a method of recording information. Dynamics within the scientific community were an important influence on those attempting to calculate the Earth's age in the Victorian era. Another example of the influence of social dynamics on science is provided by the discussion of Vladimir Obruchev, a Russian geologist whose studies were greatly influenced by the political environment of his time. The absence of a strong scientific community during the California gold rush also impacted scientific progress in the field of mineral exploration. Through the specific examples of the practical applications of Earth Science discussed in this chapter, the reader should develop an appreciation for the complexity of the scientific community and its importance in motivating discovery.

From Sir Isaac Newton to Walter Alvarez, Ancient Greece to modern-day Russia, the bottom of the ocean to the peaks of mountains, this book explores the diverse field of study that is Earth Science. It is clear to see that although Earth Science is its own unique entity, it is formed by the integration of ideas from other disciplines. Just as biology cannot function without chemistry, and physics without mathematics, the study of the Earth is driven by collaborators from different fields coming together to form a multidisciplinary theory. Much has changed in both how we study the world around us and what we know about it, however one thing that is constant is our drive to find out more about our planet: the Earth.



A modern satellite image of the Earth generated by NASA's Earth Observatory. Compare to the hand drawn map of the world on page 118 to see how both human technology and understanding of the Earth have changed with time.

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Glossary & Index

Académie des Sciences **89**

The French Academy of Sciences is a scholastic society designed to protect the spirit of French scientific research. It was founded in 1666, and lead much of the Scientific development that occurred in Europe during the 17th and 19th centuries. Was dissolved during the French Revolution and later reformed, as the *Institut National des Sciences et des Arts*.

Academy of Science (France) **55-56**

See *Académie des Sciences*.

Accretion **62**

The process of growth or increase, typically by the gradual accumulation of additional layers or matter.

Adhémar, Joseph **36**

1797-1862. A French mathematician who was the first to think that glaciations could be a result of celestial mechanics, specifically variation in precession.

Aerobic **71**

In relation to life, describes organisms that require oxygen to live.

Aether **50**

A substance defined by Aristotle that made up the outer atmosphere. It was a pure substance suitable for the living conditions of the Gods.

Agassiz, Louis **32-36**

1807-1873. A Swiss geologist who developed Glacial Theory in the 19th century.

Age of Enlightenment **88, 92**

A cultural and intellectual movement that occurred throughout Europe in the 18th century. The movement strongly opposes superstition, and sought to change society and advance knowledge with the power of reason.

Alexandria **100**

Major Egyptian port city established by Alexander the Great c300 BCE.

Algoma Type BIF **71**

Sequences of banded iron formation that are thought to be associated with volcanic activity and are found to occur earlier than S-type BIFs (see *Banded Iron Formations*).

Alps **16**

A mountain range in Europe that stretches from Austria and Slovenia in the east through Italy, Switzerland, Liechtenstein and Germany to France in the west.

Alvarez, Luis **76-79**

1911-1988. An experimental physicist at University of California, Berkeley who was the father of Walter Alvarez and formed the asteroid impact hypothesis to explain the K-Pg extinction event. Won the 1968 Nobel Prize in Physics.

Alvarez, Walter **76-79**

1940-present. A geology professor at University of California, Berkeley who collaborated with his father Luis Alvarez on the asteroid impact hypothesis explaining the K-Pg extinction event.

Ammonite **78**

One of a group of extinct marine molluscs, related to the modern day octopus. They typically had a spiral shell and died out during the K-Pg extinction event. Commonly used as index fossils.

Anaxagoras **4**

500BCE-428BCE. Pre-Socratic Greek philosopher who was interested in understanding the natural system, including the Sun, rainbow and eclipses. He is considered to be one of the earliest scientists.

Angle of Elevation **100**

The angle that the observed object makes with the horizon. Historically measured using an astrolabe, later replaced by the sextant.

Apennines **16**

A mountain range in Europe that stretches through Italy and San Marino.

Application Goniometer **55-56**

Used to measure angles in crystals. Also known as a contact goniometer (see *Carangeot, Arnould*).

Aquifers **24**

A geologic formation that usually contains underground layers of porous rock or sand that allows for the movement of water. Water infiltrates into the soil through pores and cracks until it reaches the saturation zone where water can no longer penetrate further into the earth. Water held in aquifers is known as groundwater.

Argand, Émile **16**

1879-1940. A Swiss geologist who is known for his application of tectonics to the continent of Asia and the formation of the Alps.

Aristotle **4, 106**

384BCE-322BCE. A famous Greek philosopher who wrote about a wide variety of disciplines including biology, physics, politics and psychology. He is also said to be the father of meteorology, due to his groundbreaking work in the science.

Asaro, Frank **76-79**

1927-present. A nuclear chemist at University of California, Berkeley who worked with the Alvarez team by measuring iridium levels in clay.

Astrolabe **25**

An instrument formerly used to make astronomical measurements, typically of the altitudes of celestial bodies, and in navigation for calculating latitude, before the development of the sextant. In its basic form (known from classical times), it consists of a disk with the edge marked in degrees and a pivoted pointer.

Athabasca Oil Sands **117**

A very large reservoir of bituminous oil located near Fort McMurray in Alberta, Canada (also known as the Alberta Oil Sands). The thick, viscous oil is hosted in sedimentary rocks, making extraction and processing difficult (see *In Situ Extraction* and *Open-pit Extraction*).

Atoll **73-75**

One of the three types of coral reefs. It is a ring-shaped coral reef or series of closely spaced small coral islands that enclose or nearly enclose a shallow lagoon.

Attenuate **25**

Reduce the amplitude of a signal, electric current, or other oscillation.

Banded Iron Formations (BIF).. 71

Sedimentary rocks made up of thin alternating layers of magnetite and silica (see *Magnetite* and *Silica*).

Barometer.. 109

An instrument used to measure atmospheric pressure. Evangelista Torricelli is often cited as the inventor of the device in 1643.

Barrage 31

An artificial barrier containing multiple concrete structures of turbines and sluices (see *Sluice*) called caissons and each weighing over 100 000 tonnes. Also contains embankments joining deep water structures to shore.

Barrier Reef..73

One of the three types of coral reefs which runs parallel to the shore but is separated by a channel of deep water.

Basal Ice...35

Ice located at the base or bottom of the glacier. Contains entrained fragments of eroded sediment and bedrock which are transported and may be directly deposited as till.

Becher, Johann Joachim.. 69

1635-1682. A German scientist who, in an attempt to explain the processes of combustion and the rusting of metal, proposed the Phlogiston Theory (see *Phlogiston Theory*).

Becquerel, Henri...58

1852-1908. A French physicist who is co-credited with a Nobel prize for his discovery radioactivity in 1896.

Bedrock 83

Rock found beneath unconsolidated sediments or materials on the surface of the Earth. Bedrock can be eroded and weathered by a variety of geomorphological agents such as wind, ice, and water.

Belemnite...78

One of a group of extinct marine cephalopods, resembling modern day squid, although they had an internal skeleton. They died out during the Cretaceous-Paleogene extinction event.

Binary Accretion Theory..4

Developed in the early 1800s, the theory states that the Earth and the Moon were formed simultaneously from the dust cloud in the solar nebula.

Blasphemy Act.. 68

An act of the British Parliament passed in 1697 that made the denial of the Trinity punishable by imprisonment.

Bolide...76-79

A large impacting meteor or meteorite.

Bolshevik... 110

A Marxist-Leninist political party that took control of Russia in October, 1917, ultimately establishing the Union of Soviet Socialist Republics.

Bonaparte, Napoléon.. 56

1769-1821. Leader of the French Revolution (1789-1799), and later the emperor of France (1804-1815).

The first book of the Christian Bible and the Jewish Torah.

A characteristic sequence that describes a set of sedimentary beds deposited by turbidity currents in areas of deep water sediment deposition. The Bouma sequence consists of five distinct beds labelled A through E that fine upwards.

A special case of the ideal gas law that shows the inversely proportional relationship between the pressure and volume of a gas.

1784-1856. An English geologist and paleontologist who worked at Oxford University. His religious beliefs would push him to be a diluvial theory advocate until discussion with Louis Agassiz would turn him into a Glacial Theory supporter in the British Isles.

1707-1788. A French naturalist, mathematician, and cosmologist who determined the first principle of biogeography or Buffon's law.

A mineral that is composed of calcium carbonate ($CaCO_3$).

Developed around 1900, the theory states that the Earth and the Moon had entirely different origins, and the Moon entered the Earth's orbit by chance.

1742-1806. A French inventor of the application goniometer and discoverer of the Law of Constant Angles, both of which are credited to Romé d'Isle, his teacher (see *Application Goniometer*).

A form of dating using the radiometric characteristics of the radioisotope carbon-14 (^{14}C) with a half-life of 5730 years. The half-life is the time it takes for half the substance to convert from ^{14}C to ^{13}C, and these ratios can be used to date the specimen.

A class of chondritic meteorites comprising at least seven known groups and many ungrouped varieties. They are thought to have brought water to the Earth during its formation.

A mountain range in Europe that stretches through Czech Republic, Poland, Slovakia, Hungary, Ukraine, Romania, and Serbia.

1578-1643. An Italian mathematician most recognized for his publication of the *Mensuration of Running Water*, an important work on fluids in motion, and *Geometrical Demonstrations of the Measure of Running Waters*.

Theory in geology which states that the formation of the Earth and its surface features occurred through a series of catastrophic events over a short (and often Biblical) time span (see *Uniformitarianism*).

Catastrophist 73

See *Catastrophism.*

Charpentier, Jean 32-33

1786-1855. A German-Swiss geologist who extensively studied the Swiss glaciers. He was the first advocate for a larger glacier extent in the Alps. His pupil, Louis Agassiz, would further develop this theory and eventually bring it forth to the European geological community.

Climate Proxy..39

A preserved physical characteristic that may be used to indicate former climatic condition. Examples include gases contained within ice cores, tree rings, deep-sea cores and fossils.

Coalesce.. 63

To come together and form one large mass.

Coercivity 46

Reverse magnetic field required to demagnetize a material. Highly coercive materials are termed "hard" magnets, while those with low coercivity are termed "soft" magnets.

Conduction.. 102

Process by which energy is transferred between or within matter due to the presence of a temperature gradient. Heat flows through the body without the bulk movement of material.

Conservation Biology...95

A scientific discipline that aims to study and protect the Earth's biodiversity.

Continental Margin..9

Thin area of crust that separates oceanic crust from continental crust.

Copernican System...48

A system first openly declared by Copernicus grounding planetary motion to orbits about a central Sun. The system did not restrict planetary motion to circular orbits and accepts ellipses as possible paths.

Copernican Theory..29

Copernican theory places the Sun near the centre of the solar system with the Earth and the other planets orbiting around it.

Coprophagy...83

Coprophagy is the consumption of fecal matter. Certain species, such as elephants and koalas, practice coprophagy at a young age to accumulate the bacteria required to digest vegetative food.

Coral Bleaching..75

The whitening of corals, due to stress-induced expulsion or death of their symbiotic algae, zooxanthellae. The zooxanthellae produce oxygen for the coral through photosynthesis and in turn, the coral shelters the algae. Coral bleaching indicates a harmful change in environment.

Cosmic Radiation..61

Charged particles entering the Earth's atmosphere at high velocities consisting mostly of protons and alpha-particles. They are able to ionize atmospheric particles.

Cosmogonal 103

Pertaining to cosmogony, the branch of science that deals with the origins of the universe and galaxies.

Deep-sea Fan **18**

Submarine geological structures caused by large-scale sediment deposition. They are formed by turbidity currents and contain sediments that can be described by the Bouma sequence (see *Bouma Sequence*).

Deluge **92**

A great flood sent by a deity in order to punish humankind for their wrongdoings.

Density Current **17**

A current in a liquid or gas caused by gravity acting on density difference between distinct parts of the fluid. Factors that influence density currents can include temperature, salinity, and amount of suspended sediment.

Descartes, René **13, 47**

1596-1650. Known as the Father of Modern Philosophy for his breaking away from the tradition Scholastic-Aristotelian philosophy, which depended largely on sensation, and his move towards the new, mechanistic sciences.

Deuterium **62**

An uncommon form of hydrogen containing a proton and two neutrons in the nucleus.

Deuterium/Hydrogen Ratio **62**

The amount of deuterium (two neutrons in nucleus) over the amount of hydrogen (one neutron in nucleus) in water. This ratio is used to identify where different water sources originated.

Diagenetic **39**

Changes caused by physical or chemical processes after the initial deposition of sediment.

Diffraction Pattern **57**

The pattern produced when waves bend around obstacles. Produced in X-ray crystallography from the interaction of X-rays with electrons.

D'Isle, Romé **54-55, 56**

1736-1790. A French scientist who contributed to the early study of modern crystallography. Credited with the Law of Constant Angles and the invention of the application goniometer. Was the first to suggest that crystals are made up of particles in a regularly repeating pattern. Introduced the widespread use of crystal models.

Diluvial **33**

In association with floods, the 'diluvial theory' proposed that the Earth's primary geomorphological agent was a series of floods. Noah's flood was believed to be the last one of these floods.

Distorted Habit **54**

Crystals that have a different size, shape, colour or appearance than an ideal sample.

Diurnal Inequality **28**

The difference in amplitudes of the two high tides per day and the two low tides per day relative to one another caused by the position of the moon.

Don Cossacks **110**

Members of a semi-autonomous community that existed in the Don Basin region of Russia. Revolted against Bolshevik rule in the Russian Civil War.

Dubois, Eugene **85**

1858-1940. A Dutch paleoanthropologist and geologist who discovered Java Man.

Earth Tides 28

Physical deformations of the elastic Earth's crust resulting from the gravitational influences of the Moon and the Sun.

Eccentricity...37

A measure of the amount an orbit deviates from a perfect circle. An orbit with high eccentricity is closer to an ellipse while an orbit with a low eccentricity is close to a circle.

Ecological Niche..95

The role an organism plays within their ecosystem. An organism's ecological niche is affected by both biotic (living) and abiotic (non-living) factors.

Elastic Deformation 77

An object changes in physical shape and then returns to its original dimensions.

Electromagnet 46

Conductor (often a loop or coil) which produces a magnetic field proportional to the current it carries. Discovered by Oersted in 1820, these magnets now predominate applications requiring strong or adjustable magnetic fields.

Electrometer..58

A device used to measure the electric charge or potential difference between two objects.

Energy Product 46

Density of potential energy which can be obtained from a magnet. Rare earth magnets have energy products up to ten times greater than those of permanent iron magnets.

Epicureanism 47

A philosophical doctrine introduced by Epicurus in which the external world is composed of atomic particles and the interaction among these particles is interpreted as a series of fortuitous combinations. Epicureanism also views the highest good to be distant from disturbance, i.e. associated with pleasure.

Ewing, William.. 17

1906-1974. An American geophysicist who conducted research on seismic reflection and refraction in ocean basins, ocean bottom imaging, submarine sound transmission, and abyssal plains and submarine canyons. Along with Heezen (see *Heezen, Bruce*), he hypothesized that the telegraph cable breaks that had occurred during the Grand Banks Earthquake in 1929 were caused by turbidity currents.

Exhalations.. 108

Two substances coming from the Earth, as described by Aristotle. One is moist and vaporous, and originates from the water present on the Earth, while the other is dry and comes directly from the Earth itself.

Exosphere...52

The outermost layer of the Earth's atmosphere. This area is largely devoid of matter except for hydrogen and helium atoms that move at incredibly high velocities.

Facies.. 16

The characteristics of a sedimentary deposit formed under certain conditions. These characteristics can be used to infer the processes that occurred and the environment in which they took place.

Fission Theory of Moon Hypothesis...5

Developed by George Darwin in 1898, the hypothesis suggests fission of the Moon from the Earth due to centrifugal force.

Glaciation 32

Period of time in which colder temperatures and glacier advances are experienced. Glaciations play a critical role as geomorphological agents of erosion. Glacial activity during glaciations can also create depositional features that allow for the identification of glacial limits, such as till and moraines.

Global Positioning System (GPS) 98

A system of satellites that provide location and time information to receivers on earth. The system uses triangulation to locate the GPS receiver when it has an unobstructed line to four or more GPS satellites.

Gnomon.. 100

Used to cast a shadow for a sun dial. Typically tall and thin and ideally with a fine pointed tip for accuracy. Ancient Greek translation is "indicator".

Gradualism.. 110

Theory stating that change is a cumulative product of smaller, but continuous processes. Originally developed by James Hutton in 1795.

Gravimeter...49

A device used to measure the acceleration due to gravity in a localized region. The measured value is dependent on variations in rock and atmospheric conditions.

Gravimeter Drift...49

Fluctuations in the measurement of gravity due to variations in the inherent properties of the device. Some gravimeters are capable of compensating for this deviation.

Gravimeter Elevation...49

The elevation of the gravimeter dictates the measurement the gravimeter records. Some gravimeters are capable of compensating for this deviation.

Gravitational Contraction.. 102

Astronomical process described in the works of Lord Kelvin and Hermann von Helmholtz by which the contraction of a planet or star would cause a decrease in its gravitational potential energy and the release of heat from the core. Developed to explain solar energy, prior to the discovery of nuclear fission in the 1930s.

Gravity Anomaly...49

A gravity anomaly occurs when the measured value for the acceleration due to gravity differs from the actual value.

Greenhouse Effect...78

The warming of the Earth due to thermal radiation trapped by atmospheric gasses.

Guyots 11

Flat topped mountains found on the ocean floor formed by ancient volcanoes whose tops have been eroded by waves.

Hall, James 8

1811-1898. An American paleontologist who first proposed the theory of geosynclines that was later revised by Dana (see *Dana, James*).

Hampton, Monty 18

n.d. An American geologist who, along with Middleton (see *Gerard Middleton*), classified sediment-gravity flows based on sediment-support mechanisms.

1743-1790. A Catholic priest and scientist who contributed to the early study of crystallography. Most famous for his Law of Rational Intercepts. Known as the Father of Modern Crystallography.

The energy in an incompressible fluid associated with various factors such as movement of fluid (velocity head), pressure in the fluid (pressure head), height of fluid (elevation head), and friction (head loss).

1924-1977. An American geologist who is known as the leader of a team from Columbia University which mapped the Mid-Atlantic Ridge during the 1950s.

1796-1861. An English clergyman, botanist and geologist.

1906-1969. American geologist who proposed the concept of sea floor spreading while working as an officer for the Navy during World War II.

A gold-silver deposit located in northeast Japan. Geophysical surveys were a contributing factor in discovering the major ore deposit in 1981. The deposit was a significant find, estimated to have an average of 70 grams of gold per metric ton.

1890-1965. A British geologist who was the first to perform a method of dating rocks. Holmes was a supporter of Wegener's continental drift theory.

Graphical/mathematical model that describes the evolution of a closed uranium-lead system (see *Isochron*).

1726-1797. A very influential scientist in the 18th century who was a physician, geologist, and naturalist. Scientist known as the father of modern geology for his Theory of Uniformitarianism (see *Uniformitarianism)* as well as his recognition of subterranean heat as the driving force in geologic processes.

1825-1895. An English biologist and advocate of Charles Darwin's theory of evolution, a formidable speaker and powerful figure in the Victorian science sphere (see *Darwin, Charles*).

A measurement of a material's ability to transmit water when subjected to a fluid gradient. It is the proportionality coefficient in Darcy's Law (K). The slope of a discharge versus hydraulic gradient plot allows the calculation of hydraulic conductivity.

A mining technique first used in the California gold rush. Miners would aim high pressure water jets at cliffs with gold deposits to dislodge gravel, then sift through the gravel to extract gold.

Ice-albedo Feedback 37

A positive feedback process in which snow reflects light, inhibiting melting and allowing more snow to accumulate.

Ice Age 33

Term Louis Agassiz coined for extensive periods of glaciation in 1836. (see *Glaciation*)

Ichnology 32

Branch of geology that focuses on the study of trace fossils such as tracks, trails and burrows.

Igneous Intrusion 13

A rock formation created when liquid magma from the mantle is forced upward through cracks in the overlying crust and solidified.

Ikoma, Masahiro 64

n.d. Assisted Hidenori Genda in hypothesizing that water was present on earth in the early stages of its formation

***In Situ* Extraction** 117

An extraction method used in oil sands. This extraction method injects hot air or water (more common) into the oil sands to reduce the viscosity of the oil, allowing it to flow to a drilled well.

Infinitesimal Calculus 48

A geometrical and analytical techniques for finding various properties of curves, such as the area underneath a curve. Newton founded infinitesimal calculus in the 1660s along with Gottfried Leibniz who independently discovered similar techniques around the same time.

Ingenhousz, Jan 69

1730-1799. Dutch scientist who determined that the green parts of plants clean the air when placed in strong light.

Inner Core 4

A solid ball in the center of the Earth, consisting of heavy elements including iron and nickel. The core has high temperature (approximately 5505°C).

Insolation 37

A measure of the solar radiation energy received on a surface area over a given length of time.

Institut National des Sciences et des Arts 56

See *Academy of Science (France)*.

Interglacial Period 34

Period of time in which global average temperatures are relatively warm and glaciers retreat. Interglacial periods separate periods of glaciation creating a cycle of alternating glacial and interglacial episodes.

Ionization 58

The addition or removal of an electron in an atom creating an electric charge.

Ionosonde 52

A device developed by Edward Appleton that both sent out, and received a wide range of radio frequencies. It was used to determine the distance from which a radio wave rebounded, and was a primitive form of what turned out to be radar.

Isochron **105**

A normalized plot of the ratio of parent to daughter isotope from which a radiometric age of a sample can be found. An important tool in radiometric dating. (see *Radiometric Dating*).

Isostacy **9-10**

A state of equilibrium between a continental or oceanic plate and the layer beneath such that the plate floats at a level dependent on its thickness and density.

Isotope **39**

Variations of a chemical element which contain different amounts of neutrons but the same amount of protons.

Java Man **85**

Homo erectus remains found on the island of Java by Eugene Dubois in 1891.

Jeffreys, Harold **10**

1891-1989. An English geophysicist and mathematician who disagreed with Wegener's theory stating the Earth is completely solid.

Johnson, Douglas **17**

1878-1944. An American geologist who introduced the term "turbidity current" to describe sediment-laden density currents (see *Density Current*).

Joly, John **10**

1857-1933. An Irish geologist who agreed with Wegener, stating that while the Earth may be solid now, it might not always have been that way.

Kant, Immanuel **102**

1724-1804. An 18th century German philosopher whose major contributions included the laying out of the nebular hypothesis as a possible model for the formation of the Solar System (see *Nebular Hypothesis*).

Kepler, Johannes **29, 47, 54**

1571-1630. A late sixteenth-century and early seventeenth-century mathematician and astronomer most well known for his advances in laws of planetary motion. He observed planetary orbital data and developed his laws of planetary motion, describing the planets' orbital form and period.

Köppen, Vladimir **38**

1846-1936. A Russian climatologist who among contributions to other branches of science developed the Koppen climate classification.

Kuenen, Philip **17**

1902-1976. A Dutch geologist who collaborated with Migliorini (see *Migliorini, Carlo*) on a classic paper that describes the relationship between turbidity currents and graded bedding.

Kuiper Belt **62**

A disk-shaped region of minor planets in the Solar System outside the orbit of Neptune.

Laminar Flow **18**

A type of flow without disruption in its direction.

Lanthanide Element **46**

(Rare earth element) Element with electrons in a partially filled f-shell orbital. Because these electrons can be aligned in a magnetic field, and are highly shielded from the influence of neighbouring atoms, lanthanide elements, such as neodymium and dysprosium, are used to

Lyell, Charles **10, 37, 73-75, 80, 93, 102**

1797-1875. A prominent geologist who authored the *Principles of Geology*. He helped to popularize the theory and concepts of uniformitarianism. A close friend of Charles Darwin.

Magma **13**

Hot, melted rock under the Earth's crust.

Magnetic Declination **44**

Angle between magnetic north pole and geographic north pole. Changes in magnetic declination occur due to complex currents in the outer core which generate the Earth's magnetic field, along with rotation of the Earth's inner core.

Magnetic Dip **44**

Angle between the direction a compass needle points and the horizontal direction. Due to the fact that compass needles align along the direction of the Earth's magnetic field, dip is the greatest at the poles, and the smallest at the equator.

Magnetic Moment **46**

Vector quantity that is proportional to amount of torque an object experiences in a magnetic field, as well as the strength of the magnetic field produced by the object. Magnetic moments can be generated by current loops, and are also inherent properties of particles such as electrons, protons, and neutrons.

Magnetic Reversal **76**

The process by which the magnetic North pole of the Earth switches places with the magnetic South pole of the Earth.

Magnetite **42, 71**

Naturally magnetic, black iron oxide mineral, with chemical formula Fe_3O_4. Magnetite comprises lodestone (see *Lodestone*), a rock employed greatly in the study of magnetism.

Manometer **25**

A device consisting of a U-shaped tube of glass filled with liquid, usually mercury, to measure water pressure based on the principle that fluids at the same height have the same pressure. Pressure is given by the multiplication of the fluid density (ρ), fluid height in tube (h), and gravity (g).

Marconi, Guglielmo **51**

1874-1937. An Italian inventor who worked in the late 19th century, he is credited with being the first person to successfully transmit a radio message across the Atlantic Ocean.

Marnoso-arenace Formation **17**

Marnoso-arenace formation consists predominantly of siliclastic sediments of the Miocene Age (see *Miocene*). The formation stretches through north-central Apennines (see *Apennines*) in Italy.

Marshall, James **114**

1810-1885. The man who found gold in 1848, a find that started the California gold rush. He was an employee of John Sutter, at Sutter's Mill (see *Sutter, John*).

Mass Spectrometry **39**

An analytical technique which can be used to determine the elemental composition of a substance.

Mesosphere **52**

The middle layer of earth's atmosphere. The area in which comets burn up most frequently.

Mesozoic Era 76-79

Lasted from 250 million years ago to 65 million years ago, known as the age of reptiles. The K-Pg extinction event marks the conclusion of the Mesozoic Era.

Meteoroid 76

A particle of debris that ranges from sand to boulder sized that enters the Earth's atmosphere.

Meteorology 106

A natural science concerning the study of the atmosphere. Aristotle is said to be the father of meteorology. The word comes from the Greek word *meteor* meaning falling from or suspended in the sky.

Michel, Helen 76-79

1932-present. A nuclear chemist at University of California , Berkeley who worked with the Alvarez team by measuring iridium levels in clay.

Middleton, Gerard 18

1931-present. A Canadian geologist whose influential publications include those on turbidity currents and on the classification of sediment-gravity flows based on sediment-support mechanisms.

Migliorini, Carlo 16

1891-1953. An Italian geologist known for his famous joint publication with Kuenen (see *Kuenen, Philip*) in 1950 on the origin of graded beds and turbidity currents. He was the first to fully interpret graded sandstone beds of the Marnoso-arenace Formation in Italy (see *Marnoso-arenace Formation*).

Milankovitch, Milutin 37

1879-1958. A Serbian mathematician and engineer who developed a mathematical model showing how variations in precession, eccentricity, and obliquity could affect insolation and therefore climate.

Minute of Arc 100

Measure of angle, defined as one sixtieth of a degree. This leads to the notation 28°38' where the number preceding the ' signifies the number of minutes of arc.

Miocene 17

Geological epoch of the Neogene Period 23 to 5 million years ago.

Missing Link 85

A term often used to refer to the transitional forms in the evolution of species, particularly hominins.

Mitochondrial DNA (mtDNA) 87

DNA separate from the nuclear DNA that is passed on from the mother through inheritance of mitochondria in the egg.

Montreal Protocol 53

A global treaty signed in 1987 with the goal to reduce the amount of CFC's released into the atmosphere.

Moraine 33

Ridge or mound of sediment deposited by glaciers. Various types of moraine exist which are classified by type of deposition and shape (e.g. end moraine, hummocky moraine).

Morbidelli, Allesandro **63**

1966-present. From the Observatory of the Cote d'Azur in France; created simulations which hypothesised that water and volatiles were brought from the outer solar system into the inner solar system.

Mudflow **81**

Mass flow of material that contains large amounts of water. These flows can occur on steep slopes from heavy precipitation and where easily erodible source material is available.

Muséum d'Histoire Naturelle **89**

The National Museum of Natural History located in Paris, France. The Museum was founded during the French Revolution, and had the purpose of instructing the public, assembling collections, and performing scientific research.

Natural History **89**

The scientific study of plants and animals with a observational rather than an experimental bias.

Naturalist **72**

A person who specializes in natural history and the study of plants and animals in their natural surroundings.

Neap Tide **29**

The smallest amplitude tides occurring when the Moon is 90 degrees to the Earth relative to the Sun resulting in the smallest net gravitational pull. Corresponds with a 1st Quarter and 3rd Quarter Moon.

Nebular Hypothesis **102**

Widely accepted cosmogonal theory for the formation of the Solar System and other systems in the universe which posits the collapse of a giant and rotating gaseous cloud into dense regions that become stars (see *Cosmogonal*).

Newton, Isaac **29**

1642-1727. A famous mathematician, physicist and astronomer who discovered gravity and developed classical physics through his famous three laws of motion.

Noachian Deluge **80**

Also known as the flood myth, it is the great flood sent by God upon civilization. Associated with Noah's Ark in a biblical context.

Normark, William **18**

1943-2008. An American geologist who is well known for his work on the characteristics and depositional patterns of turbidite-fan deposits (see *Deep-sea Fan*).

Obliquity **37**

A measure of the angle between the axis of an object and the plane perpendicular to that in which it orbits.

Obruchev, Vladimir **110**

1863-1956. Noted Russian/Soviet geologist and writer. Contributed much to knowledge of Siberian geology.

Oceanic Subsidence **8**

The idea that as the earth cooled, the ocean plates sank from the level of the continents. This theory was put forth by Charles Darwin (1809-1882) in 1843.

October Revolution... 112

Refers to the seizing of power by the Bolshevik Party on the night of October 25th-26th, effectively disposing of a bourgeoisie government that had come to replace the Tsar in Russia.

Open-pit Extraction... 117

An extraction process used to mine oil sands. This extraction method requires the large scale removal of oil-hosting sediment from an area, for later processing and separation. This is the most rudimentary and environmentally damaging extraction method used in the oil sands industry.

Orogenic 16

Referring to the process of mountain formation caused by structural deformation of the Earth's lithosphere. Orogens result from the folding and faulting caused by tectonic movements.

Owen, Tobias 63

n.d. From the University of Hawaii; found that the ratio of xenon to kryptin in the Earth's atmosphere differed significantly from that found in carbonaceous chondrites.

Ozernoy, Leonid 63

1939-2002. He worked at Harvard and Boston universities and suggested that asteroid size planetismals could have contributed to the late veneer of water on Earth.

Ozone Layer 63

A layer of the atmosphere with an extremely high concentration of ozone, O_3 molecules.

P-forms...35

Type of subglacial erosional feature characterized by smoothed and often sinuous depressions eroded into bedrock. The origin of these features is widely debated.

Paleoclimate 9

Studies of climatic changes over Earth's history.

Paleogene Period (Pg)...76

This geologic period lasted from about 65 million years ago until 23 million years ago. It was preceded by the Cretaceous period and followed by the Neogene period. Mammals and birds both evolved significantly during the Paleogene period.

Paleomagnetic Reversals...39

Reversals in Earth's magnetic field that are recorded in sediments and rocks containing ferromagnetic minerals.

Paleontologist...8

A person who studies paleontology, which is the field of study pertaining to prehistoric life.

Paleontology 88

A branch of science that focuses on the study of prehistoric life.

Paleosols 111

Literally "ancient soil". Soil preserved through burial beneath other sediments (usually loess).

Pangea 9-10

Name given to a former supercontinent by Alfred Wegener. It formed around 300 million years ago and began to break apart 200 million years ago.

Panning **116**

A simple method used to retrieve gold. A sieve is used to gather rubble from the bottom of a stream, and the gravel is washed in a pan to separate the heavy gold from lighter rocks. This was the predominant form of mining for a number of years.

Panpsychism **54**

The belief that inanimate objects have souls. Pliny the Elder's writing inspired the belief that crystal posses life, which was carried forward into the Renaissance by the work of alchemists. This theory was discredited by Nicolas Steno in 1669.

Paramagnetism **25**

(Of a substance or body) very weakly attracted by the poles of a magnet, but not retaining any permanent magnetism.

Pascal, Blaise **24**

1623-1662. A French mathematician, physicist, inventor, and writer whose earliest work was in the natural and applied sciences where he made important contributions to the study of fluid and pressure. His name has been given to the SI unit of pressure, the Pascal triangle, and the Pascal's Law.

Piezometer **27**

An instrument typically used in the field to measure the static liquid pressure (unlike the Pitot tube) of groundwater in aquifers where in a confined aquifer, the water level in the piezometer indicates the aquifer pressure.

Peking Man **85**

Fossilized specimen of *Homo erectus,* found in Zhoukoudian, China.

Pelagic **16**

Referring to the water in an ocean marine environment.

Périer, Florin **50**

1605-1672. A 17th century, French scientist credited with first understanding the change in relationship between altitude and pressure.

Perihelion **36**

The point closest to the sun in a planet's orbit. The point furthest away is called the aphelion.

Permafrost **81**

Soil at or below freezing temperature (0°C) for two or more years. Most permafrost includes ice cement, lenses, or masses that result from subsurface freezing of water.

Permanence Theory **8**

Version of contraction theory proposed by James Dwight Dana that was popular in America. The theory stated that low-temperature minerals formed the continents and high-temperature minerals formed the ocean basins and continual contraction caused mountain formation. The theory got its name because it proposed that the continents and oceans do not move.

Permeameter **27**

An instrument used in the field that measures water infiltration in the soil to provide estimates of soil hydraulic conductivity. The constant-head permeameter is similar to Darcy's column experiments in that the discharge is measured by measuring the volume of water that flows through sample over a period time.

Perraudin, Jean-Pierre 32

1767-1858. A mountaineer who lived in the southern Swiss Alps. His conclusion that at one point Alpine glaciers were more extensive would indirectly lead to Agassiz' Glacial theory.

Phlogiston Theory.. 69

The theory that an element called 'phlogiston' is present in materials that burn and is liberated upon combustion.

Photoautotrophs 71

Describes organisms that use oxygen to undergo photosynthesis in the presence of light.

Phreatomagmatic Explosion... 14

Volcanic eruption resulting from an interaction between magma (see *Magma*) and water. High magnitude explosions may result from rapid conversion of thermal energy to kinetic energy.

Phytoremediation 27

A treatment method of contamination through the use of plants for pollution uptake. This process exploits the plants' natural abilities to bioaccumulate and degrade harmful contaminants in soils, water, or air. Plants that have been successful at eliminating toxic waste include mustard plants and alpine pennycress.

Piezo-electric 25

Electric polarization in a substance (especially certain crystals) resulting from the application of mechanical stress.

Piltdown Man 85

The infamous fake remains of a species suggested to be the oldest Englishman, found in Sussex, UK in 1912. Named *Eoanthropus dawsoni*.

Pitchblende Ore (Uranite) 58

A mineral composed mainly of uranium oxide and other radioactive elements.

Planetary Embryos.. 64

Moon-sized or larger planetary bodies within protoplanetary discs that have undergone internal melting to produce differentiated interiors.

Planetesimal.. 63

A minute planet; a body that could come together with many others under gravitation to form a planet.

Plate Subduction 14

Geological process in which the edge of a lithospheric plate slides underneath an adjacent plate.

Plate Tectonics... 8-11, 14

Theory that describes the movement of the continental and oceanic plates of the Earth's lithosphere. Its four points are that: a) The Earth's surface is covered by a series of crustal plates; b) the ocean floors are generated at mid-oceanic ridges and spread apart from there; c) convection currents beneath the plates move the plates in different directions, and; d) the source of the heat driving convection is radioactivity deep in the Earth's mantle.

Plato.. 106

424BCE-328BCE. Noted Greek philosopher who was taught by Socrates and would eventually teach Aristotle after establishing his famed Academy.

Pleistocene Epoch 80

The geological epoch that spanned from 2.6 million to 11 700 years ago. Many megafauna lived during this epoch, including the woolly mammoth, saber-toothed tiger, and the giant sloth.

Pliny the Elder 14, 54

23-79 CE. A Roman philosopher and naturalist, famous for writings contained in his encyclopedia *Naturalis Historica ,* a staple in general education until the work was first attacked in 1492.

Point Bar 82

Depositional environment found mainly in meandering streams. Point bars are located on the inside bend of the stream, and are composed of well-sorted (commonly sand-rich) sediments.

Precession 36

A phenomenon in which the orientation of Earth's axis traces out a circle approximately every 26 000 years. Caused by variations in gravitation pull due to the equatorial bulge.

Primordial 71

Elementary or beginning; term used to describe the first life forms on Earth.

Protosolar Nebula 62

A large rotating disk of gas and grains largely made of molecules of hydrogen and helium.

Quadrant 25

An instrument used for taking angular measurements of altitude in astronomy and navigation, typically consisting of a graduated quarter circle and a sighting mechanism.

Radial Flow Equation 26

A diffusion equation that relates flux to hydraulic heads via Darcy's Law in a three-dimensional cylindrical coordinate system. Assumes a bounded circular drainage area and a fully penetrating well with vertical flow.

Radioactivity 58

A term introduced by Marie Curie to describe the phenomenon of the emission of particles because of instability of the atomic nucleus.

Radioisotope 61

An unstable form of an element, resulting from excess neutrons. Radioisotopes decay and release energy in the form of alpha, beta, and gamma radiation.

Radiometric Dating 105

Sample dating technique based on the changing composition of a radioactive isotope and decay product system. The technique yields accurate results for uncontaminated samples and compositions which have not been partially or entirely reset by metamorphic processes (see *Isochron*).

Recent African Origin Hypothesis 84

Hypothesis originally proposed by Darwin, that humans have one progenitor that originated in Africa.

Remote-sensing Image 75, 95

An image obtained through a device not in contact with the object being recorded.

Renaissance 89

A cultural movement spanning from the 14th to the 17th century. The Renaissance began in Italy, spreading across Europe, and brought advances in a wide range of fields.

Robert, Francois 63

1951-present. From the Museum of Natural History in Paris, he suggested that cometary bombardment could not be the only source of water on Earth.

Roches Moutonneé..35

Feature formed by the subglacial erosion of bedrock. These forms have a tear-drop shape, with a gentle sloping face pointing up-glacier and a jagged end pointing down-glacier.

Rock Grooves..34

Trough-like erosional features formed by the abrasion of boulder sized clasts beneath glacier ice. Similar to striations but of larger scale.

Röntgen, Wilhelm..58

1845-1923. A German physicist who is credited with a Nobel prize for the discovery of x-ray radiation in 1895.

Rutherford, Ernest.. 58, 60

1871-1937. A New Zealand-British scientist known for his contributions in atomic theory, especially in discovering the nucleus in an atom.

Sanders, John.. 18

1926-1999. An American geologist who was a major figure in the 1980s in a plan to clean up the Hudson River contaminated with polychlorinated biphenyls. He was the first to recognize the controversies concerning the definition of the term 'turbidite'.

Saturated Till..35

Water saturated glacial till composed of an unsorted mixed clay, sand, gravel and boulders.

Scanning Electron Microscopy.. 91

A form of electron microscopy that analyzes a sample with a beam of electrons. The electrons interact with the atoms of the sample, and produce signals that illustrate surface topography, composition, and other significant properties of the sample.

Scientific Revolution.. 88

An era spanning the 16^{th} and 17^{th} century in which the foundations of modern science were made due to advances in physics, astronomy, biology, medicine, and chemistry.

Second Pendulum.. 101

A pendulum which has a half period of exactly one second. Used in the manufacturing of the first accurate clocks. Currently used in modern day Grandfather clocks.

Sedgwick, Adam..72

1785-1873. A geologist who lived from 1785 to 1873 and is considered one of the founders of modern geology. He proposed the Devonian period of the geological time scale and later the Cambrian period.

Sedimentology.. 16

The study of modern sediments such as sand, mud, and clay, and the processes that result in their deposition.

Seismic Wave.. 19

Energy waves that result from tectonic activity such as an earthquake, explosion, or a volcano. Seismic waves are able to travel through various media such as fluids and rock.

Seismograph.. 19

Device used to measure seismic waves generated by seismic sources (see *seismic wave*).

Seneca, Lucius.. 13

3BCE-65CE. Philosopher, chief minister of Roman empire under Nero. Contributions to geology mainly *Naturales Quaestiones*, a book on natural science inspired by Poseidonius.

Sexual Selection **84**

Concept introduced by Darwin in *The Origin of Species* to explain elaborate traits, seemingly useless in the struggle for life. These traits are proposed to be selected for by the opposite sex, and thus propagated.

Signorini, Roberto **17**

n.d. An Italian geologist who first recognized graded sandstone beds of the Marnoso-arenace Formation in Italy (see *Marnoso-arenace Formation*).

Silica **71**

Naturally occurring silicon dioxide with the chemical formula SiO_2. Commonly white or brown in colour.

Siskiyou Trail **115**

A trail leading from Portland, Oregon to California. The first immigrants to California during the California gold rush used this trail to travel.

Skłodowska-Curie, Marie **58-61**

1867-1934. A French scientist known widely for her early work in discovering the properties of radioactivity and the discovery of the elements polonium and radium.

Sluice **31**

A controlled gated water channel that allows the influx of tidal water. The Sluice traps water for a sufficient amount of time for the tide to ebb and create a gap large enough to provide the trapped water with enough potential energy to turn the turbines in the barrage upon release (see *Barrage*).

Slumping **79**

A form of mass movement in which a layer of rock or loose material moves downslope.

Socialist Realism **112**

Philosophy of art espoused by the Communist government of the Soviet Union. Mandated that art had to reflect the reality of the working class.

Spectral Line **59**

Lines of emission or absorption of light in a material largely explained from quantum mechanics. These lines are commonly used to determine the types of elements contained in a mass (e.g. a star).

Spherule **77-79**

A round particle that was ejected into the air while molten and solidified while in flight.

Spring Tide **29**

The largest amplitude tides occurring when the Earth, Moon, and Sun are aligned, such that the largest gravitational pull from the Moon and Sun acts on the Earth. This alignment corresponds to a New Moon or a Full Moon.

Steno, Nicolas **54, 89**

1638-1686. A Danish Catholic Bishop is credited as one of the fathers of stratigraphy. His 1669 treatise on matter explained crystal growth as the accretion of particles from an external fluid to an external body. This treatise discredited panpsychism, the prevailing theory at the time (see *Panpsychism*). First to identify the Law of Constant Angles, although he applied it only to quartz.

Stratigraphy **19, 89**

A branch of geology that studies rock layers and bedding (especially their distribution, deposition, and age) in an attempt to understand the geologic history.

Stratosphere 52

The second most inner layer of Earth's atmosphere. Home of the ozone layer.

Striations 35

Lineations or 'scratches' on bedrock formed by glacial abrasion by rock fragments and sand grains held in the ice base. These subglacial erosional features can be used to infer direction of former glacier movement.

Studer, Bernard 16

1794-1887. A Swiss geologist who first recognized turbidites as 'flysch'. He prepared geological maps of Switzerland and was the first professor of mineralogy at University of Bern.

Subglacial Meltwater 35

Water at the base of a glacier formed by the melting of the basal ice. Geothermal heat is a great contributor for the melting process. This meltwater also acts as the lubricant for basal sliding of a glacier.

Subsidence 74

The gradual caving in or sinking of an area of land caused by the loss of moisture in sediments or erosion of foundation.

Suess, Edward 8

1831-1914. An Austrian geologist who proposed the contraction theory for the formation of continents and oceans.

Superior Type BIF 71

Also known as S-type BIFs. Are associated with oxygenation and trace back to the Archean to the Proterozoic time periods (see *Banded Iron Formations*).

Supernova 76

An explosion of a star. They are extremely luminous and accompanied by a large emission of radiation. Mistakenly proposed to have caused the K-Pg extinction event.

Superposition 88

The law or Principle which states that sedimentary layers are deposited in a time sequence, with the oldest at the base and the youngest at the top.

Sutter, John 114

1803-1880. One of the first men to find of gold in California in 1848. He owned a mill on the American River, near where his employee (see *Marshall, James*) found the first gold which started the California gold rush.

The Terror 89

The period of the French Revolution that lasted from 1793-1794. It marked a time of radical violence, and mass executions during tense conflict between opposing factions.

Tertiary 16

Geologic period from 65 million to 1.8 million years ago.

Theory of Evolution by Natural Selection 92

A scientific theory that states that the change in composition of a biological population is caused by the differential reproductive success of its constitutive members.

Theory of Geosynclines 8, 16

Theory proposed by James Hall and refined by James Dana. The theory accounts for the development of sedimentary basins (geosynclines) and the subsequent uplift of mountains.

Turbidite 16

A type of sedimentary rock composed of layered particles that grade upward from coarser to finer sizes. Turbidites are thought to have originated from turbidity currents in marine or lacustrine environments.

Uniformitarianism.. 10, 73, 93, 102, 110

Uniformitarianism is the assumption that the same natural laws and processes that operate on the Earth now, have always operated on the Earth in the past. This theory is therefore in direct opposition to the theory of catastrophism (see *Catastrophism*) and is widely accepted today. First theorised by James Hutton and popularised by Charles Lyell.

Unit Cell 57

The smallest repeating unit in a crystal, called a '*molécule intégrante'* by René-Just Haüy.

Unsaturated Zone.. 27

The zone between the land surface and the water table where soil pore spaces typically contain air or other gases, in addition to groundwater. It is also referred to as "zone of aeration" and "vadose zone".

Vassoevich, Nikolai... 16

1902-1981. A Soviet geologist whose principal works were on methods of studying flysch deposits and on the theory of the sediment-migration origin of oil.

Victorian... 102

Era of British history from 1831 to 1901, during the reign of Queen Victoria.

Von Humboldt, Alexander.. 36, 93

1769-1859. A German naturalist who contributed a great deal to the field of biogeography by publishing a detailed illustration of the variations in plant distribution on the surface of the Earth.

Wallace, Alfred Russel 8-11, 92

1823-1913. An English naturalist who discovered the theory of evolution by natural selection independently of Darwin and who did a great deal of pioneering research in the field of biogeography. Also invented the Wallace Line (see *Wallace Line*).

Wallace Line 14

An imaginary line dividing the group of islands that is modern-day Indonesia. Wallace (see *Wallace, Alfred Russel*) observed that each side of this line is host to a different set of animal and plant species. The divide was caused by continental drift bringing the Australian plate and the Indian plate into proximity with one another, but not close enough for migration to occur.

Wegener, Alfred 8-11, 38

1880-1930. A German geophysicist and meteorologist most notable for proposing continental drift.

Whaleback 35

A subglacial erosional feature similar to a roche moutonnée. Unlike the roche moutonnée a whaleback has smooth surfaces on all sides.

Wilson, John Tuzo... 14

1908-1993. A geophysicist, major achievement was in explaining plate tectonics (see *Plate Tectonics*) but was also respected for work on glaciers, mountain building, geology of ocean basins and structure of continents.

Also known as the tundra mammoth, the woolly mammoth is an ancient species from the Pleistocene era and found throughout North America and northern Eurasia (especially Siberia). Although closely related, the woolly mammoth is smaller than the Columbian mammoth, but larger than the modern day elephant.

An international United Nations agency established in 1950. It seeks to provide information about the Earth's atmosphere, climate, and hydrology.

Form of electromagnetic radiation with a wavelength on the order of one ångstrom.

A technique used in the modern analysis of crystal structures. X-rays shone on a crystal lattice are reflected. The reflected waves interfere constructively and destructively to produce a diffraction pattern. Interpretation of the diffraction pattern gives information about the size and shape of the unit cell.