5 800119 126142

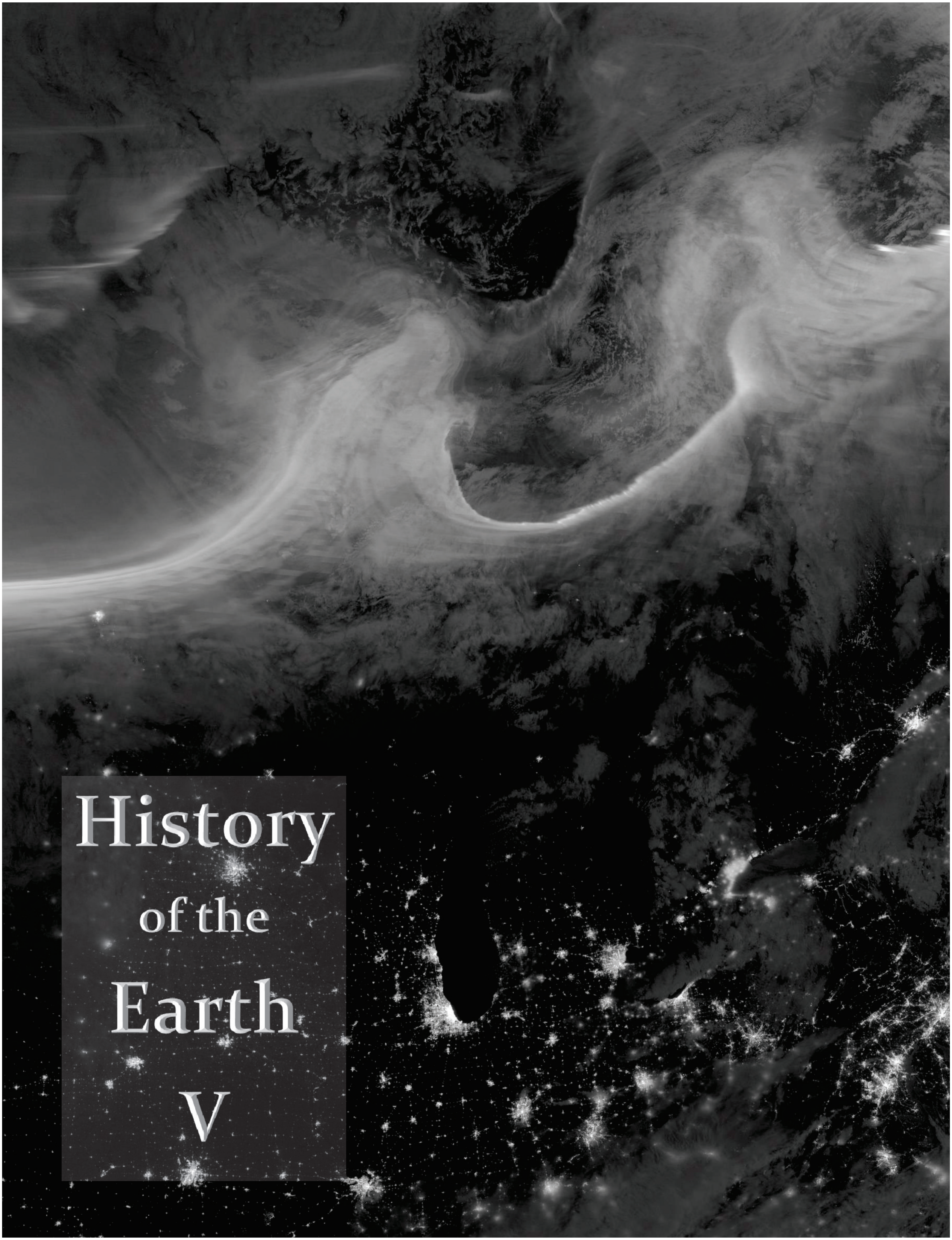
History of the Earth V

ISCI 2A18 2014/15

History of the Earth

Vol V

ISCI 2A18 2014/15



History of the Earth V

History of the Earth

Volume V: An Integrated and Historical Perspective

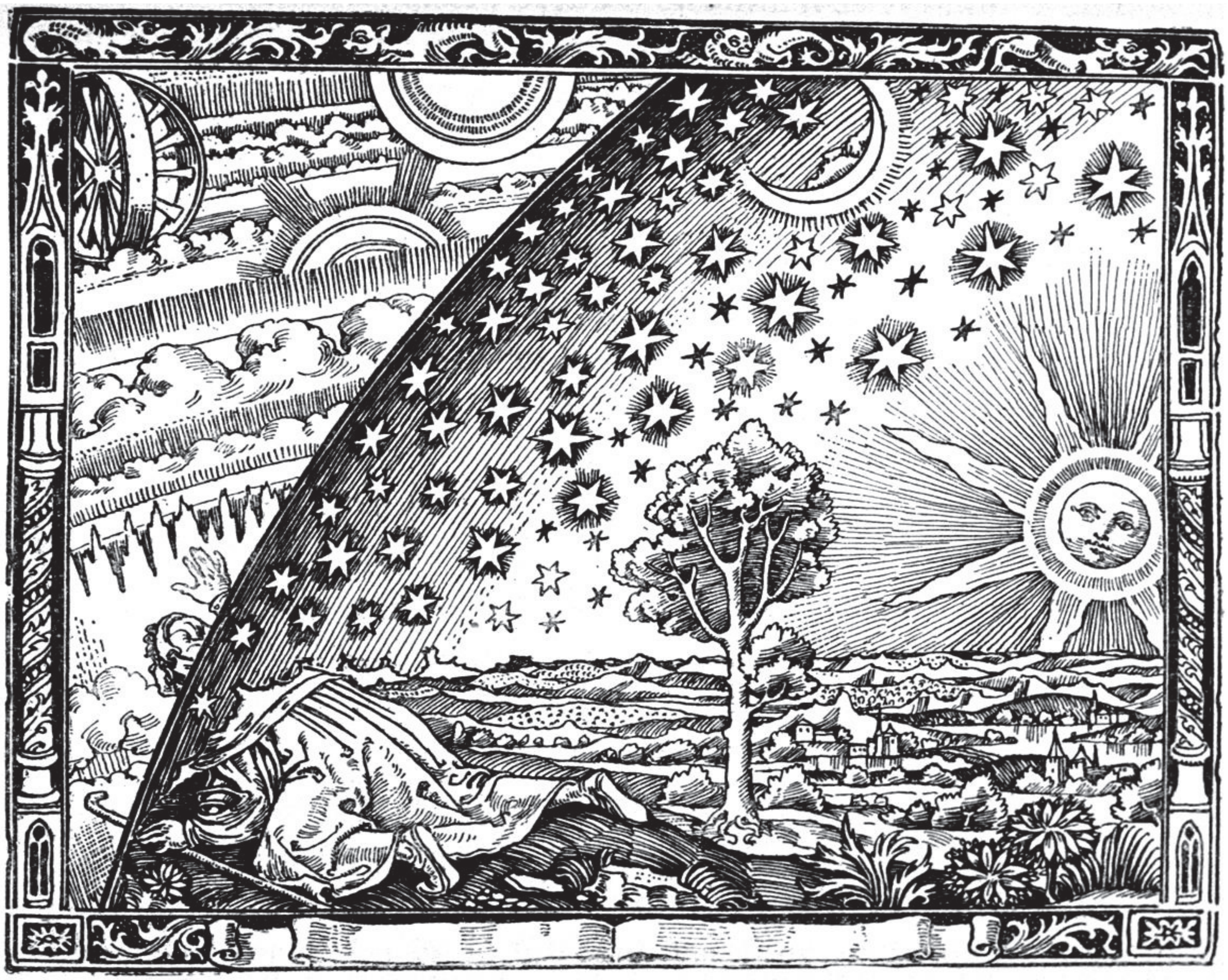
Authors

Meena Al Saigh
Dakota Binkley
Stephanie Black
Thomas Burrows
Loryn Byres
Lindsey Carfrae
Mindy Chapman
Evangeline Clark-Lepard
Alexander Dhaliwal
Biran Falk-Dotan
Timothy Fernandes
Tristan Goodwill
Deep Inamdar
Kylee Innes
Jaime Knoch
Lucia Krivankova-Smal
Miriam Krzyzewska
James Lai
Maximilian Lauch
Angelico Obille
Jesse Provost
Shakeel Qureshi
Elizabeth Sangster
Martyn Siek
Kyra Simone
Supriya Singh
James St. Pierre
Julianna Stagroom
Heather Summers
Charlotte Tousaw
Michael Wang
Jacqueline Watt
Nafis Wazed

Edited by

Carolyn Eyles and Sarah Symons

Contents



The Flammarion Engraving (1888) that depicts a traveller peering out of the firmament, the dome of the Earth, as he realizes the deeper intricacies of the universe that he lives in.

Introduction

It was like the stars themselves had come down to meet us. The flames licked their way up the charred branches and sparks arced through the air and landed in the damp ground at our feet. Other creatures scurried for places to hide, frightened by the terrific display, but we stood firm. Perhaps it was the heat that drew us in or it may have simply been some inherent sense of wonder within us. As the sparks flew from the tree, sparks flew in our minds. As the flames lit the branches, flames reached inside us. It could have been nature's way of showing off its raw energy, ensuring we knew our place in its domain. Whatever the reason, this energy lit a fire inside us. It lit the fire of curiosity, the thirst for knowledge and understanding. We understood our place in this world, we understood the power nature held over us, but we also saw all that can be learned from it and all that can be exploited. We took the fire and we used it. We used it to light our way. We used it to cook our meals. We used it to create new tools from our surroundings to make life easier for us. Most importantly, we used it to peer into the dark corners of knowledge, to study and explore all that made the Earth the way it is. The ability to ponder and reflect upon the universe that we live in truly identifies us humans as intellectual beings. Like a spreading fire, the curiosity within humans drives us to explore and seek answers.

This curiosity is the driving force of science. Over centuries, we have developed a scientific method to answer questions about the world around us. Asking questions and making hypotheses about our own planet has provoked a more intricate perspective on nature. We have made incredible progress in exploring the unknowns of our world. This volume is an account of this progress that will describe the history of The Earth, how we studied it, and how we – as a species – have developed intellectually over the course of natural history.

Figure 1.0.1: An image of cephalopod fossils. These fossils and many others have been found and slowly identified as key creatures in early life.

Chapter 1: Paleontology

While life as we know it has inhabited the Earth for billions of years, the human race itself has seen only a small fraction of the innumerable life forms that once walked the land, swam the seas, and soared the sky. These mysteries continue to inspire curiosity about beings that previously occupied the world that we now call our own. This curiosity has taken us up mountains, into caves, and deep beneath the ocean. Over time, humans have slowly reconstructed the puzzle of what came before. Fossils from across the globe led us to our current understanding of primordial life and the evolutionary pathways from which modern beasts emerged. While interpretation of this fossil record allowed us to visualize ancient creatures and environments, this endeavour was no easy task. The reconstruction of these paleoenvironments took hundreds of years, as it necessitated the challenging of scepticism and the distinguishing of the natural from the artificial.

This chapter investigates specific instances in history where the fossil record and other geologic evidence has been interpreted, expanded upon, revolutionized, or argued. These historical events and discoveries have provided the impetus to explain the events of the past, including mass extinctions and the evolution of avian species. More recently, there has been significant development in the field of strategic fossil exploration. Certain geological techniques, such as radiometric dating, allow us to determine when these ancient creatures roamed the Earth. Utilization of new discoveries and technology has led us to a better understanding of the origins of life. However, recent exploration attempts have not all been without issue. The delicate nature of paleontological excavation calls for measures to be taken to protect sites of geological and anthropological significance.

Just as the process of scientific discovery has undergone change throughout the thousands of years of human existence, so too has life evolved since the emergence of the first cell on primordial Earth. There is no way to know what missing link will be discovered next, but we can be sure that the next discovery is waiting just around the corner.

Nicholas Steno: The Father of Stratigraphy

In 1668, the Danish scientist Nicholas Steno (originally Niels Stensen and later latinized to Nicolaus Stenonius) wrote one of the foundational works of modern stratigraphy and the process of relative dating, the act of determing the age of rocks relative to other rocks. *Nicolai Stenonis De Solido Intra Solidum Naturaliter Contento Dissertationis Prodromus*, translated to *The Prodromus of Nicolaus Steno's Dissertation Concerning a Solid Body Enclosed by Process of Nature Within a Solid* and often refered to as simply the *Prodromus,* is a work that is remarkable in many ways, which extend far beyond the ground-breaking revelations in geology that it describes. To understand the remarkable nature of this work, it is important to know more about Nicholas Steno.

Figure 1.1.1: A portrait of Nicholas Steno painted around the time of his death in 1686 (above). Steno was an avid anatomist, geologist and theologian, and is now referred to as the father of modern stratigraphy.

Steno was a passionate anatomist determined to map all of the glands in the body (Steno 1669, p.4). In 1665, Steno's studies took him to Florence and the court of the Grand Duke of Tuscany, Ferdinand II. Recognizing Steno's knowledge, Ferdinand II appointed Steno as his physician and as a surgeon at the hospital of Santa Maria Nouva (Kardel and Maquet, 2013). These positions gave Steno the ability to travel through the surrounding area and pursue the scientific questions that he found interesting.

Towards the end of 1666, some French fishermen captured a 1200kg great white shark, pulled it onto land, and beheaded it (Cobb, 2006). After news of the beast reached Ferdinand II, he ordered the head to be taken to Florence and asked Steno to dissect it in front of the court. Steno found the experience very rewarding and published his observations in his 1667 work *Canis Carchariae dissection Caput*. During the dissection, Steno noticed that the teeth very closely resembled stones from Malta that he had studied in his student days in Copenhagen (Kermit, 2003). This observation likely contributed to his fascination with the origin of fossils.

In late November 1664, Robert Hooke had published his *Micrographia*, which included a theory that fossils were the remains of petrified organisms, something highly controversial at the time. Steno likely saw this work in early 1665 and, after he dissected the shark, Steno decided to travel and make scientific observations of the geology of Tuscany and the island of Elba (White, 1968). Believing that Steno had been gaining insight into that issue, the Grand Duke requested that Steno write a work on the origin of fossils (Steno, 1669).

Steno's Conversion

While working in the court, Steno conversed with many people. Two individuals that are reported to have deeply effected Steno were an elderly nun named Sister Maria Flavia del Nero, who worked at a store that supplied Santa Maria Nouva; and Emilio Savignani, a Jesuit priest who was the rector of the Jesuit College in Florence (Miniati, 2009). Steno is known to have been a Lutheran when he moved to Florence, though he is not believed to have been a devout follower since his time in Holland a few years before (Kardel and Maquet, 2013). As Steno became acquainted with Sister Maria Flavia, he asked her opinion on many questions of faith (Kermit, 2003). Those conversations are known to have affected Steno to the extent that, when Sister Flavia suggested that they recite the Angelus prayer together one morning, he agreed. He is also known to have taken her advice to visit the Basilica della Santissima Annunziata. Steno's conversations with Savignani are less well documented, but many academics, including Steno himself, believe them to have had the largest influence on Steno's faith (Miniati, 2009). After several years in the court, Steno decided to convert to the Catholic faith and was received by the church on December 8, 1667 (White, 1968).

This conversion is believed to have been genuine, and Steno's new faith strongly affected the way that he made his decisions after this point in his life (Kardel and Maquet, 2013). Steno's faith was so great that he decided to become a bishop in 1677 and was beatified in the 20th century.

This leads to the first way in which his work is remarkable: its balance of science and religion. In reading the *Prodromus*, it is apparent that while Steno did not doubt the young Earth theory, which was accepted at the time, he made clear distinctions between his observations of the environment and his hypotheses about why the environment appears the way that it does. Even within the hypotheses that he put forward, he did not state that those things that he could not understand were due to divine action; instead, Steno acknowledged that the cause may be something mundane that he did not yet know. To a modern reader, this may not seem remarkable, but it should be noted that this was not the norm in a time heavily influenced by the church (Kardel and Maquet, 2013). Steno's rationality even went so far as to lead him to refer to "the great Galileo," only a few decades after the Church's severe response to Galileo's theory of heliocentrism (Steno, 1669, p.50). Steno's rationality, however interfere with his faith and Steno requested that Vincentius Viviani read his work and ensured that there was nothing "in it which is contrary to the Catholic Faith or to good morals" (Steno, 1669, p.77). These two points show the skill that Steno had in maintaining his faith without letting it mar his perceptions of the world.

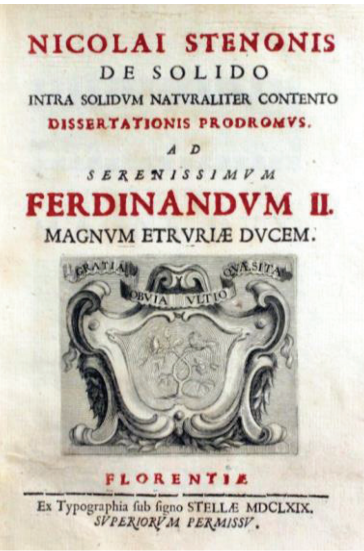
A Hasty Draft

Around the time of his conversion, the king of Denmark, Fredrick III, summoned Steno back to Denmark (Kardel and Maquet, 2013). Before Steno responded to the summons, he wanted to ensure that the king would accept his new religion and sent a letter to inform the king of his recent conversion. Knowing that he would likely have to leave Florence shortly, and not wanting to break his promise to Ferdinand II, Steno quickly drafted the *Prodromus*, a preliminary work on his observations, intending to write a longer dissertation later (Steno, 1669, p.4). Unfortunately, the main dissertation never appeared, possibly because Steno became fascinated with theology around the same time as writing the *Prodromus* (White, 1968).

The draft was finished before Steno left Florence on July 4, 1668. The short time frame of this drafting has been said to give the writing a "sketchy character" (Kardel and Maquet, 2013, p.209), and it is likely the reason for the lack of structure throughout the work. Despite the fact that it was only intended as a preliminary work, the *Prodromus* is still one of the most fundamental works in the study of stratigraphy and the reason that Steno is known as the father of stratigraphy (White, 1968).

Steno's scientific method is also notable. Steno notes that "those points which cannot be definitely determined, are not distinguished from those which can be settled with certainty" (Steno, 1669, p.9). In this statement, Steno recognizes that there are some things beyond his understanding, and that those things are not clear. In the same paragraph, Steno pointed out that many other scientists of the time suffered from contributing too many things to a single category and that it hindered their work. In an attempt to prevent himself from doing to the same, Steno clearly delineated what was certain and what he believed to be true. Steno's criteria for something to be certain were that either it could be physically observed in the environment or it was a well-accepted fact by all schools of thought in the scientific community, from the most conservative to the most progressive (Steno, 1669, p.10).

The theories that Steno put forward in the *Prodromus* were not based on mere speculation, but on logic that he recorded in the work. Steno usually did this by stating a series of points about a topic that started from what he believed to be certain and then built off each other until he had arrived at his final idea.



NICOLAI STENONIS
DE SOLIDO
INTRA SOLIDVM NATVRALITER CONTENTO
DISSERTATIONIS PRODROMVS.
AD
SERENISSIMVM
FERDINANDVM II.
MAGNVM ETRVRIÆ DVCEM.

FLORENTIÆ
Ex Typographia ſub ſigno STELLÆ MDCLXIX.
SVPERIORVM PERMISSV.

Figure 1.1.2: The cover page of the Prodromus *(above). The* Prodromus *was a preliminary work to a larger dissertation that was to be written later, but never appeared. Despite only being preliminary, it is the first work on relative dating and is the basis of modern stratigraphy.*

His Findings

As an answer to his original purpose, Steno justified the idea that fossils were the remains of organisms, as suggested by Hooke a few years before. He based this on the idea that, due to the preservation of the shape of fossils, the surrounding solid must originally come from a fluid, a theory not previously stated (Kardel and Maquet, 2013). Within the *Prodromus*, Steno also laid down many other important principles and theories that touch upon crystallography and, perhaps more importantly, stratigraphy.

Based again on the idea the solids are formed by liquids, Steno developed a theory that mineral crystals form through nucleation and growth out of a fluid. Steno also provided a limited explanation of the formation of mountains, an understandable feat given the low relief locality from which he drew his observations.

The concepts for which the *Prodromus* are most frequently referenced are those pertaining to stratigraphy. Based again on the idea that solids come from liquids and other observations, Steno developed the foundational principles of stratigraphy. However, the modern names for these principles came after Steno's time. His simplest idea was that, as solids are formed from fluids, they are formed horizontally. Today, this is known as the principle of original horizontality. Steno also pointed out that for a solid to be formed, there must be an older solid beneath it to provide support, an idea known as the law of superposition. Steno was also fascinated by solids containing fragments of other solids, and stated that if a solid containing another solid contained the properties of the surface of that solid, then the solid contained within it is older than the surrounding solid: the law of included fragments. Steno pointed out that if a solid or discontinuity cuts through other strata, the strata must have existed prior to the cross-cutting, so it must be older. Today, this is known as the principle of cross-cutting relationships. Steno also spent a large amount of time examining the properties of solids and stated that they are based not only where they are found, but also on where they formed. This led him to the idea that laterally adjacent solids with the same properties were formed through the same processes, so they can be considered the same body of rock: the principle of lateral continuity.

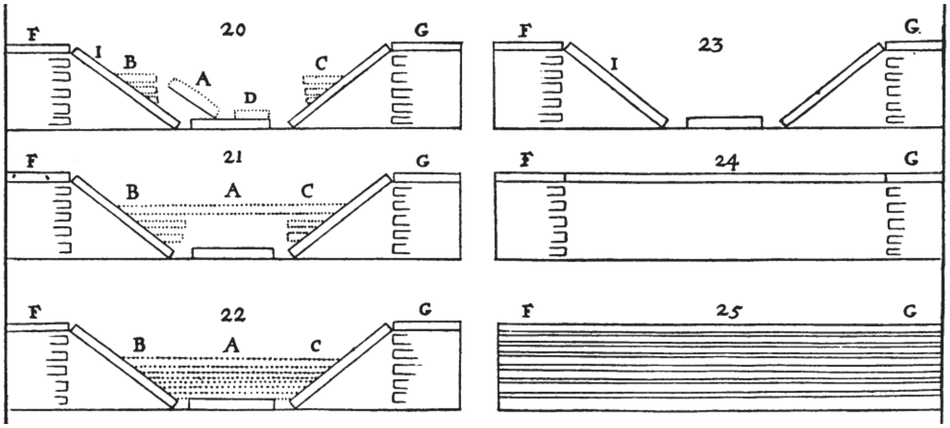


Figure 1.1.3: Theses six images (right) were included by Steno in the Prodromus. *In these figures, Steno uses the geologic principles that he developed to work backwards through the geologic history of Tuscany. Starting with broken beds of sediment contained within a valley (20), he goes back to a time that they were continuous and flat, and then he does the same things with the older rock strata found in the region.*

The logic behind these ideas is well laid out in the *Prodromus*, though it is noticeable that there are certain observations that were intended for the dissertation but were not included in this preliminary. Considering the quality of the work that Steno had produced when rushed, one can only imagine what the full length work would have looked like if Steno had not been distracted by his study of theology. However, the *Prodromus* is so concise and complete that it has been able to stand alone for three and half centuries as the foundational work on stratigraphy.

The Response

Following the approval of the work by Viviani in August, 1668, the *Prodromus* was printed in 1669 (Kardel and Maquet, 2013). Copies of the work were dispersed to friends of Steno by Vivani, but interest in his work also came from outside of Italy. By 1671, the work had been translated into English, though interest in the work began to fade after that. The work was largely ignored in the 18th century apart from the 1757 French translation found in the *Collection Académique* and the 1771 English translation by Henry Oldenburg of the Royal Society. The work began to make more appearances in the 19th century, but only truly became popular due to the efforts of the Danish professors A. Krogh and V. Maar (Kardel and Maquet, 2013). In 1910, the Maar edition of the *Prodromus* became easily accessible in a good translation.

Radiometric Dating

While Steno's observations allow us to determine the age of rocks relative to the other rocks around them, they do not allow us to determine the absolute age of the rock. Attempts to determine the time of formation of a rock were made in early geology, primarily based on the rates of accumulation of sediment; however, these estimates were difficult and often inaccurate (Stanley, 2005). In 1896, Antoine-Henri Becquerel submitted a new discovery to the Académie des Sciences. Becquerel had discovered spontaneous radioactivity, something that would revolutionise attempts to absolutely date rocks, though not through his work alone. In her 1903 doctoral thesis, Marie Curie developed a better understanding of what radiation was and, in 1905, Rutherford suggested that this could be used to determine the relative age of rocks. After seeing these works, Bertram Boltwood used radioactivity to estimate the age of a rock in his 1907 paper *On the Ultimate Disintegration Products of the Radio-active Elements. Part II. The Disintegration Products of Uranium.*

Early Radiometric Dating

In his paper, Boltwood observed that that the ratio of uranium to lead within rocks was very close to other similar rocks found in close proximity but very different to rocks found in different locations. Knowing that uranium decays into lead over time, Boltwood hypothesised that the ratio of uranium to lead could be used to determine the age of the rock, based on the rate of decay of uranium to lead. While the rate of decay of uranium was not known at the time, he knew the rate of decay of radium and used this to estimate the rate of decay of uranium to be 0.1 billionth of the remaining uranium per year. He used this number to estimate the ages of the rocks that he had analyzed.

This process is known as radiometric dating and has been used since Boltwood wrote this paper in 1907. Boltwood's method, while revolutionary, was not entirely accurate. Boltwood did not know about the different isotopes of uranium. As a result, he did not realise that the rate of decay was not directly related to the amount of uranium. In fact, it was related to the amount of two uranium isotopes, each with different rates of radioactive decay (Parrish and Noble, 2003). The development of mass spectrometry in the early 1940s introduced a good way to determine the ratio of different isotopes within a sample, and, in 1946, this was used to make radiometric dating more accurate (Roth, 1989).

Modern Radiometric Dating

Since the time of early radiometric dating, the technique has been refined and new isotopes have been identified that expand the possibilities of radiometric dating. Radiometric dating works based on a few simple assumptions: all of the daughter products produced by radioactivity prior to the cooling diffuses out of the sample, so no daughter product is present at the time of cooling; all daughter product produced after cooling is still present at the time of measurement; and that there are no other pathways through which the parent product can decay or the daughter product can form (Plummer et al., 2004). Even if these assumptions are not valid, absolute dating can still be possible, though it is more complicated (Roth, 1989).

Using these assumptions and the known half-life of an isotope, geochronologists can determine the age of rocks. While the original amount of the isotope may not be known, geochronologists can compare the amount of isotope remaining to the amount of daughter product produced and back calculate the time it took for that daughter product to form. This, of course, only works if there is enough of both the parent and daughter isotopes to be measured accurately, which constricts radiometric dating to the half-life of the isotope, which leads to the idea of using isotopes with different half-lifes for rocks of different ages (Figure 1.1.4).

Parent isotope	Daughter Isotope	Half-Life (years)
^{14}C	^{14}N	5370
^{235}U	^{206}Pb	713 million
^{40}K	^{40}Ar	1.25 billion
^{238}U	^{207}Pb	4.15 billion
^{232}Th	^{208}Pb	14.1 billion
^{87}Rb	^{87}Sr	48.8 billion

Figure 1.1.4: Some of the major radioisotopes used in radiometric dating.

George Cuvier: Fossils and the Geologic Record

Biography

Baron George Cuvier (Figure 1.2.1) (1769-1832) is often portrayed in history as a villain who, with his vocal and unbending rejection of evolutionary concepts, held back scientific progress by decades (Ager, 1993).

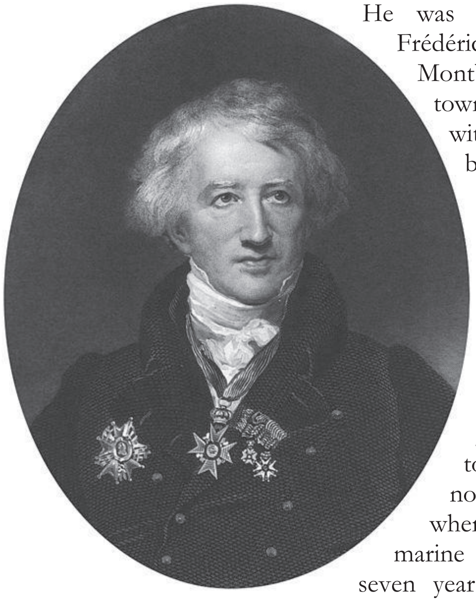


Figure 1.2.1: A portrait of George Cuvier (1769-1832) painted by W.H. Pickersgill in 1831 and engraved by George T. Doo in 1840.

He was born Jean-Léopold-Nicolas-Frédéric Cuvier in 1769 in Montbèliard, a French speaking town near the modern border with Switzerland, to a protestant bourgeoisie family that deeply respected education as a means to improving social standing (Lee, 1833). In 1784 he was sent to Karlsschule, a university in Stuttgart, where French speaking "George" became fluent in German. Upon his graduation four years later, he took a job as a tutor with a noble family in Normandy, where he was first introduced to marine mammals (Lee, 1833). His seven years in Normandy profoundly influenced his later work. He utilized the time and location to explore mollusks and the geology of Normandy. Cuvier wrote a number of papers on these subjects, which he sent to Paris. This put him in touch with academics there who facilitated his transition into the Paris academic community (Lee, 1833). In 1795, at the age of 26, he moved to Paris, where the French Revolution allowed him the opportunity to rapidly rise to prominence in scientific circles. His work there in comparative anatomy and geology has informed scientific debate for centuries (Rudwick, 1997).

French Revolution

The French Revolution began in 1789 while Cuvier was still in Normandy, and its more violent, radical phase destroyed many of the previously established scientific institutions in Paris, driving away many of the established academics (Rudwick, 1997); this provided a number of unique opportunities for Cuvier. The chaos dismantled institutions, redistributed collections, and disrupted the old system, which required strong political and academic connections to establish a career in science. These factors allowed Cuvier to gain a strong foothold in Paris.

He obtained a position as the junior understudy to Mertrud, the Chair of Anatomy at the Muséum Nationale d'Histoire (National Museum of History) (Rudwick, 1997). The Muséum had an extensive collection of resources for him to study, a collection made even more extensive by the addition of collections from the conquered ruler of the Netherlands, a conquest of the revolutionary wars. With this multitude of resources at his disposal, Cuvier quickly became an expert in the field of comparative anatomy (Rudwick, 1997). The Royal Academy of Sciences was one of the many organizations that was disassembled after the revolution. A new National Institute was being founded to replace those destroyed, and Cuvier was quickly elected to it. This provided him with a means by which to present his many findings (Rudwick, 1997).

Extinction as a Fact, Not Fiction

Prior to Cuvier's time, the concept of extinction did not exist, in part due to religious beliefs that governed the world at the time (Kolbert, 2014). Cuvier's research at the Muséum Nationale d'Histoire changed this. Previously it was assumed that the fossils that were beginning to fill collections and museums throughout Europe were those of currently existing species. Fossils that resembled species no longer found in that region were thought to have been moved there by flooding or other natural processes, or were used as evidence of different historical climates in that region (Kolbert, 2014). In the case of some of the strangest fossils, the living species was simply thought to not yet have been found.

One of these strange cases, was that of the Ohio animal. It was the subject of intensive international debate following its discovery in 1739 (Kolbert, 2014). The Ohio animal consisted of a great many bones similar to those of elephants, which were being found throughout the northern hemisphere in the 1700s, including those of the mammoth in Siberia. A number of theories were proposed to explain both the unusual location of these fossils, and the differences between them and the extant elephants found in Asia and Africa. One theory proposed that the Earth had been warmer, and that as it cooled the species moved towards the equator; others suggested that the fossils had been moved to their current location by a giant flood, such as that described in Genesis.

The anatomical differences between the fossil creatures and the extant elephants were not so easy to explain. In particular, the molars of the fossils differed both from each other, and from the extant elephants (Rudwick, 1997). In the case of the Ohio animal it was theorized that this discrepancy was due to the fact that the Ohio animal was in fact two separate animals, with the limbs and tusks being from an elephant, and the molars coming from another species, the hippopotamus. To accommodate other anatomical differences, this was later expanded upon to suggest that the remains also included a third species, one which was not yet known (Kolbert, 2014).

The museum's collections included the skulls of both African and Asian elephants, which were at the time thought to be the same species. Through examination of their molars, Cuvier determined them to be different species (Rudwick, 1997). He then applied the same technique to the remains of both the Ohio animal and those of a mammoth from Siberia, and found that not only did the fossil creatures differ significantly from the extant, but also from each other. The Siberian fossil was that of a mammoth, while the Ohio animal was a mastodon (Figure 1.2.2). He presented these findings in 1796 to the Institute, and published a paper on it 1799, effectively establishing extinction as a fact (Rudwick, 1997). By 1812 he had increased the number of extinct species from zero to forty-nine (Kolbert, 2014).

Figure 1.2.2: An artist's rendition of the Ohio animal, now known as the American mastodon, created by Charles R. Knight in 1897.

Comparative Anatomy: A Geologic Tool

Cuvier's obsession with fossils extended into the field of geology. He began to collaborate with a man called Alexander Brongniart, and together they began to record the stratigraphy of the area around Paris. Cuvier and Brongniart brought a novel approach to previously conducted work by paying specific attention to the fossils within the beds (Rudwick, 1997). In particular they looked at the anatomy of the mollusks to determine if the beds were marine or freshwater beds.

They discovered alternating beds of marine and fresh-water deposits. A number of these beds also contained the remains of terrestrial animals (Cuvier and Brongniart, 1822). From this information, Cuvier and Brongniart were able to form a relatively detailed history of the region around Paris. They described a history in which the region alternated between marine and freshwater, with intermittent terrestrial environments (Cuvier and Brongniart, 1822). Cuvier believed that fossils were the key to understanding geology and the history of the Earth and he used his work on the Paris region to illustrate that point (Cuvier, 1825).

Catastrophism and Transformism

The concept of extinction brought with it a new set of questions, chief among these being how and why species went extinct. Cuvier's answer to this question was that the world had undergone a number of what he called "revolutions", or large-scale changes in the environment which led to the extinction of large numbers of species (Rudwick, 1997). He described these revolutions as sudden and violent. This theory likely stemmed from how Cuvier viewed the animals he studied: as machines which were well adapted to the environment in which they lived. From this point of view, those species would have had to have been destroyed in a sudden, and likely violent, catastrophe. His theory went on to propose that new creatures also arose following these catastrophes (Rudwick, 1997).

This work evolved into Catastrophism, the theory that geologic features are the result of relatively short, violent events (natural disasters), and it has often been associated with religion (Huggett, 1990). It has been proposed that Cuvier designed his theories to fit with the Great Flood, mentioned in Genesis, however, while he consistently argued against evolutionary concepts, his writings show no indication of him supporting religious explanations, or designing his theories to support the bible. In fact, his numerous works show consistent skepticism for all religious and ancient texts (Rudwick, 1997).

A different answer to the same question was developed by his colleague Jean-Baptiste Lamarck. Transformism was an early version of evolution, and Lamarck suggested that Cuvier's extinct species were not extinct, rather they had been extensively transformed into the animals we see today (Kolbert, 2014). Cuvier repeatedly rejected this opposing theory of transformism; this strong rejection of what is currently considered a well-established concept explains why Cuvier is so consistently vilified even today (Ager, 1993).

Throughout his texts, Cuvier displayed a strong reluctance to theorize on either the origins of life or on the specific type of catastrophe involved in the revolutions he described. He relied solely on empirical observations, and shunned hypotheses and theories of any kind (Rudwick, 1997). This was in great part why he was so reluctant to consider transformism. During Cuvier's time, fossils which showed a transition from ancient species to modern ones had yet to be discovered. He himself remarked on this lack of transitional forms in one of his papers, and stated that if the current species were in fact transformations of the old, there would be transitional forms in the fossil record (Cuvier, 1825). These forms would eventually be found, but not until after his time. Cuvier was for the most part successful in defending his views until his death in 1832, however by the mid-1800s they had been almost entirely discredited in favour of evolutionary theories (Kolbert, 2014).

The Return of Catastrophism

Uniformitarianism, the idea that current geologic processes, at current, uniform rates, account for all the geologic and biological phenomena we see today, has dominated the field of geology for the last one and a half centuries (Courtillot, 1999). However, there is increasing evidence that the earth has undergone a number of catastrophic events, or mass extinctions which has led to a resurgence of catastrophist concepts. To separate the current concept from the religious connotations of catastrophism, the new theory is often referred to as neo-catastrophism (Huggett, 1990).

Mass extinctions have been neglected in scientific study and have only begun to attract attention in the last few decades. They can be generally defined as an event in which a significantly large proportion of the world's species become extinct in a geologically short time interval (Hallam and Wignall, 1997). There have been five major extinction events, "the Big Five", within the last 500 million years: the Late Ordovician, the Late Devonian, the Late Permian, the Late Triassic, and the Late Cretaceous (Hallam and Wignall, 1997).

The first of these, the Late Ordovician event, took place around 440 Ma ago and is thought to have been the second most severe event of the Big Five, with 57% of all marine genera and up to 86% of all species being lost. It is thought to be the result of the onset of glaciation and the associated changes in climate, and sea levels (Barnosky et al., 2011). It was followed by the Late Devonian event, 360 Ma ago was not quite as severe, with only 35% of marine genera and 75% of species being lost. It is associated with a period of global cooling, then warming, as well as with an anoxic marine environment (Barnosky et al., 2011).

The largest of the Big Five is the Late Permian event 250 Ma ago, and is often referred to as The Great Dying (Allen and Briggs, 1990). During this period it is thought that up to 56% of marine genera and 96% of species were lost. The cause of this widespread destruction is thought to be volcanism. The volcanic gasses would have led to increased atmospheric and aquatic concentrations of CO2 and H2S, resulting in global warming, anoxic marine conditions, and acid rain, which would have increased the acidity of aquatic environments (Barnosky et al., 2011). The Late Triassic event 50 Ma later is thought to have resulted from the similar causes of global warming and volcanic activity, and resulted in the loss of 47% of marine genera and 80% of species (Barnosky et al., 2011).

The Late Cretaceous event, around 65 Ma ago, is the last of the Big Five, and the most famous as it is responsible for the extinction of the dinosaurs (Allen and Briggs, 1990). 40% of marine genera and 76% of species are estimated to have been lost and is thought to be the result of an asteroid impact in the Yucatán (Figure 1.2.3), which had widespread environmental and climatic impacts (Barnosky et al., 2011).

Figure 1.2.3: An artist's rendition of an impact event, similar to that which may have caused the Late Cretaceous extinction event 65 million years ago.

Each of these events was associated with a drastic decrease in biodiversity, however, the resulting available niche allowed for the surviving species to radiate and evolve in ways which may never have been possible without the extinction events (Hallam and Wignall, 1997). Some scientists see the current rapid decline in biodiversity as an indicator that we may be on the brink of a sixth extinction, one in which we are the primary cause (Kolbert, 2014).

These events show that the theories of catastrophism that were so readily dismissed and ridiculed in the mid-1800s may have more validity that originally thought; perhaps Cuvier did not deserve to be completely vilified over the years. Current theories combine both catastrophism and evolutionary concepts, describing periods of prolonged, gradual changes and evolution, punctuated by catastrophic events, where both components play a significant role in shaping the world as we know it today (Kolbert, 2014).

Discovery and Controversy of Avian Evolution

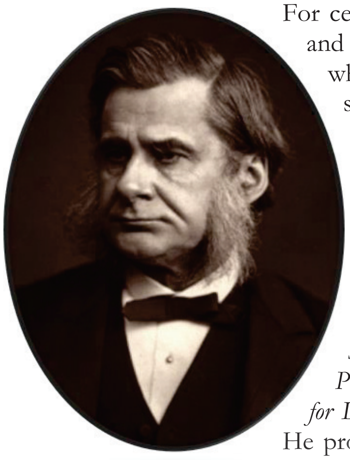


Figure 1.3.1. Thomas Huxley was born in 1825 and died in 1895 (Davis, 1907). His contributions to palaeontology and the evolution of birds are notable.

For centuries humans have gazed at the sky and dreamt about reaching the clouds, while avian animals have been able to soar across the firmament for millions of years (Norell, 2005a). Controversy from the late 19th century to the 20th century surrounded the idea of flight and evolution of the avian feather.

Charles Darwin was the first to observe and propose the idea of evolution in his book *The Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* published in 1859 (Darwin, 1859). He proposed the ideas of common ancestry and natural selection stating that every species evolved from an earlier species. Thomas Huxley (Figure 1.3.1), a dear friend of Darwin, agreed with these ideas and after conversing with Darwin regarding his findings became a supporter of evolution (Huxley, 1903; Foster and Lankester, 1898). Though Huxley argued with Darwin over certain aspects of his observations, he largely appreciated the idea and concepts of evolution (Davis, 1907; Huxley, 1903). These feelings were evident in the letters he exchanged with Darwin in the early 1860s (Huxley, 1903).

Thomas Huxley's Observation

Huxley was an English upper-class zoologist who studied the anatomy of modern birds and quickly became a major figure of Victorian paleontology (Norell, 2005a). Before discovering his interest in both biology and paleontology he focused his time on educating himself in medicine to become an assistant to an English doctor, Dr. Chandler (Davis, 1907). During his training he attended the University of London where he received countless academic awards and medals. He later began working at Charing Cross Hospital and soon joined the Navy to assist naval surgeons with their medical duties. While serving as a medical assistant on naval ships Huxley was introduced to Dr. MacGillivary, a naturalist on the ship hired to take detailed notes while voyaging in Australian and East Indian waters. Huxley joined the exploration whenever he could and this led to his interest in biological organisms. As a result, Huxley decided to transition from medicine to biological research.

Throughout his early research career Huxley focused his time and energy on a variety of subjects including anatomy and cell theory (Foster and Lankester, 1898). In some of his most notorious work in 1868 and 1870 he concentrated on publishing articles on the bone structures of small modern birds, including drawings outlining the main skeletal features of the birds. Despite Huxley's interest in modern avian creatures, he was gradually introduced to diverse fossils of reptiles in 1859 and began to ponder the origin of all these animals (Switek, 2010).

Huxley has been credited with being the first to claim that birds are very distant relatives of dinosaurs after viewing many fossils in London (Norell, 2005a; Switek, 2010; De Bont, 2010). This fact however, is considered to be under historical debate since many reputable scientific institutions and individuals disagree on the interpretation of Huxley's work (Norell, 2005a; Natural History Museum, 2014; Switek, 2010). Some claim that Huxley was first shown a variety of *Megalosaur* fossils (Norell, 2005a). After seeing these he noticed that the bones in these fossils were oddly similar to both the *Archaeopteryx* specimen (considered the first specimen to show a relationship between birds and dinosaurs) and the modern birds from his previous publications. Huxley continued to analyze the similarities between the three types of specimen, counting 35 similarities such as hollow bones and long necks. From this observational data Huxley deduced that birds were related to dinosaurs and published his paper titled *Further evidence of the affinity between the dinosaurian reptiles and birds* (Dodson, 2000). Others believe that the interpretation of this paper throughout history has been incorrect and Huxley mainly focused on the relationship between reptiles and birds, hardly discussing dinosaurs and birds (Switek, 2010). Nevertheless, it is clear that Huxley saw some sort of relationship between birds and reptiles and potentially dinosaurs.

Fossil Forgery and Authenticity

One of the fossils Huxley analyzed was *Archaeopteryx* (which translates to "ancient wing"), a fossil that is considered the missing link between dinosaur and bird (Figure 1.3.2) (Norell, 2005a; Dodson, 2000; Dyke, 2010). The first *Archaeopteryx* fossil was unearthed in 1861 in the Solnhofen limestone quarries in Southern Germany (Swinburne, 1988; Dyke, 2010). *Archaeopteryx* has the body of a small reptilian dinosaur with distinct features such as a boney tail, claws, and sharp teeth (Norell 2005; Swinburne 1988; Natural History Museum 2014). Its body has small distinct barbs sticking out of it, which are similar to modern bird feathers. The specimen also shows perched feet and a retroverted pubis (Charig et al., 1986). The fossil was dated to be from the Jurassic, meaning it is about 150 Ma old.

Archaeopteryx, like most landmark discoveries, had its fair share of doubts and disbeliefs from certain members of the scientific community (Swinburne, 1988). For years the authenticity of the fossil was not questioned. Controversy was not apparent until the 1970s due to publications stating that fossils discovered centuries ago could have been misinterpreted since there could have been a lack of knowledge in the past (Ostrom, 1975). One of the most publicly known arguments against *Archaeopteryx*'s authenticity was lead by a physicist Fred Hoyle and his college Chandra Wickramasinghe in 1985 (Charig et al., 1986; Swinburne, 1988). Some of the uncertainty regarding the fossil's authenticity arose once it was noticed that this discovery heavily aided in Darwin's arguments about evolution published only two years prior to the unearthing of the fossil (Charig et al., 1986). Hoyle and colleges published very opinionated material arguing against the authenticity of *Archaeopteryx* titled *Archaeopteryx*, *The Primordial Bird: a Case of Fossil Forgery*, which caught the attention of the media and soon the controversy swept across nations (Hoyle and Wickramasinghe, 1986; Swinburne, 1988). One of Hoyle's main arguments was that the feathers seen on the *Archaeopteryx* specimen should not be considered substantial evidence for plumage. He believed that the feathers on the fossil were the imprints of modern day feathers around the body of the dinosaur. Additionally, Hoyle declared that the fossil was really a *Compsognathus* (which translates to "pretty jaw") fossil, which had previously been found in the Solnhofen quarries (Hoyle and Wickramasinghe, 1986).

Figure 1.3.2. Archaeopteryx in the limestone of the Solnhofen quarries in Germany.

The curators at the Museum of Natural History quickly rebutted Hoyle's claims by reporting on various aspects of the fossil and its authenticity (Swinburne, 1988). First, they demonstrated that the hairline cracks on the fossil spread across the entire fossil and the sediment of the feather imprints were indeed the same sediment in which the entire original fossil is found. Likewise, the Museum showed that many of the fossils features, such as cracks in the host limestone sediment were identical to other reputable fossils found in the quarries. To make these claims the geology of the Solnhofen limestone quarries had to be investigated.

It is understood that the previous environment of the Solnhofen quarries was a large lagoon (Dyke, 2010). The sediment is layered in beds, with small alternating laminates in between them (Swinburne, 1988). Bed size ranges from a few centimeters to tens of meters thick. These beds, known as quarried slabs, are comprised of micrite limestone, which have been given the name "flinz". These flinz surfaces have idiosyncratic surfaces, where the upper bed has sharp ridges and the underside has gentle bulges.

These characteristics help identify which side of the fossils found in this region is ‘up’. Most fossils discovered here have been found under the overlaying slab or in between the upperslab and lower counterslab. In the case of *Archaeopteryx*, the counterslab shows the sharp texture described above while the upperslab has bulging features.

This information was pertinent when analyzing the *Archaeopteryx* fossil for authenticity (Swinburne, 1988). One feather on the fossil seemed to have both textures; half the feather was on the sharp rock while the other half was on the more rounded rock described above. To Hoyle, this was absurd while to geologist this was a common feature of the Solnhofen limestone quarries (Hoyle and Wickramasinghe, 1986; Swinburne, 1988). Most fossils found in the Solnhofen limestone are disturbed asymmetrically, meaning the fossil is found in the upperslab while the counterslab has furrows in which the bones of said fossil would fit (Swinburne, 1988). The *Archaeopteryx* specimen was no exception to this; most of its bones are seen in the upperslab with small furrows and slight feather imprints seen on the counterslab. The upperslab shows more detail than the counterslab such as feather shafts, barbs, and other small details. Based on this analysis and further support from the paleontological scientific community, it is now understood and accepted that the *Archaeopteryx* specimen is in fact authentic and a link between dinosaurs and birds within the fossil record (Mayr, Pohl and Peters, 2005; Norell, 2005a).

Disagreement Never Ends

However, the argument of fossil forgery and disbelief in evolution did not stop here (Norell, 2005a). In the 1980s, when more fossils of various potentially avian specimens such as *Sapeornis*, *Confuciusirnis*, and *Liaoxiornis* (with some demonstrating all the required physical features for flight) were discovered and reported, members of the scientific community again disagreed with the findings and theories presented. At the time, these dissenting members of the scientific community were given the name BAND, standing for “birds are not dinosaurs” by those who agreed that birds were related to theropods. A member of BAND, Alan Feduccia (a researcher at North Carolina State University at the time) was even quoted as saying, “Theropod origin of birds will be the greatest embarrassment of paleontology in the 20th century” (Norell, 2005b; Harrub, 2006). In the opinions of some paleontologists such as Mark Norell (a modern paleontologist who is a strong advocate for birds being related to dinosaurs) and his colleagues, BAND’s claims were not based on science nor were supported by original research (Norell, 2005b; a). One popular claim of BAND was that larger species of dinosaurs were related to birds, which Norell and many others strongly disagreed with (Norell, 2005a; University of Maryland, 2014).

For about 30 years, BAND attended many international conferences arguing and debating with many famous paleontologists (Norell 2005a). At these meetings BAND also proposed a very linear model of feather to bird. One that states feathers simply evolved from scales in a hierarchal manner, similar to the evolution theories unknowingly proposed by the ancient Geeks (Norell, 2005a; Durrer, 2009). Some scientists still claim to be BAND enthusiasts; however the majority of the scientific community continue to support the theory that birds did in fact evolve from theropods such as *Archaeopteryx*(Norell, 2005a).

All of the arguments made about these fossils, including those proposed by BAND, have only encouraged paleontologists to work harder in their field. Similarly, the fact that Hoyle refuted *Archaeopteryx*’s authenticity, which seemed to be a setback to the scientific community in the late 1800’s, in many ways strengthened Huxley’s discovery. Scientists were able to find further evidence regarding the specimen’s authenticity and over time were able to discover other *Archaeopteryx* fossils (Norell, 2005a; Mayr, Pohl and Peters, 2005). Progress in science is impossible without some intellectual disagreement. Where would we be without disagreements on fundamental concepts such the Earth being spherical and the focal point of the solar system? Different perspectives and varying opinions shape the scientific community while evidence solidifies the theories that we eventually come to accept as fact.

Dr. Richard Prum and the Sophisticated Evolution of Feathers

Since the discovery of the origin of birds, paleontologists have continued to ask pressing questions such as why and how feathers evolved (Norell, 2005a; Bock, 2000). Some argue that feathers evolved for flight while other believe that feathers were developed for warmth (Bock, 2000). Before it can be determined why feathers evolved it is important to establish how they evolved.

A professor at Yale, Dr. Richard Prum (Figure 1.3.3) has created a classification method for the various stages of feather evolution (Prum, 1999; Yale University, 2014). Specifically, Prum focused on pennaceous feather evolution, which are quill-like feathers that can be found on many modern day birds and some ancient dinosaur specimens (Turner, Makovicky and Norell, 2007). He proposed that these feathers evolved in four stages, the first being the initial growth in the undifferentiated follicle collar (considered the bottom or base of the feather) (Prum, 1999). Stage two was when these differentiated cells yielded the first feather, being a hollow sheath. Stage three occurred when barbed ridges of the sheaths formed and began to branch and cross over one another. Stage four was the creation of the pennaceous vane (the vane near the middle of the feather structure), by the distal and proximal barbules. Lastly, stage five was when the pennaceous feather closed over the vane creating a proper structure. Once understanding the concepts of how these feathers evolved, it was critical to understand the specific molecular pathways associated with the evolution and growth of feathers.

It has been almost unanimously agreed that feathers evolved from scales (Turner, Makovicky and Norell, 2007; Norell, 2005a; Bock, 2000; Harris, Fallon and Prum, 2002). Prum has concentrated his recent research on hypothesizing how this process occurred. Before 2002 Prum began to investigate the Sonic Hedgehog (shh) gene pathway and Bone Morphogenic Protein-2 (Bmp2) (Norell, 2005a; Harris, Fallon and Prum, 2002). Prum and his collages analyzed bones of primitive birds in attempts to see a relationship between where and how feathers formed. He noticed that the barbs of the feathers mainly grew out of the same regions of the bones.

Figure 1.3.3. Dr. Richard Prum, professor at Yale, who has devoted his life to gaining as much information as possible about the origins of birds, their feathers, and other interesting details such as feather colour.

Both shh and Bmp2 can be found in modern birds and reptiles, which lead Prum to believe that these pathways could be linked to the evolution of the feather. To determine that these pathways indeed do effect feather and scale development Prum and his colleagues investigated the regulation of the expression of shh and Bmp2 of extant archosaurian lineages by testing the down regulation in a chicken (Harris, Fallon and Prum, 2002). They recognized that the genes were closely linked to epithelial appendage morphogenesis. Specifically, this pathway is directly related to the formation of barb ridges in feathers, similar to those outlined in his stages of feather evolution. From these observations it has been deduced that these pathways indeed induced the initial step of feather evolution.

Prum has continued his work on ancient feathers and has recently published a paper regarding how various feather colours developed over time (Mendes-Pinto). Prum continues to take stabs at important questions regarding the evolution of birds and their feathers (Yale University, 2014). He is one of the many paleontologists whose curiosity of the unknown evolutionary puzzle drives their research. He intends to continue researching the evolution of birds and feathers at Yale in attempts to further his understanding of the evolution of birds.

Life Before Feathered Flight: The Historical View of Ornithic Anatomy

In the late 19th century, the two palaeontologists at the frontier of illustrating evolution as a process through the fossil record, Harry Seeley and Thomas Huxley, may have argued through the literature, however their work converged towards the same conclusion (Larson & Brauer, 2009; Switek, 2010). Between 1860 and 1880, Huxley proposed that birds were not direct descendants of dinosaurs, but rather the similarities seen between them was a result of "adaptive modifications" (Huxley, 1867; Huxley, 1870). Huxley himself recorded and published a vast array of observations and research papers on Ornithic bone anatomy in dinosaurs that were incredible in their complexity (Switek, 2010). These works became of particular interest in the mid to late 20th century, as previously undisturbed transitional fossils relating birds and dinosaurs were unearthed (Switek, 2010). In the years following the release of The Origin of Species, however, Huxley supported a theory more related to convergent evolution than adaptive radiation, with regards to dinosaurs and birds (Huxley, 1867). Huxley outlined that, over time, species exhibiting similar environment-driven tendencies will evolve similar functioning parts (Huxley, 1867).

An example of Huxley's "adaptive modification" theory was displayed in the bone anatomy of Pterodactyles (Huxley, 1867). He noted the pneumatic foramina present in fossilized specimens of Pterodactyles, and denoted similarities within the flight-bearing requirements of bird and Pterodactyle species to efficiently oxidize organ and muscle tissue, while metabolizing carbonic acid (Huxley, 1867). This similar physiological characteristic was a result of their flight-bearing similarities, apparently dictating that Pterodactyles required similar respiratory and circulatory characteristics (Huxley, 1867). It was Huxley's belief that the most Ornithic anatomical features of an organism were its manus and pes, or wings and feet (Huxley, 1868). However, Harry Seeley strongly disputed these claims and stated, "…Professor Huxley launches this scientific dictum without facts to support it" (Seeley, 1875). Seeley proceeded to discuss the lack of pneumaticity in bat species, regardless of their ability to fly. Thus, it cannot be definitively concluded that the air sacs once present in Pterodactyles are wholly a result of their ability to fly, but rather represent an evolutionary relationship with modern birds. Furthermore, Seeley elaborates on the significance of the brain and lung structures as the most Ornithic anatomical traits, for identification purposes. The evolutionary dictum for the transition from dinosaurs to birds is still under debate, but it is quite intriguing to see how the disputes have persisted through the centuries (Seeley, 1875).

Before the 20th century, an extensive gap in the transition between bird-like dinosaurs and extant birds was cause for much conflict regarding the fossil record's ability to support evolution, as proposed by Darwin in 1859 (Switek, 2010; Darwin, 1859). Incredibly, by 1859, it was believed by the scientific community that geological data had been adequately sampled, and holistically represented the diversity of ancient life at each time period (Switek, 2010). Given the fact that the researcher responsible for the first suggestion of a direct evolutionary relationship between birds and dinosaurs, Ernst Haeckel, presented his hypotheses just a year later, the controversial nature of bird evolution has been truly historic (Richards, 2008). Although Thomas Huxley furthered the anatomical and evolutionary relationships between dinosaurs and birds, Haeckel was the first to suggest it in 1860 and may have been Huxley's inspiration for future research (Larson & Brauer, 2009; Switek, 2010).

The Ornithic Anatomy of: Ornithosauria

As mentioned by Harry Seeley in 1875, "No one has specified with sufficient detail the osteological structures which constitute an animal a reptile or a bird." (Seeley, 1875). Through Seeley's work with palaeontology from 1875 to the early 20th century, he was able not only to present historically accepted theories, but also, even, to rebut Thomas Huxley himself (Seeley, 1875). When looking at Ornithosauria specimens, Seeley identified two specific areas of anatomical similarity with modern birds in 1875 and 1877 that are not conserved across any other extant group (Seeley, 1875; Seeley, 1877). The first of these pertained to the presence of pneumatic foramina within the Ornithosaurian skeleton, followed by the characteristics of the cerebral cavity (Seeley, 1875). The presence of pneumaticity in the bone structure is a result of the prevalence of pulmonary air sacs throughout the skeletal system, forming circular indentations on individual bone structures, which appear as hollow bones (O'Connor & Claessens, 2005). These air sacs are an imperative component of the avian respiratory system, and are viewed as an optimized method of gas exchange (O'Connor & Claessens, 2005). Given the appearance of this respiratory attribute, Ornithosaurs were inferred to be hot-blooded organisms, similarly to their avian kin, by Huxley and Seeley (Huxley, 1867; Seeley, 1875; Lydakker, 1891; Switek, 2010).

When correlating the Ornithosaurian bone pneumaticity to that of similar bird bones, in 1875, Seeley commented on specimens of the former being nearly identical in the arrangement of the indentations seen, relative to the latter (Seeley, 1875). In some cases, exact replication of air sac placement was observed in Ornithosaurian bones in comparison to the contrasted bird bones (Seeley, 1875). Similarly, the cerebral cavities of skulls attained from both extant bird and Ornithosaurian specimens displayed similar osteological characteristics, with additional nervous system similarities (Seeley, 1875).

Although the specific Ornithic structure most able to identify avian relatedness was strongly disputed, identifying the bird-like nature of the cerebral cavity further substantiated evolutionary similarity (Seeley, 1875; Lydekker, 1891). In the species, *Pterodactylus longirostris*, the cerebral cavity was particularly notable given its near identical relationship with that of extant birds (Seeley, 1875). The cast-like fit of bird skulls permits the bone itself to display the brain structure and segmentation of given species, substantiating Seeley's support of it as the main Ornithic structure in his 1875 paper (Chatterjee, 1991). As a result, the similarity of the Ornithosaurian skull bone structure to *Aves* specimens permitted Seeley to view the similarity of the brain structure itself (Seeley, 1875). The cerebral cortex appeared identical in cavitation and shape (Seeley, 1875). According to the principle of form and function, it may be expected that bird and Ornithosaurian brains displayed similar operational processes (Larson & Bauer, 2009). This may well have been the case, provided their vertebral similarities (Seeley, 1887).

Figure 1.4.1A small Ornithomimus *fossil from the middle Dinosaur Park Formation of Alberta, Canada.*

Geology Snapshot

Huxley and Seeley collected all of the aforementioned Ornithosauria specimens collected from slate facies (Figure 1.4.1) (Huxley, 1867; Seeley, 1875; Seeley, 1887). This common attribute can be seen as a result of the low-grade, regional metamorphism associated with slate formation, allowing the majority of fossils to remain intact (White, 1917). The dead organisms were most likely deposited in a low-energy, subaqueous environment that experienced fine sediment burial, such as a river delta or floodplain. By looking at the depositional environments of particular fossils, researchers, such as Huxley, Seeley and Haeckel could deduce the preferred living conditions of particular fossilized creatures. Also, by using radiometric dating and paleomagnetism, the age of the fossil can be approximated. Through these methods, early Ornithosaurs and Theropods were shown by Elliot Coues to have both appeared in the late Triassic time period (Coues, 1890).

The Ornithic Anatomy of: Theropoda

After a comprehensive review of the anatomical structures identified in the 19th century, of the clade Dinosauria, E.C. Case was able to identify key Ornithic features in the suborder Theropoda (Case, 1898). Case separated the different suborders of dinosaurs seen in the fossil record across the geologic time scale, beginning with the Triassic period. At this point in scientific history, the oldest known dinosaur was the *Anchisaurus*, although it is currently accepted that it is most likely the *Nyasasaurus*, existing at around 245 Ma (Case, 1898; Nesbitt et al., 2013). However, *Anchisaurus* may still be the oldest Theropod, estimated to have diverged around the mid to late Triassic (Case, 1898). This ancient suborder exemplifies the historical conservation of Ornithic anatomical structures, as it displays a multitude of bird-like features. The skull in particular perfectly represents that of a bird, as previously described by Seeley (Case, 1898; Seeley, 1887). Pneumaticity throughout the bone structure was observed, with a pes structure also resembling that of ancient bird species (Case, 1898). Thus, a component of both Huxley and Seeley's previously outlined anatomical conditions dictating Ornithicity are met in this ancient Theropod (Huxley, 1867; Seeley, 1887). The foot structure also resembles that of ancient birds such that the fossilized tracks were believed to be bird tracks up until the late 19th century, when Ermine Cowles Case analyzed more closely the pes bone structure (Case, 1898). The sandstone housing these trace fossils is able to show the 4 functional digits of Anchisaurs, given the comprehensive expansion of Anchisaur digit anatomy by Othniel Marsh in 1893 (Case, 1898; Marsh, 1893).

Figure 1.4.2: Fossil of Anchiornis huxleyi, *named in honour of Thomas Huxley, showing imprints of preserved feathers. This species fills an important evolutionary gap between dinosaurs and modern birds.*

Plateosaurus and *Massopondylus* were two Jurassic specimens of particular interest to Ernest Ingersoll and W.C. Wyckoff, as they displayed a biconcavity of individual vertebrae, which is a fish-like characteristic (Ingersoll & Wyckoff, 1879). However, some ancient bird species display this unique anatomical character, suggesting a direct line of lineage (Ingersoll & Wyckoff, 1879). In the *Ichthyornis*, an ancient extinct bird of the Cretaceous, a similar biconcavity of individual vertebrae was observed (Ingersoll & Wyckoff, 1879). However, in this particular specimen, a transitional anatomical structure is present: a vertebral component that is midway between the biconcave phase and saddle phase, seen in modern birds (Ingersoll & Wyckoff, 1879). The saddle shape facilitates vertebral flexibility, which is a key characteristic in the necks of extant species (Ingersoll & Wyckoff, 1879).

The final Theropod that will be used to substantiate why this suborder was deduced as the ancestral suborder of *Aves* by Case is the *Ornithomimus* (Case, 1898). The lineage of this species was highly disputed, as Marsh, Huxley, and Seeley all provided substantiating evidence, but none could claim any accepted relationship of *Ornithomimus* with *Avialae* (Huxley, 1870; Seeley, 1887; Marsh, 1893). Throughout the 20th century, attempts were made to represent *Ornithomimus* in an accurate, phylogenetic manner; however, it was not until 2003 that a comprehensive conclusion was made, placing *Ornithomimus* in the Maniraptoriformes clade (Ji et al., 2003; Clarke & Middleton, 2006). This conclusion is what is currently accepted and is used to illustrate phylogenetic trees (Brussatte et al., 2014). It is because of this ultimately conserved high density of Ornithic traits that the Theropod group is distinguished as the most probable to diverge into the *Avialae* and *Aves* genera (Ji et al., 2003). Through the bouts of controversy and dispute, the historic notions of great palaeontologists and anatomists have truly shaped dinosaur and bird phylogeny as we see it today. Even with our wealth of aggregated knowledge, newly discovered fossils still rouse the biological community.

The Strange Case of *Aurornis xui*

Aurornis xui was an archived Jurassic fossil, recently reconsidered by Pascal Godefroit in 2012. Initially unearthed in China's Liaoning Province, this feathered dinosaur lived from 150 to 160 Ma. Godefroit has proposed the *Aurornis xui* as the predecessor of the *Archeaopteryx* in the clade *Avialae* (Woolston, 2013). Given the controversial nature of bird evolution, this claim has brought another conundrum to the scientific community.

According to Godefroit, the feather and hipbone structures have provided ample morphological evidence to classify *Aurornis* as a true bird (Woolston, 2013). This phylogenetic adjustment would shift *Archaeopteryx* closer to *Avialae*, suggesting only one emergence of flight among birds and dinosaurs (Woolston, 2013). The analysis of this fossil, if the claims pertaining to its significance are eventually accepted, may be the most significant component of Ornithic lineage when tracing flight. However, with such lofty propositions, much criticism has followed the analysis of *Aurornis xui*, and is rooted deeply within the scientific community (Switek, 2013). The fundamental definition previously understood to classify a true bird dictated that the organism morphologically fit between *Archaeopteryx* and *Aves*; this definition proves arbitrary when classifying *Aurornis* (Switek, 2013). According to Luis Chiappe, a palaeontologist at the Natural History Museum of Los Angeles, "…in the Jurassic, many different dinosaurs were experimenting with 'birdness,' and it is from this 'birdness soup' that true birds originated" (Switek, 2013). Chiappe believes that *Aurornis* should be placed within this 'birdness soup' rather than within *Avialae* (Switek, 2013; Woolston, 2013). He identifies the shoulder arrangement as too distant from *Archaeopteryx* to be classified within the clade Avialae (Switek, 2013).

Questioning the Role of *Archaeopteryx*

In the same Liaoning Province of China, palaeontologist Xing Xu and his colleagues identified a small, *Archaeopteryx*-like Theropod that they named *Xiaotingia zhengi* (Figure 1.4.3). The group attempted to correlate it with known Deinonychosauria and Avialae through salient synapomorphies. They were able to identify key similarities between *Xiaotingia*, *Archaeopteryx*, and basal Deinonychosauria. Such morphological correlations include the presence of five sacral vertebrae and the protrusion and arrangement of vertebral processes, relating to Deinonychosauria and *Archaeopteryx* respectively. The group determined that both *Xiaotingia* and *Archaeopteryx* should be located in the Deinonychosauria clade, provided that particular traits previously deemed characteristic of Avialae were rather inclusive of Deinonychosauria (Xu, You, Du & Han, 2011).

Unfortunately, a swift rebuttal from the scientific community reclaimed the former lineage of *Archaeopteryx*, via maximum-likelihood and related Bayesian methodologies. Although the conclusions of Xu, You, Du and Han were deemed inaccurate, it is intriguing that historic discoveries and the theories that confine them are still in question. It truly puts into perspective the significance of the word "truth."

Figure 1.4.3: A Xiaotingia zhengi *fossil.*

Disturbance of Geological and Anthropological Evidence

The disturbance of fossilized remains, geological structures, and cultural artifacts poses a seemingly-inescapable obstacle on the road to historical scientific truth. From as early as the Stone Age, this phenomenon influenced the perception of ancient artifacts. As a result, modern researchers have developed a greater capacity to critically observe the state of artifacts and their surrounding environment. This heightened observation assists to determine the extent of disturbance, as well as piece together the resulting puzzle in the case of missing objects.

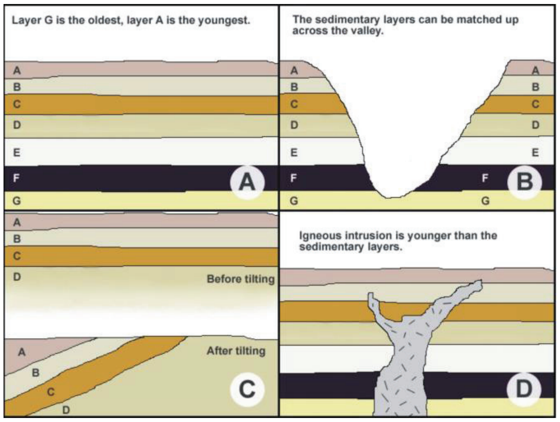


Figure 1.5.1: Principles of stratigraphy as applied to relative dating of geological units.

Humans certainly contribute greatly to the disruption of geological and anthropological evidence. However, natural events and other organisms can also contribute to the shifting of geological units and fossils after their deposition. Sediment churning by burrowing organisms, or bioturbation, freeze-thaw cycles, plant roots, and natural disasters can disrupt the normal stratigraphic sequence or clear bedding of a geological unit and make relative dating difficult (Stein, 2014). Researchers must therefore observe the setting of a fossil or artifact with a critical eye in order to accurately determine the origin of a specimen.

In order to establish a timeline of events, the Principle of Superposition is often used for relative dating of both geological units and fossils. This principle states that the upper-most sedimentary layers in an un-disturbed geological unit were formed most recently, while those lower in the unit are oldest (Plummer et al., 2007). As such, the relative position of sedimentary layers is indicative of their chronological formation (Figure 1.5.1), and the geological unit in which fossils are found correlates with the successive existence of different species.

As a result, the precise position in which fossils and artifacts are found indicates their relative age. Tourists or curious passersby may come across partly-buried objects and remove them from the ground in order to see them more clearly. However, this removes the object from its unique depositional context and prevents researchers from estimating its relative age or environmental conditions of the time. Even the movement of one bone in relation to another in a fossil skeleton can interfere with the scientific understanding of causes of death, posthumous treatment of carcasses, and burial processes (Ringel, 1995; Baxter, 1999; Reinhardt, 2014). Site disturbances can be the result of cultural practices, human ignorance and curiosity, malicious vandalism, or financial, ambitious, or status motivation.

Early Occurrences

One early case of the disturbance of human remains took place in Madagascar during the Neolithic Era, through a practice that today seems macabre. The bodies of the dead were buried once, shortly after death, and later removed and handled by living individuals as part of a mortuary rite. This may have involved cleaning the remaining soft tissue from bones before the ceremonious burial of skeletal remains. Movement of bones may have taken place in order to bring the deceased "home", to allow the burial of numerous family members in the same tomb, or to build monuments (Baxter, 1999). The exact reason for these post-mortem manipulations, however, is unclear. As the bodies were not found in their original resting places, anthropologists have difficulty painting a picture of Neolithic culture. From the modern human perspective, such disruption of remains could indicate the action of vandals, scavenging animals, or even cannibals (Baxter, 1999).

Evidence of Re-Opening

In some cases, tampering with human remains stemmed from belief in ancient tales of supernatural beings. For example, the exhumation of a century-old corpse in Griswold, Connecticut revealed skeletal rearrangement indicative of practices in Gothic New England thought to ward off vampires

(Tucker, 2012). During the 1850s, the Ray Family in Jewett City suffered terribly from consumption, and took action to attempt to prevent future deaths in the family. They believed that it was necessary to "kill" their dead to ensure that they did not feed on the living, and did so by placing the skull face down and crossing the femurs on the chest of the deceased (Ringel, 1995). Such rearrangment of the original skeletal position perpetuated the local vampire lore, but more importantly made it difficult for archaeologists to recreate the circumstances surrounding the burials and this strange practice (Tucker, 2012).

Through careful observation of several such cases, researchers have been able to identify characteristic signs of site re-opening or disturbance. An additional layer of sediment deposition surrounding an artifact, usually a different colour than the surrounding soil, is indicative of the un-earthing of such an object after its burial (TARL, 2009). This additional layer would have been deposited when sediments accumulated in the re-opened site while it was exposed, and would likely have different composition than that surrounding the object at the time of burial. In some cases, carbon dating of this layer could even be used to identify the time period during which the buried artifacts were disturbed.

Figure 1.5.2: The growth of delicate cave formations may be disrupted by contact with oils on human skin.

Human Curiosity and Ignorance

Human interference with anthropological and geological sites is often unintentional. The average tourist does not have the knowledge necessary to take the required precautions to conserve materials. Physical contact with artifacts, such as cave drawings, leaves behind oil that attracts debris and contributes to degradation (Whitley, 1996). Scraping with backpacks or other gear can also gouge or dislodge parts of artifacts. Contact with cave formations, or speleothems (Figure 1.5.2), is also very disruptive as it prevents further growth of these slowly-forming geological structures (Burger, 2006). Some natural changes to the surrounding landscape at fossil sites are to be expected, including ground compaction, and have a relatively insignificant impact on site integrity. However, other seemingly-benign human activity has damaging effects on artifacts, including the building of fires, which can cause smoke damage to cave drawings (CDPR, 2014).

Financial and Status Motivation

Other site disturbances are much more intentional. Some are financially motivated, because private collectors are willing to pay large sums for fossils and artifacts. For example, a shipment of dinosaur fossils, weighing over 8000 pounds and worth approximately $400,000, was recently stolen; but the fossils were subsequently intercepted at a gem and mineral show. They were determined to be from a sauropod nesting site in Argentina, and smugglers were likely responsible for the theft (Pagan, 2008).

More recently, tensions have erupted between parties interested in fossils for very different reasons. Paleontologists intend to study the organisms and their interactions, while private collectors wish to acquire fossils merely for their aesthetic appeal and rarity. It has become difficult for museums to financially compete with collectors for some fossil acquisitions, which is greatly disappointing for those interested in the scientific value of such specimens. For example, dinosaur bones smuggled from Mongolia were recently sold at an auction for $1 million, but were only valued around $15,000 (Ortiz, 2014). Such inflated prices make it difficult for educational institutions to augment their collections.

Similarly, sixteen pieces of rock containing world-famous ammonite fossils were recently stolen from Portrush National Nature Reserve in Northern Ireland. These fossils, while not of great monetary value, contributed greatly to the tourist draw of the Reserve (BBC News, 2014).

In other cases, the prospect of commercial reward led more indirectly to the careless treatment of historical sites. In the Eastern Sahara Desert, mining for gold took place between 1550 and 1070 BCE. The techniques used were identifiable as precursors to modern processes, including milling, and separation of gold-containing material by hand and in tailing ponds (Klemm, Klemm and Murr, 2002). While the study of such methods would provide insight into financial and economic systems of the time, such analysis is no longer possible. Unfortunately, much of the evidence of New Kingdom gold mining was destroyed by modern attempts to extract gold from the tailings through leaching with cyanide (Klemm, Klemm and Murr, 2002).

Vandalism

Some disturbances of fossil sites have been executed with a more malicious and destructive intent. A team from the University of Alberta was dismayed to find four dinosaur fossils destroyed and several more stolen from their dig site. The loss of one of the fossils, a hadrosaur skeleton to be displayed as a large museum exhibit, is especially devastating. While the motivation behind these incidents is not entirely clear, litter at the site indicates the possible involvement of alcohol (Bell, 2012).

Figure 1.5.3: Beautiful elk pictograph covered by carelessly-misspelled modern graffiti.

The allure of academic recognition or elevated status has also lead to some elaborate hoaxes, including the curious case of the Piltdown Man. In 1911, amateur geologist Charles Dawson claimed to have discovered the fossilized remains of a “missing link” in human evolution (Thomson, 1991). With the discovery of different fossil species, archaeologists struggled to piece together the timeline of human evolution. The Man, discovered in the Piltdown Commons in Sussex, seemed to contradict the wealth of other emerging evidence.

Forty years later, it was revealed that the Piltdown Man consisted of bones not only from different species, but also vastly different time periods. The jawbone had in fact been stained to give the appearance of immense age, and came from a modern ape (Thomson, 1991). To this day, the perpetrators of the fraud remain contested.

This year, a 20 centimetre fragment was removed from a Pompeiian fresco with a chisel and stolen. The missing piece is glaringly obvious; a bright white against the rosy depiction of Artemis. This theft took place regrettably soon before the commencement of a large-scale makeover of the ancient Italian city (ABC News, 2014).

One of the largest archaeological sites in Egypt is also under constant siege by vandals. The government has failed to protect Antinoupolis from locals that dig up the site for agricultural fields or cemeteries. Unfortunately, these “construction” projects are often fronts for the excavation and theft of artifacts (Osman, 2013).

More disheartening still is the pointless defacement of archaeological sites. Several etchings and cave paintings, including those in Keyhole Sink in Arizona, have been covered by haphazard, spray-painted graffiti (Figure 1.5.3). Clean-up of this vandalism will certainly be expensive, and may not be entirely effective or may damage the artifacts below (Creno, 2010).

Protection of Artifacts and Excavation Sites

Ground-Penetrating Radar

In order to understand historical environments, organisms, and even evolutionary relationships, geological and anthropological evidence must be preserved to the greatest possible extent. Furthermore, many Native American peoples believe that disturbance of burial sites causes the spirits of the deceased to become displaced and restless (Amato, 2002). Physical disruption of such sites is to be avoided wherever feasible. Therefore, some “excavation” sites do not involve physical unearthing, but rather use ground-penetrating radar (GPR) to image objects below the ground. For example, GPR is used to observe the spatial distribution of ancient gravesites, which allows for increased precision of future excavation (Conyers, 2006). GPR has also been used to map the region below Komochi-mura in Japan, where there lies an ancient village covered by igneous rock (Tohge et al., 1998). This technique has allowed for the visualization of the layout of the near 1500-year-old settlement without any physical disruption of the surrounding volcanic rock.

Figure 1.5.4: Signage in National Parks prohibits the destruction, disturbance, or defacing of sites or artifacts.

The use of GPR before excavation of construction sites may also prevent the destruction of valuable artifacts. Unfortunately, numerous artifacts have been destroyed through the uninformed clearing of sites. This has been especially devastating for burial grounds, such as the St. Michael at Thorn site in Norwich, where a large percentage of the bones were damaged by bulldozers (Wells, 1968).

Geological Structures

Visitation of sites of geological importance must also be regulated in order to preserve their structural integrity. It is extremely important that fossils or other minerals are not removed in quantities large enough to reduce site stability. Any material removal must be executed with precision, so as to extricate only the material necessary and leave behind no unsightly scarring (Gray, 2013). The use of areas surrounding landforms is also regulated to prohibit harmful activities, such as the setting of campfires, which can discolour stone structures. Chemical use in areas above cave systems must also be carefully monitored so as to preserve speleothems and cave biodiversity, and visitors must be warned to avoid physical contact with cave formations (Lockwood, Worboys and Kothari, 2012).

Legislation and Enforcement

The prevention of vandalism, theft, and other disturbance of geological and archaeological sites by the public is also necessary, and requires the establishment of costly site protection programs. Various pieces of legislation regulate the treatment of sites, and prohibit such activities as the disruption of ancient burial grounds or objects of archaeological or paleontological interest (Amato, 2002). Other programs must be implemented to regulate visits to public sites, including restriction of access solely to pedestrians, erection of anti-vandalism signs (Figure 1.5.4), and even the installation of cameras, should the threat of destruction be substantial (Creno, 2010). It may also be necessary to increase the punishment associated with the execution of such crimes, such as the size of the fine, in order to deter future disturbances (Zubieta, 2014).

The iconic Earthrise photograph by the crew of Apollo 8. As science progressed, humans turned their curiosity towards understanding their place in the universe.

Chapter 2: Beyond the Globe

As various scientific fields developed, people began looking past the world immediately around them. Interest in our place in the universe sparked developments in many fields. Humans have since explored both Earth's place in the solar system, as well as the Moon. Furthermore, life's place in the universe has been studied through astrobiology and the idea of the noosphere. The quest to understand the world around us has also led to climate modelling. Finally, as our understanding of the world around us changed, so too did science's relationship with religion.

Humans have always been interested by the place of our planet in the universe. From geocentrism to heliocentrism, our understanding of the universe has changed immeasurably. Selenology has also shaped the history of the space race and continues to shape our understanding of the early solar system today.

Life's place in the universe has also been a topic of fascination. Since its birth in the mid-1900s astrobiology has experienced both great advances and major setbacks. Our role in the universe has also been examined from another perspective: that of the noosphere. The impact that humans have on the Earth is substantial and the concept of a sphere of human interactions may help us to understand human interactions on Earth.

In addition to understanding how the Earth fits into the universe, humans have also been interested in understanding how processes on Earth operate. While statistical methods played a role in the understanding of weather patterns in the past, meteorology was not accepted as a science until mathematicians and scientists developed formulae and models to predict weather. These equations have led to the development of climate modelling today.

Throughout these scientific developments, the relationship between science and religion has changed. Scientific discoveries in the past few centuries have led to a paradigm shift towards a secular age. In light of this, some view the history of science and religion as one of conflict. In reality, the relationship between science and religion is complex and the apparent conflict between them is a more recent philosophical development.

From Heliocentrism to Geocentrism

From the modern understanding of a spherical Earth, to the acknowledgement of a collective consciousness, humans have attempted to unravel the mysteries of the universe for thousands of years. In the pursuit of absolute knowledge, our perception of the universe has changed indefinitely. What was once limited by the domain of the Earth has now been expanded past the Solar System and galaxy; the universe is seemginly unbound, housing billions of celestial bodies distinct in orbital movement.

In hindsight, the intricacies of the universe were not obviously apparent. All of our current knowledge stems from our perception of the solar system across time, from the early ideals of geocentrism, to the reality of helicoentrism that is studied today.

The Age of Geocentrism

The geocentric model of planetary motion can be traced back to ancient Greek astronomy. The first cosmological theory was provided by Anaximander, an ancient Greek philosopher, in the 6th century BCE. In this model, the Earth was thought to be a stationary cylinder, fixed at the centre of the universe. The inhabited world was proposed to exist on the top face of the cylinder. Furthermore, it was believed that the Earth was contained within a celestial sphere composed of an unknown medium. This sphere was surrounded by compressed masses of air, filled with fire. To Anaximander, the surrounding fire represented the heavens. With that in mind, all celestial bodies were circular orifices in the medium that exposed small amounts of the surrounding heavenly fire. Although there was very little supporting evidence, this theory was the first to propose an Earth centred universe, which is the basis for geocentrism (Kahn, 1994).

Later, in the 5th century BCE, the Greek philosopher Philolaus proposed an alternative theory. In this model, all celestial bodies, including the Sun and Earth, were independent masses that revolved around a central fire at the origin of the universe. Although it was not well supported, the model was the first to introduce the basics of orbital planetary motion around a fixed point. In fact it was the first functional model to be fundamentally representative of heliocentrism. As such, it challenged Anaximander's geocentric ideas (Huffman, 1993).

Through the remainder of the 5th century BCE, both models were acknowledged by Greek philosophers abroad. However, this was not without due criticism. Both systems only broadly accounted for the apparent daily motion of celestial bodies across the sky. Since they presented almost no specific supportive evidence, philosophers found it difficult to accept certain concepts; Greek astronomers could not conceive of either a heavenly fire, or a central flame. As such, they attempted to alter and combine these models, in order to remove each of these elements. Although no functional model was produced by the end of the 5th century BCE, most believed the Earth to be a spherical entity at the centre of the universe. To date, this is considered the most primitive model of geocentrism (Fraser, 2006).

In the 4th century BCE, Greek philosopher Plato wrote works based on geocentrism which effectively compiled the ideas of Philolaus and Anaximander. According to Plato, Earth was a stationary sphere located at the centre of the universe. In this schematic, celestial bodies rotated around the Earth in perfect circles. Each celestial body was located on a distinct circular path, defined by its radius from the Earth (Figure 2.1.1). From the Earth outward, the celestial bodies in the Universe

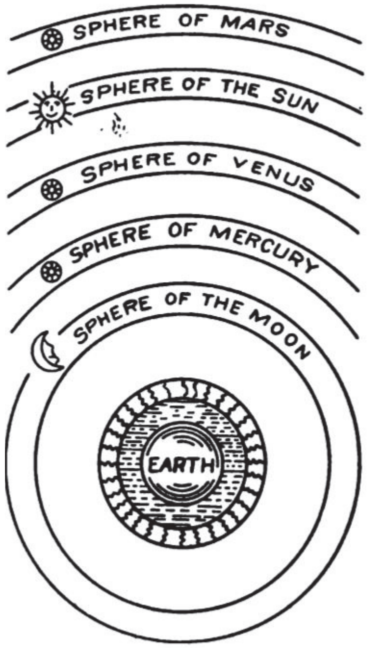


Figure 2.1.1: A visual representation of Plato's geocentric model of planetary motion. In this image, only the Moon, Mercury, Venus, Mars and the Sun are present.

included the following: Moon, Sun, Venus, Mercury, Mars, Jupiter, Saturn, and the remaining fixed stars. Although this system was effective in explaining daily apparent motion without the need of a heavenly fire or a central flame, it was not fully developed (Sharples and Sheppards, 2003).

Plato's work in geocentrism was continued by his disciple Aristotle. To Aristotle, the rotating celestial bodies were held in place by many transparent concentric spheres. In this expanded model, planetary motion was attributed to uniform rotational movement of these crystalline spheres. Although Aristotle's work was inherently flawed, the theory was based on several celestial observations which were widely held at the time. For instance, astronomers could not detect movement in stars due to the underestimation of their distance to the Earth. As such, astronomers attributed the static nature of the interstellar constellation to a centred immobile Earth. Another observation used in favor of the geocentric model at the time was the apparent consistency of Venus' luminosity. This observation implied that the planet remained at a constant distance from Earth while moving, and is consistent with geocentrism. Overall, this evidence was sufficient to establish the basic tenets of geocentrism (Bos, 1973). Despite this fact, the details of Aristotle's system were not standardised in the scientific community.

A detailed model of geocentrism was not standardised until the works of Claudius Ptolemaeus (Fraser, 2006). In 200 CE the Greco-Egyptian writer released the *Almagest*, a document in which the renowned scholar proposed his geocentric model, the Ptolemaic system. This model differed from the works of Aristotle in the mechanism of planetary motion. More explicitly, Ptolemaeus attributed the movement of each planet to a bi-spherical system. The first sphere, called the Deferent, was consistent with the transparent concentric spheres in the ancient Greek model of geocentrism. However the second sphere was an expansion of the original model. Known as the Epicycle sphere, this addition was embedded inside the Deferent sphere. (Figure 2.1.2) In the Ptolemaeus system, celestial bodies are in constant motion around an Epicycle sphere, which in turn rotates around a Deferent sphere. These combined movements cause the given planet to move closer to and further away from the Earth at different points in its orbit. This explained the observed motion of planets that varied in their distance to the Earth, while accounting for the stationary appearance of stars (Jones, 2011).

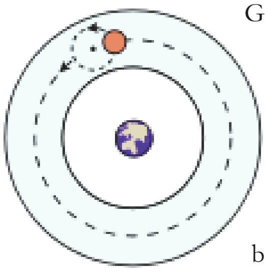


Figure 2.1.2: A visual representation of the Ptolemaic system. In this model, Earth remains stationary. Planets orbit around an Epicycle, which in turn rotates around a Deferent cycle.

The Age of Heliocentrism

In 1543, Nicolaus Copernicus published a document similar to Ptolemy's *Almagest*, called the *De Revolutionibus*. To date, many historians believe that this document initiated the scientific revolution of the 17th century (Fraser, 2006). In this work, Copernicus discussed a novel model of planetary motion in full geometrical detail. He explained the various astronomical observations that were used to support the model and even presented a table which enabled one to compute the past and future positions of the planets. In this model, Copernicus suggested that all planets revolved, in uniform circular planetary motion, around the Sun which was centred at the origin of the universe. Copernicus accounted for the movement of the Moon by suggesting epicyclical motion around the system defined by the Earth and the Sun (Figure2.1.3). In doing so, Copernicus provided the first supported model of heliocentrism (Swerdlow and Neugebauer, 1984). Heliocentrism was no longer considered philosophical speculation but predictive geometrical astronomy. Although this was revolutionary in itself, it is important to note that the model was no better than the Ptolemaic system in its predictive abilities. With this in mind the Ptolemaic system was not overtaken; the novel heliocentric model only presented competition. At the time, this competition was very limited due to the prominence of the Church. Even amongst well educated individuals of the era, there was strong religious adherence to the geocentric model due to the abundance of biblical references supporting a stationary Earth. In addition, the model had no clear mechanism to explain the apparently stationary stars. Although a small issue, it was used as a scientific argument against heliocentrism (Fraser, 2006).

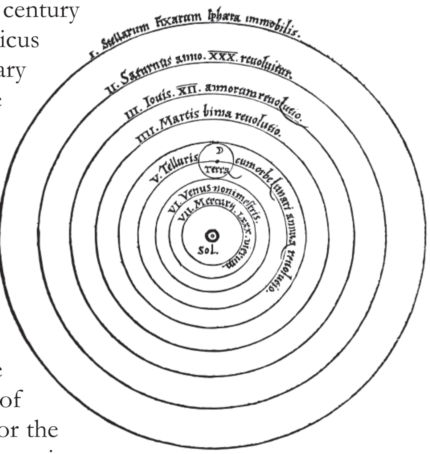


Figure 2.1.3: The Coperinican model of heliocentrism, as depicted in De Revolutionibus. *The Sun is at the centre of this system, surrounded by Mercury, Venus, Earth, Mars, Jupiter, Saturn, and the remaining stars.*

In the era of the Renaissance, the Italian scholar Galileo Galilei made major contributions to the scientific revolution initiated by Copernicus. Most notably though the refinement of the telescope, Galilei was able to study astronomy to a depth that was previously not possible, sparking the modern age of astronomy. Through his research, Galilei was able to make detailed observations on the Moon, Venus, Jupiter and the Sun, which were published as a part of the *Sidereus Nuncius* in 1610. His observations of Venus and Jupiter were of greater importance due to their implications. Jupiter was found to be orbited by four celestial bodies that were consistent with the Moon. On the other hand, in correspondence with its orbit, Venus was found to orbit the Sun. These findings directly contradicted the basic tenets of the Ptolemaic model, in which everything orbited the stationary Earth (Galilei and Drake, 1957). As such, Galilei conformed to heliocentrism and even attempted to defend it against the church through his letter to the Grand Duchess Christina in 1615. In the document he argued that it was not contrary to biblical texts as the literature is not to be taken literally. Unfortunately for Galilei, this letter was not well received. In the preceding year, the Inquisition declared heliocentrism to be formally heretical. Heliocentric books were banned and Galilei was ordered to refrain from believing in, defending or teaching heliocentric ideas. In 1632 Galilei published the *Dialogue Concerning the Two Chief World Systems*. In the literature Galilei explicitly defended heliocentrism and even ridiculed the church's beliefs. In response the Roman Inquisition tried Galilei in 1633 and found him "gravely suspect of heresy", sentencing him to indefinite imprisonment. Galilei was kept under house arrest until his death in 1642 (Finocchiaro, 1989).

Tycho Brahe was a Danish nobleman who lived in the same time period as Galilei. Brahe was a famous astronomer who was known for his accurate naked eye measurements of planetary positons. Brahe did not believe in the Copernican system due to its inability to explain the stationary nature of stars. Instead he proposed a hybrid theory in which the Sun and Moon orbited the Earth. In this system all other celestial bodies were proposed to orbit the Sun in a manner consistent with the Copernican model. (Figure 2.1.4) His system provided a safe position for astronomers who were dissatisfied with the older geocentric models but were reluctant to accept the Earth's motion.

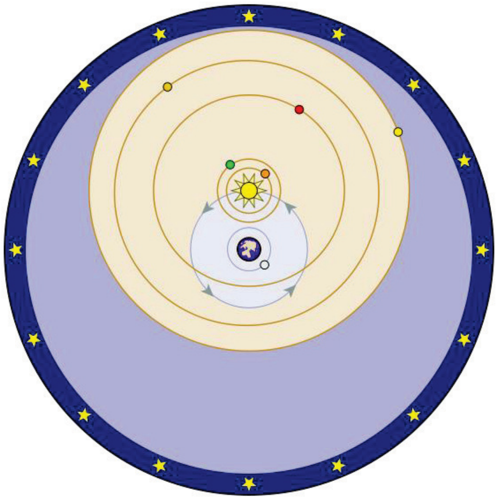


Figure 2.1.4: A visual representation of Brahe's Hybrid model of planetary motion. In essence, it is the Copernican system with a geocentric base.

The theory was prominently acknowledged in 1616 when Rome officially decided that the heliocentric model was a computational convenience that was contrary to biblical scripture and had no connection to fact. Despite having the required data, this system could neither be confirmed nor denied, at least by Brahe. In 1600, following extensive correspondence, Brahe met with astronomer Johannes Kepler. Brahe eventually offered Kepler a position of formal employment in Prague, and allowed him to use his planetary observations for his work. However, Brahe unexpectedly died shortly after Kepler began working.

Johannes Kepler was a German astronomer who had an understanding of both the Copernican and Ptolemaic system. Inherently, he was a supporter of the heliocentric model; his first professional work was a defense of the Copernican system. Generally speaking, Kepler did not obtain astronomical observations for himself. Brahe had named Kepler his successor as an imperial mathematician, and left to him all of his observations (Glider, 2005). Using these observations, Kepler was able to devise a geometrical model that expanded on the Copernican system. In Kepler's model, planets rotate in an elliptical path around the Sun, which is centered at one focus. Each planet orbits in a unique manner, at different speeds and distances from the Sun; the overall movement of each planet is distinct.

Kepler's three laws of planetary motion can be defined in more explicit terms:

1. Planets travel in an elliptical path around the Sun, which is centred at one focus
2. An imaginary line drawn from the centre of the Sun to the centre of a planet will sweep out equal areas in equal intervals of time.
3. The ratio of the squares between the periods of any two planets is equal to the ratio of the cubes between their average distances from the Sun (Figure 2.1.5).

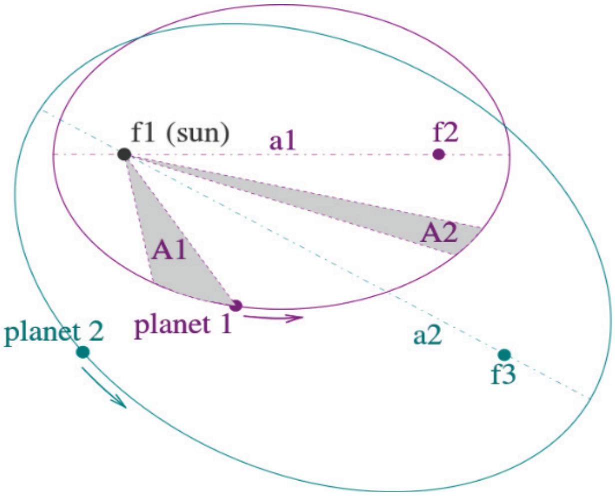


Figure 2.1.5: Two planetary orbits that illustrate Kepler's laws.

1. Two planets rotate around two distinct elliptical orbits. The Sun is placed at focal point f 1.

2. A1=A2. Each area is swept out in equal time intervals.

3. The ratio between $a1^{3/2}$ and $a2^{3/2}$ is equivalent to the ratio between the periods of the two planets respectively.

Though these postulates, Kepler expanded on the Copernican system of planetary motion and defined the movement of all celestial bodies, including Earth. His ideas not only revolutionized the approach to orbital modelling, but also paved the way for future scientists to expand on his work (Job, 1994).

Discovering Inhabitable Planets

Although originally designed to model the solar system, Kepler's laws can be accurately applied to almost any orbiting body (Job, 1994). As such, his contributions are heavily noted in the field of astronomy, especially by the National Space National Aeronautics and Space Administration. In fact, on March 7th, 2009, NASA launched the Kepler Mission, the association's 10th discovery initiative. (Figure 2.1.6) The scientific objective of the Kepler Mission was to explore the structure and diversity of planetary systems, inodrer to identify celestial bodies capable of sustaining life. The climate of such a planet must be capable of supporting liquid water (Koch et al., 2010).

The climate of any planet is dependent on its orbit parameters. This phenomena is known as orbital forcing and is attributed to the variance in the radial exposure associated with the trajectory and nature of planetary motion. With this in mind, all the celestial bodies that meet the criteria of the Kepler mission are limited by a specific range of orbital parameters. This range is more commonly known as the habitable zone (de Boer and Smith, 1994).

In order to establish celestial bodies within the habitable zone the Kepler spacecraft was launched into space. This ship was equipped with a specialized photometer which had the ability to continually monitor brightness of over 145,000 main sequence stars in a fixed field of view. The orbital parameters of each distal planet was determined by analyzing its transit across the Sun and the associated change in brightness. In this model, highly repeatable signals are associated with periodic planetary motion, consistent with Kepler's laws. From the amplitude and period of this signal, the parameters of a planet's orbit can be calculated in correspondence to Kepler's third law. Under the postulates of orbital forcing, it is possible to determine if this body is within its corresponding habitable zone (Koch et al., 2010).

Figure 2.1.6: The Kepler space-craft: Ignition of the Delta II 7925-10L rocket. On board is the Kepler photometer.

To date, the Kepler Mission has identified nearly 1000 planets within the habitable zone. Of these, one body, Kepler-186f, was found to be consistent with both the size and envirmental conditions of Earth, presenting the possibility of extraterestrial life (Quintana et al., 2014). We may not be alone in the pursuit of knowledge.

The Moon: Early Exploration and the Space Race

Figure 2.2.1: Galileo's sketches of the Moon from Siderius Nuncius

On July 20, 1969, an American astronaut named Neil Armstrong said the first words ever spoken from the surface of another world. "The Eagle has landed," signified the first successful lunar landing by any manned mission. Armstrong and Edwin "Buzz" Aldrin then used scientific instruments to collect experimental data in the first of only six manned Moon landings in history, all of which were Apollo missions (Cortright, 1975; Orloff and Hartland, 2006; National Aeronautics and Space Administration, 2013b). The Apollo missions were highly dependent on technological advancement and availability. Progress in lunar science (selenology) has been shaped by the technology available for lunar exploration. Lunar science exemplifies the influence of technology on scientific research in its progression from naked eye and telescope observations to robot landings and manned missions.

With the Naked Eye

For much of history, lack of adequate technology made detailed study of lunar geology impossible. The Moon was studied through direct observation only, and focussed on predicting and explaining eclipses. Around 450 BCE, the ancient Greek philosopher Anaxagoras proposed that the Moon is an enormous round stone that reflects light from the Sun (Russell, 2008). Near 830 CE, the Persian astronomer Habash al-Hasib was able to calculate the perigee and circumference of the Moon to within 15% of currently accepted values (Langermann, 1985). While these are impressive achievements, further progress in selenology was severely limited by the dependence on naked-eye observations.

The Telescope

Although some controversy surrounds the invention of the first telescope, Hans Lippershey, who attempted to patent the telescope in 1608, is most often credited with the invention (Beatty et al., 2008). The design was improved and utilized by Galileo Galilei, who first noted in *The Starry Messenger* (1610) that the Moon was not perfectly smooth, as previously thought. Galileo sketched the Moon (Figure 2.2.1) and noted that its surface was "just like the Earth's surface, with huge prominences, deep valleys, and chasms" (Drake, 1957). For many years, it was assumed that the Moon's imperfections were due to volcanic activity, with craters representing ancient volcanic calderas or maars (Wilhelms, 1993). In the late 19th century, Karl Grove Gilbert became the first to suggest that these craters were too large to result from volcanism, and were more likely caused by collision (Gilbert, 1893). Gilbert's ideas were not well-received, and it was not until Ralph B. Baldwin's *The Face of the Moon* (Baldwin, 1949) that the scientific community began to accept the plausibility of lunar craters as a result of impact (Wilhelms, 1993). Although ground-based optical telescopes provided additional insight into the surface of the Moon, the resolution and proximity needed to accurately study lunar geological processes could not be achieved using this technology. Major advances required observation from space.

The Space Race Begins

By the time Baldwin had released his work, the Cold War had begun. On October 4, 1957, the Soviets successfully launched Sputnik 1, an 84 kg satellite, into low Earth orbit. Sputnik 1's only designed function was to send a meaningless radio signal, "beep, beep, beep," down to Earth, but its effects were profound; Sputnik 1's beeps signaled the start of a new era – the Space Race. Suddenly, America and the Soviet Union were engaged in an intense competition for technological dominance in space exploration (Dickson, 2009). This technological competition fueled the greatest scientific effort in history aimed at studying space, including the Moon.

After the success of Sputnik 1, Soviet Premier Nikita Khrushchev wanted another launch to celebrate the 40th anniversary of the October Revolution, only 1 month after the launch of Sputnik 1. With only a month's work and without quality checks, Sputnik 2 was successfully launched on November 3, 1957. At 508 kg, Sputnik 2 was over six times heavier than Sputnik 1. Sputnik 2 also carried the world's first space passenger, Layka the dog. Layka did not survive the flight, but the success of Sputnik 2 so soon after Sputnik 1 intensified the crisis in the United States. This prompted the creation of a parallel American space program, Explorer, an addition to the previous Vanguard program, and later the creation of the National Aeronautics and Space Administration (NASA). Further advances and launches by both the US and the USSR led to the launch of larger payloads and the mapping of the Van Allen radiation belts (Launius, Logsdon and Smith, 2013).

Luna Impact

Early in the Space Race, most American space scientists were uninterested in the Moon. Sky scientists, as they were called, were primarily physicists interested in the properties of the upper atmosphere and interstellar space. On January 2, 1959, the USSR launched the Luna 1 probe. Luna 1 missed the Moon by less than two lunar diameters, and became the first human-built probe to escape from Earth orbit. Nonetheless, Luna 1 collected data indicating the existence of the solar wind (a strong flow of ionized plasma from the Sun) and that the Moon had little or no magnetic field (National Aeronautics and Space Administration, 2011). The partial success of Luna 1, combined with pressure from American geoscientists, influenced the adoption of lunar exploration as part of the NASA program (Wilhelms, 1993).

On September 14, 1959, the USSR's Luna 2 probe became the first human-made object to impact another celestial body. Luna 2 confirmed that, unlike the Earth, the Moon does not have a strong magnetic field or radiation belt (National Aeronautics and Space Administration, 2010b).

The Luna 3 probe, launched on October 4, 1959, was the first human-made craft to view the far side of the Moon. It took 29 photographs, of which 17 were usable (National Aeronautics and Space Administration, 2013c). Luna 3's photos showed that there were clearly fewer maria (dark basaltic plains; a result of volcanism) on the Moon's far side. Images from Luna 3 were used by American scientists to create the first iteration of the lunar astronautical charts (LAC), a set of geological maps of the Moon's surface (Wilhelms, 1993). Higher-resolution photographs were eventually taken by the Apollo 16 mission in 1972 (Figure 2.2.2).

On February 3, 1966, Luna 9 made the first survivable landing on the Moon, and showed that, contrary to some predictions, a lunar lander would not sink into a thick layer of dust. Luna 9 sent the first-ever photographs from the surface of the Moon (National Aeronautics and Space Administration, 2010c).

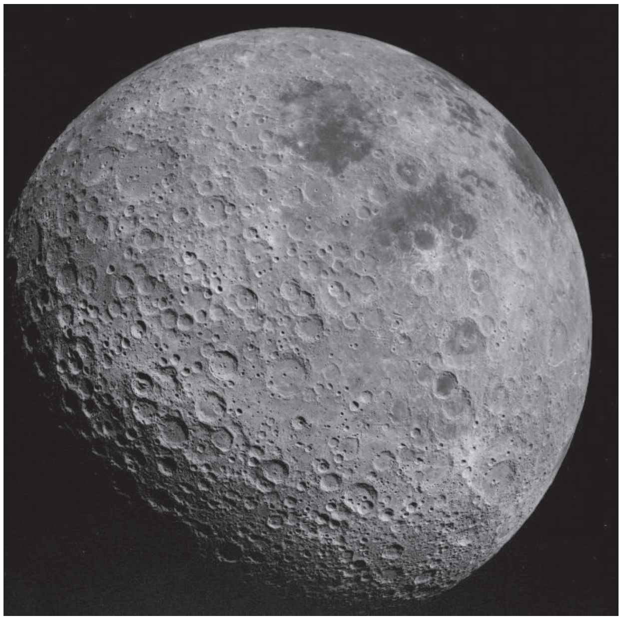


Figure 2.2.2: The far side of the Moon, photographed by Apollo 16 in April 1972

Two months later, the USSR's Luna 10 became the first spacecraft to orbit the Moon. Luna 10 spent 56 days in lunar orbit and completed 460 orbits before its batteries were depleted. In the meantime, Luna 10 collected information on the Moon's extremely weak magnetic field, atmosphere, and radiation belts, as well as its surface composition. Tracking data showed that Luna 10's orbit trajectory was being distorted by the Moon's gravitational field, allowing Soviet scientists to study the Moon's internal composition (Akim, 1966). The Luna program was incredibly successful, dominating lunar exploration for a decade after its inception. The Space Race appeared to have been won.

Men on the Moon

The Soviet's Luna 15 probe was intended to be the first spacecraft to return lunar material to Earth. However, on July 21, 1969, Luna 15 failed on descent and crashed on the surface of the Moon (National Aeronautics and Space Administration, 2010a). At the same time, NASA's Apollo 11 lander was already on the Moon's surface (specifically, Mare Tranquillitatis), and its two human astronauts, Neil Armstrong and Buzz Aldrin (Figure 2.2.3), had collected samples and were preparing to return them to Earth (National Aeronautics and Space Administration, 2013b). Five subsequent Apollo missions, culminating in 1972 with Apollo 17 (Apollo 13 was aborted after an oxygen tank exploded), represent the only other human visits to the Moon (Orloff and Hartland, 2006).

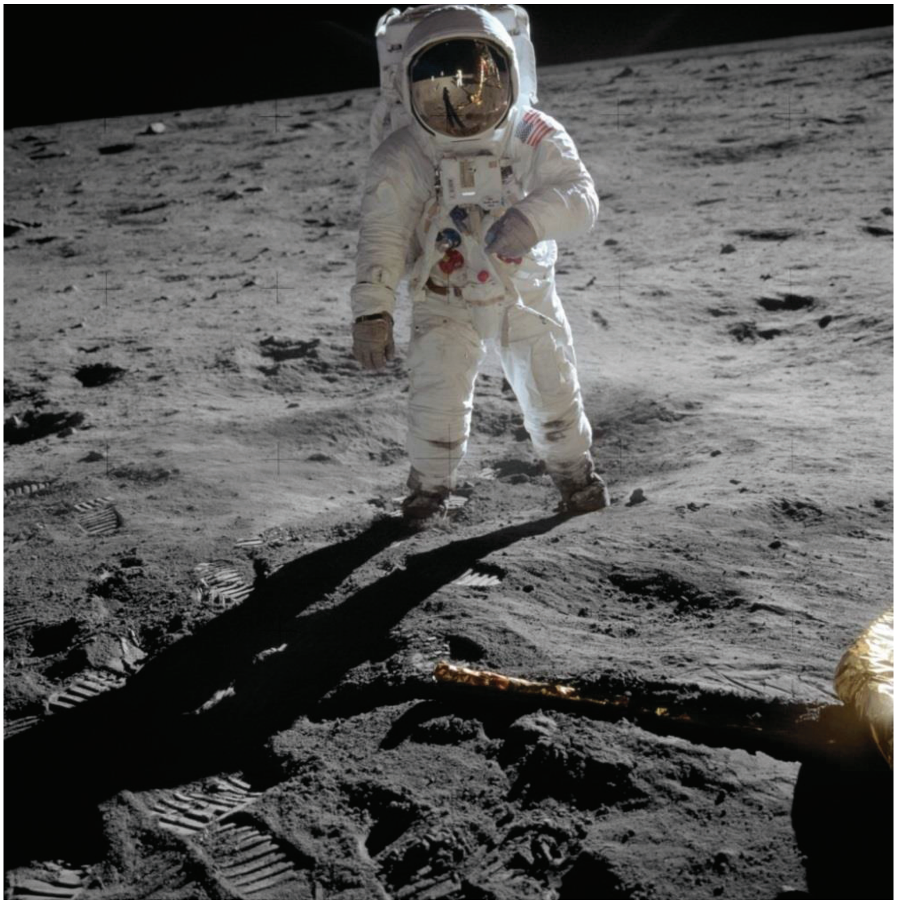


Figure 2.2.3: Buzz Aldrin on the Moon. This photograph was taken by Neil Armstrong, whose reflection can be seen in Aldrin's visor.

The Apollo missions brought back virtually all of the lunar material that has ever been studied on Earth. Analyses of lunar material and observations have produced many key findings. For example, radiometric techniques date most rocks on the Moon's surface at about 4.6 Ga old, similar to the oldest rocks on Earth. However, basalts in the dark areas (mares) were dated at 3.2 Ga old, suggesting early volcanic activity (Papike, Karner and Shearer, 2003).

The success of the Apollo program was based on years of work, aimed explicitly at a manned mission to the Moon. Four manned Apollo missions successively approximated the landing before Apollo 11 consummated it. The five missions following brought successively more sophisticated instruments to measure the Moon.

Each person in the chain of events leading to the 1969 Moon landing could only play a small role. It was only by the accumulation of individual actions that the technological wonders enabling lunar exploration were possible. From a technological perspective, reaching the Moon was, as Neil Armstrong famously said, "One small step for man… one giant leap for mankind" (Cortright, 1975).

Selenology Today

After six successful lunar landings, the Apollo program was brought to a halt by budget cuts. The subsequent hiatus in lunar missions was ended in the 1990s by NASA's Clementine and Lunar Prospector missions. Further missions have been conducted in the 21st century by other space organizations, as other nations develop their space programs (National Aeronautics and Space Administration, 2013a). Much of recent selenological research has focussed on aspects relating to the Earth's formation and the formation of the solar system. The Moon is ideal for the study of ancient conditions in the solar system, as it may reveal events that are not preserved on the constantly-changing terrestrial surface (Langmuir and Broecker, 2012).

The most commonly accepted hypothesis for the formation of the Earth and Moon is the giant impact hypothesis, sometimes called the Big Splash. It suggests that the proto-Earth collided approximately 4.6 Ga ago with another proto-planet called Theia, which was approximately the size of modern-day Mars. Conservation of momentum during the impact resulted in a smaller object, the Moon, being ejected from the Earth (Canup and Asphaug, 2001). Although the hypothesis emerged from mathematical modeling, it has since been supported by a collection of empirical evidence.

Because the Moon's orbit has a similar orientation to the Earth's spin, it seems likely that these properties emerged from the same event (Canup and Asphaug, 2001). Oxygen isotopic ratios on the Moon are similar to those on Earth, suggesting that the Moon and the Earth likely formed from an identical mix of components (Wiechert et al., 2001).

The Moon's surface is rich in iron but, as it lacks a large iron core, the Moon is less dense than Earth and relatively iron-poor overall. This suggests that the Moon formed from previously differentiated material, and this material may have differentiated in proto-Earth before the impact of Theia (Canup and Asphaug, 2001). The properties of the lunar crust and mantle suggest that the Moon's surface was once partially molten (Shirley, 1983), which may have resulted from the energy of the Theia impact.

Basins and Craters

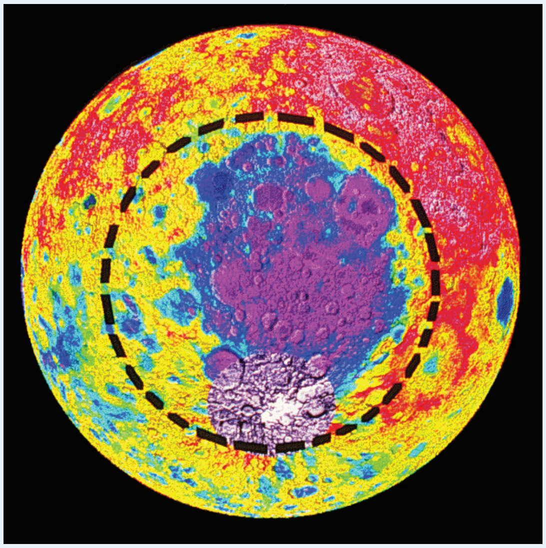


Figure 2.2.4: The South Pole-Aiken basin of the Moon, as photographed by the Clementine spacecraft. Purple represents low elevation and red represents high elevation.

As it cooled, the Moon's surface solidified from the outside in, meaning that the crust solidified before the mantle. A series of large impacts in the Moon's early history created enormous basins, which were filled with basaltic magma from associated volcanic events. These structures are visible today as the dark patches on the Moon's surface (National Aeronautics and Space Administration, 2012).

The oldest of the Moon's basins is the South Pole-Aitken (SPA) basin (Figure 2.2.4). The SPA is more than 8 km deep and extends from the lunar South Pole to the Aitken crater (15º south of the lunar equator). Its diameter is approximately 2400 km, making the SPA the largest known basin on the Moon (Pieters et al., 2001; Garrick-Bethell and Zuber, 2009). The SPA impact was so large that it has removed the anorthosite upper crust from almost all of the basin (Pieters et al., 2001).

The sizes, shapes, compositions, and distributions of lunar craters represent various conditions in our solar system's history. For example, the distribution of lunar crater sizes differs for craters less than 3.8 Ga old, relative to older craters. This suggests two different populations of impactors in the asteroid belt from those times, indicating a turning point in the formation of the solar system (Strom et al., 2005; Head et al., 2010).

Besides informing our understanding of our closest celestial neighbor, studying the Moon informs our understanding of the history of the Earth and of the solar system. Thus, the rich history of selenology is itself a study of cosmic history.

Astrobiology: Development of a Science

Figure 2.3.1: Earth is the only planet on which we know life exists. Astrobiology studies how life began on this planet, whether it could occur elsewhere, and what the future of life in the universe may be.

Throughout history, many people have wondered: how did life on Earth arise? Is there life on other planets? Today these questions fall into the field of astrobiology, the study of the origins, evolution, distribution, and future of life in the universe, including on Earth (Figure 2.3.1) (Dick and Strick, 2014). Astrobiology is inherently multidisciplinary: understanding the origins of life requires integrating knowledge from biology, chemistry, and the Earth and space sciences. The creation of astrobiology in its current form is often credited to the National Aeronautics and Space Administration (NASA), which envisioned astrobiology in its form as a "superdiscipline" (Dick and Strick, 2004). However, the questions and interest in astrobiology existed prior to NASA's creation of the discipline, beginning in ancient times. The development of astrobiology was also partly driven by factors external to NASA. These external factors include the scientific developments that provided scientists with the means to test their hypotheses in a scientific manner, as well as public interest and the political climates of the times. However, NASA did play an instrumental role in the development of astrobiology by formalising the discipline.

Prior Interest in the Origins of Life

Questions regarding the origins of life on Earth and its presence elsewhere are not new. In 500–300 BCE Greece, Democritus, Epicurus, and other atomists suggested that the Earth was one of many worlds and that life could exist in the other worlds (Gale, 2009; Sullivan and Carney, 2007). However, this school of thought was overshadowed by the Aristotelian school of thought, which alloted the Earth a special place at the centre of the universe (Gale, 2009), and suggested that life formed through spontaneous generation from inorganic matter (see also pp. 128-131) (Magner, 2002). The ideas of the atomists, however, were later echoed by Roman philosopher Lucretius (Gale, 2009). Likewise, Nicolaus Copernicus suggested that the Earth is not special and that there could be other planets on which life may exist (Sullivan and Carney, 2007). The idea that Earth is not unique, now known as the Copernican principle, is important not only in astrobiology but also in most of science.

Throughout most of the 1900s, the idea of spontaneous generation of life continued to be a topic of debate. In the 1600s, cells and bacteria were first observed, and experiments were performed that both supported and refuted the spontaneous generation of these organisms (Sullivan and Carney, 2007). It was not until 1861 that Louis Pasteur demonstrated that these lifeforms could not arise spontaneously (Pasteur, 1861). Instead, he suggested that microorganisms could only arise in the presence of other microorganisms of the same kind: his results favoured the theory that life must come from life (see also pp. 128-131).

This led scientists to wonder where the first lifeform originated. Alexander Oparin and John Burdon Sanderson Haldane independently proposed that life may have arisen from a primordial "soup" in a reducing environment with an energy source that led to the production of simple organic compounds (Oparin, 1938; Haldane, 1929). These compounds were then exposed to more energy in the reducing environment, producing increasingly complex organics. These theories formed the basis of the now-famous Miller-Urey experiment, in which Stanley Miller and Harold Urey re-created the conditions proposed by Haldane and Oparin and produced several basic building blocks of life, including amino acids (Sullivan and Carney, 2007). By showing that the building blocks of life could be generated from inorganic compounds in an environment thought to be similar to that of early Earth, Miller and Urey opened the door to the possibility that life arose in a similar fashion elsewhere (see also pp. 128-131).

The Birth of Astrobiology

The predecessor to astrobiology, exobiology, came into being in the late 1950s and early 1960s (Dick and Strick, 2004). Exobiology, a term coined by Joshua Lederberg (Figure 2.3.2), was narrower in focus than modern astrobiology: it focussed only on life outside of Earth (Dick and Strick, 2004), while astrobiology today focusses on life in the universe as a whole.

Since NASA's formation in 1958, exobiology has been an important aspect of its research: by 1960, NASA had created an Office of Life Sciences, of which exobiology was a major component (Dick, 2007). Two factors appear to have been instrumental in making exobiology such a large part of NASA from its outset. First, the creation of NASA occurred during the space race as part of the Cold War. Oparin was a Soviet scientist, and it was feared that the Soviets were close to solving the origins of life and being able to create synthetic life forms (Dick and Strick, 2004). Not wanting to be outdone by the Soviet Union, NASA thus made the study of life a large part of its focus.

In addition, Lederberg was a driving force for the creation of astrobiology. He was not only interested in the origins of life, but he was also concerned about the potential for biological contamination from and of Earth due to recklessness that could occur as part of the space race (Dick, 2007). Lederberg worried that in the rush to explore space, terrestrial organisms could contaminate other celestial bodies and lead to the loss of a chance to study those environments properly (Dick and Strick, 2004). On the other hand, he was also cocerned that organisms could be brought back to Earth from extraterrestrial sources, and these could have negative impacts (Dick and Strick, 2004). His interest and advocacy led to his appointment as the first head of NASA's Space Science Board's panel on extraterrestrial life.

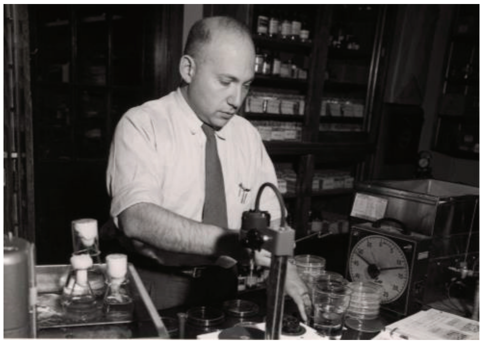


Figure 2.3.2: Joshua Lederberg (May 23, 1925–February 2, 2008) played a large role in the creation of exobiology, the predecessor to astrobiology. This is a photograph from 1958 of him working in a lab.

Exobiology, however, faced criticism for the fact that its subject matter, life outside of Earth, had not been proven to exist (Simpson, 1964). This posed a problem, since a science requires testable hypotheses and falsifiability (Hung, 2014), and hypotheses in exobiology could not be tested due to the absence of its subject matter. However, as space exploration entered the 1970s, it became possible to test hypotheses as missions to other celestial bodies became possible. The Viking missions provided the first opportunities to search for life outside Earth. During the 1970s and 1980s, various scientific advances provided new lines of study for astrobiology: the discovery of life near deep-sea hydrothermal vents, the discovery of the Archaea (see also pp. 132-135), the Alvarez hypothesis regarding the end-Cretaceous mass extinction, and the RNA world hypothesis (Dick and Strick, 2004). Exobiology was born in a time when it was first becoming possible to test the hypotheses it proposed.

Exobiology Becomes Astrobiology

By the 1990s, however, exobiology was facing a crisis (Smith, 2004). Public and political interest had declined due to the disappointing results of the Viking missions, which failed to produce conclusive evidence for life on Mars (Smith, 2004). NASA's search for extraterrestrial intelligence (SETI) program was ridiculed in Congress and had its funding cut (Dick and Strick, 2004). In addition, NASA was facing financial pressure from the American government. This led Daniel Goldin, administrator of NASA, to order a zero-base review to streamline NASA and eliminate overlap in research roles between different groups within NASA (Dick and Strick, 2004). The Ames Research Centre historically was NASA's centre for exobiology and conducted research in life, Earth, and space sciences; thus its scope overlapped with other research centres, and Ames was slated to be split apart to these other centres (Dick and Strick, 2004). This proposal was not well received by divisional chiefs at Ames. Lynn Harper, chief of the Advanced Life Support Division at the Ames Research Centre, argued that the interdisciplinary research being conducted

Figure 2.3.3: ALH84001 is a meteorite from Mars. In 1996, NASA scientists announced that they had discovered what they believed to be evidence for past life on Mars.

there was important, and suggested that the multiple areas of research be focussed under the topic of "life in the universe", a redefined version of exobiology (Dick and Strick, 2004). NASA administration was receptive to this idea, and, after renaming "life in the universe" as astrobiology, made Ames NASA's lead centre for astrobiology (Dick, 2007).

Subsequently, several discoveries once again sparked public interest in astrobiology. In 1995, the first detection of an extrasolar planet around a Sun-like star was announced (Mayor and Queloz, 1995), and in 1996, scientists announced the discovery of evidence suggestive of past life on Mars in their analysis of a Martian meteorite found in Antarctica, ALH84001 (Figure 2.3.3) (McKay, et al., 1996). These discoveries and the subsequent public interest in astrobiology led to increased government funding for astrobiology research, allowing for even more advances. Clearly, politics and public interest have also played a large role in shaping the developing field of astrobiology.

As part of its restructuring, in 1998, NASA created the NASA Astrobiology Institute (NAI), a virtual institute, where members communicate through electronic communication technologies like videoconferencing (National Aeronautics and Space Adminsitration, 2014; Dick and Strick, 2004). Other astrobiology institutes also began to be formed in Spain (1999) (Centro de Astrobiología, 2012), Australia (2001) (Australian Cenre for Astrobiology, n.d.), and Europe (2002) (European Astrobiology Network Association, n.d.). By 2002, the NAI was receiving $40 million in funding per year; two new journals, *Astrobiology* and the *International Journal of Astrobiology*, had been started; and the second biennial astrobiology science conference held that year was attended by 700 people (Dick and Strick, 2004).

While NASA has played a large role in the development of astrobiology as a science, from the creation of its first exobiology program in 1960 to the formation of the NAI 38 years later, it is clear that other factors have made important contributions too: scientific and technologic advances finally made it possible to approach questions in astrobiology scientifically, and both political and public interest have guided the directions in which astrobiology developed.

The State of Astrobiology Today

Although it is still a relatively new discipline, astrobiology has grown rapidly and continues to do so. Various space agencies around the world have planned missions that can contribute to astrobiology. Mars continues to be a prominent focus of astrobiological studies: for example, the European Space Agency and Russia's Roscosmos's planned ExoMars mission will examine sources of methane in the Martian atmosphere using an orbiter while an associated rover is planned to obtain sub-surface soil samples with a drill (European Space Agency, 2014). The drill is designed to obtain samples from up to 2 metres below the surface in order to retrieve soil samples that have not been exposed to ultraviolet radiation, which can destroy organic compounds that would used as an indicator for past or present life (Vago, et al., 2006).

However, Mars is not the only location of interest in the solar system to astrobiologists. Jupiter's moons Europa (Figure 2.3.4) and Callisto, and Saturn's moons Titan and Enceladus, are suspected of having subsurface oceans that could harbour life (National Aeronautics and Space Adminsitration, n.d.). The Europa Clipper is a planned NASA mission to determine if Europa has such an ocean, and if so, to characterize it (Phillips and Pappalardo, 2014).

On Earth, astrobiologists are studying viruses (Griffin, 2013), which could help them understand possible characteristics of extraterrestrial life. Another area of research which can be considered a subset of astrobiology is xenobiology, the study of life with foreign chemistry (see also pp. 128-131). Xenobiology can help scientists understand the possibilies for the types of chemistry that can and cannot produce life (Schmidt, 2010). Alternative chemistries proposed have included ammonia-based and silicon-based life forms (Bains, 2004). Increasingly powerful supercomputers are also allowing scientists to model and study ideas from the RNA world hypothesis (Meng and Higgs, 2012) to water distribution during solar system formation (Cleeves, et al., 2014). Astrobiology is not only expanding rapidly, but it is doing so in many directions at once.

Figure 2.3.4: An artist's rendition of the surface of Europa, one of Jupiter's moons. Europa is of interest to astrobiologists because of the possibility that it has a subsurface ocean.

Education

With increasing public interest in the topic, astrobiology has also begun to appear in the educational system. The University of Washington created the first Ph. D. program in astrobiology in 1999 (Dick and Strick, 2004). In a reflection of the multidisciplinary nature of astrobiology, students take a class that introduces them to the basic concepts in various disciplines related to astrobiology, as well as participating in a research rotation outside of their regular field of study (Wells, Armstrong and Huber, 2007). Other astrobiology graduate programs, including Ph. D. programs, minors, and certificate programs, have now been created at universities including Pennsylvania State University (Penn State Astrobiology Research Centre, n.d.) and McMaster University (Origins Institute, n.d.). Astrobiology courses also exist at many universities at both graduate and undergraduate levels (University of Washington Astrobiology, 2012), and material has been created for using astrobiology to teach high school students as well (Harman and DeVore, 2009). Astrobiology, with its popular appeal, has become a way to introduce an interdisciplinary approach to education.

A World of Spheres: Journey to the Noosphere

The twenty-first-century culture recognizes human impacts on the Earth and the organisms that live on it to be significant. However, this has not always been the case. In his *Principles of Geology,* Charles Lyell wrote that humans had no more effect on the Earth than the brute force of animals (Lyell, 1970). Our perspective changed as humans began to use more energy and create technology to perform tasks bigger than us. In conjunction with these changes, scientists started to look for a way to describe humanity's place on the Earth. A few questions that shaped the concept of the noosphere are as follows: are humans superior to animals? Do we understand the consequences that our actions have on the Earth? The noosphere can be described simply as a stage of the Earth's succession that is defined by human consciousness. The development of this complex concept began from the notion of spheres.

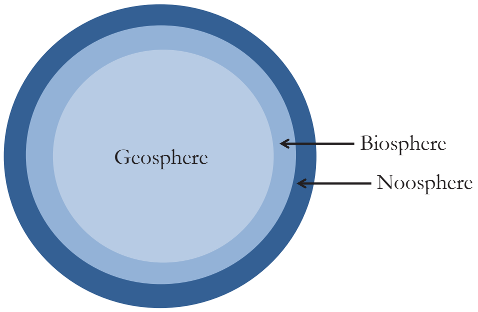


Figure 2.4.1: Visual representation of the geosphere, biosphere, and noosphere.

The concept of the noosphere is built on the geological description of the Earth composed of concentric envelopes (Figure 2.4.1). As early as 1564, Giovanni Camillo Maffei published his idea of fourteen spheres that contained all the knowledge of the universe (Samson and Pitt, 1999a). The first appearance of modern sphere terms was Eduard Suess' description of the barysphere, lithosphere, and biosphere (Suess, 1875). In 1995 Richard Huggett built on this concept, describing a dozen sphere terms that are still in use today (Huggett, 1995). Ecologist E.P. Odum applied the concept of ecological connectivity to the geological interpretation of the Earth as envelopes (Odum, 1993). He postulates that in an ecological hierarchy wherein each unit of the chain is connected intimately with the next, ecosystems functioning on a global scale are created. These global systems can be extended to include the noosphere (Odum, 1993).

The focus of this discussion of the evolutionary concept of spheres includes the geosphere, the biosphere, and evidently the noosphere itself, wherein the noosphere is a use concept that can be used to understand humanity and its place in the World. The development of the spheres began with the geosphere: the creation of the physical earth (Samson and Pitt, 1999a). The geosphere is described as the inanimate matter of the Earth comprising the atmosphere (gaseous sphere), the hydrosphere (water sphere), and the lithosphere (solid sphere). The emergence of life was the next phase of the Earth's evolution (Samson and Pitt, 1999a). This is described as the biosphere. With the appearance of this new sphere, the geosphere was transformed. The final sphere was created by the emergence of human consciousness (Samson and Pitt, 1999a). Similarly to the biosphere, the birth of the noosphere transformed the biosphere. This transformation is not static, but instead there is a dynamic relationship between the three spheres. They each depend on the presence of the others, act, and are acted upon by the other spheres (Samson and Pitt, 1999a).

Geosphere and Biosphere

The words "geosphere" and "biosphere" both have Greek and Latin origins. "Geo" means ground and "bio" means life, while "sphoera" means sphere in Latin (Samson and Pitt, 1999b). The term biosphere was coined by Australian geologist Eduard Suess in 1875 in the last and most general chapter of his book *The Origin of the Alps* (Suess, 1875) . He then expanded on it in his book *The Face of the Earth* in 1883 (Suess, 1924). This included a description of the interdependency between the biosphere and the geosphere. It also indicated that the particular conditions of the geosphere (temperature, chemical composition) allowed the biosphere to come into existence (Suess, 1875). However, the concept of the biosphere wasn't incorporated into the scientific community until its use by Vladimir Vernadsky in the publication of *La Biosphere* in 1929 (Hutchinson, 1970). This interpretation was influenced by French naturalist Jean-Baptiste Lamarck from texts such as *Hydrologie* in 1802 (Hutchinson, 1970; Samson & Pitt, 1999b). Since then, the biosphere has been pivotal in our understanding of ecology. In the same light, the noosphere has done this for our understanding of human interactions.

Origins of the Noosphere

Similar to the geosphere and the biosphere, the term noosphere has Greek origins as "noos" means mind in Greek (Samson and Pitt, 1999b). The history of the concept stretches back to Anaxagoras (c. 500-428) who postulated that the mind was a new entity that was significant, yet distinct from matter (Samson and Pitt, 1999b). The term "noetic" was used since the seventeenth century to describe "that which applies to the mind" (Samson and Pitt, 1999b). As mentioned previously, the idea of humanity as a dominant force on the planet is relatively new. Charles Lyell, in his 1830 work *Principles of Geology*, stated that human impacts on the environment were not more significant than those of animals (Lyell, 1970). Overall, scientists were against the idea of humans as geological agents until the end of the 19th century with the influence of scholars such as Lamarck (Samson and Pitt, 1999b). By the 20th century, humans were viewed as the significant geological agents. Terms like "psychozoic era", "anthropozoic era", and "mental era" were used to describe a new geological period with humanity as a new geologic force (Samson and Pitt, 1999b). These terms lead to the conceptualization of the noosphere by Edouard Le Roy, Pierre Teilhard de Chardin and Vladimir I. Vernadsky.

Eduard Le Roy, French mathematician and professor at La Sorbonne, was the first person to publish on the noosphere. He describes the noosphere as the human envelope of the biosphere that is slowly evolving to separate itself from the biosphere and form a new entity (Le Roy, 1928). In Paris during the 1920s, Le Roy and Teilhard became intimiate collegues and discussed many scientific concepts including the noosphere. Teilhard De Chardin was a French palaeontologist who had a spiritual perspective on the noosphere, describing a "psycho-biological" dimension. In his book *The Phenomenon of Man* he describes the noosphere as a layer of consciousness that began its growth at the end of the lower Pleistocene period with the emergence of humanity's early ancestors (De Chardin, 1955). He compares it to an invasion that conquers the Earth to claim its place above previously existing forms of life (De Chardin, 1955).

Vladimir Vernadsky encountered Le Roy during the former's lectures in Paris from 1922-1924 (Grenet, 1960). It is possible that Le Roy made the connection between Vernadsky and his colleague De Chardin, but correspondences from this period are unclear (Grinevald, 1998). Vernadsky, mineralogist and pioneer interdisciplinary scientist, didn't use the term "noosphere" until the 1930s, when he accredited the word to Le Roy (Samson and Pitt, 1999b). He used his research on the evolution of the natural world to inspire his research and description of the noosphere. He believed that the noosphere grew to take a significant role in the biosphere, eventually transforming it (Jones, 2012; Samson and Pitt, 1999b). As an individual, Vernadsky was optimistic in regards to humanity's role in the universe. He believed that the pivotal scientific feats at the time, such as Einstein's discovery of relativity and the exploration of space, were evidence for the development of the noosphere (Jones, 2012). Even from its infancy, the development the noosphere came from a place of wonder at the universe and as such it is still useful today.

Perspectives of the Noosphere

The current idea of the noosphere can be analyzed from multiple perspectives. One such perspective is the examination of the noosphere's impacts on the biosphere. One feature of the biosphere that distinguishes it from the geosphere is its energy production (Hutchinson, 1970). With the appearance of man, there have been substantial changes in the biosphere due to our production of energy (Jones, 2012). Before 1800, the primary sources of energy were human and animal power. Organisms would obtain energy from the metabolism of food and then use it through biological oxidation of stored solar energy (Singer, 1970). Humans would initially burn wood, burn oil or use moving air or water. Overall, energy was not generated in vast quantities, and it could not be transported far distances (Singer, 1970). Today humanity is speeding up the natural processes of releasing energy. We have found ways to produce and transport energy on a global scale, and we have discovered new energy sources such as fossil fuels, nuclear fuels, and geothermal energy (Figure 2.4.2). Without humans, the energy of these sources would never have been harnessed, lessening the impact on the geosphere. This impact highlights the concept of a new era of the human impact: the noosphere.

Figure 2.4.2: Hellisheiði Geothermal plant in Rekjavík, Iceland.

From a geoarchaeological perspective, humanity has been altering the geosphere almost since its existence. The use of fire is one of the first ways that humans started changing the natural environment in a way that is unique to all other organisms. The use of fire could burn vegetation to facilitate hunting, provide protection from predators, and get rid of unwanted insects (Wilson, 2011). It also created more open spaces, created species that could tolerate fire, and changed the distribution of forests and animals. These relatively large-scale changes, beginning several hundred years ago, are testament to the unique nature of human impacts (Wilson, 2011).

While the terms geosphere and biosphere have been relatively accepted into today's scientific vocabulary, the same cannot be said about the noosphere. In part, this can be explained by the many obstacles that the creators had to overcome in sharing their concept with the remainder of the scientific community. For one, when Le Roy published his initial works describing the noosphere they received little attention from the scientific community (Samson and Pitt, 1999d). Furthermore, the Church forbade Teilhard from publishing his works, forcing him to move to China, and then eventually retire to the United States of America (Samson and Pitt, 1999d). His works were completed in the 1920s and 1930s, but were only printed posthumously. Vernadsky also experienced scientific censorship. Vernadsky was born tsarist Russia and died in the Soviet Union, living through the revolutions, Stalin's purges and the Second World War. While he was afforded some privileges such as the ability to fly abroad as a Soviet in the 1930s, his origins hindered the sharing of the noosphere concept with the western world (Samson and Pitt, 1999d). His perspective on the noosphere has experienced much rejection by western society and Russia has also altered the reality of the emergence of the noosphere concept. Despite these challenges, Vernadsky supporters, such as G. Evelyn Hutchinson, helped to publish Vernadsky's final paper on the noosphere in America in 1945 (Samson and Pitt, 1999d). American historian's biography of Vernadsky in 1990 also assisted in decreasing the stigma against this Russian scientist (Samson and Pitt, 1999d).

In addition to the barriers of stigma and censorship, the concept of the noosphere has also been thoroughly criticized. One such critique is that it implies that humanity understands the results of all its actions, and that mankind's ability to affect the geosphere and biosphere is advancing much quicker than its capacity to comprehend it (Odum, 1959). Similarly, biologist David Ehrenfeld claims that humans are not yet able to comprehend the entirety of the vast amount of knowledge at our disposal (Ehrenfeld, 1978; Ehrenfeld, 1993). While there are differences in scientists' ideas about the noosphere concept, there is still potential for it to be applied to the problems that the Earth is facing. In the words of geologist and emeritus professor of geophysiology, Peter Westbroek: "For the moment, noosphere is only a descriptive term with little scientific meaning... but we lack a comprehensive theory that explains the integration of culture and natural science as a global phenomenon" (Samson and Pitt, 1999b). It appears that the noosphere will continue to be useful until we can discover more about the intricate relationship between Earth and humanity.

Collective Consciousness and the World Wide Web

The noosphere truly is an integrated concept; drawing from aspects of psychology, physics, sociology, geochemistry and many others. Different perspectives on the meaning of the noosphere use concepts from a variety of disciplines. The perspective of "the noosphere [as] a manifestation of the global brain" uses the sociology concept of the collective consciousness to investigate the emergence of modern technology (Samson and Pitt, 1999b). There are many definitions of the collective consciousness. According to Anna Piepmeyer, it is a consciousness shared by many people (Piepmeyer, 2007). It can also be described as the sum of our total consciousness (Safdie, 1975). The collective conscious was coined by Émile Durkheim, a French sociologist who participated in the creation of the foundations of modern sociology in the late 19th and early 20th century (Carls, 2014; Piepmeyer, 2007). The concept was used by social theorists to describe how individuals identify with groups and how unity is created. Durkheim investigated the cause of commonality: why humans act the same or in a predictable way. He proposed that this was because the collective conscious trains humanity how to behave to fit the norm (Piepmeyer, 2007). The concept of the collective conscious was further developed in the 20th century with psychologists such as Swiss psychologist Carl Jung. He introduced the concept of the collective unconscious. It is defined as the part of the unconscious mind that is shared with all of humanity. Unlike the personal unconscious, it doesn't come from personal experience but is hereditary (Jung, 1981).

The concept of a global consciousness is intertwined with that of the noosphere and can be used to provide a complete understanding of the notion. It can also be applied to the phenomenon of globalization in the 20th century. Globalization is the increased proximity of communications with people around the globe, through the advancements in transportation and computer technology (Global Policy Forum). Humans have been altering the geosphere through the creation o roads, railways, and runways for hundreds of years; today we see changes in our technological landscape to increase of cultural connectivity. Marshall McLuhan proposed that globalization would lead to a "noosphere or a technological brain for the world" (Samson and Pitt, 1999c). This "technological brain" can be identified as the World Wide Web. Even as early as 1872, one of Darwin's most outspoken critics suggests the future emergence of a "digital wilderness" with its own evolution and a greater intelligence than that of humanity. While there may be differences in regards to the nature and origins of this new entity, it is inextricably connected with the noosphere. Frenchman Joel de Rosnay claimed that the early Earth was expanding via the Internet to create a hybrid life form (Samson and Pitt, 1999c). Allerd Stikker asserted that we are reaching a saturation point of the evolution, and we will be transformed into a new configuration. Finally, Media theorist Katherine Hayles described code as the new version of the human genome. She explained how we have become post-human and have entered coded human existence (Piepmeyer, 2007).

Figure 2.4.3: Dr. Carl Jung, taken September 12, 1912.

While emerging ideas on the evolution of humanity, the noosphere and its relationship with the Internet may appear to be nothing more than science fiction, which is always the way with new scientific ideas. Modern technology and the globalization of mankind are relatively new phenomena and humanity is still developing ways to describe them. In this modern age, the noosphere is a useful tool in understanding our ever-changing environment as we delve deeper into the newly technological wildness.

The Development of Climate Modelling

The initial ideas and perspectives leading to modern climate modelling began in the late 17th century. During the development of meteorology as a science, there was disagreement between scientists analysing atmospheric processes through thermodynamics and hydrodynamics, and weather forecasters viewing weather prediction as more of an art. This divergence of philosophies separated the physical understanding of processes that caused the weather changes from the forecasters predicting weather through statistics.

In 1686, Edmond Halley investigated the causes of wind, and he was the first to make a connection between the circulation of the atmosphere with the distribution of radiation from the Sun, on the Earth's surface (Frisinger, 1977). Halley's experiments showed that warm air rises, and that wind was a result of air flowing into areas where solar radiation had caused the original air to rise up. This was a milestone in studying atmospheric processes, and was a starting point for further research. Following Halley's work, Jean le Rond d'Alembert, a French mathematician and philosopher began to express atmospheric motion mathematically (Frisinger, 1977). For an established mathematician to view meteorology through equations was an important step for meteorology to be accepted as a science. Overall, Halley and d'Alembert provided the initial context for nineteenth-century scientists to begin further investigation in meteorology.

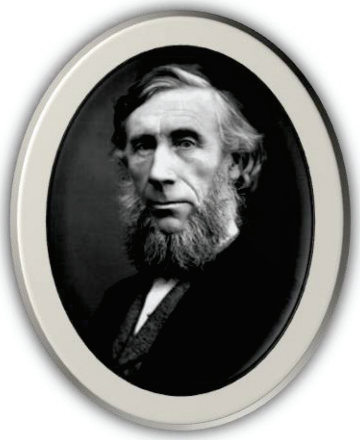


Figure 2.5.1: Portrait of John Tyndall (1820-1893), the physicist who discovered that complex or compound gases were better absorbers of heat in comparison to simple gases.

Establishing Meteorology as a Science

Theories and models of atmospheric processes began to proliferate in the 19th and 20th centuries (Friedman, 1989). Joseph Fourier (1768-1830), was a French physicist and mathematician who first formulated the idea of the 'greenhouse effect' (Rodhe, Charlson and Crawford, 1997). Fourier proposed that the atmosphere acts as an insulator, which traps radiation from the Sun (Fleming, 1999). This led to the discovery of the gases responsible for keeping the Earth warm, which John Tyndall (Figure 2.5.1) experimented on. Tyndall was a 19th century physicist who was a master of laboratory experimentation (Eve and Arthur, 1945). Atmospheric sciences were just one of his interests, as he made contributions to biology and medicine as well. Tyndall showed an interest in the occurrences of dew, hoarfrost, precipitation, and solar radiation, and he believed that molecular bodies were responsible for the phenomena of radiation and absorption. In fact, in the closing pages of his third memoir he applied his discovery of aqueous vapour to the hot days and chilly nights of Siberia and the Sahara.

In 1859 Tyndall developed an interest in examining gases. He experimented with gases including oxygen, hydrogen, nitrogen, and ammonia to determine their absorption of heat. Through modifications of his original experiment, his results indicated that simple gases and vapours were weak absorbers compared to compound gases (Eve and Arthur, 1945). Tyndall was able to show that good absorbers were good radiators, and if liquids exhibited high absorptive capabilities, their vapour would have the same property. Later in 1890, an American meteorologist, Cleveland Abbe, acknowledged that meteorology is principally the application of thermodynamics and hydrodynamics in the atmosphere (Lynch, 2008). He suggested using mathematics and equations to forecast the weather, a much more scientific approach than was in general use at the time.

With the onset of World War I, the gap between meteorology as a science, and forecasting as an art remained to exist (Friedman, 1989). However, WWI began to reduce the magnitude of that gap. Before WWI, a sub-discipline of meteorology had developed known as aerology, which is the observation of the atmosphere by the means of balloons and airplanes (Friedman, 1989). Soon enough, meteorologists became interested in studying the weather conditions in the upper layers of the atmosphere. They needed to understand these conditions to determine when a gas attack would be the most ideal to launch, or when a plane could safely travel to its destination to bomb an enemy. This all transformed the concept of weather. During WWI, commercial aviation and military activities demanded fast, detailed, and precise forecasts. At this time, meteorologists wondered how they could modify their forecasting practices.

Vilhelm Bjerknes was a physicist who developed theoretical meteorological equations that treated forecasting in a scientific manner in the early 20th century (Eve and Arthur, 1945). Through this, he revolutionized the social significance of meteorology as well. Bjerknes was an expert in mechanics and mathematical physics at the University of Stockholm (Friedman, 1989). His interest within the field of meteorology was more theoretical rather than practical. He believed that his methods would be used for forecasting in the future. His main goal was to demonstrate that the present state of the atmosphere could be determined from previous states through the application of science.

Bjerknes developed a two-step approach to forecasting (Lynch, 2008). The first step is the diagnostic step, where the initial state of the atmosphere is determined through observations. The following step is the prognostic step where the laws of motions are used to explain how the atmosphere changes over time. For the prognostic step, Bjerknes developed formulas from physics by breaking the problem down into numerous partial problems (Ashford, 1985). For instance, he broke down the movement of air masses over an interval of time, and then took into account thermodynamic conditions. The issue with using mathematical equations to determine forecasts is that the calculations require a long time. At the time there was an absence of computers, and it would have taken possibly three months to forecast the weather for the following three hours. Though Bjerknes developed a scientific method to forecast, he was unable to solve the equations numerically in an effective time period (Lynch, 2008)

Meanwhile, Lewis Fry Richardson had been developing his ideas during WWI (Ashford, 1985). As a child in his school days, Richardson had shown interest in weather. But it was not this that motivated him to focus his energy and time in the study of meteorology. His actual motivation resulted from his realization that approximate solutions to specific types of differential equations could be used to forecast weather. Richardson had admiration for an observatory in Benson that was associated with one of Britain's most acknowledged atmospheric scientists. This observatory was the most ideal place for him to develop his ideas, and to begin his numerical weather prediction applications. The idea first came to him in a dream in 1911. However, he began his work when WW1 came to an end. Richardson was informed about the work of Bjerknes, and he attempted to continue where Bjerknes had left off. Richardson considered detailed processes that could affect weather such as the movement of ground water, vegetation on soil, evaporation rates of different surfaces, and even solar radiation was accounted for in his equations (Richardson, 1922). Richardson enriched the work of Bjerknes, and was the first to attempt to forecast the weather using a numerical process. Although he was able to numerically solve these equations, the computations were still very time consuming. Richardson believed that one day in the future it would be possible to have technology to solve the equations faster than the advancement of weather (Figure 2.5.2) (Lynch, 2008).

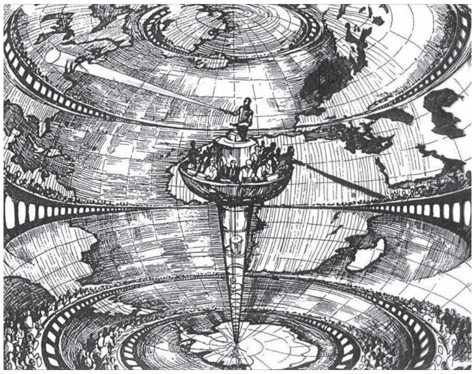


Figure 2.5.2: Richardson's dream of a "forecast factory". It involved several people analysing global weather patterns at the same time.

The Discovery of Climate Change

Guy Stewart Callendar was one of Britain's most renowned steam and combustion engineers in the 1920s (Fleming, 2007). He was keenly interested in weather and climate and this led him to collect weather measurements that were precise enough to use as official temperature records for the central region of England. Through analysis of the data he collected, he observed a warming trend. He then formulated the carbon dioxide theory of climate change, which stated that carbon dioxide concentration in the atmosphere was increasing due to human activities and affecting climate (Fleming, 2007). In the 1930s, he reformulated his theory by adding the argument that the burning of coal was linked to the rising of global temperatures. To defend his theory he collected weather data from stations around the world that also showed a trend of increasing temperatures. He then calculated the global use of fossil fuels, and the uptake of carbon dioxide by the oceans and biosphere. It was officially in 1938 that Callendar identified and proposed the connection between the increase of anthropogenic carbon dioxide in the atmosphere and the warming of the Earth (Fleming, 2007). This overall supported Fourier's 'greenhouse effect' theory. Fourier described the effect using a glass bowl analogy where a bowl allows incoming solar radiation to travel through, but retains the emitted radiation from the ground (Figure 2.5.3). The findings of Tyndall and Callender linked together that carbon dioxide and other complex gases are both good absorbers, and good radiators- they trap heat, and release it back to the ground acting as the "bowl" within Fourier's analogy.

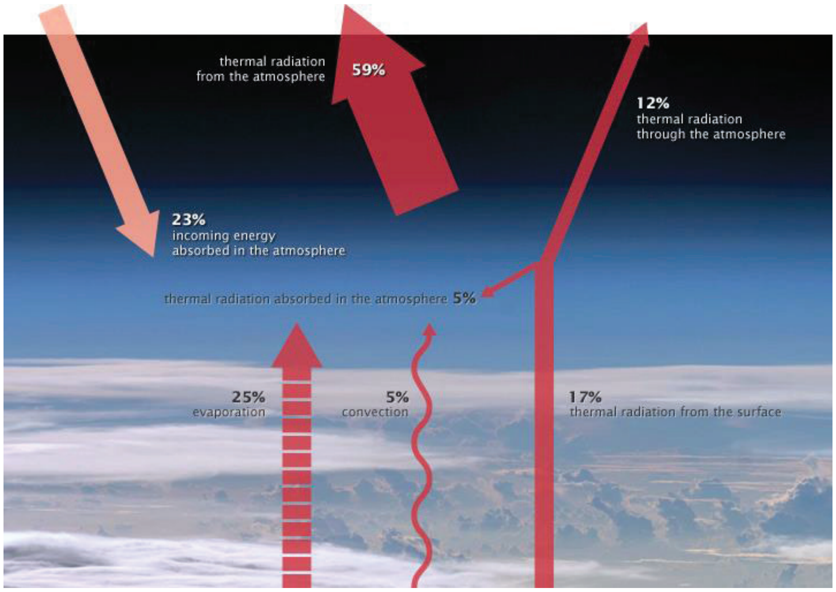


Figure 2.5.3: The net radiation budget of the Earth. The greenhouse effect traps the radiation leaving the Earth's surface, within the atmosphere. Greenhouse gases in the atmosphere absorb the 17% thermal radiation from the surface.

Climate Modelling

The need for climate modelling became more important with recognition of the greenhouse effect, and the possibility of human activities altering future climate (McGuffie and Henderson-Sellers, 2001). However, at the time limited computational capabilities were still a problem. As a result, a large range of modelling tools had been developed beginning in the early 20th century.

John von Neumann, a prominent Austrian-Hungarian mathematician in the 20th century, recognized that weather forecasting was a problem that an automated computer could solve (Lynch, 2008). He developed the design of an electronic computer, and this machine was built between 1946 and 1952. Neumann estimated the computational capability needed for a machine to integrate the equations proposed by Richardson. With the development of the Electronic Numerical Integrator and Computer (ENAIC), the first computer, weather forecasts could finally be electronically computed. With these improvements in computer technology, the capabilities of weather forecasting were greatly enhanced. The first computer that was successfully used to forecast weather was the IBM 701 in 1955, and it was fully dedicated to weather prediction (McGuffie and Henderson-Sellers, 2001).

The first climate general circulation models were developed in the 1950s to 1960s as computer technology advanced sufficiently to deal with the required calculations and about of data (McGuffie and Henderson-Sellers, 2001). Overall, the advancement of numerical weather prediction led onto climate modelling development.

Predicting Climate Today

In the 21st century, climate modelling revolves around computer models that use mathematical and physical laws to predict the behaviour of the atmosphere (Burroughs, 2003). The models are centred on the principles of conservation for mass, energy, and momentum – considering water in every phase: Newton's laws of motion are applied to air masses, and thermodynamics must be incorporated to analyse incoming radiant energy, and outgoing infrared radiation. It is also vital for the models to include factors such as the geography and topography of the Earth, the daily and seasonal temperature variations, and the surface temperatures of the land and ocean. Climate models aim to answer long-term questions, so numerical simulations are tested on observations of current climate evolution in addition to the climate change reconstructions from the past. Future climate evolution can then be computed. These are known as global climate models. They are based on weather forecasting models, but differ from them because they require greater grid space and greater time steps.

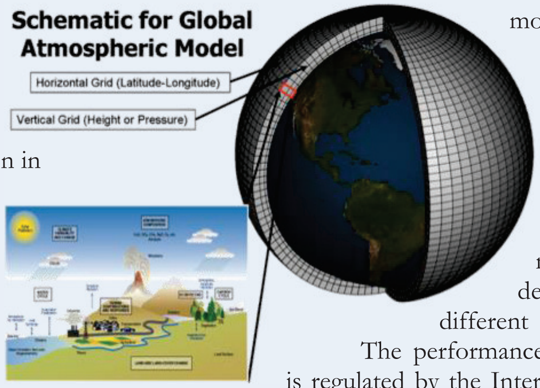


Figure 2.5.4: The atmosphere and oceans of the Earth are divided up into elementary cells for climate models. In each cell, equations based on the laws of physics and thermodynamics are applied. The models calculate values such as radiation, winds, and humidity along with the interaction with neighbouring cells.

One exceptional model that has been developed is the general circulation model (GCMs), which models the atmosphere and the ocean (McGuffie and Henderson-Sellers, 2001). With this, weather can be forecasted for several days in advance with great accuracy, and climate can be understood.

How Climate Models Work

An atmospheric model comprises values of temperature, pressure, wind, and humidity. The atmosphere and oceans are divided into many elementary cells (Figure 2.5.4). Matter and energy exchanges are calculated for each cell in relation to the surrounding cells (Burroughs, 2003). Computers run numerical models based on the previously mentioned physical laws that have thousands of coupled equations. Following this, new values are assigned for a short increment of time later (approximately 15 minutes). This approach can determine forecasts up to 10 days in advance. The final output of the calculations are predictions regarding details of weather features such as atmospheric pressure, rainfall, and humidity.

Challenges

In the past twenty years, weather forecasts have become more accurate and have increased in lead-time (Burroughs, 2003). However, explicit forecasts beyond 6-10 days in advance are difficult to determine as a result of the disordered nature of the atmosphere. One of the main challenges for weather and climate modelling is that the models need to run much faster compared to real time atmosphere and ocean processes. As a result, different models have been developed to model different facets of climate. The performance of climate models is regulated by the Intergovernmental Panel on Climate Change (IPCC) which is a panel that monitors climate related data and regulates government policies (Burroughs, 2003). In 2001, the 3rd IPCC report (TAR) stated, that climate modelling still needs improvement. For instance, there is still uncertainty in models regarding cloud cover. The 5th IPCC report (AR5) was published in 2014 and used the Coupled Model Intercomparison Phase 5 (CMIP5) , a framework climate model that coordinates experiments related to climate change, and creates climate simulations (IPCC,2014). AR5 stated that the climate models had improved since AR4. With rapidly advancing technology, climate modelling is continuously being improved upon, and increasing in accuracy and proficiency.

Science vs. Religion

As exemplified by the other chapters of this book, the task of the historian is a daunting one. History is not as concrete as most would assume; it is a forever changing view of the past that can be influenced by present day trends and rationale. This is particularly important to remember when examining the history of science and religion. Both the words "science" and "religion" are dense with meaning. They encompass large bodies of knowledge with various subsets and have very different connotations today than they did only a few centuries ago (Cunningham and Williams, 1993). Thus, examining their intertwining history can be exceedingly frustrating and difficult. It requires a researcher to disassemble the prevailing philosophies, cosmologies, and methodologies of many different eras, intellectual movements, and geographies. One must determine the parts of history that we would constitute as science and religion based on our current understanding of those words today.

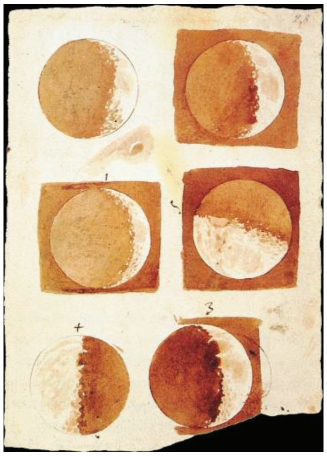


Figure 2.6.1: Phases of the Moon drawn by Galileo outlining patterns produced by Earth's revolution around the Sun in accordance to the Copernican model.

The Conflict Thesis vs. the Complex Thesis

We live in a secular age, which benefits from a bedrock of scientific discoveries and revolutions, one where modern science is shown to be increasingly in conflict with religion. As such, it is often assumed that this conflict is an ongoing battle of an even longer war. It is a historiography asserting that the pursuit of scientific knowledge and progress has been consistently hindered by religion (Draper, 1874; White, 1896). This "conflict thesis" was the central argument of academic John William Draper's *A History of the Conflict between Religion and Science*. Published in 1874, Draper's paper credited the pagan Greek philosophers of antiquity as the originators and facilitators of science (Draper, 1874). He characterized the rise of the Judeo-Christian religion and its subsequent politicization, as an impediment to the progress of science. Modern historians would later elaborate on Draper's thesis and form a more historically nuanced relationship between science and religion. This elaboration examined the birth of modern day science, and its many branches, as an evolution and culmination of aspects of philosophy, theology, and cosmology of the past. They would also seek to re-evaluate the role of the Judeo-Christian religion in Europe as one of both antagonist and facilitative involvement with the development of science (Lingberg and Numbers, 1983). This shift of perception is best exemplified by the subsequent re-examination of the Galileo affair.

The Galileo Affair

Draper and his contemporaries, specifically, academic Andrew Dickson White, viewed the 1633 trial of Galileo by the Roman Inquisition as a major conflict which directly pitted scientific theory against religious doctrine (White, 1896). Subsequent research would yield a more complex scenario. Specifically, it was not merely Galileo's scientific claims of a heliocentric universe that provoked the Church's ire, but also his forays into theology (Wilson, 1999). Being a Catholic himself, Galileo sought to reinterpret scripture traditionally used to support geocentrism to validate the Copernican model of the universe instead (Figure 2.6.1). This was in direct opposition to the Church's recent move to a more literal approach to the Bible and contributed strongly to his trial and eventual house arrest (Wilson, 1999). Proponents of the conflict thesis also overlooked the scientific origins of the Church's stance on a geocentric universe.

Science in Early Roman Times to the Middle-Ages

Contrary to assertions made by White in his seminal work, *A History of the Warfare of Science with Theology*, there was a philosophical and scientific movement during the Middle-Ages (Lingberg and Numbers, 1983). Early Roman Christians, such as philosopher Boethius, recognized the value of Greek works on mathematics, astronomy, and other natural philosophies and set about translating them into Latin, thus preserving them for later generations.

Conservation of classic texts continued into the Middle-Ages and was greatly aided by the advent of monastic schools, which evolved into chapel schools and eventually universities. The Church recognized the benefit of practical branches of natural philosophy espoused in classical works, particularly medicine and mathematics, but struggled with their pagan origins and cosmologies (Wallace, 1978). Medieval theologians would reconcile these issues by reinterpreting them through a Christian worldview. One of the most successful and influential of these medieval philosophers was Thomas Aquinas (1225–1274). A Dominican friar, Aquinas was instrumental in reconciling the recently translated works of Aristotle into a natural theology that advocated the exploration of the natural world as a route to better understand God through his Creation. Aristotle espoused a world view that encompassed Ptolemaic teachings of a geocentric model of the universe. This resurgence of Aristotelian physics during the thirteenth century heavily influenced the Roman Catholic's position during the aforementioned Galileo trial (Wallace, 1978).

Scientific Methods and Theology

Though the conflict thesis did have demonstrable flaws with regards to its historiography of the Medieval Ages, it was a succinct expression of the growing conflicts White and his contemporaries felt were arising between science and religion at the time of its infancy (Youmans. 1875). The Scientific Revolution and Enlightenment of the proceeding centuries had resulted in a schism between scientific philosophy and religious theology. Newtonian physics had not only undermined the Church's traditional model of a geocentric universe, but called into questions its basic cosmologies as well (Bristow, 2011). The emergence of a scientific method through the rationalism of Rene Descartes and the empiricism of Francis Bacon further alienated the emerging scientific culture from the Church (Gaukroger, 2008). In the face of such profound discoveries natural philosophers drifted further away from scripture and dogmas in favour of deism. Deists believed in a non-intervening God, one who created the world and natural laws, but did not interfere beyond that. They concluded that the path to understanding God was through further understanding the natural world and the laws that governed it. This move to deism allowed a theology to exist during the transition from natural philosophy to modern science (Bristow, 2011). Theology would remain an aspect of scientific study into the nineteenth century, but even deism would have a hard time reconciling itself with the advent of newer branches of science and the conflicts that were about to occur.

The development and progressions of geosciences during the nineteenth century, specifically geology, paleontology and evolutionary biology, would begin to create real tension between theologians and scientists, tensions which have lasted into present day.

Figure 2.6.2: Portrait of James Hutton, the founder of modern geology and the principle of uniformitarianism.

The Birth of Modern Geology

James Hutton is considered by many historians to be the father of modern geology (Narin, 1964; Tomkeieff, 1946; Dean, 1975; Figure 2.6.2). He published his *Theory of the Earth* in the late eighteenth century, outlining the foundations for uniformitarianism (Hutton, 1795). Uniformitarianism is the principle that the slow geological processes observed today are the same processes that have been occurring for millions of years, which eludes to an Earth much older than that described within the biblical story of Genesis (Hutton, 1975). As a result, Hutton had initially written a preface to his *Theory of the Earth* which provided a logical argument as to why his theory was consistent with Genesis. He argued that since the Sun was created on the fourth day in the story of Genesis, the 24 hour day as we currently conceive it did not exist (Dean, 2006). The three "days" prior to the creation of the Sun could have represented much longer time periods, and after receiving advice from a friend, Hutton removed this preface before his draft was published. In 2006, the preface was published along with an analysis of it by Dennis R. Dean (Dean, 2006). Despite Hutton's fears of a religious backlash, his theories didn't make a big impact initially (Dean, 2006; Narin, 1964). According to Narin, 1964, the publication of the *Theory of the Earth* coincided with three other significant events in the history of geology. These include the 1795 reading of a paper by Cuvier in which the remains of extinct mammals were accurately described for the first time, William Smiths method of strata identification by the use of organic fossils, and Goethe's first published outline of contemporary anatomy, a precursor for work in vertebrate paleontology (Narin, 1964). These set the foundation for modern geology; however, it was not until later geologist Charles Lyell reexamined the work of Hutton and popularized his 1833 publication, *Principles of Geology* (Lyell, 1833; Kölbl-Ebert, 2009).

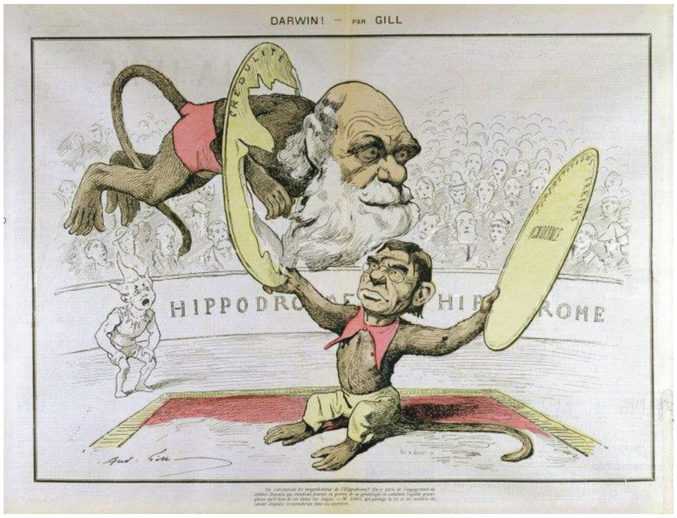


Figure 2.6.3: A caricature drawn by André Gill depicting Charles Darwin and Émile Littré as performance monkeys at a circus breaking through gullibility, superstitions, errors, and ignorance.

Religious Criticism of Geosciences

By the mid-1800s, the field of geology had developed and even members of the clergy had become geologists. Criticism of the field by biblical literalists was common at the time (Kölbl-Ebert, 2009). Dean Cockburn of York attacked clerical geologists William Buckland and Adam Sedgwick at a meeting of the British Association for the Advancement of Science in 1844. (Roberts, 2008). Cockburn also preached against Mary Somerville in York Cathedral after she published her work on physical geography in 1848 (Somerville, 1873).

This all poignantly came to a head when Darwin published his *On the Origin of Species* in 1859. His theories had already been in existence, but his paper, which offered further evidence for these theories, created a rift in the scientific community (Figure 2.6.3; Hesketh, 2009). There were those who objected to its science, but also a strong proponent that this latest work was a direct attack on the Church and theology in general. A year after Origins publication, the British Association for the Advancement of Science hosted an event which became known as the Oxford Evolution Debate (Hesketh, 2009). The aforementioned Draper read a paper there, but his reading was not the highlight of the evening. The more important part of the night occurred afterwards when a member of the society, Bishop Samuel Wilberforce, spoke out against Darwin's paper and made allusions that attacked both Darwin (who was not in attendance) and biologist Thomas Huxley, a personal friend and supporter of Darwin's. Famously Wilberforce implied that Huxley had no problem having an ape as an ancestor, this was received well, until Huxley replied with;

"A man has no reason to be ashamed of having an ape for a grandfather. If there were an ancestor whom I should feel shame in recalling, it would be a man, a man of restless and versatile intellect, who, not content with an equivocal success in his own sphere of activity, plunges into scientific questions with which he had no real acquaintance, only to obscure them by an aimless rhetoric, and distract the attention of his hearers from the real point at issue by eloquent digressions and skilled appeals to religious prejudice." (Knowles, 1999)

Theological Aspects of Science Removed

Development of the Earth sciences had made it difficult for western theology and science to exist simultaneously, as its theories of gradual change directly opposed biblical scripture. Further advancing the disassociation was the field of human paleontology and the search for the missing link in human evolution, which suggested that humans too were simply the products of evolution and not of intelligent design (Kölbl-Ebert, 2009).

A Secular Age

Though Draper and White's theory of an ongoing battle between science and religion throughout history has been proven false, there remains an ongoing conflict between certain religious groups and scientific development. The current conflict is more of a recent development that arose when theology became increasingly separated from science throughout the early modern period.

Creationism

Currently, Creationists maintain a large amount of political power in the United States of America. In 1999, the Kansas State Department Board of Education (KSDE) removed curriculum requirements involving patterns of cumulative change, including the biological theory of evolution (KSES, 1999). By removing this segment, the KSDE made the teaching of evolution in schools optional. The scientific community was outraged by the alteration, however, the policy remained intact until February 14th, 2001. On August 9th 2005, the KSDE approved a draft of the Kansas Science Education Standard that required teachers to partition equal time instructing the theories of evolution and intelligent design. The policy lasted another two years until February 13th, 2007, when the amendment was rejected (Slevin, 2005).

Christian Political Power

The educational power that Christian groups hold in the US is directly related to their political influence. A large proportion of the American population do not affiliate with any religion. Consistent with this fact is the religious composition of the 114th congress. On January 5th, 2015 Pew Research Center released a poll comparing the religious demographics of members of congress with that of the general public. It was stated that 91.8% of congress members affiliate with a Christian theology, while only 73% of American adults confirm themselves as Christians. In contrast, religiously unaffiliated congress members compose only 0.2% of all members, compared to 20% of American adults identifying as unaffiliated. There remains only one unaffiliated congress member in the 114th congress (PRC, 2015).

Atheism

Throughout the twentieth century, the frequency of atheistic belief began to rise. One of the most influential members in the rise of the atheist movement is the famous evolutionary biologist Richard Dawkins. In 1976, Dawkins published a book entitled The Selfish Gene. It involved the discussion of evolution through the perspective of the gene, and identified all organisms as mere carriers of genetic material that seek to self-replicate (Grafen and Ridley, 2006). Dawkins went on to become an influential writer of 21st century atheism and in 2006, he published the God Delusion, and sold over 1.5 million copies (Thomas, 2010). In the God Delusion, Dawkins describes how all faith is without reason, logic, and honest doubt, and how organized religion has led to many atrocities in the world (Thomas, 2010; Dawkins, 2006). He argues how the atheist movement should aim to eliminate the power and influence of religion (Dawkins, 2006).

Another influential atheist writer of the 21st century is Christopher Hitchens. In 2007, Hitchens published a short essay titled God Is Not Great: How Religion Poisons Everything (Hitchens, 2007). The piece is one of pure outrage, as Hitchens claims that "as a menace to civilization, it [religion] has become a treat to human survival." (Hitchens, 2007)

Coexistence

Consistent with Wilson's thesis, there is definitely a complex relationship between science and religion. The two entities can coexist, however, it requires a certain level of cognitive dissonance to be a scientist and a believer in organized religion.

Figure 3.0.1: As technology advances, humans continue to push the boundaries of scientific exploration, endeavouring to find what no one has yet seen and learn what no one has ever known.

Chapter 3: Charting, Mapping, Exploring

The desire to question and wonder is one of the most fundamental aspects of the human condition. This desire has driven us to explore, investigate, and challenge the unknown. As our knowledge of the world around us expanded, so did our understanding and appreciation of its inherent beauty and scientific intricacies. Uncharted waters became prosperous seaways, foreign lands became traversed cities, and our understanding of the planet beneath our feet grew and grew.

Though the art of map-making has changed drastically throughout history, it has always reflected the physical and social environments in which mapmakers lived. This resulted in distinct civilizations expressing their own unique cartographic styles. Mapping techniques continued to evolve with further exploration of the Earth. As explorers delved into the deepest mysteries, cartographers ensured methods of projecting sphericity onto flat paper and mathematicians triangulated distances for more accurate navigation and mapping. With the development of the compass came the confidence to expand the trade routes of the time and broaden the exploration of the oceans. For the longest time, scientists had thought that the ocean floor was a flat, featureless plain filled with sediments eroded from the surrounding continents. As the technology used to measure the depth of the ocean has continued to develop, so to have the knowledge of the ocean floor landscape and the geological processes responsible for its creation. The development of geodesy has coevolved with advancements in mathematics and technologies. Today, technologies are used to create abstract mathematical surfaces, called geoids, which represent the surface of the Earth. With the widespread usage of the compass as a tool for charting as well as navigation, scientists such as Edmond Halley began to investigate the underlying processes responsible for the Earth's magnetic field. This culminated in the creation of many theories, such as Halley's Hollow Earth theory. The discovery of Earth’s magnetic field through magnetite has led to the development of many ancient and modern technologies, such as the modern electricity generator. These developments were made possible by the discoveries of many scientists over the span of hundreds of years, culminating in the formulation of Maxwell’s equations. Models built on the Hawaiian volcanic island chain brought novel insights that changed accepted paradigms that previous theories failed to explain. These insights galvanized more recent endeavours to develop better methodologies that would be more effective at predicting volcanic events. Even as the globe becomes more and more familiar to us, the desire to discover continues to bring humans to new levels of understanding about our planet.

Ancient History of Maps

Since the origin of the human species, it has been important to take note of one's surroundings. In the earliest of civilizations, the location of important resources would need to be remembered and from this necessity, the art and science of cartography was conceived. Map-making throughout history has reflected the physical and social environment in which the mapmakers lived. The needs of civilizations changed in a way that mirrored their political, spiritual and intellectual progression, which was evidently expressed in the maps produced.

Prehistoric Maps

Cartography of the Old World is more often than not a subject that is host to discussion and controversy. Since there is no strict definition of what a map actually is, cartography from prehistoric times (2.5 million years ago and is subject to individual differences in opinion. One such case, a piece of wall art in Konya in West-central Turkey, that depicts a twin peak mountain, underneath of which appears to be a leopard pattern print. The mountain appears to be erupting, which is in agreement with the community's major resource called obsidian, a material produced by volcanic eruptions (Smith, 1987). The pattern of blocks beneath the mountain would have likely seemed meaningless at first glace, if it were not for its striking resemblance to the map used as an excavation plan for the site. The wall piece, which dates back to 6200 BCE, is considered by some to be the oldest map in the world (Smith, 1987). Other notable prehistoric maps include those found in North America, South America and Eastern European countries, however, all are subject to debate and opinion.

Babylonian and Egyptian Maps

Perhaps the earliest maps which are not so controversial are those created by the Babylonians. The Babylonians used clay tablets for writing and were quite advanced in many areas such as mathematics (Arabia, 1987). There was no real attempt at cartography before or during the fourth millennium BCE, however, at this time writing and mathematics were becoming increasingly popular, providing the necessary circumstances under which geological knowledge could be transcribed in the form of maps (Virga et al., 2007). One of the oldest Babylonian maps depicts an area of land flanked by mountains with a river or stream running through it. This map, dating to 2300 BCE has clearly marked direction and is possibly the first example of a map with orientation and scale (Arabia, 1987). Other maps from this civilization include a plan of fields for the city (1500 BCE) of Nippur depicting the intricate canal systems that were integral for both trade and irrigation (Figure 3.1.1) (Virga et al., 2007). The most well known to cartographers and historians is the Babylonian World Map circa 600 BCE. The map displays the belief system of the time, showing Babylon as the center of the world, surrounded by the seven mythical

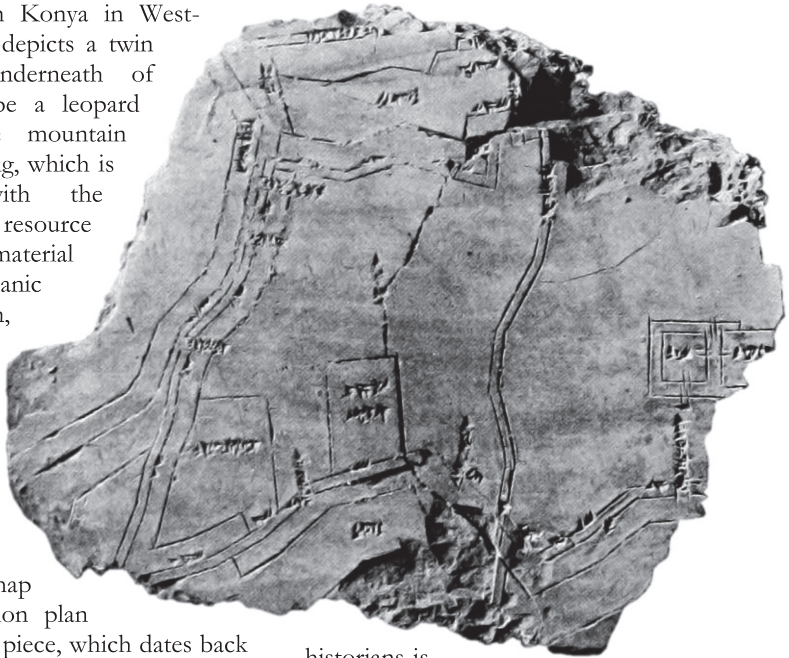


Figure 3.1.1: Plan of fields in Nippur (right) drawn on a clay tablet, illustrating the canal system of the ancient city. The tablet dates back to 1500 BCE.

realms.

Just west of the Babylonians lived the ancient Egyptians, who thrived for nearly three millennia until they were incorporated into the powerful Roman Empire in 30 BCE (Virga et al., 2007). In 3100 BCE, with the unification of Upper and Lower Egypt, came advancements in writing and the development of very sophisticated tools that could be used for mining (Virga et al., 2007). The most well known map of this time is the Turin map of the gold mines from 1150 BCE. The map is the first geological map in history, depicting various rock types and locations of natural resources that were highly valued at the time (Harrell, n.d.). The map was made to depict the route to various mining sites. Topographical maps of this sort were not common in ancient Egypt, however, civil documents, specifically those pertaining to taxation information, were abundant. The Egyptians were the first to survey land, based on the annual flooding of the Nile River and consequently the flourishing of crops. With the information provided from these survey maps, the Egyptians were also the first to predict annual tax revenues (Shore, 1987). Much like the Babylonians, Egyptian cartography was often intertwined with religious beliefs. Some of the most detailed and elaborate graphic material is located in tombs and on sarcophagi (Shore, 1987). Many of these depict the landscape of the underworld and map the journey to the deceased's desired locale.

Greek and Roman Maps

The Greeks, who are known as the forefathers of modern cartography, have little physical cartographic material from before 600 BCE except perhaps the Thera Fresco from 1500 BCE, of the land controlled at the time by the Minoans (Bingham et al., 2000; Aujae, 1987). The fresco depicts the local geographic features of (what is proposed to be) Crete, including coastlines and harbors. The Minoans were conquered by the Myceneans (another Greek state), but eventually the Myceneans slowly died out and eventually collapsed, commencing a period known as the Dark Ages in Greek history (Virga et al., 2007; Bingham et al., 2000). This Dark Age accounts for the lack of advancements cartographically speaking and otherwise. It wasn't until 8th century BCE, when the Greek Empire began gaining more power and monetary stability that cartographic articles could once again be produced (Bingham et al., 2000). Geological sciences and cartography began too flourish in 600 BCE, a time in which Greek philosophies were changing rapidly, chiefly those pertaining to religious beliefs and Greek gods (Virga et al., 2007). Miletus, one of the many Greek states around the Mediterranean Sea, was the epicenter of geographical studies and home to the Ionian school of science (Virga et al., 2007). It was here that Anaximander constructed his first world map, which would later be revised by Hecataeus (Aujae, 1987b). The map depicts the Earth as a circular plate, surrounded by ocean (Figure 3.1.2).

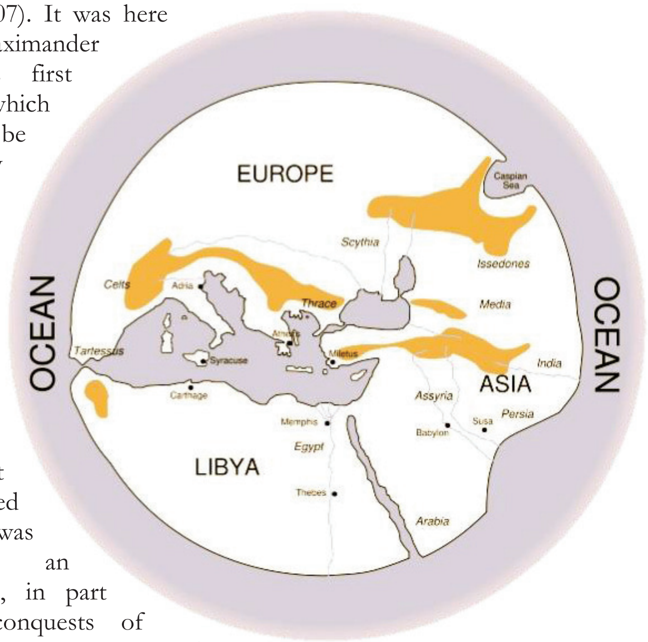


Figure 3.1.2: The World According to Hecataeus (above) is an edited version of Anaximander's earlier version of a world map.

Over the next several hundred years, mapping was advancing at an exponential rate, in part due to the conquests of Alexander the Great. On several of his expeditions, Alexander would bring scholars of all sorts, including geographers and surveyors, whose detailed and keen observations would later be compiled into accurate maps (Aujac, 1987b). Advancements in mathematics and geometry by Pythagoras and later by Plato and Exodus led to the first celestial globe (Virga et al., 2007). Dikaiarhos of Messina was the first to propose a coordinate system, which was later expanded upon by Eratosthenes, who developed a scheme of horizontal and vertical reference lines (Papadimitriou et al., 2010; Aujac, 1987a). This was the cartographic element that would prove to be essential in the practical use of maps.

By 146 BCE the Roman Empire had gained control over Greek civilization (Bingham et al., 2000). The Romans were far more concerned with political conquests than pursuit of theoretical knowledge as the Greeks were, and this is reflected in the cartography of the time. Many of the maps were for practical use, depicting roads and routes, essential for military endeavours (Misra & Ramesh, 1989). Ptolemy, the most famous Greco-Roman cartographer, had access to the great library of Alexandria from which he could extract practical and theoretical knowledge gained by the Greeks (Misra & Ramesh, 1989). Ptolemy, in true Roman fashion, criticized much of the work done by the Greeks, and eventually compiled lists of instructions on map making. These principles and instructions were used through to the sixteenth century (Virga et al., 2007). Ptolemy was also the first to compile a world atlas, titled *Geographia,* which utilized the growth in geographical knowledge and experience, corresponding to the expansion of the Roman Empire (Dilke, 1987b). Much of Ptolemy's work was lost in the demise of the Western Roman Empire but later resurfaced in the twelfth century (Virga et al., 2007).

Medieval Times and Ancient China

During Medieval times (400 CE – 1200 AD), Western civilizations had few cartographic advancements, and in some cases, cartography actually regressed. Many of the maps were far more influenced by Christianity than by Ptolemy (Misra & Ramesh, 1989). The Byzantine Empire in the East and the Arabic Empire did, however, build off of Ptolemy's work (Dilke, 1987a). Sea charts were becoming more popular by the thirteenth century and it was during this time that a renewed interest in cartography began to emerge (Misra & Ramesh, 1989).

In the Far East, the earliest extant Chinese maps show detailed representations of coastlines and land. The Yu Ji Tu map, circa 1080 CE, has a measurable scale, drawn on a grid to achieve a level of accuracy far in advance of maps produced in the Western world (Figure 3.1.3) (Virga et al., 2007). Chinese maps were written in a unique style, and served a higher purpose than to simply illustrate the observed world. Maps in China recorded political history in a symbolic manner, while often simultaneously maintaining geographical accuracy.

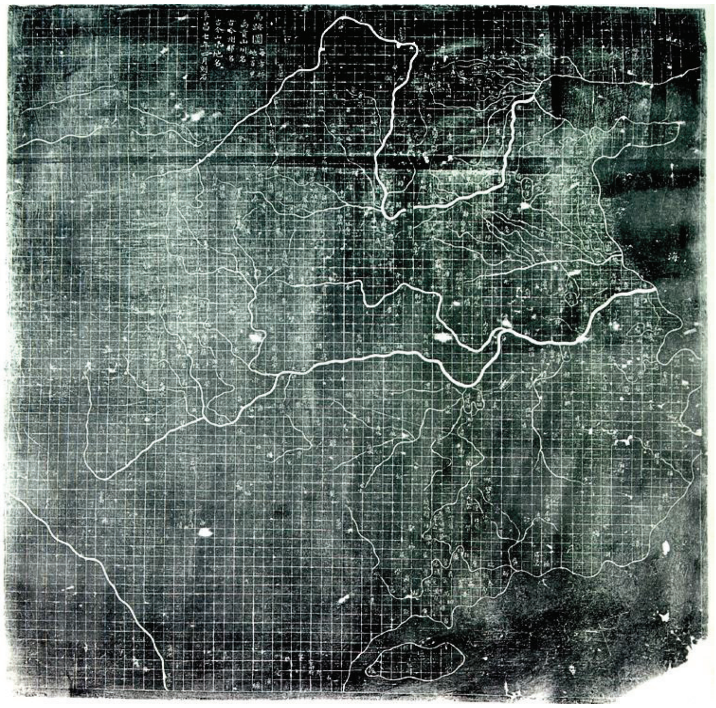


Figure 3.1.3: Yu Ji Tu (right), an ancient map of the Song Dynasty circa 1080 CE has a level of detail and accuracy far greater than those of the Western world at the time.

Although the origins of mapping are still unknown and heavily debated by modern historians and cartographers, it is clear that taking note of one's surroundings has always been an integral part of human life. Through historical investigation, it's evident that cartography did not follow a perfectly linear progression throughout time. Rather, distinctive civilizations illustrated cartographic advancements in different areas such as scale and colour. It was only when civilizations began to expand and dominate that these individual advances were amalgamated into the principles of cartography we know today. It is upon these principles that cartography could advance throughout the new world and continues to advance today.

Mapping the Human Brain

Like cartography of the Ancient world, modern day mapping is a tool used to learn about one's surroundings. With the expansion and advancements in modern technologies, humans as a species are able to observe the farthest corners of the Earth in great detail. Just as the function of maps changed with respect to the ever-changing political and intellectual landscape of the Ancient World, maps today can take many forms, depending on their purpose in modern society. One of these particular cartographic endeavours is that of the human brain. The Allen Institute for Brain Science in Seattle is intending to do just that.

Researches like Christof Koch from the institute have been working for almost three years on constructing a road map of genetic information and protein production throughout the brain. Using high-resolution magnetic resonance imaging, researchers fully image each brain before they slice it into microscopically thin sections. Using a variety of chemicals, the genes expressed in each of these sections are deduced. What researches found in the data is that, in some regions of the brain, gene expression is highly differentiable between individuals, and in others, expression and gene regulation is almost identical (Zimmer, 2014). The Allen Brain Atlas was subsequently constructed from these data, to show the areas of high and low variability of gene regulation within the brain.

This brain atlas doesn't appear to be much of a map, more of a mosaic of colours and thermal readings; however, upon closer inspection, biologically relevant structures of the brain emerge from the map. For example, a blue square in the uppermost left corner of the map corresponds to the cerebral cortex, which, according to the data shows little variation between individuals in gene expression (Allen Institute for Brain Science, 2014). On the contrary, a yellow cross, within the homogeneity of the cerebral cortex represents the visual cortex, which is known to be a highly specialized structure that differs between individuals.

The maps and all of the data collected by the institute is available online to researchers, students and everyday people around the world. A research team in from Brazil is currently using the maps to learn more about a brain disorder called Fahr's disease, after finding that the gene (SLC20A2) linked to the disease is highly expressed in precisely the regions of the brain where the disease manifests (Zimmer, 2014).

Similar research is being conducted at Stanford University, where scientists like Karl Deisseroth hope that one day they are able to visualize the locations of just one protein in one whole, intact human brain. Because the brain is unmistakably opaque, researchers are usually forced to use dyes or slice the brain into microscopic pieces, as the Allen Brain Institute has done. Karl Deisseroth has discovered a way to turn the brain translucent, so that "you don't have to take it apart to show the wiring" (Zimmer, 2014). Already Deisseroth has been able to turn mouse brains translucent and map out pathways and proteins within the brain, similar to Christof Koch. With information like this, the possibilities for discovery are endless, opening avenues for the development of innovative treatment modalities of brain disorders.

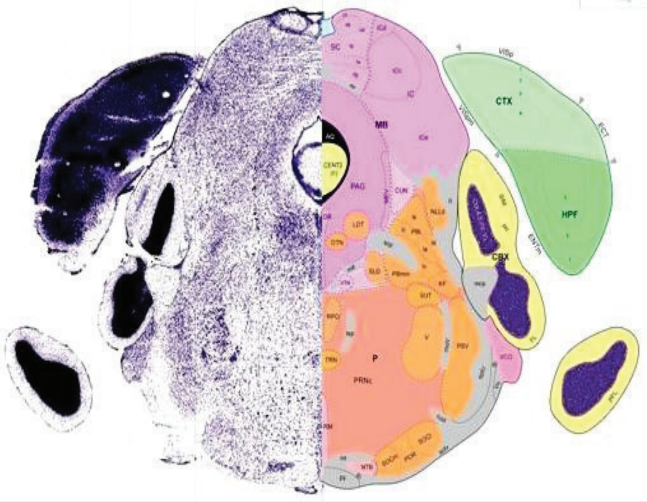


Figure 3.1.4: A section of a brain is systematically coloured to show the varying expression of the LNRR3 protein.

Although much of the brain is still a mystery, the scientific advancements in imaging technologies and innovative research techniques like those of Deisseroth and Koch, should allow us, to one day, read our brains as easily and efficiently as we read everyday maps.

The New World

The view of the world in the fifteenth century was largely based on the second century maps made by Claudius Ptolemy (Black, 2003). Along with his maps, compiled to form his *Geographia*, Europeans constantly traded geographical information, navigational techniques and cartographical technologies with Asia and the Middle East through their lucrative trade routes. Both European and Asian economies were booming and there was little need to look west, across the vast uncharted territory of the Atlantic Ocean.

In 1453 the Ottoman Empire secured a position in the center of the Europe-Asia trade corridor it effectively controlled the European foreign market (Virga, 2007). Instead of accepting the extra taxation, Europeans sought to find a new way to reach the Orient. In 1497, Vasco de Gama, a Portuguese explorer, traveled south along the western coast of Africa in an attempt to find a way around the massive continent. Along with other explorers, he mapped the coastlines of Africa and ensured un-tariffed trade between Europe and Asia, albeit with a much longer route.

At the time, it was known that the Earth was round and accurate estimates of its circumference had been made. It was thought to be possible to reach China and Japan by simply sailing west around the world. Christopher Columbus gained funding from Spanish monarchs to sail west to the Orient, colonizing new lands and securing trade routes and resources. Despite the circulation of accurate estimates for the Earth's circumference Colombus used Ptolemy's maps to estimate a distance of around 4500 kilometres to reach Asia. In reality he would have had to sail roughly 18500 kilometres (Black, 2003). He set off in 1492 and despite his underestimation he made landfall earlier than he thought, deducing that he must have discovered new parts of Asia. He thus named them the "West Indies" (Black, 2003).

These islands, and the surrounding coast of what is now mainland South, North and Central America, were mapped by Colombus' pilot Juan de la Cosa (Black, 2003). It has been said that to his dying day Christopher Colombus believed that these Islands were part of Asia and not simply a new continent. Johannes Ruysch created a map in 1507 (Figure 3.2.1) that followed Colombus' beliefs that the West Indies were in fact part of Asia, and that the findings of other explorers, like John Cabot, were also simply western parts of Asia (Virga, 2007). Ruysch's map was entered into the newest edition of the *Geographia* despite other expeditions proving that Colombus' assessment was incorrect.

Some of these expeditions, and arguably the most important (and controversial), were done by Amerigo Vespucci. Vespucci's expeditions are recorded in a series of letters. He embarked on three, or four depending on the accuracy of his letters, expeditions to explore the east coast of South America between 1497 and 1503 (Tooley, Bricker and Crone, 1969). In a letter describing his third voyage he claimed that his findings contradicted Colombus' idea that this land was a continuation of the Asian continent and should instead be considered a "New World" (Tooley, Bricker and Crone, 1969).

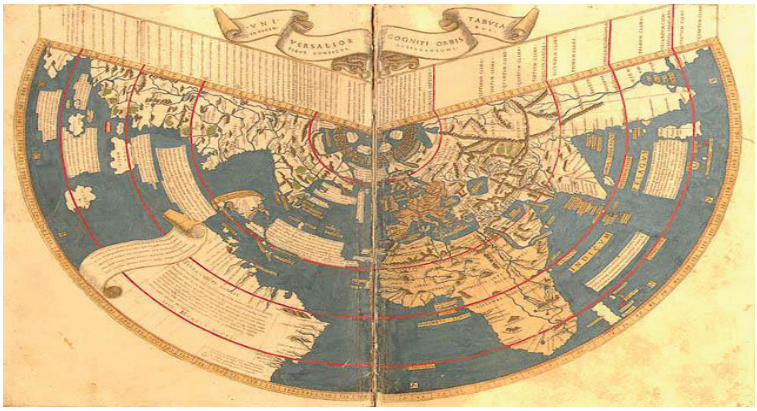


Figure 3.2.1 Johannes Ruysch map (right) depicts the world following the belief that Christopher Colombus landed in Asia and not in the Americas.

From Vespucci's findings, in 1507 the German cartographer Martin Waldseemüller developed the first modern map of the world (Figure 3.2.2) (Virga, 2007). He gave the name

Figure 3.2.2 Martin Waldseemüller's world map (left), the first time the new continent was ever named "America".

"America" to the new continent, crediting Amerigo Vespucci for the revolutionary discovery of a brand new continent. Mysteriously, Waldseemüller's map indicates the breadth of the Pacific Ocean, a measurement that was not known until Vasco Núñez de Balboa crossed into the Pacific from the Atlantic, through the Isthmus of Panama in 1513, thus noting the western most point of the ocean (Virga, 2007). He also demonstrated the approximate shape of the western coast of the continent which led historians to a few possible, and unproven, theories.

A sixth century expedition by Hoei-Shin, a Chinese monk, supposedly sailed east of china and found new lands that he dubbed "Fusang" (Ruskamp, 2009). He recorded that he had to sail 20 thousand Chinese li (roughly 8000 kilometers) east of the Kamchatka Peninsula. This is supported by modern measurement as well as Native American glyphs that could be interpreted as Chinese ships (Ruskamp, 2009).

Eventually all controversies and inaccuracies were laid aside as different nations rushed to explore new territories and control new resources. Vasco Núñez de Balboa was followed by a Portuguese explorer in 1519, Ferdinand Magellan, sailing around the southern tip of South America and completing the first circumnavigation of the globe (Black, 2003). Still most cartographers drew a land connection between North America and Asia until the 18th century expedition of Vitus Bering (Black, 2003).

Through the influx of explorers and territorial claims cartographic methods became heavily influenced by politics (Branch, 2011). Longitudinal lines were made solely for territorial gains and each nation had its own coordinate centering system. Different countries tended to center theirs on their capital cities, the current center on the Greenwich Meridian is due to the English cartographers using Greenwich as a center.

Map making became a huge part of European culture and maps were constantly being created, refined and published. With no small thanks to the advent of the printing press the most accurate map of the time could be widely distributed. With the constant alterations and advancements of geographical information, cartographers and explorers needed to establish new methods of map making and interpretation. Some of the most important advances in cartography during the age of discovery include the Mercator projections and the idea of triangulation.

Mercator Projection

With the advances in the field of cartography and its widening importance and popularity in European society, mapmaking techniques were constantly being changed. The old methods of drafting rectangular maps were inaccurate projections of the sphericity of the Earth. While other projections were attempted arguably the most famous, and still used today, are Mercator projections. Developed by the proficient cosmographer, mathematician and pupil of Gemma Frisius,

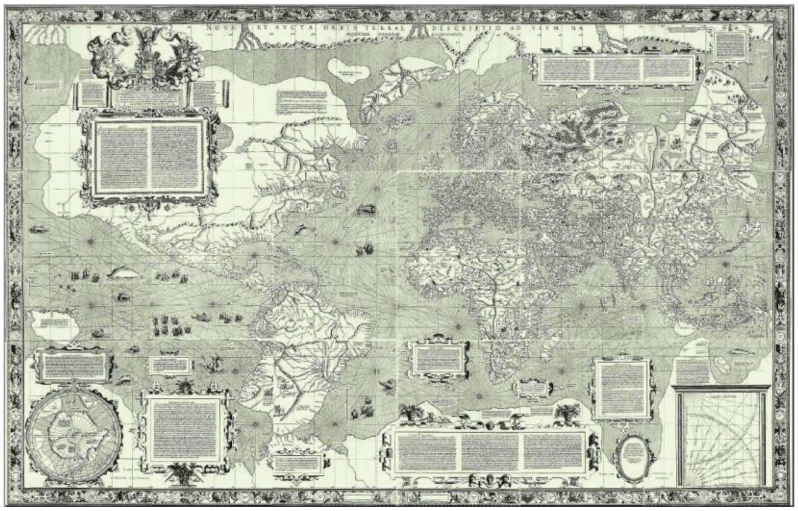


Figure 3.2.3 Mercator's map of the world (above) depicting his projection method. Note how exaggerated the northern hemisphere landmasses are compared to those in the south.

Gerhard Kremer (also known as Gerardus Mercator), the Mercator projection provided a method to maintain geometric simplicity while compensating for the curvature of the Earth's surface (Tooley, Bricker and Crone, 1969).

Mercator maintained the right angles between coordinate lines and instead opted to remove the convergence at the poles (Crone, 1953). Mercator therefore created a map that accurately represented the Earth's surface if it were shaped like a cylinder. This projection also skewed the sizes of landmasses within the hemispheres. As if from some sort of testament to the idea that Europeans believed themselves to be the center of the world Mercator placed Europe at the top center of his projection effectively making it, and all of the northern hemisphere landmasses, larger than all the others. Nevertheless he created a fundamental way of representing constant bearings, or loxodromes, as straight lines on a chart (Crone, 1953). Loxodromes are lines that cut each longitudinal meridian at the same angle. Without the cylindrical projection this line becomes a spiral. In 1569 Mercator used his globe (from 1541) to mathematically determine how to represent loxodromes on the flat surface of a nautical chart (Crone, 1953). He then created and published his great world map using his projection method (Figure 3.2.3). Unfortunately, higher mathematics was not well known to most sailors and his projections didn't catch on for some time (Tooley, Bricker and Crone, 1969).

It has been argued that Mercator was not the first to recognize the significance of loxodromes. Instead, it is said, that Portuguese mathematician Pedro Nunes had already been investigating them. It is not known, however, how close Nunes was to actually applying them to a two-dimensional chart and whether Mercator and Nunes had any contact or if they derived these systems independently (Crone, 1953).

Triangulation

As maps were beginning to be used for more than general navigational guidelines it became increasingly important to create accurate maps with applicable scales. It wasn't as simple as measuring the distance in a straight line as the Earth had a curved surface. Instead, surveyors used the method of triangulation. Triangulation requires the accurate measurement of a baseline with a third point visible from both ends. Then, using trigonometry and measured angles, it is possible to find the distance between the baseline and the third point. The actual methods of triangulation date back to ancient times from mathematicians like Pythagoras and Thales, but accurate applications in the field of geography and mapmaking really advanced during the 16th century (Black, 2003). The cartographer Gemma Frisius first proposed using triangulation to determine large distances applicable to mapmaking. These new and accurate methods of measuring distance created a rise in demand for the field of surveying. Many monarchs and countries desired surveyors to measure their borders and areas of control in order to accurately delineate nations' territories.

Maps were used for more than navigation. Early on, they were used to further political goals by creating borders and visually associating territorial control. In this way, they were used for both military conquest and peace negotiations. A breakthrough came in 1815 when geologist William Smith created the first national-scale geological map of England, titled "A Delineation of the Strata of England and Wales With Part of Scotland" (Winchester, 2009). Smith used maps to visually represent his ideas that, through analysing fossils, each local rock strata is actually part of a much larger strata that could also be found far away This map not only led to revolutionary understanding of England's geology and underlying strata it also helped pave the way for maps as a scientific tool.

Topography

Cartography as a field has always been heavily influenced by advances in technology. It may be difficult to relate to explorers and cartographers in the age of discovery as nowadays coastlines and land masses can be precisely mapped with aerial photography and satellite imagery, but there is still a need for mapping, and there are still areas of this world that hold many mysteries. Until modern methods were created, topographical data (geological formations and elevations) was still limited to what land surveyor's and cartographers could acquire through basic means.

Bathymetry, or ocean floor topography, is the measurement and imaging of the geological formations and elevations that make up the ocean floor. Early methods were limited to the information gathered from laying telegraph cables but the creation of accurate bathymetric maps really rose in the 20th century with the use of sonars, satellites, aircrafts, submarines, and ocean floor bore holes. Satellites and aircrafts used advances in radar technology to measure the effects of submerged topography on the ocean's surface (Black, 2003).

Submersibles allowed modern explorers to delve into the depths of the ocean in order to visually (and using sonar) map the physical contours of oceanic crust. In 1960, Jacques Piccard voyaged into the deepest part of the ocean, the Marianas Trench (Black, 2003).

Launched on June 27, 1978 the SEASAT satellite carried a radar system that was able to measure the satellite's altitude above the ocean's surface, as well as the topography data of the ocean floor (Tapley, Born and Parke, 1982). From these data a full map of the ocean floor was made. This map allowed a better understanding of the geological processes that formed certain features hidden beneath the ocean, as well as ongoing processes. For example, topographical maps showed that the mid-Atlantic ridge pushes new material to the surface and causes tectonic plate divergence (Black, 2003). This helped confirm continental drift and lend huge support to theories on plate tectonics as the physical processes involved could be actively seen for the first time.

An international effort to effectively and accurately map the Earth's surface topography was made in 2000 when NASA launched their Shuttle Radar Topography Mission (SRTM). It collected data on a near global scale, over 80% of earth's land surface (Nikolakopoulos, Kamaratakis and Chrysoulakis, 2006). One year earlier NASA also saw the launch of the Japanese created Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) which, unlike the SRTM's 11-day imaging time, is continuously collecting elevation data (Nikolakopoulos, Kamaratakis and Chrysoulakis, 2006).

Topographic data are incredibly useful in a variety of interdisciplinary fields. Biologists utilize topographic data to study the behaviours, adaptations and evolution of plants and animals. Topography can be related to soil types, as well as the history of geological processes that formed the modern world. It can visually represent evidence of ancient glaciation, fluvial environments, and orogeny. Topography is also fundamental for environmental hazard mapping, city planning, aircraft navigation, and cellular phone companies (Ramirez, 2005).

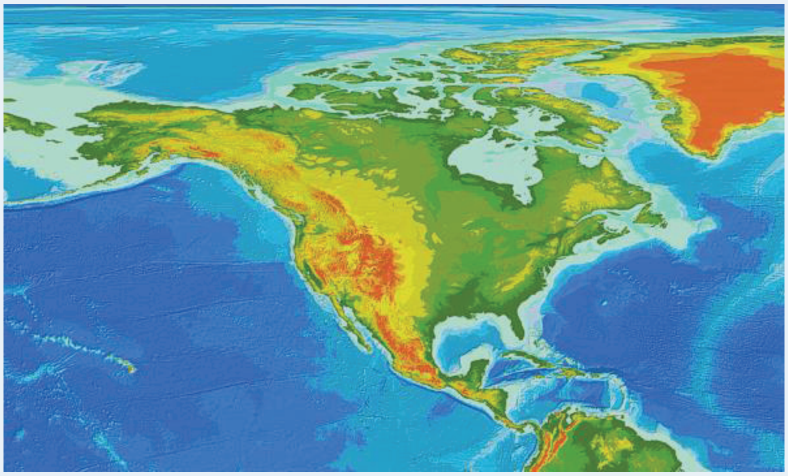


Figure 3.2.4 colour-encoded shaded topographic image of North America (above), taken from the SRTM project.

Starting in 2014, NASA is releasing SRTM's high-resolution data to the general public (Figure 3.2.4) (Boggs, 2005). In the same way that the printing press created a medium for sharing geographical knowledge to the world's literate populace, NASA is using the internet to share data about the surface form of our world.

The Discovery and Evolution of the Compass

The discovery and early development of the compass is a mystery that has remained insolvable for centuries. While there are many theories to when and where the compass was first discovered, numerous errors in translation, minimal extant records, and unsubstantiated claims continue to fuel the mystery (Smith, 1992). From the evidence available, the earliest compasses were made from lodestone. This is a rock made almost entirely of magnetite, an iron-rich mineral that acts as a permanent magnet (see also pp.80-83) (Charvatova, et al., 2010). The first uses of the lodestone and the major hypotheses for the development of the magnetic compass will be discussed.

Olmécs and Maya

Figure 3.3.1: A Mayan temple that was most likely oriented using a magnetic compass.

The earliest evidence for the use of a magnetic compass dates back almost 4000 years with the Olmécs and the Maya around 1500 BCE (see also pp.122-125) (Klokocnik, Kostelecky and Vitek. 2007). The core hypothesis and evidence for this use comes from Robert Fuson (1969) and John Carlson (1975). Fuson's hypothesis states that the Olmécs and the Maya knew and used a lodestone compass for the orientation of pyramids, ceremonial and other important buildings (Figure 3.3.1). If these ancient people did use a magnetic compass to orient their buildings, the current deviation of their orientation from the geographic North Pole could be compared to paleomagnetic declination patterns for their time period and location (Klokocnik, Kostelecky and Vitek. 2007). If the deviations of the buildings correspond to the declination of the magnetic North Pole, then it could be concluded that they used a magnetic compass. It is important to note that the magnetic North Pole wanders in position randomly and frequently, therefore a difference in a few hundred years on the dating of a structure would have a huge impact on the comparison (Klokocnik, Kostelecky and Vitek. 2007). Unfortunately, at the time Fuson published his hypothesis there was no sufficiently accurate paleomagnetic declination data to support his idea.

Decades later the Fuson hypothesis was revisited by Jaroslav Klokočník, Jan Kostelecký, and F. Vítek (2007) with updated paleomagnetic data. They found all important Olméc and Maya buildings to have a clear eastward deviation from geographic North Pole that was too large and widespread to be an inaccuracy of planning, especially with the Maya's revered skill in astronomy and mathematics. This deviation also corresponded to the paleomagnetic declination for that time period, thus supporting Fuson's hypothesis. However, due to the inability to get an accurate absolute date on many structures of the Olméc and Maya, there is still much debate regarding the hypothesis.

Further support for the Olmécs and Maya being the first to discover the compass are findings of magnetic artefacts. The excavation of the most important one, Michigan 160 sample (M160), is described by Carlson (1975). This artefact is a piece of rock made of almost pure hematite, and is considered to be part of a lodestone compass. The rock is finished in such a way that it would have been able to float on liquid mercury, giving a possible mechanism for a compass. Previous evidence of their ceramics shows that the Olmécs and Maya knew how to make liquid mercury and had the proper resources available (Klokocnik, Kostelecky and Vitek. 2007). Regardless of all of the support for the Olmécs and Maya being the first to discover the magnetic compass, we do not yet have the technology available to provide accurate enough data to completely accept the hypothesis.

Ancient China

Based on extant written records, the next well supported hypothesis for the discovery of the magnetic compass dates back to the Zhou

Figure 3.3.2: The earliest known design for a Han Dynasty (206 BC – 220 CE) South-Pointer. A spoon-shaped lodestone placed on a square brass plate with a circle at its center.

dynasty (1046-200 BCE) in ancient China, nearly 1000 years after the Olmécs and the Maya (Charvatova, et al., 2010). The same idea as purported by the Fuson hypothesis can be applied to ancient China as important buildings were also oriented using a compass. The advantages the Chinese theory of discovery has over the Olmécs and Maya are that more accurate dating of the structures and paleomagnetic declination data are available to support the hypothesis and artefacts of ancient Chinese magnetic compasses have been found (Charvatova, et al., 2010). The earliest artifacts are of a spoon-shaped lodestone placed on a square brass plate with a circle at its center (Figure 3.3.2). This was known as a "South-Pointer" and could be the design of the first Chinese magnetic compass (Charvatova, et al., 2010). It is interesting to note the south directionality as we are accustomed to thinking of a compass always pointing north. Their compasses are believed to point south as this was the direction their gods faced while sitting on the throne (Charvatova, et al., 2010).

Medieval Europe

Magnetic compasses are not seen again in history until the 12th century BCE in Europe when church building boomed (Abrahamsen, 1992). Again, the same idea and technique as the Fuson hypothesis can be applied to the orientation of Romanesque village churches in Denmark. A study by Niels Abrahamson (1992) shows, through statistical differences, that approximately 2000 churches were originally oriented using a magnetic compass. His study is important as it illuminates one possible early and common use for the compass in Europe.

It is an important observation that the motivation for use of the ancient compass was always rooted in faith, however, we begin to see the development of the compass for navigation purposes during this period.

Mariner's Compass

The earliest mentions of a mariner's compass in Europe used for navigation on the ocean, is in Alexander Neckam's *De Naturis Rerum*, and in Jacques de Vitry's *Historia hierosolimitana* (1459) where he calls the compass "valde necessaries…navigantibus in mari." There are many theories for the inventor of the mariner's compass in Europe, the most prominent one being of Flavio Gioja (Smith, 1992). This theory begins with the Italian historian Flavio Blando who wrote, around 1450, that Amalfian navigators invented the marine compass and used it for the first time. This claim was repeated until in the 16th century when Lillio Gregario Giraldi incorrectly named Flavio as the inventor; later in 1586 Scipione Mazzella gave Flavio the last name Gioja. This error of Flavio Gioja being

Figure 3.3.3: Statue of Flavio Gioja in Naples, Italy.

the inventor of the compass went unnoticed for over 300 years (Smith, 1992). There is even a statue and annual celebration in Naples dedicated to Flavio Gioja (Figure 3.3.3). It was not until modern day that historians realized the mistake when they traced the family history of the Gioja family and found no one named Flavio among its members (Smith, 1992). Accordingly, the inventor of the mariner's compass in Europe is still under debate.

Another common misconception about the mariner's compass is that before its invention, navigators did not travel out of sight of the land. This idea is seen throughout historical writings and was strongly believed into the 1950's with Encyclopedia Britannica (1951) stating, "Before the introduction of the mariner's compass in the fourteenth century, the only practical means, among western nations, of navigating ships was to keep within sight of land." We now know this to be widely inaccurate, with the largest contrasting example being the settlement of Iceland in 870-930 B.C.E. This mass transatlantic travel was done by means of celestial navigation and was carried on for more than 400 years before the introduction of the mariner's compass.

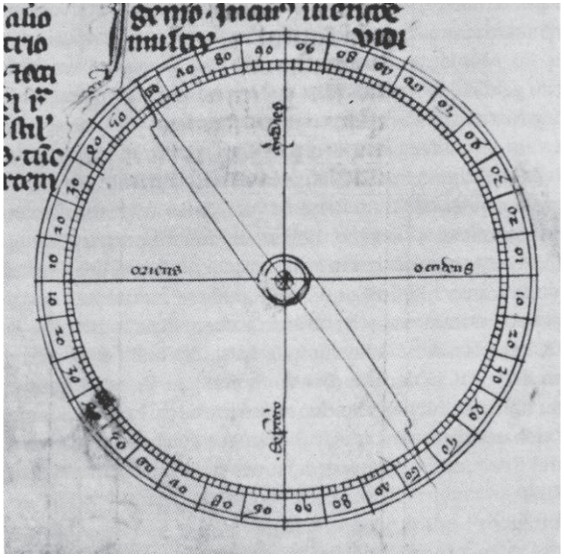


Figure 3.3.4: Sketch of a pivoting mariner's compass needle in a 14th century copy of Epistola de magnete of Peter Peregrinus.

Soon after the invention of the compass in the early 13th century its use became very common and was known as a valued aid in navigation (Marcus, 1956). This stimulated much curiosity about magnetism and how the magnetic compass worked. The earliest detailed and authoritative work on the magnetic compass is the *Epistola de Magnete* of Petrus Peregrinus de Maricourt (1269). This book gives a measured account of the properties of the magnet, proposes two magnetic poles, details a theory of magnetic attraction, considers a magnetic 'perpetual' motion machine, and explains in detail the construction of two types of mariner's compasses (Figure 3.3.4). While Petrus Peregrinus was not the first to state any of these ideas, he was the first to organize all of this knowledge, which is why his work is considered a cornerstone of our entire science of magnetism (see also pp.80-83) (Smith, 1992).

As a result of the greater understanding of the magnetic compass, its use began to boom. By the mid-15th century all English trade routes had been mapped with a compass (Marcus, 1956). Its expanded use also lead to greater exploration of the oceans opening up new passages that had not been recorded before the era of the compass (Marcus, 1956). One of the most significant new discoveries enabled by the compass was Christopher Columbus's discovery of North America (see also pp.60-63) (Marcus, 1956).

Conclusion

Each of these theories on the discovery and first uses of the compass from the Olméc and Maya to the European are to be treated as separate events. Although some early uses are similar, to date, there are no accepted hypotheses for the movement of the compass from the Maya to the Chinese nor from the Chinese to the Europeans (Smith, 1992). However, in each case the compass can be seen as a positive and progressing discovery for the civilization. The advanced knowledge of the Olméc, Maya, and Chinese is seen through their carvings and workings of the lodestone. Also, the innovation of the early Europeans is demonstrated in their use of the compass for navigation on the ocean. Overall, the discovery of the compass was an essential point in our scientific history as it gave the confidence for increased exploration of the oceans and is the basis for many navigational tools we use today.

GPS: Global Positioning System

From the discovery of the compass, our tools for navigation have developed rapidly. The most important development occurred in the latter half of the 20th century with the Global Positioning System or GPS by the US Department of Defense in the 1960s (Pace, et al., 1995). Declared operational on December 8, 1993, this system measures a user's location based on coordinates established by GPS satellites that orbit the Earth (Pace, et al., 1995). The seemingly simple system of GPS has become an integral part of our daily lives (Figure 3.3.5).

Although GPS revolutionized navigation, it was not the first satellite navigational system. This title belongs to Transit, a two-dimensional navigational system developed by the American Navy and Applied Physics Lab (Getting, 1993). The advantage that GPS has over Transit is that it gives a three-dimensional coordinate (latitude, longitude, and altitude) for the position of the user. The idea for the system came from the navigation study directed by Phil Diamond, being designed to meet the requirements of a tactical aircraft (Getting, 1993). From here the three basic features of GPS were developed: to accurately pinpoint position of the satellite, to be used in all weather conditions, and to measure relative time (Getting, 1993). The Global Positioning System consists of three segments: the space segment, the control segment, and the user segment. The space segment includes 24 satellites that orbit the Earth every 12 hours, 20200 km above the surface at 4 km/s. Four satellites are located in each of the six planes, inclined at 55^o to the plane of the Earth's equator, each continuously transmitting pseudorandom codes (Getting, 1993). The satellites are all managed by the control segment while the user segment manages activity related to the development of GPS user equipment and services. The development of this complex system would not have been possible without a combination of scientific and engineering advances. Most importantly was the invention of the atomic clock, establishing the world's most accurate timepiece and used for syncing digital communication (Enge and Pratap, 1999).

From the beginning, invaluable military applications were known, and while civil use was expected, it has grown beyond anything imaginable at the time. One of the first civil GPS markets was for surveying and mapping. Now the markets have grown to encompass land transportation, civil aviation, maritime commerce, construction, mining, agriculture, earth sciences, electronic power systems, telecommunications, and outdoor recreational activities (Enge and Pratap, 1999). The full power of GPS is most notable in its combination with other technologies, specifically communication systems such as cellular phones (Enge and Pratap, 1999). One of the most unsuspecting fields that benefitted greatly from GPS is geophysics. Geophysicists are able to use GPS to aid in their studies of tectonic plate motion, crustal deformation, earthquakes, volcanic processes, ice sheet processes, post glacial rebound, and variation in Earth's rotation (Enge and Pratap, 1999).

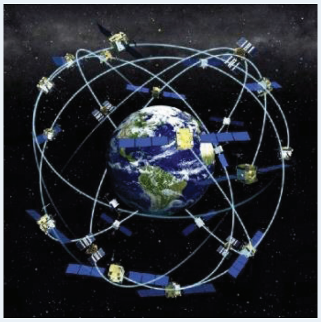


Figure 3.3.5: GPS satellite constellation. The 24 GPS satellites that constantly orbit the Earth in 6 different planes, 4 in each plane.

However, despite the major advancement of GPS technology, it can still be obstructed by foliage and buildings. This causes the largest problems in land vehicle navigation. To help combat this problem, land vehicles require dead-reckoning sensors, such as the compass, to augment GPS (Enge and Pratap, 1999). While the compass cannot provide absolute position, it can measure the change in position over a short period of time to help fill in the gaps of GPS when needed (Enge and Pratap, 1999).

Overall, in its short history GPS has dramatically changed daily navigation and consequently our outlook on the world. Even though the system is not yet perfect, new and improved satellites are continuing to be developed every day. The development of GPS is by far the most significant development for safe and effective navigation to date.

The Discovery of Earth's Underwater Landscape

On any map of the world created prior to World War II, three-quarters of the Earth was a featureless blue border for the many continents (Woods Hole Oceanographic Institution, WHOI, 2006). For the longest time, scientists had thought that the ocean floor was also just as featureless: a flat, unchanging plain filled with sediments that had eroded from surrounding continents (WHOI 2006). The vast amounts of seawater contained within the unexplored oceanic basins provided a grave barrier to the formation of a picture of what lay at the bottom of the ocean (Embley, 2002; WHOI, 2006). As a result, the question of "What is at the bottom of the ocean?" has dragged on throughout most of human history (Lienhard, 1997).

At first, the Ancient Greeks speculated that the underwater landscape would mirror the dry land above; however, at the time there was no evidence to prove this theory (Lienhard, 1997). Minimal efforts to explore the depths of the ocean were made prior to the 18th century. Perhaps this lack of effort was due to the fact that scientists and explorers alike were occupied with exploring new areas at the surface of the earth instead. Fortunately, major developments in the techniques used to map the ocean floor have been made over the past 250 years. These methods have come a long way from conventional sounding strategies used to find potential shipping hazards on the ocean floor near shorelines (Embley, 2002). Ultimately, the development of advanced techniques, such as Sound Navigation and Ranging (Sonar), has provided a clearer but still incomplete picture of what really lies at the bottom of the ocean (Hotspot Ecosystem Research and Man's Impact on European Seas, HERMIONE, 2009).

Conventional Sounding Strategies

In 1521, Portuguese explorer Ferdinand Magellan made his own attempt at measuring the depth of the ocean (Allaby, 2009). During his expedition around the globe, he had one of his sailors aboard the *Trinidad* cast a sounding line over the side of the ship (Allaby, 2009). In theory, if the weight attached to the hemp line had reached the ocean floor, the length of the line paid out would have been a reasonably accurate measure of the ocean depth at that specific location (Allaby, 2009). However, the sounding line used by Magellan was only 730m long, and thus failed to reach the bottom of the ocean (Allaby, 2009). With only one failed attempt to measure the depth of the ocean, Magellan deemed the ocean immeasurable, at least for the time being (Leinhard, 1997).

Another complication that presented itself in Magellan's first attempt was the issue of taking a sounding from a moving ship (Allaby, 2009). This problem was not too serious for Magellan because sailing ships were rather slow, which meant that the weight at the end of his sounding line would have descended almost vertically (Allaby, 2009). This method allowed for the creation of depth charts to aid naval and merchant shipping by the early 19th century. However, the arrival of much faster steamships soon after made traditional sounding devices inaccurate (Allaby, 2009). This is because the sounding line would trail behind the ship at an angle as the ship moved forward, which caused the depth reading to be deeper than it actually was (Allaby, 2009). In order to obtain an accurate reading, the ship would need to be slowed or brought to a stop, which greatly increased the number of shipwrecks on the sea (Allaby, 2009). A solution to this problem evolved over the years and was refined by the distinguished British physicist, Lord Kelvin (Allaby, 2009).

In collaboration with James White in 1873, Lord Kelvin developed the Kelvin White sounding machine with piano wire wound around a small hand-operated winch (Allaby, 2009). The weight at the end of the piano wire was a solid cylinder with a hollow end to collect samples of ocean floor sediments (Allaby, 2009). The collecting of seabed materials with a sounding probe had been in use since the early 19th century. These samples provided information on the ocean floor composition beneath the ship, as well as evidence that the weight had reached the bottom of the ocean (Allaby, 2009). Attached to this weight was a glass cylinder coated with an internal layer of silver chromate, which has a red colour (Allaby, 2009). The cylinder was closed at the top but open at the bottom so it would be filled with air as the weight entered the water (Allaby, 2009). As the weight sank, increasing pressure would force water into the bottom of the cylinder and compress the air contained within it (Allaby, 2009). This seawater would then react with the silver chromate coating to form silver chloride, which has a white colour (Allaby, 2009). Instead of measuring the length of wire used to reach the bottom of the ocean, one could calculate the depth of the ocean to greater accuracy than soundings based on changes in atmospheric pressure with depth (Allaby, 2009). Thus, the Kelvin White sounding machine improved the drift problem of conventional sounding methods and was widely used until it was replaced by the modern echo sounder (Allaby, 2009).

The Development of Echo Sounding

The fundamental idea behind echo sounding was nearly as simple as listening to the echo of one's voice in a mountainous region. Acoustic signal processing is far from a human invention, since bats in the air and dolphins in the sea use natural echolocation systems to navigate. However, the application of this fundamental idea to take echo soundings of the ocean floor presented several difficult technical problems to overcome (Wille, 2005). The most critical problem to be solved was achieving precise measurements of the time travelled by the returning signal (Wille, 2005). The invention of the echo sounder in the late 19th century was credited to the Canadian engineer Reginald A. Fessenden, with impressive technical sound imaging of the ocean coming from German physicist Alexander Behm shortly afterward (Wille, 2005). Several other scientists had the same fundamental idea as Fessenden and Behm; however, they were unable overcome or even identify the associated technical problems (Wille, 2005).

Behm worked to devise an acoustic method for protecting ships from collisions using an early warning system (Wille, 2005). His idea came to be as a result of the infamous collision between the RMS Titanic on its maiden voyage and an iceberg, which led to the loss of approximately 1500 lives on the 15th of April, 1912 (Ansei, 1997). His initial method involved the horizontal propagation of sound waves to reflect off obstacles ahead. However, this method was unsuccessful due to weather conditions causing severe downward refraction of the sound signals (Wille, 2005). At this time, the varying refraction by sea water of different temperatures and salinities was not yet understood and thus could not be accounted for in Behm's approach (Wille, 2005).

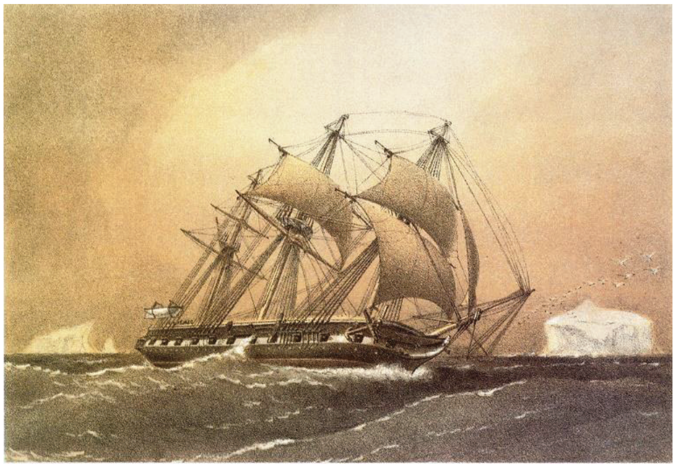


Figure 3.4.1: A painting of the HMS Challenger ship in 1858. Artist William Frederick Mitchell originally published by the Royal Navy in a series of illustrations which are located in the National Maritime Museum Collection in Greenwich, England.

Over the next several years, Behm refined his ability to precisely measure very short time intervals of sound propagation in a small laboratory test tank (Wille, 2005). By February 13, 1916, Behm was able to use an experimentally determined speed of sound in seawater to take echo soundings of the ocean floor (Wille, 2005). Using the time travelled by a sound wave and the speed of sound in seawater, the distance from the surface to the seafloor could then be calculated (HERMIONE, 2009). These soundings were accomplished by using a transducer attached to the hull of a ship. This transducer would emit a pulse of sound which would reflect off of the ocean floor and be detected by a receiver on the ship's hull (HERMIONE, 2009).

Putting the Pieces Together

Before the development of acoustic sounding methods, scientists aboard the HMS Challenger expedition from 1872-1876 took a large number of measurements of ocean temperature, salinity, and depth (Figure 3.4.1). Their data indicated a broad rise in the central Atlantic Ocean basin, but they could not piece together the single soundings to create a complete picture of the ocean floor topography (WHOI, 2006). Even with echo sounding, one common problem remained in that a single sounding could not provide sufficient information on the ocean landscape as a whole (Lienhard, 1997). It was not until the coming of continuous echo sounding that scientists were able to formulate theories about the formation of the ocean floor based on a clearer image of its landscape (Laughton, 1959). With the continuous echo sounder developed by Maurice 'Doc' Ewing and Joe Worzel during World War II, a wide-beam transducer was used to measure the depth of the ocean over the course of several kilometers (WHOI 2006; Laughton, 1959). This allowed scientists to gather multiple profiles of the ocean floor and produce contour charts of its geological features (Laughton, 1959).

During the Cold War, funding for a variety of geological projects became plentiful. Studying and mapping the ocean floor became an important development as nations were preparing for it to be a battlefield in a future submarine war (Bressan, 2013). Since men were primarily occupied with the military, there were plenty of opportunities for women to become involved in these geological projects. One fortunate woman by the name of Marie Tharp had a direct role in putting together the puzzle that was the ocean floor. Marie Tharp worked closely with Doc Ewing and one of his graduate students, Bruce Heezen, to create an initial map of the ocean floor (WHOI, 2006). Tharp was not allowed on board the marine research vessels due to the restrictions placed on women in science at the time (Bressan, 2013). Instead, Tharp remained at home and plotted Heezen's sounding profiles by hand on a drafting table and interpreted this data to create a map of the ocean floor (Bressan, 2013).

As the features at the bottom of the ocean floor unfolded, it was easier to uncover more information about the processes behind the formation of the earth. The most consistent pattern in Heezen's sounding profiles was a V-shaped indentation cutting each of the large ocean basins in half. Heezen and Tharp recognized these spreading centres of oceanic crust as a mid-ocean ridge system which stretched for thousands of kilometers in long continuous mountain chains throughout the globe (Figure 3.4.2; Bressan, 2013). Both researchers were astonished by this result, as it seemed to support the idea of continental drift, a controversial theory developed by Alfred Wegener in 1915 (Sant, 2014).

By creating a complete visual representation of the abyssal plains, the deep channels, and the submarine mountain peaks, Marie Tharp played an indirect role in one of the most revolutionary ideas in geology: plate tectonics (Laughton, 1959). In proving the existence of

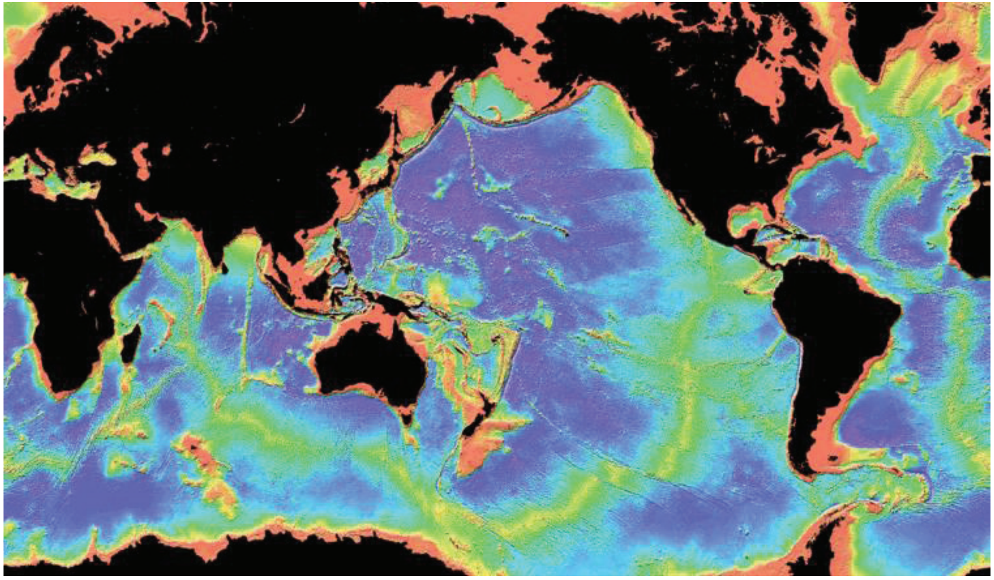


Figure 3.4.2: Map of the mid-ocean ridge system in the Earth's oceans.

the mid-ocean ridge system, the field was prepared for other researchers to develop the unifying plate tectonic theory that explains the fundamental processes that shape the face of the Earth. Although she will never receive the true recognition for this role, her accomplishments were exceptional because she overcame educational and employment barriers for a woman of her generation (Bressan, 2013).

The Search for the Titanic

It is often quoted that the Earth's oceans are "95% unexplored," but what does that really mean? The entire ocean floor has recently been mapped to a resolution of 5km using satellites, meaning that most features greater than 5km across can be identified from a map (Copley, 2014). It can be said that the surfaces of the Moon and Mars have been explored more thoroughly than the Earth's surface since the surfaces of these planets have been mapped to a resolution of around 100 meters (Copley, 2014). From these 5km resolution maps, geologic features such as the mid-ocean ridge system can be identified; however, searching for objects only tens of meters across at the bottom of the ocean can be considered to be "looking for a needle in a haystack".

Satellite Altimetry

According to the laws of physics, the earth's surface is an equipotential surface, which means that it is a perfect sphere (Sandwell, n.d.). The surface of the ocean actually bulges outward and inward due to minute variations in the earth's gravitational field caused by the topography of the ocean floor (Sandwell, n.d.). These bumps are too small to be seen by the human eye, but can be measured using a radar altimeter aboard a satellite (Copley, 2014). Satellites can measure the height of the sea's surface quite accurately, including enough measurements to account for the effects of wave and tidal action (Copley, 2014). However, the landscape of the ocean floor cannot be directly measured by satellites, since ocean water blocks the electromagnetic waves emitted by the radar altimeter (Copley, 2014).

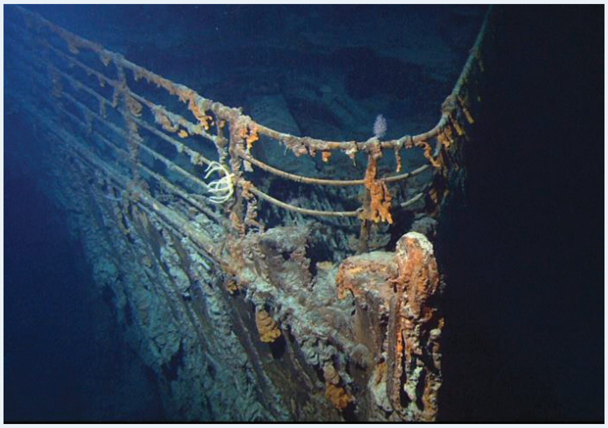


Figure 3.4.3: View of the bow of the RMS Titanic *photographed in June 2004 by the remote operated vehicle Hercules during an expedition to the shipwreck of the* Titanic *(middle).*

The Wreck of the RMS Titanic

The luxury steamship *RMS Titanic* is famous for meeting its catastrophic end in the North Atlantic after colliding with an iceberg during its maiden voyage on April 15, 1912, which caused the loss of over 1500 lives. The remains of this shipwreck were not discovered until 1985, when the steamship was found 600km southeast of Newfoundland, approximately 21.2km from the location where it began to sink (WHOI, 2012). The wreck of the *RMS Titanic* was found by *Argo*, the Woods Hole Oceanographic Institution's new imaging vehicle on its first deep-sea mission. *Argo* was a system of television cameras and echo sounding devices which was towed by the research vessel, *Knorr* (Figure 3.4.3; WHOI, 2012). By using an imaging vehicle close to the ocean floor, objects that are only a few meters in size can be found using the same sound propagation method which mapped the ocean floor to a resolution of 5km (Copley, 2014).

With the development of remote imaging vehicles, 0.05% of the ocean floor has been mapped to the highest possible resolution through specific exploration missions. Thus, the "95% unexplored" saying does not accurately reflect current knowledge of Earth's underwater landscape.

The Development of Geodesy

The development of the representation and measurement of Earth has coevolved with advancements in technologies and mathematics. Once the belief that the Earth was spherical was widespread, around 500 BCE (NOAA, 2008), many people attempted to calculate its circumference. This was the beginning of geodesy. Eratosthenes was the first person to calculate the circumference of the Earth and did it with remarkable accuracy given the resources available at the time. Following Eratosthenes, Al-Biruni calculated the circumference within 1% of today's accepted value. Each different attempt involved different mathematical techniques. After Al-Biruni's calculation of the Earth's circumference, there were no significant advancements in geodesy until the 1600's. When Isaac Newton developed his theory of gravity, he and Christiaan Huygens predicted that the Earth had the shape of an oblate spheroid, also known as an ellipsoid. The Earth's shape is still accepted today as an ellipsoid; however, Newton and Huygens' value for flatness differs from the value accepted today due to the assumptions made in their calculations. In the 1800's Carl Friedrich Gauss extended this idea to the concept of the geoid, which is the shape of Earth's gravity field at sea level. The geoid is still referred to today but the measurements that define it have become more accurate with the advancement of technology.

Eratosthenes

Eratosthenes was a Greek philosopher who calculated the circumference of the Earth around 250 BCE (NOAA, 2008). He did so by using his mathematical skills and what he could measure. During that time, it was known that on the summer solstice at noon, the Sun shone directly into a well in Syene (modern day Aswan) and at the same time on the same day, it cast a shadow in Alexandria (Roller, 2010). Eratosthenes also knew that Alexandria and Syene lie on the same meridian and deduced that the path from Alexandria to Syene would represent a section of the Earth's circumference. Eratosthenes measured the angle of the shadow cast in Alexandria to be about one fiftieth of a circle and he made the connection that the distance between Alexandria and Syene must be a fiftieth of the circumference of the Earth (Figure 3.5.1). His measurement between the two cities was about 5000 stades, which, at 1/50th of the circle is equivalent to an estimated Earth's circumference of 45455 kilometers (Roller, 2010). Today, the accepted value for the Earth's circumference is 40030 kilometers, giving Eratosthenes only 13.5% error (NASA, n.d.). This is incredibly accurate given the resources available at the time.

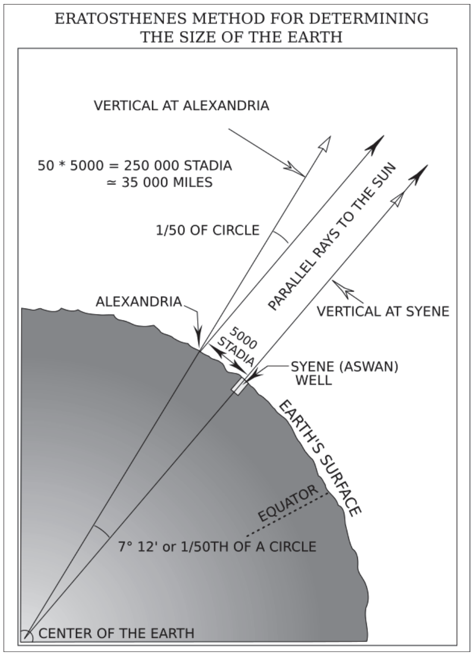


Figure 3.5.1: Schematic of the information Eratosthenes was able to work with.

Al-Biruni

Al-Biruni was a Persian scholar well versed in mathematics and many other subjects. He was born in 973 and died in 1048 (Kamiar, 2006). Although he had many achievements, he is mostly known for developing a technique to calculate the radius and circumference of Earth. His measurement for the radius of Earth was a result of solving a complex geodesic equation (Gomez, 2014).

Al-Biruni had plentiful experience in measuring the heights of mountains. He did this by measuring the angle at which he saw the peak of a mountain from two points in a line and taking the distance between the two points (Gomez, 2014). From these measurements, he could calculate the height of the mountain using the following equation:

$$h = \frac{d tan\theta_1 tan\theta_2}{tan\theta_2 - tan\theta_1}$$

Al-Biruni does not describe what instrument he used to make these measurements, but an astrolabe was traditionally used to measure the angles and he was known to improve a variety of astrolabes (Kamiar, 2006).

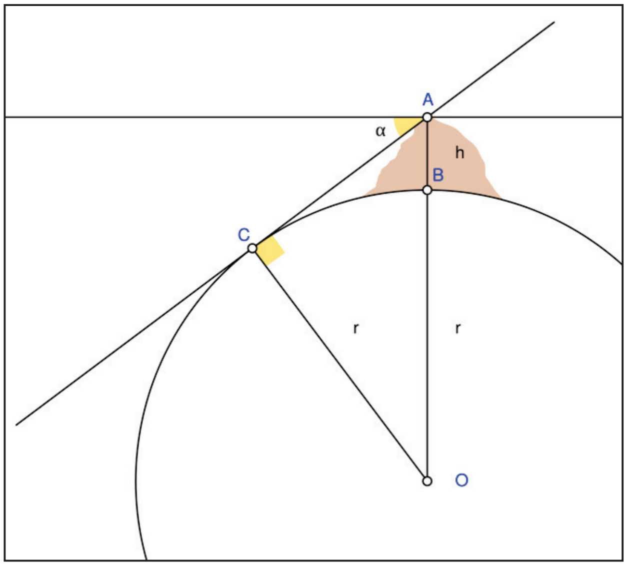


Figure 3.5.2: Depiction of the information and measurements Al-Biruni had to work with to determine the radius of Earth, 'h' is the height of the mountain and 'α' is the angle from the top of the mountain to the horizon.

Determining the height of a mountain was only the first problem he had to solve to arrive at a calculation for the Earth's circumference. With just two measurements, the height of the mountain and the angle from the peak of the mountain to the horizon, he was able to accurately estimate the radius of earth (Figure 3.5.2). Al-Biruni realised that the figure linking the centre of the Earth, the peak of the mountain, and the horizon was a very large right triangle (Gomez, 2014). Using the two measurements previously mentioned Al-Biruni was able to come up with his famous equation for the radius of the Earth:

$$R = \frac{h cos\theta}{1 - cos\theta}$$

He used the sine law among other geometrical properties of triangles to derive the equation seen above. Al-Biruni's calculation was extremely accurate. He measured the radius to be about 5,883 kilometers, which gives a circumference of about 39964 kilometers; only 66 kilometers from today's accepted value (Scheppler, 2006). Al-Biruni's calculation was much more accurate than Eratosthenes' because the measurements he made were done over a much smaller scale which left him less room for error. The main problem with Al-Biruni's measurement was that he assumed the Earth was a perfect sphere, which Isaac Newton and Christiaan Huygens later showed to be incorrect.

Newton and Huygens

With the invention of calculus, the centrifugal force, the force that draws a rotating body away from its centre of rotation, was discovered (Price, 1889). This force led to the belief that the Earth has the shape of an oblate spheroid due to its rotation. Newton and Huygens arrived at the same conclusion even though they had different opinions of how the centrifugal force should be calculated (Grant, 1852). Newton knew that gravity was the force of attraction between all particles of matter. Huygens supposed that the centre of force is located at the centre of mass of an object (Greenberg, 1995). However, they both assumed that the Earth was a homogenous spherical body. Their preferred method of calculation was irrelevant due to the constant magnitude of the attraction associated with a homogenous spherical body. With this in mind the calculation will be the same (Greenberg, 1995).

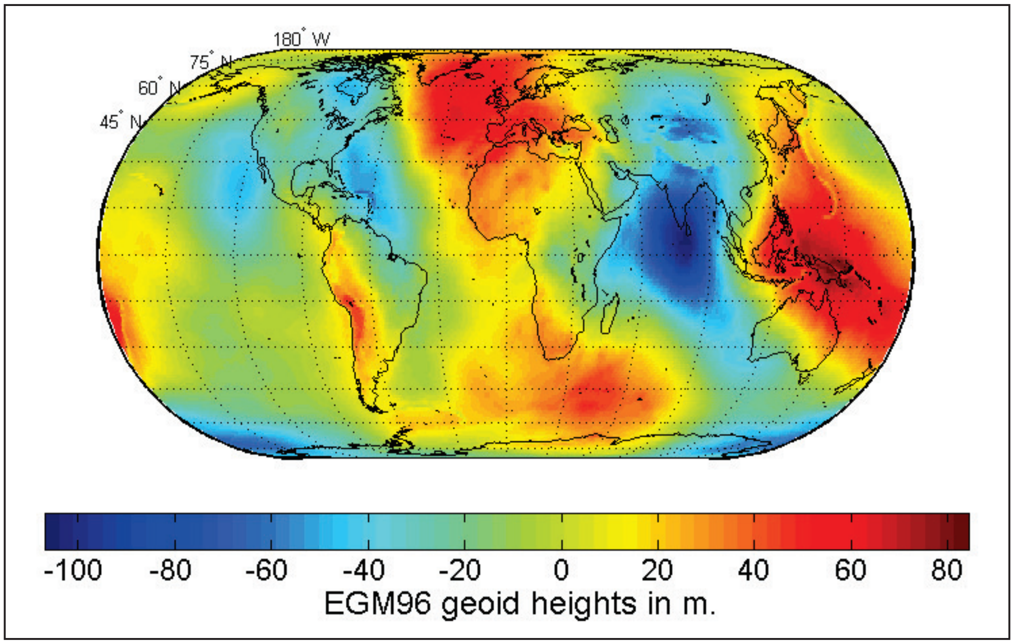
By making the same assumption, both scientists could calculate the ratio of the magnitude of the centrifugal force per unit of mass to the magnitude of the gravitational force at the equator. This ratio is needed to find the flattening of Earth. Flattening describes the oblateness of a sphere, in this case the Earth, and the amount of flattening depends on the balance between the gravitational force and the centrifugal force (Grant, 1852). Flattening can be represented by the equation:

$$f = \frac{e - p}{e}$$

In this equation f is flattening, e is the distance from the centre of the Earth to the equator, and *p* is the distance from the centre of the Earth to either pole (Greenberg, 1995). The distance between the centre of the Earth and its poles is only dependent on gravity because the Earth rotates around the axis that intersects the poles.

The value Newton found for the flattening of Earth was 1/230 (Torge, 2001). The value that is accepted today is 1/298, which shows Newton was 29.6% off in his calculation (McCarthy and Petit, 2003). This development in estimations of the shape of the Earth led many to calculate the flattening more accurately, eventually leading to a geoid, which is a mathematically defined surface that approximates the reference ellipsoid (Torge, 2001).

Figure 3.5.3: Representation of the EGM96 geoid. Blue areas are less dense and lie below the reference ellipsoid. Red areas are denser and lie above the reference ellipsoid.



Geoids

Geoids are the modern and more accurate way to depict the shape of the Earth rather than only using an ellipsoid. The geoid is the equipotential surface of Earth's gravity field (Torge, 2001) where the force of gravity at all points on the surface is perpendicular to the surface (Jekeli, 2003). These perpendicular lines are also known as plumb lines. The actual surface displays differences in density around the globe (Figure 3.5.3). In 1828, Gauss described this surface as the mathematical figure of Earth (Torge, 2001). It is not a physical representation, rather a theoretical surface that describes the Earth's densities with respect to the mean sea level (Fraczek, 2003). It is important to note that the geoid does not take into account the effects of wind or tide. With this in mind, if the sea level were extended under the continents, the sea level would closely fit the shape of the geoid.

The geoid is used as a reference surface, a vertical datum, for heights and depths (Torge, 2001). For example, it is used to estimate the orthometric height, or the distance from the geoid to an arbitrary point above or below the geoid (Torge, 2001). The equation used to make an estimate of orthometric height was derived using the relationship between the gravity vector and its potential (Jekeli, 2003). The potential difference between the geoid and an arbitrary point is known as the geopotential number. The equation used to estimate the orthometric height has two variables: the geopotential number and the gravity vector at the geoid. The gravity vector can only be estimated since it is dependent on the composition of the crust. Therefore, the orthometric height cannot be determined exactly because its calculation depends on a model for the density of the Earth's crust (Jekeli, 2003).

Calculations of the geoid have been developing for almost two centuries and its representation has been getting evermore accurate, as technology and mathematics have evolved. In Canada, the geoid is called CGG2010 and it is used to calculate orthometric heights across Canada (Natural Resources Canada, 2014). GPS is one of the technologies that when combined with a geoid model increases the accuracy of the measurement of altitude at any spot (Fraczek, 2003). The development of geodesy has come a far way since the first attempt to measure the Earth's circumference. Advancements in technologies and mathematics has significantly attributed to how we now represent Earth, with a theoretical surface of gravitational potential.

The Shape of the Moon

Today, as space exploration is becoming more important, ideas from Earth science are being extended to celestial bodies. As such, our closest celestial neighbour, the Moon, is of particular interest. Determining its shape has been a perpetual problem in the past century (Bethel, et al., 2014). Studying the shape and orientation of the Moon is particularly important as it allows one to study its origin, structure, and composition (Iz, et al., 2011).

Orientation and Topography

The Moon's general shape has been related to that of a lemon and, like Earth, the Moon is flattened. When the Moon cooled and solidified during its formation, its rotation caused the flattening. However, the gravitational pull of the Earth on the Moon also had an effect on its shape during solidification, and this shape is also known as a fossil bulge (Bethel, et al., 2014). During solidification, the Moon would have been relatively smooth and have its largest principal axis pointing towards Earth, that is, the longest line that could be drawn thought the Moon would be directed towards Earth (Bethel, et al., 2014). This is contrary to the topography and the orientation of the Moon relative to the Earth as it is seen today.

The Moon's topography is not nearly as smooth as it was once thought to be. As it is well known, the Moon has many impact craters. Furthermore, the Moon loses mass when it gets hit with asteroids and various celestial objects. This makes it difficult to analyse the overall shape of the Moon (Bethel, et al., 2014). However, there are techniques to minimize the error when estimating the overall shape. Recent research done by Bethel, et al. has provided evidence indicating that the formation of impact craters has changed the orientation of the Moon with respect to Earth. The mass that is lost during the impact events changes the way the Moon responds to the Earth's gravitational pull (Bethel, et al., 2014). Over time the Moon has changed its orientation with respect to the Earth depending on where the mass was lost on the Moon.

Analysing the Moon's large-scale lemon-shaped topography reveals part of its geology and evolution. Investigating the shape of celestial bodies gives valuable information that is important to the development of space exploration.

Figure 3.5.4: The Moon as seen from Belgium.

Hollow Earth Theory as a Commentary on the Scientific Method

Modern technology and scientific thinking have allowed humans to develop a fairly good understanding of the ground beneath our feet. However, just as the planet itself has undergone thousands of physical changes over its 4.6 billion year lifetime, our current theory for the structure of the Earth has evolved substantially throughout history (Dalrymple, 1994). Although this can be partially accredited to the development of new technology and experimental techniques, it is only because of a much larger paradigm shift in the scientific method that humans have been able to substantiate theories about the world at large. Ideas that appear completely absurd in hindsight may have been well accepted in their time, and it is only due to a global progression in the modern scientific approach that flaws in historical theory can be understood and appreciated.

Figure 3.6.1: A portrait of Sir Edmond Halley (1656–1742), the famous English astronomer and geophysicist. In 1692, Halley published the first writings concerning Hollow Earth Theory.

An appropriate example of this scientific coevolution can be found within Hollow Earth Theory. This idea was first proposed by Edmond Halley in one of his many publications within the *Philosophical Transactions of the Royal Society of London*, the first scientific journal in European history (Atkinson, 1998). Although the details of this theory are often misconstrued in modern interpretations, the central tenets of Hollow Earth Theory lie within the idea that the Earth is constructed of three nested spherical shells. These shells were thought to be of equal thickness, and the size of the interior parts roughly corresponded in size to Venus, Mars, and Mercury (Halley, 1692).

Overview of Hollow Earth Theory

Halley proposed this theory as part of a larger study in which he attempted to discover why compass bearings varied when collected from different areas around the world. By analysing the available records of compass variation, he noticed that the position of magnetic north and the rate of change in magnetic declination were not consistent over time. Halley suggested that there were actually four magnetic poles, two of which were fixed within the external shell of the Earth. The remaining two poles originated from the internal shells of the Earth, which acted as a separate magnetic entity. Using this theory, Halley could explain anomalous compass readings, insisting that one's proximity to different magnetic poles would cause geographic variations between readings.

Furthermore, Halley used his theory to explain how declination changed over time. He posited that all parts of the globe were fixed upon a common axis of diurnal rotation; however, the outer sphere was thought to move slightly faster than the internal parts. After many years, this small difference in rotational velocity would cause the magnetic poles of the internal parts of the Earth to recede by a few degrees from the external, resulting in a net movement of the poles. This change would be eastwards or westwards depending upon the location of the observer with the compass.

Halley's postulations, albeit slightly abstruse, were reasonably well accepted by the scientific community at the time of their publishing in 1692. This was largely due to the fact that Halley brought empiricism to a discipline of science rarely supported by hard evidence. Although all modern scientific theories require a great deal of supporting evidence and must exhibit reasonable predictive power, theories were often accepted upon the basis of favourable opinion in the past. However, alongside the rise to prominence of the Royal Society of London toward the end of the 17th century, the necessity of providing substantiated reasoning increased. This meant that Halley was required to provide a larger amount of evidence to support his claims to the point that the inductive reasoning of a hollow Earth became plausible.

The Influence of Sir Isaac Newton

The flaws within Halley's attempts to provide substantial reasoning for Hollow

Earth Theory can be retrospectively analysed. In order to muster more evidence for his theory, Halley utilised the theories of one of his great friends and well-respected colleagues - Isaac Newton. Five years earlier, under the encouragement and financial support of Halley, Newton published his groundbreaking work *Philosophiae Naturalis Principia Mathematica* to high critical acclaim in the scientific community (Feingold 2004). As a rising figure within the scientific community and the Lucasian Professor of Mathematics at the University of Cambridge, Halley's use of Newton's work gave his theory an increased sense of validity.

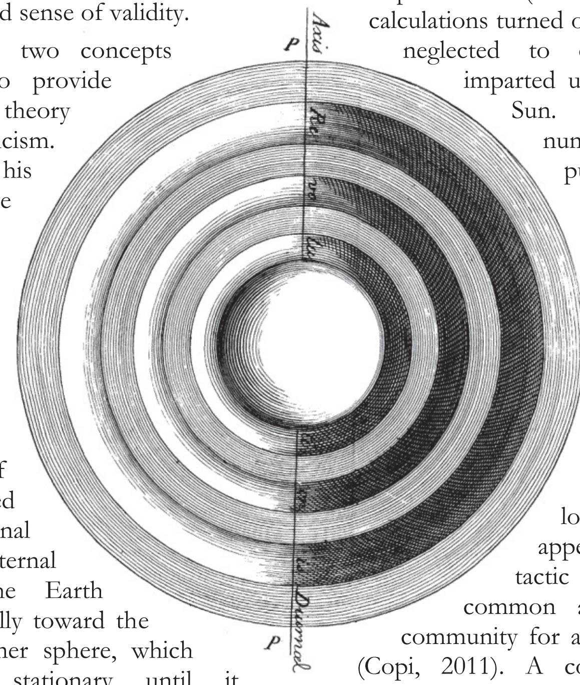


Figure 3.6.2: One of Halley's original diagrams of Earth's structure as proposed by Hollow Earth Theory. The text on the figure reads "Axis Revolution is Diurnal", indicating that all of the shells rotated about the same axis, albeit with slightly different velocities. Halley also theorised that the interior concave surface of each shell was composed of magnetic material.

Halley borrowed two concepts from *Principia* to provide support for his theory and dispel criticism. Halley knew that his conjecture of the Earth as nested spherical shells was contestable on the basis that such a huge structure would not be stable over time due to the great force of gravity. He stated that the gravitational force upon the internal elements of the Earth would press equally toward the centre of the inner sphere, which would remain stationary until it encountered an impulse from an external force. The concept of an object requiring an external force to alter its acceleration was heavily enforced in Newton's work, and it would later become one of his eponymous laws of motion. Since all outward forces could be sufficiently shielded by the outermost shell, Halley claimed that the nucleic shells could remain fixed as nested spherical shells once they were placed in such an orientation. Halley addressed the concern that these shells would collapse under the gravitational force by suggesting that an even stronger force held together the concave portions of the shells — magnetism. He placed magnetic material on the inner surface of each spherical shell, attempting to justify that this would prevent the deterioration of the shells (Figure 3.6.2).

Additionally, Halley attempted to provide circumstantial evidence for his theory using Newton's estimates of lunar density. Based on the Moon's ability to influence the tides, Newton theorised that the relative density of the Moon to the Earth was 9 to 5 (Newton *et al.*, 1833). Under this assumption, Halley compared the Moon with the Earth by asserting "this Globe to consist of the same Materials, only four ninths thereof to be Cavity, within and between the internal Spheres: which I would render not improbable" (1692, p.575). Newton's calculations turned out to be flawed, as he neglected to consider the force imparted upon the tides by the Sun. He corrected this number in later publications of *Principia*, but Halley neglected to update his theories (Kollerstrom, 1992).

Halley's use of Newton's stature as a way to give his theory credibility is an example of a logical fallacy known as appeal to authority. This tactic was extremely common across the scientific community for a large part of history (Copi, 2011). A combination of poor education and the inability to publicize new opinions contributed to the perpetuation of the inevitable fact that more well renowned scientists faced less opposition to their theories than those with less prestige. Halley's failure to reevaluate his theory after Newton discovered his mistakes enforces the possibility that he was using an appeal to authority rather than an honest application of Newton's lunar density estimates. Unfortunately, this problem persists to some degree within the modern scientific community; however, open-access scientific journals and the peer-review process have helped to make scientific literature more transparent and accessible to all inquiring minds.

Halley's Use of Rhetoric

The scientific basis of Halley's writing is further flawed by his employment of other logical fallacies and persuasive literary techniques. The structure of scientific writing at the time was extremely varied, and rightfully so; as the first scientific journal, *Philosophical Transactions* had very few guidelines to evaluate the scientific rigour of submitted articles. As a result, much of the writing used decorative prose, a tactic unseen in modern scientific writing.

For instance, Halley entertained the idea of function for the interior parts of the Earth asides from their contribution to the magnetic field surrounding the globe. He believed that the inner shells of the Earth may be habitable, hosting a wide range of new and diverse forms of life. Acknowledging that such life would require a source of energy, he hypothesized that a luminous medium may be present within the Earth hitherto unknown to those above. However, the previous empiricism with which he treated his theory is lost within these portions of his papers. Instead, Halley extensively used a logical fallacy colloquially known as No True Scotsman (Copi, 2011). As a way to dismiss criticisms that deem his claims implausible, Halley wrote,

"The Concave Arches [of the Earth] may in several places shine with such a substance as invests the Surface of the Sun; nor can we, without a boldness unbecoming of a Philosopher, adventure to assert the impossibility of peculiar Luminaries below, of which we have no sort of Idea." (Halley, 1692, p.576)

Without providing any evidence to substantiate his claims, Halley was effectively dispelling controversy surrounding his point, claiming that the true scientist should not dispute theories of the unknown unless they are able to propose a more suitable theory. By this clever implication, Halley had reversed the responsibility of proving the validity of his claim to the reader rather than having to provide sufficient justification himself.

Halley's Innovative Style

Despite the many criticisms that can be made regarding Halley's theory and the techniques used to enforce it, Halley's work makes very mature statements about the nature of scientific thinking and its evolution through time. After explaining his compass data and proposing Hollow Earth Theory, Halley continued to describe the limitations of his observations. He mentioned that his collections contained measurements made by many different individuals and noted that this would result in inconsistency in the accuracy of provided information. His acknowledgement of uncertainty and measurement error was a very sophisticated practice, as it wasn't until the late 19th century that consideration of uncertainty became a standard practice (Peat, 2002; Wagner, 1983).

Finally, the most interesting aspect of Hollow Earth Theory may not lie within the substance of the theory, but within Halley's attempt to engage the scientific community. Halley made note that the difference in rotational velocities of the inner and outer elements of the Earth grew very slowly and that his measurements provided only a small window through which to observe this phenomenon. Rather than trying to monopolize his findings, he explicitly made a statement to "Masters of Ships, Lovers of natural Truths [and] all others" to contribute to his study (1692, p.571). Within his paper, Halley provided detailed, specific instructions about how to accurately measure magnetic variation. By doing so, he had extended an invitation of collaboration to all those that his article would reach.

Halley continued with this appeal, commenting, "...all that we can hope to do is to leave behind Observations that may be confided in, and to propose Hypotheses which after Ages may examine, amend or refute" (1692, p.571). In this respect, Halley alludes to the most important aspect of the scientific method. The acceptance that science is a process that evolves alongside technology, culture, and individuals is a fundamental driving force for the growth of knowledge. Although Halley's attempts to elucidate a universal truth about the nature of our planet's structure have been found to be dated, controversial, and completely incorrect, his policy of arriving at conclusions through universal accessibility embodies the core values of the scientific practice.

Seismic Tomography

Although Hollow Earth Theory seemed plausible upon the basis of the compass records available to Halley, the advent of new technology quickly brought about overwhelming contradictory evidence. Most importantly, the invention of modern seismology in the 1800s provided scientists with a more direct method of determining Earth structure. Whereas Halley extrapolated the structure of the Earth based upon the dynamic magnetic field that it creates, seismology studies the waves that result from earthquakes in order to determine the compositional, rheological, and thermal properties of the Earth.

Seismic tomography is a method of imaging the Earth's interior by compiling seismic wave propagation data (IRIS, 2014). The success of this technique is based upon the physical principle that the speed of a wave is dependent upon the medium through which it travels. Additionally, the characteristics of the wave – whether it oscillates perpendicular (transverse wave) or parallel (compressional wave) to the direction of propagation – affect its movement through various materials.

Equipment and Techniques

The technique used to deduce the Earth's internal structure requires the coordination of sensory equipment across the entire surface of the Earth. These machines, known as seismometers, are extremely sensitive to seismic activity, able to detect movements that are one thousand times smaller than the width of a human hair (IRIS, 2014). During a large-scale seismic disturbance, such as an earthquake, both compressional and transverse waves emanate from the focus of the fault. Compressional waves apply force along this axis of propagation, allowing them to travel at fast speeds through the incompressible interior of the Earth. As a result, these waves are the first to be received, earning them the nickname of primary waves, or P-waves. Transverse waves arrive slightly later, so they are denoted as secondary waves, or S-waves. By comparing the relative arrival times of the two wave pulses at a variety of locations on Earth's surface, the origin of an earthquake can be determined with exceptional precision (Adams and Ware, 1977).

The practice can be extended further using mathematical modeling. After the location of the earthquake has been well characterized, the received signals are subject to a mathematical operation known as a Fourier transformation. This accounts for the attenuation that occurs along the raypaths of waves as a result of the variable absorptive properties of different materials within the Earth. The image constructed from these transformed data represents a slice through the Earth denoting areas of varying wave velocity (IRIS, 2014). In a process similar to a CT scan, individual images are compiled together in order to create a three-dimensional image (Figure 3.6.3).

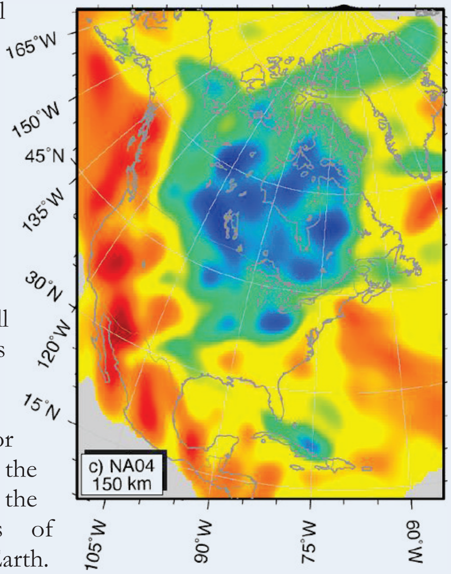


Figure 3.6.3: A tomographic image of seismic velocities for North America using surface waves, created by Susan van der Lee in 2013. Although this image shows only a two-dimensional representation of seismic velocities, many such images can be compiled together to create three-dimensional models of the planet.

Limitations of Tomography

While an extremely useful technique, seismic tomography is has its shortcomings. The wave velocity information that this technique provides can be attributed to a variety of structural features. For instance, waves travel faster through colder sections of the Earth, but they also travel faster through more brittle sections. Similarly, they travel more slowly through both warm and ductile regions. As a result, the final image can be interpreted in several ways. By incorporating this technique with other methods that give information about subsurface temperatures and rheology, these images shed new light on Earth's structure.

Seismic tomography has already revealed that the Earth's structure is much more complicated than the layered model often depicted in textbooks. As more seismometers are placed around the Earth, the resolution of these images will increase, and more information about the true nature of the planet can be discovered. The advent of new practices such as seismic tomography emphasizes the dynamic and growing nature of Earth science.

Our Discovery and Understanding of Earth’s Magnetic Field

Our understanding of Earth’s magnetic field begins with our discovery of magnetite. Magnetite, or Fe2+Fe3+2O4, is a mineral that is naturally magnetized by Earth’s magnetic field because its dipoles are oriented in the directions of Earth’s North and South poles. Magnetite is special because it is naturally oriented in this way, whereas in other magnetizable materials, such as iron, the dipoles are misaligned and need to be oriented through exposure to an external electric field before they become magnetic (Angrove, 2011).

There are various accounts of where the first discovery of magnetite occurred. Some scientific historians believe that the first experimentation was done by Plato at around 400 BCE, while others believe that the ancient Chinese were first when they created Si Nan, a ladle-like compass fashioned out of magnetic rock. Some even believe that a shepherd was the first to discover the natural magnetism when fragments of rock stuck to the nails of his shoes one day (Campbell, 2003). Regardless of this discrepancy, it remains that humanity’s discovery of Earth’s magnetic field remains linked to its discovery of magnetite, which was then called “lodestone” (Campbell, 2003).

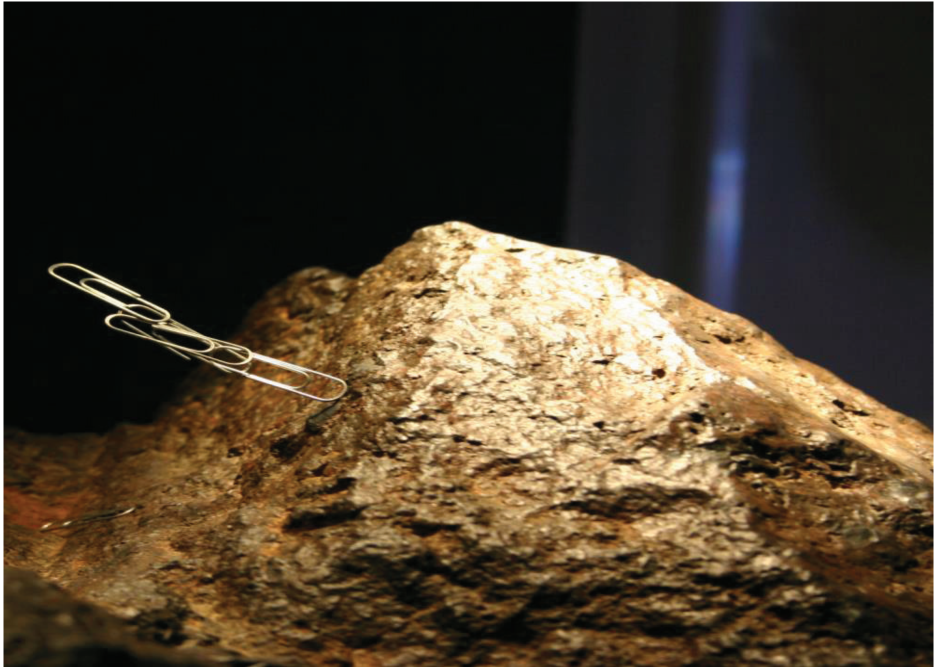


Figure 3.7.1: The dipoles in magnetite are naturally aligned with Earth’s magnetic field, so when these ferromagnetic paperclips are brought near it, it magnetizes them and they become magnetic (Angrove, 2011).

The philosopher and engineer Petrus Peregrinus de Mancourt in his *Epistola de Magnete* wrote some of the first documented experiments with lodestone in 1269. He was the first to describe the laws of repulsion and attraction between like and unlike poles of magnets. He also was the first to acknowledge that every lodestone fragment is a complete magnet, no matter what the size, which is an important step toward the molecular theory of magnetism (Peregrinus, 1269).

By the 15th century, compasses had been in use in navigation for hundreds of years. Magnetic declination is the variation in the direction of geographic North and magnetic north, and is generally measured as an angle (Gubbins and Herrero-Bemera, 2007).

Peregrinus was unaware of the magnetic declination of Earth, and this is evidence in Chapter X of *Epistola de Magnete*, where he states, “Wherever a man may be, he finds the lodestone pointing to the Heavens in accordance with the position of the [geographical] Meridian” (Peregrinus, 1269). The field of geomagnetism came about much later, with the work of William Gilbert: *De Magnete Magnetisque Corponibus*, *et de Magno Magnete Tellure,* which was published in 1600. Gilbert was the first to theorize that the Earth was magnetic, and also the first to make connections between electricity and magnetism. Because of these accomplishments, he is often called the “Father of Electricity and Magnetism” (Gilbert, Magnetic, 1600).

William Gilbert’s knowledge of magnetic declination from expeditions of other scientists during his time allowed him to make an impressive assertion: “magnus magnes ipse est globus terrestris”, which translates to “The Earth globe itself is a big globe magnet”. Along with this assertion, *De Magnete* is the compilation of hundreds of years of thought and experimentation in the field of magnetism, and definitively marked the end of any wild speculations in this area of thought (Merrie, 1998).

By the 17th century, many famous minds were working on the problem of the origin of Earth’s magnetic field. Even well-known French philosopher René Descartes had a well-supported theory. Descartes believes that the Earth’s magnetism was due to the “threaded parts” that were channelled in singular directions through the Earth, and that the main entrances and exists of these parts were through the North and South poles. The parts were subdivided into two types: one that entered the North pole and exited the South pole, and vice versa. The threaded parts had “closed field lines”, and travelled through the air to connect with the field lines in the Earth. If a lodestone happened to be in the path of the field lines, they would interact with it and creates more complex vortices of field lines. Although incorrect, this theory still finds its way into modern descriptions of the magnetic field, as “field lines” are still used as a tool to visualize the concept of the magnetic field emanating from a source (Merril and Melhinny, 1984).

With the continuing expansion in exploration in the years following the publication of GIlbert’s work, the first geomagnetic chart was created by Edmond Halley in 1702. His work will be examined in more detail in the next section. This spawned many more explorations into our knowledge of geomagnetism and Earth’s magnetic field and in the late 18th and early 19th centuries by a few scientists, including von Hemboldt, Sabine, and de Rossel. The data collected from these expeditions served to derive the mathematical expression for the magnetic intensity and period of oscillation of a needle moved from rest by a magnetic field:

$$T = 2\pi\sqrt{\frac{\tau}{|\vec{\rho}||\vec{B}|}}$$

Where T is the period of oscillation of the magnet, τ is the moment of inertia, ρ is the magnetic moment, and B is the magnetic field strength (Merril, 1998).

These measurements exemplify the principle that the magnetic field intensity becomes greater at higher latitudes (Merril, 1998).

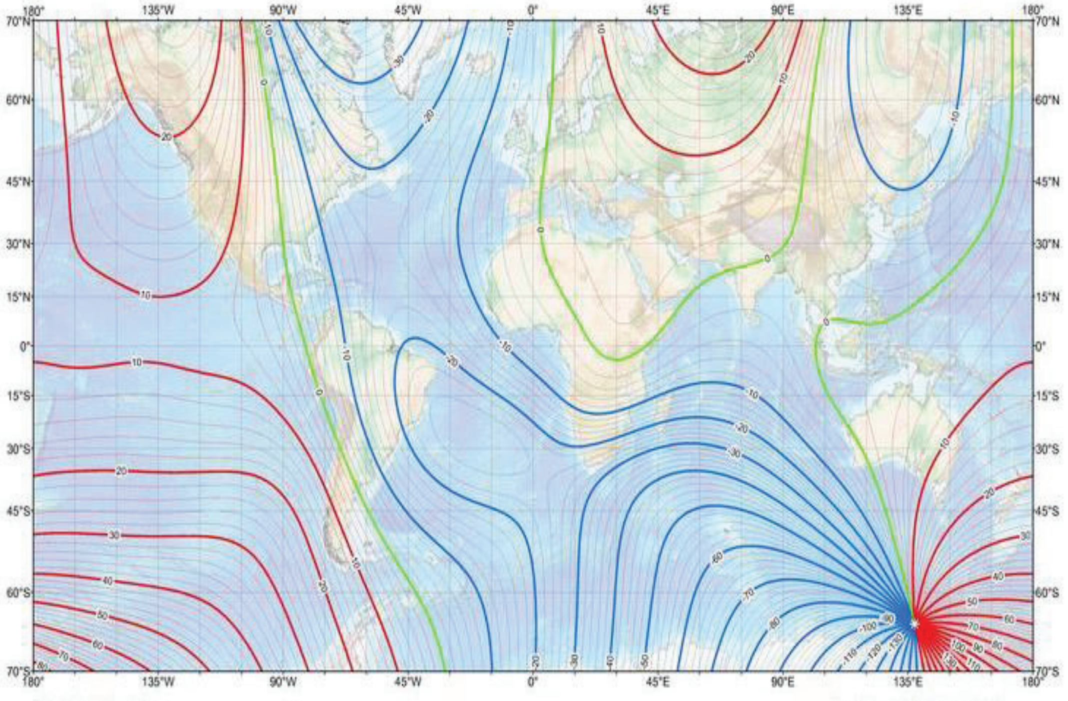


Figure 3.7.2: A modern map of the world’s magnetic declination. The colours denote increasing angles of declination, from blue to red.

This, along with many other mathematical formulations in geophysics, came from the workings of the German mathematician Carl Friedrich Gauss. In his work *Allgemeine Theorie des Erdmagnitismus*, published in 1838, Gauss uses mathematics to distinguish between the components of the magnetic field felt on Earth that were from inside the Earth and from space (Campbell, 2003). He, along with his peer Wilhelm Weber, worked hard in their lab to unravel the secrets of magnetism. They invented some incredible magnetic instruments for their experiments along the way, including the magnetic telegraph, and a method to determine the direction and intensity of Earth's magnetic field. Today, physics students often perform this method at a standard laboratory – an exercise often performed without full knowledge of its historical significance (Leiter et al., 2009).

This magnetic telegraph was the first ever created, and in the hands of Gauss and Weber, it was kept private for scientific purposes only. The telegraph was not commercialized until Samuel Morse invented it in America years later. Gauss and Weber wired this telegraph from Gauss' lab to Weber's lab, and they used it to coordinate their studies of geomagnetism (Huurdeman, 2003).

Gauss was able to mathematically predict the position of the geomagnetic poles. Early explorers of the polar regions then attempted to locate these poles. James Clark Ross discovered the location of the North magnetic pole at 70º05'N, 96º46'W, and the position of the south magnetic pole was discovered to be 71º36S, 152º0'E years later (Merrill & McElhinny, 1984).

James Clerk Maxwell would consult all of the workings of Gauss and Weber before he derived his famous equations of electromagnetism. Maxwell is considered the greatest theoretical physicist of the 19th century. Maxwell was a Scottish scientist and a child prodigy. He published his first paper at the age of 14, and at the pinnacle of his scientific career, derived his famous equations relating electricity and magnetism. Since their derivation, they have aided geophysicists, theoretical physicists, and mathematicians alike, but their contribution to our knowledge of the interior structure of the Earth and its generation of the magnetic field has been extraordinary.

Maxwell's equations (shown below) encompass the fundamental laws of electromagnetism.

1. $\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_o}$
2. $\vec{\nabla} \cdot \vec{B} = 0$
3. $\vec{\nabla} \times \vec{B} = \frac{-\partial \vec{B}}{\partial t}$
4. $\vec{\nabla} \times \vec{E} = \mu_o(\vec{J} + \varepsilon_o - \frac{\partial \vec{E}}{\partial t})$

(Serway and Jewitt, 2010).

Despite the differential forms of these equations originally being meant for differential geometry, it was soon after discovered that they could be used to describe properties of physical fields as well. The differential forms of these equations can be treated as linear, combinations of flux and work in electric and magnetic fields, and this is quite practical for geophysicists, because electromagnetic fields are often measured in terms of these physical experiments (Zhdanov, 2009).

With the use of Maxwell's equations, research in the field of geomagnetism accelerated. Sydney Chapman made some of the most notable contributions to the field of geophysics in modern times. He coined the term "geomagnetism" and conducted ground-breaking research in the interactions between Earth's magnetic field and its atmosphere until his death in 1970. Specifically, he studied magnetic storms and variation in the magnetic field, and he made the important postulation that part of the geomagnetic field is actually generated in the atmosphere (Rittner, 2009).

From ancient times to modern research, Earth's magnetism has sparked the curiosity of many researchers throughout history. The magnetosphere provides humans and animals alike with means for navigation (Gould, 1984) and protects all life from the harsh effects of solar radiation that would otherwise have devastating effects on the biosphere. It is invaluable to all life on Earth, and hence is one of the most essential areas of scientific study.

Dynamo Theory

The modern theory for the generation of Earth's magnetic field began development in 1919 when Joseph Larmor published a paper proposing that a magnetic field of a celestial body could be generated from a self-excited dynamo process. Larmor's main purpose in his paper was to provide an explanation for the generation of the solar magnetic field, but his results can be applied to the geomagnetic field as well (Gubbins and Herrero-Bervera, 2007).

In his paper, he dismissed the theory of permanent magnetization of the Earth's core and the convection of electric charges as possible explanations, but he offered three candidate theories instead. He suggested that either the electric polarization of crystals, the electric polarization by gravity, or dynamo theory could be responsible for Earth's magnetic field (Gubbins and Herrero-Bervera, 2007). Dynamo theory is the currently accepted theory for the generation of the magnetic fields of celestial bodies, including Earth.

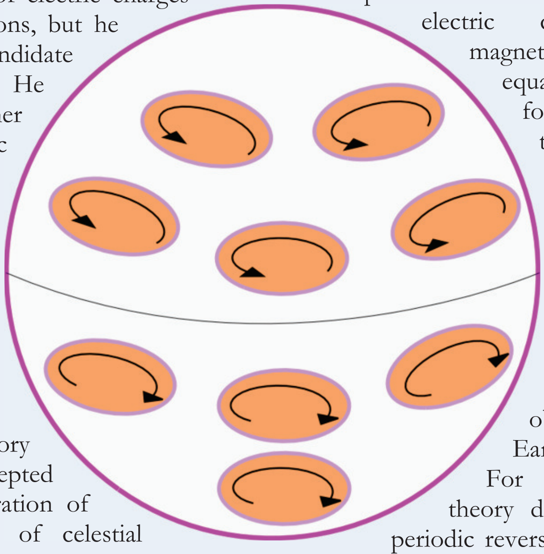


Figure 3.7.3: These rotating liquid metal disks are the cause of Earth's magnetic field according to Dynamo theory.

According to dynamo theory, the geomagnetic field is generated as a result of a system of currents in the liquid outer core of the Earth. From Maxwell's Laws that were examined earlier, magnetohydrodynamic equations can be used to describe this behaviour mathematically (Gubbins and Herrero-Bervera, 2007).

The term "dynamo" comes from the early dynamo electric machines of the 19th century. These machines were generators that produced direct current by means of a commentator, which is used to periodically reverse current direction (Schellen, 1884). The simplest model of a dynamo machine is a single disc dynamo, which comprises of a rotating metal disk on an axis with a surrounding, stationary coiled conducting wire attached to both the disk and the axis. When the disk rotates by an external torque in the presence of an external "seed" magnetic field, an electric current is generated in the direction of its radius. This current then flows through the coil, generating a magnetic field. The disk keeps spinning until the frictional force collapses it and with it, the magnetic field. After the collapse, the disc resumes spinning because of the loss of the frictional force that came with the loss of the field. The frictional force then slowly builds up again over time, and this process repeats itself periodically due to the commutator (Schellen, 1884).

Similar to this, the geomagnetic field could be generated by a self-exciting dynamo, except with fluid currents instead of electric currents. Complex magnetohydrodynamic equations relate these forces and can be used to analyze a dynamo model (Vasquez et al., 2010).

Dynamo theory, while still widely accepted, is still in development, and has not yet managed to explain all of the observed effects of Earth's magnetic field. For instance, dynamo theory does not explain the periodic reversals of the polarity of Earth's magnetic field seen in the rock record (Merril and EcElhinny, 1998). Shortly after writing his famous paper on special relativity in 1905, Einstein declared the problem of the origin of Earth's magnetic field one of the most critical unsolved problems in physics (Merril and McElhinny, 1984). Dynamo theory is a close fit to our observations of Earth's magnetic field throughout history, however it is still far from a plausible argument to fully explain the variation and generation of the geomagnetic field. Further research in years to come, especially in the complex mathematics involved in magnetohydrodynamics, will hopefully make way for great advancements to this decades-old fundamental question of science.

Evolution of Volcanism: From Legend to Mantle Plume Hypothesis

Alfred Wegener published his theory on continental drift in 1915 providing a controversial beginning to other theories related to plate tectonics that would evolve over the years (Glasscoe, 1998; Wegener, 1966). In his seminal theory, Wegener proposed that continents migrate through the sea floor so that a single originating landmass changed over time to generate the separate continents we see today (Wegener, 1966). The theory that tectonic plates move was revolutionary as it challenged the belief that repeated cycles of heating and cooling of the Earth's surface were the driving forces for land movement (Glasscoe, 1998). While Wegener's theory suffered from the weaknesses of offering no explanation for the movement of continents and the fact that it was based upon observational evidence, it was, nonetheless, instrumental in formulating current theories on plate tectonics and the role that the movement of plates have had in shaping the Earth's surface.

Figure 3.8.1: The struggle between Pele, goddess of volcanoes and Na-maka-o-kaha'i, goddess of the sea.

Over time, the movement and interactions of tectonic plates has changed Earth's surface causing earthquakes, mountain ranges, volcanoes, and other geologic features. Instabilities generated at contact points between adjacent moving plates were a compelling explanation for volcanoes and formed a natural extension of Wegener's theory of continental drift. Moreover, since the majority of the world's volcanoes are found along plate boundaries there was considerable support for the association between plate tectonics and volcanoes (Tilling, Heliker and Swanson, 2010). Many of Earth's volcanoes are located around the Pacific Ring of Fire and are formed due to the subduction of the oceanic plate beneath a less dense continental plate (Decker and Decker, 1991). The plate tectonic hypothesis provided a clear explanation for arc and ridge volcanism that occur in subduction zones (Sleep, 1992; Campbell, 2005). However, volcanoes are also found in locations distant from plate boundaries, a condition that was not satisfactorily addressed in the plate tectonic hypothesis (Campbell, 2005). These sites, located far from plate boundaries, include age-progressive chains of volcanoes that have given rise to the Hawaiian Islands (Xu, et al., 2007).

From Legend and Early Observations to Theory

The Hawaiian Islands instigated many thoughts regarding the origin of volcanoes in regions distant from plate boundaries. The distinct time-progressive volcanism along the Hawaiian chain was recognized by ancient Hawaiians long before any geologic studies were conducted (Anderson, 2004). The notion that the islands are progressively younger to the southeast was passed down from generation to generation in the legends of Pele, the goddess of fire and volcanoes (Figure 3.8.1). Pele first inhabited the island of Kaua'i but when her older sister, Na-maka-o-kaha'i, the goddess of sea, attacked her she fled to the island of O'ahu. When she was expelled from the island she continued to move eastward until Pele made it to the Island of Hawai'I (Watson, 1999a). According to the legend, she now resides in the Halema'uma'u crater at the summit of the Kilauea volcano (Clague and Dalrymple, 1994). The legend of Pele and her sister refers to the struggle between the formation of volcanic islands from eruptions and their subsequent erosion by ocean waves and it is consistent with scientific observations of the northwest-southeast alignment of the chain.

The eminent naturalist Charles Darwin first mentioned volcanic islands while developing his theory on how coral reefs formed. Geologists had previously thought that coral reefs develop on underwater volcanoes. In 1837, during his notable voyage on the Beagle, Darwin applied what his professors had taught him about the slow, gradual subsidence of rocks to create a new theory. He proposed that coral reefs develop in the shallow waters around volcanic islands, forming structures known as fringing reefs (Schaffer, 2009). As the islands subsided over time, a lagoon would form between the island and the coral reef, establishing a structure known as a barrier reef. Eventually, the island would erode below sea level leaving a lagoon circled by a coral reef known as an atoll (Schaffer, 2009). This was one of the first ideas on age-progressiveness of volcanic island chains as they change from volcanically active islands to older structures such as atolls (Anderson, 2004). His theory was well accepted until the late 1870s when Alexander Agassiz refuted the theory and proposed that atolls grew from shallow sand banks on the sea floor that, over time, created large circular coral reefs. Eventually the coral in the middle would die, resembling the characteristic shape of an atoll (Stanford University, 2012). However, the concept of age-progressive volcanism as it applies to the Hawaiian chain resides with James Dwight Dana (Anderson, 2004).

A few years after Darwin's voyage, Dana was a member of the Wilkes expedition (1838-1842) that explored the islands in the Pacific Ocean (Figure 3.8.2). This was the first American geologic exploration and similar to Darwin, Dana conducted geological studies on reefs and volcanic islands (Natland, 2003). Their scientific writings and exchange of letters show that both men were intrigued by how coral reefs are established and they arrived at similar explanations and theories (Rezneck, 1962). Dana's expedition report revealed what Darwin had already accepted; the volcanoes giving rise to islands are only active at one end of the chain and on the other end the eroded volcanoes disappear beneath sea level (Natland, 2003). In 1849, Dana suggested that many of the features of the Pacific basin are geologically young although they reside on older rocks. The volcanically active linear chain in the middle of the basin is relatively young in comparison to the arc volcanoes bounding the Pacific basin on the edge of continents. Dana theorized that the diverse topography in the area of the Pacific results from contraction of the Earth's surface as the interior of the globe cooled (Natland, 2003). This theory was a prevailing belief among the scientific community until scientists were introduced to the theory of plate tectonics that emerged almost a century later in the late 1950s and early 1960s (Natland, 2003). Dana made a number of important contributions to the study of volcanoes in the Pacific and he was credited with developing much of the early knowledge of the Hawaiian volcanoes in particular. After the Wilkes expedition, Dana was ill for a number of years before he embarked on his final expedition to the Hawaiian Islands in 1887 to study volcanism (Pirsson, 1919). From this period of his career, Dana is credited with recording, through his writings, that the islands were increasingly younger with respect to geologic time scale moving from northwest to southeast along the Hawaiian volcanic island chain (Natland, 2003). Indeed, he found that this observation held for many of the other island chains in the Pacific. From this vantage point, Dana proposed that the age progression of the volcanic islands was due to localized volcanic activity along sections of a large fissure zone (Anderson, 2004). Dana's contributions to the field of volcanology drew considerable scientific attention and helped increase awareness of the Hawaiian chain and their origins (Pirsson, 1919). As was true for work instigated by his contraction of the earth theory, Dana's perceptive observations concerning an age progression among the islands proved instrumental as a foundation for many subsequent studies, including research in the early 1960s on the subject of plate tectonics by Canadian geophysicist and geologist John Tuzo Wilson (Natland, 2003).

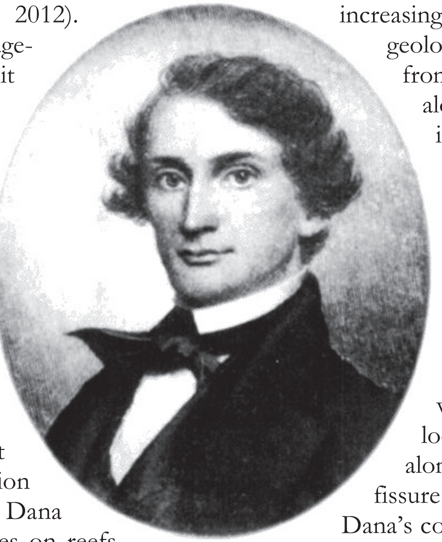


Figure 3.8.2: A portrait of James Dwight Dana, taken in 1848.

Wilson introduced the term "hotspot" in the early 1960s to explain volcanic activity located within tectonic plates that appear to be melting anomalies (Foulger and Natland, 2003). A hotspot is an area of active

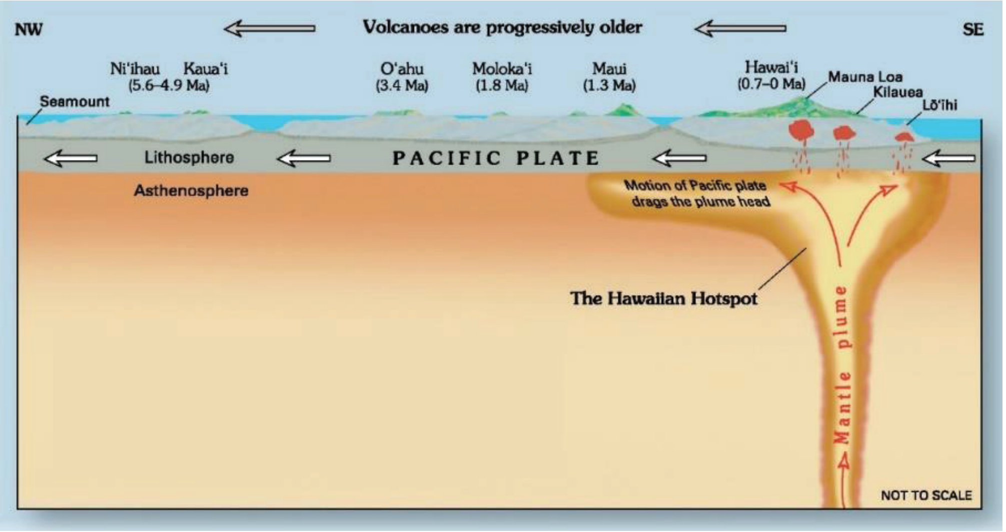


Figure 3.8.3: A depiction of the formation of the Hawaiian volcanic island chain from a hotspot plume.

volcanism underlain by a mantle plume (Anderson and Natland, 2005; Sleep, 1992). According to Wilson, when the head of the plume reaches the upper mantle, heat from the plume causes partial melting of the rocks beneath the tectonic plate thereby, producing pockets of magma (Tilling, Heliker and Swanson, 2010). Eventually, the magma reaches the surface of the tectonic plate and erupts on the sea floor forming an active seamount (Sleep, 1992). Over time, the lava from the eruptions causes the seamount to grow until it emerges above sea level to form an island volcano. Wilson believed that plumes are in a fixed position relative to the moving overlying plates (Anderson and Natland, 2005). Thus, as the movement of tectonic plates carries the island off the center of the hotspot, the volcano is cut off from its source of magma and eruptions cease. According to Wilson, the remaining active hotspot eventually produces a new island volcano and the cycle continues, creating a long chain of volcanic islands and seamounts across the sea floor (Wilson, 1963). Wilson's explanation for hotspots was not well received when proposed but was, nonetheless, published in 1963 and gained acceptance and approval in subsequent years (Watson, 1999b).

Consistent with Wilson's theory, the volcanic islands in the south end of the Hawaiian chain are the youngest formations (Anderson and Natland, 2005; Wilson, 1963). As the islands move northward away from the fixed hot spot they become volcanically inactive and, over time, wave erosion has caused a steady diminution in their size to the point where old islands in the chain have become underwater seamounts (Figure 3.8.3) (Anderson and Natland, 2005). The oldest of the main Hawaiian Islands is Kauai which was formed approximately five Ma ago and is currently volcanically inactive (Tilling, Heliker and Swanson, 2010). The Island of Hawai'i, with principal lava flows less than one Ma old, is the youngest island. Due to its position directly above the hotspot, the Island of Hawai'i has the highest volcanic activity of the Hawaiian Islands. Off the southeast coast of the Island of Hawai'i lies Lö'ihi, an active underwater volcanic region (Tilling, Heliker and Swanson, 2010). This region could designate the start of the zone of magma formation at the southeastern edge of the hotspot. If the geologic processes continue as Wilson hypothesized, Lö'ihi would be the next Hawaiian island to emerge.

Controversies Arising from Wilson's "Hotspot" Theory

When the mantle plume hypothesis was first proposed, hotspots were thought to originate deep in the core-mantle boundary and that they were fixed (Xu, et al., 2007). More recently, these beliefs have been the subject of debate with proposals raised that not all hotspots originate from deep mantle plumes and that hotspots are not fixed in position over geologic time, as previously assumed by the mantle plume hypothesis (Foulger and Natland, 2003; Tarduno, et al., 2003; Xu, et al., 2007; Smith, et al., 2009). Over the years, alternative hypotheses on the origins of mantle plumes have been formulated, but it was not until recently that scientists began to subdivide hotspots based on the depth of their mantle plumes (Xu, et al., 2007). Hotspots have been divided on the basis of whether they originated in the lithosphere, the base of the upper mantle, or in the core-mantle boundary (Foulger and Natland, 2003). The question of where plumes originate in terms of depth and how that impacts the development of a hotspot requires further research as there is disagreement among scientists based upon geological and geophysical grounds (Foulger and Natland, 2003). Progress in this research area will benefit from new technologies including Interferometric Synthetic Aperture Radar (InSAR) (Pritchard, 2006). Instruments offering high-resolution images are needed to resolve the long-standing controversies arising from Wilson's hotspot theory.

InSAR: Satellite-based Technology

Interferometric Synthetic Aperture Radar (InSAR) is an imagery tool that uses satellites. InSAR imagery is used to measure topography, ocean currents, groundwater movement, and surface deformation caused by volcanoes, earthquakes, and glaciers. InSAR uses the transmission and reception of microwave electromagnetic radiation to create daytime and nighttime radar images of Earth's surface (Pritchard, 2006). InSAR mapping is acquired by the change in phase that results from the path difference between two SAR data acquisitions (CGG, 2015). The 2D diagram of the difference in phase values is represented by an interferogram. The coloured fringes in an interferogram show the variation in phase that denotes the magnitude of deformation at a given point on the ground (Central Federal Lands Highway Division, 2011). The changing colours signal increasing deformation and is software-dependent (Geospatial Information Authority of Japan, 2014).

InSAR technology has been used to survey active volcanoes in the Andean Central Volcanic Zone and assess three indicators of magmatic activity including surface deformation, thermal anomalies, and seismic activity (Henderson and Pritchard, 2013; Jay, et al., 2013). As an indicator, surface deformation can signal subsurface movements of magma or the motion of shallow hydrothermal fluid (Figure 3.8.4). Henderson and Pritchard (2013) associated nine volcanoes with deformations but only one of them had erupted. InSAR was used to locate and evaluate the activity of volcanoes and detect thermal anomalies or hotspots in conjunction with thermal infrared satellite data from the Advanced Space Thermal Emission Radiometer (ASTER) and Moderate Resolution Imaging Spectroradiometer (MODIS) instruments. Approximately 35 of 150 volcanoes thermo-imaged by Jay, et al. (2013) showed hotspot temperatures of 4 to over 100K above the surrounding temperatures. Many of the hotspots found in this region are associated with hot springs, fumaroles, and volcanic eruptions. InSAR provides high-resolution maps of surface deformation from changes in strain before, during, and after earthquakes (Pritchard, 2006).

With the higher resolution images offered by InSAR over previous instruments, our capacity to respond quickly to natural disasters such as volcanoes and earthquakes has greatly improved. In addition, InSAR allows scientists to amass more measurements on surface deformation enabling larger areas of our planet to be observed and monitored remotely (Pritchard, 2006). When InSAR is used in conjunction with global positioning system (GPS) stations, researchers do not need to travel to inaccessible and dangerous regions to collect data and observe natural disasters (Pritchard, 2006).

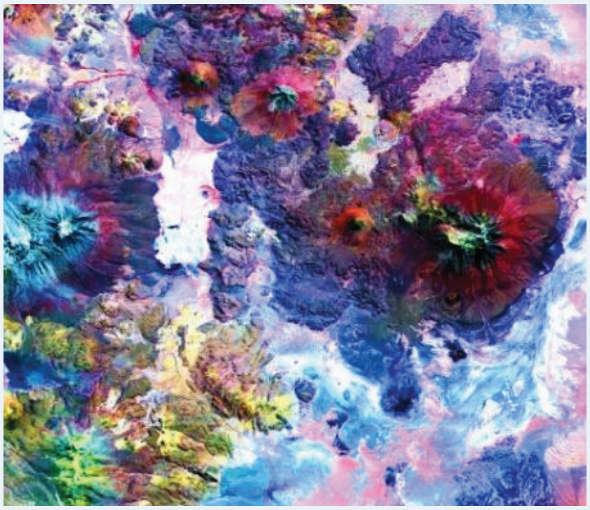


Figure 3.8.4: An ASTER image of the Andes. ASTER images can be used to monitor the volcanic activity in a region. The colour of the fringes indicates areas of surface deformation and the rate of movement of the ground. Patterns of multi-coloured swirling are indicative of areas undergoing the most surface deformation.

Fractals and Chaos

Mathematics is arguably the most versatile scientific discipline because of its ability to describe and model the world around us. The mere fact that it can reduce seemingly complex and chaotic phenomena into numbers and symbols that can then be used to make accurate predictions is one of mankind's greatest achievements. Indeed, it has been used to study our world by applying equations and graphs to our everyday experiences. However, for a long time there was uncertainty about whether or not mathematics could be used to describe natural phenomena that appear to be unpredictable. This changed in the 1970s, when a mathematician named Benoit B. Mandelbrot (1942–2010) (Figure 3.9.1) discovered a way to use geometry to describe seemingly unpredictable phenomena, such as the branching pattern of trees, with a high degree of accuracy (NOVA, 2008). Surprisingly, the events that eventually led to this discovery date back to the time of Galileo Galilei (1564–1642), Sir Isaac Newton (1642–1726), and Pierre-Simon Laplace (1749–1827) (Mandelbrot, 2004).

Figure 3.9.1: Benoit B. Mandelbrot, "the father of fractal geometry".

Order and Chaos

It was during the time of Galileo, Newton, and Laplace that simple dynamical systems, mathematical sets whose values change with time, were being studied (Anton, 2010). These scientists discovered that simple dynamical systems behave in a predictable manner, an idea that completely revolutionized how the western world viewed their universe (Mandelbrot, 2004). At the time it was thought that the world was unpredictable and full of chaos, and that it could not be described using the tools of mathematics. However, when the mathematical nature of simple dynamical systems was introduced and it became clear that scientists could use them to make predictions about the world, the general public felt more secure (Mandelbrot, 2004). The discovery created the notion that every phenomenon could be broken down into equations and graphs, allowing for harmony and order to be present in everything in the observable universe. This thought, the idea that everything could be described neatly and with a high degree of order, resonated with most of society for a long period of time (Mandelbrot, 2004). It was not until the late nineteenth century that the idea of chaos reintroduced itself into society (Mandelbrot, 2004). At this time, scientists were troubled because, among other things, they could not predict the turbulent motion of fluids and could not prove that the solar system is stable (Mandelbrot, 2004).

Julia and Fatou

In the 1910s, the French mathematicians Gaston Julia (1893–1978) and Pierre Fatou (1878–1929) were interested in studying the properties of dynamical systems and chaos (Mandelbrot, 2004). They were each fascinated by the fact that the present state of a dynamical system was directly influenced by the operations performed on the previous state of the system (Mandelbrot, 2004). Accordingly, Fatou and Julia each made contributions to the field of geometry, work inspired by dynamical systems, by further developing a theorem known as Montel's theorem (Mandelbrot, 2004). Much of their work focussed on the basic equation of a parabola, $y = x^2 + c$, and the concept of iteration (NOVA, 2008). An iteration is the repeated execution of a single set of instructions (Wolfram Alpha, 2014). It can be thought of as taking an object, placing it into a processing machine, retrieving the output, and then placing this output into the machine again. This process would repeat an indefinite number of times. Put another way, the basic idea of iterations is analogous to looping statements used in computer science.

Julia and Fatou thought about what would happen if they iterated the equation $y = x^2 + c$, starting at $x=1$ (Figure 3.9.2) (NOVA, 2008). The numerical output produced is called a Julia set; the first five outputs are 2, 5, 26, 677, and 458 330 (NOVA, 2008). What is interesting is that they extended the iteration to include both real and complex numbers. Unfortunately, Julia and Fatou were limited in their quest for knowledge because they had to perform their calculations by hand (NOVA, 2004). They could only perform so many calculations before the mathematics became too complicated to continue. Although this seemed like a dead end, it would not be long before the ideas of Julia and Fatou would be revisited and developed even further.

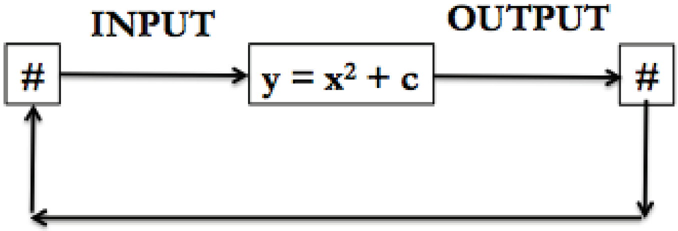


Figure 3.9.2: Visual diagram of iterations performed by Julia and Fatou.

Mandelbrot

In 1958, Mandelbrot started working as an engineer for International Business Machines (IBM) (NOVA, 2008). While working for IBM, he was presented with an unusual problem: occasionally, there were issues in transmitting data over the telephone lines and it was not clear why this was happening (NOVA, 2008). Upon analysis, the nature of this problem reminded Mandelbrot of the work of Julia and Fatou, and it inspired him to take a closer look at their mathematical research. At IBM, Mandelbrot went through the Julia set and decided to plug in the iterations into a high-speed computer (NOVA, 2008). He was able to accomplish something that Julia and Fatou could not simply because of the rapid advance of technology in his day and age. Mandelbrot ran the iterations millions of times and plotted the resulting Julia sets on a graph (NOVA, 2008). An example of the graph of a Julia set can be seen in Figure 3.9.3. In 1980, Mandelbrot's work on Julia sets allowed him to discover what is now referred to as the Mandelbrot set (NOVA, 2008). The iteration rule used to produce the Mandelbrot set can be described as follows:

$$z_{n+1} = z_n^2 + c, z_0 = 0$$

(Wolfram Alpha, 2014). When Mandelbrot iterated his equation over and over again, he produced a graph that took elements from each Julia set (Figure 3.9.4) (NOVA, 2008).

Figure 3.9.3: A Julia set.

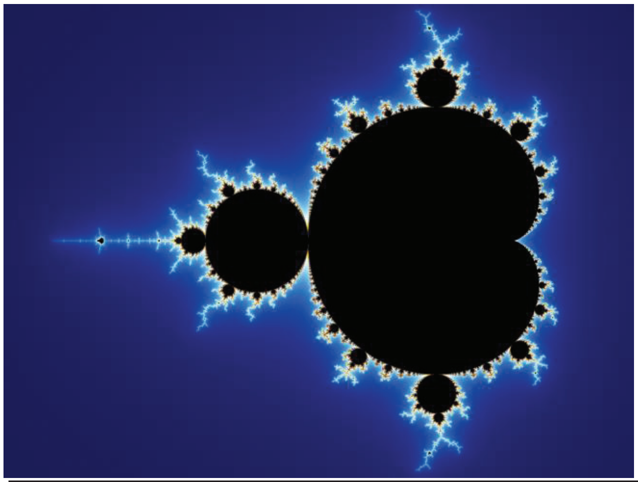


Figure 3.9.4: A Mandelbrot set.

Fractals

The nature of this set caused Mandelbrot to coin the word "**fractal**" because of its repeating nature (NOVA, 2008). Concisely, a fractal can be described as a shape that displays a repeating pattern at every scale (Falconer, 1990). Examples of different types of fractals are shown in Figure 3.9.5 and Figure 3.9.6.

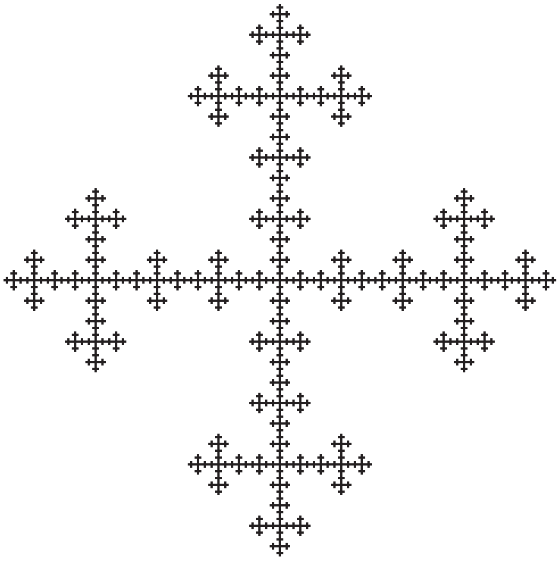


Figure 3.9.5: A box fractal.

As you can see, the pattern of a fractal repeats itself when you zoom into the image. This repeating pattern continues to appear no matter how much you zoom into the picture. Interestingly, the nature of fractals starts to get very abstract when you consider fractal dimensions, a concept used to describe the spatial properties of fractals by measuring how detail varies with scale (Falconer, 1990). Essentially, the fractal dimension is a fractal property that describes its geometry (roughness) as being in between one-dimensional and three-dimensional (NOVA, 2008). It is actually a magnitude that varies between one and three; if it is closer to one, the fractal is more closely related to a one-dimensional segment; if it is closer to two, the fractal is more closely related to a two-dimensional structure; and, if it is closer to three, the fractal is more closely related to a three-dimensional object (NOVA, 2008).

Controversy of Fractals

Although Mandelbrot put a great amount of effort into researching fractals and their application to the world of science and engineering, his ideas were initially met with much controversy from the scientific community. At the time his ideas were being published, many mathematicians did not appreciate the elegance of fractal geometry because they thought that it was not real science (NOVA, 2008). They rejected Mandelbrot's ideas because it presented a new way of perceiving the world. Since these mathematicians had become accustomed to their traditional way of viewing the universe, they became insecure when new ideas were being presented to them (NOVA, 2008). They felt fearful because Mandelbrot's farfetched ideas called for a revision of the then-current ideas about geometry (NOVA, 2008). It was not until 1982, when Mandelbrot published *The Fractal Geometry of Nature*, that the scientific community began to accept the idea that fractals were a real mathematical phenomenon that could applied to many different branches of science (NOVA, 2008).

Versatility of Fractals

Like many branches of mathematics, fractals seem to find their way into almost every single scientific discipline. For example, fractals have been applied to describe the structure of the universe and also different galaxy clusters (Mandelbrot, 1983). Another example is how fractal antennas are used in cellular phones to help increase the reception strength (NOVA, 2008). Furthermore, it appears the healthy heartbeats can also be described using fractals (NOVA, 2008). There are several other applications of fractals but, surprisingly, some of the most interesting ones are those that are used to describe natural phenomena in the earth sciences.

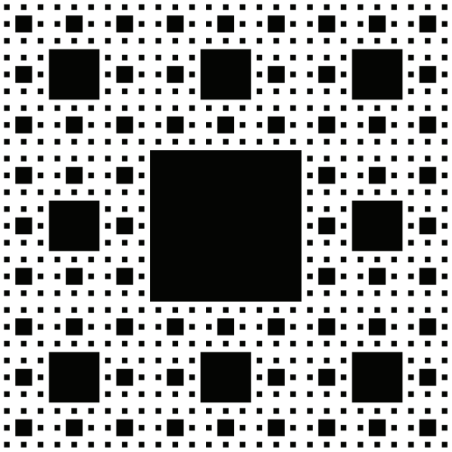


Figure 3.9.6: A Sierpinski carpet fractal.

Applying Mathematics to the Earth Sciences

In the 1940s, a British scientist named Lewis Richardson presented a problem to the scientific community (NOVA, 2008). He described that different measurements of a single coastline were inconsistent with each other (NOVA, 2008). It appeared that there was a large error margin when different scientists made the same coastline measurements, and it was troubling that an exact magnitude could not be determined. (NOVA, 2008).

Why was there so much variation?

It was determined that the variation in the measurements was caused by one main factor: the length of the measuring sticks being used (NOVA, 2008). For you see, the accuracy of your measurements increases as the length of your measuring stick decreases since longer rulers will impair your ability to measure finer details on coastlines (Figure 3.9.7).

Fractals and Coastlines

In 1967, Mandelbrot published a paper titled "How Long is the Coastline of Britain?" in *Science* magazine (Mandelbrot, 1967). In this paper, he was able to apply the patterns of a fractal known as a Koch snowflake (Figure 3.9.8) to model the measurements of a coastline (Mandelbrot, 1967). It is important to note that he did not actually use the term fractal in this paper because the word was not popularized until a few years later (NOVA, 2008). He discovered that, geometrically speaking, a coastline was essentially a fractal (NOVA, 2008).

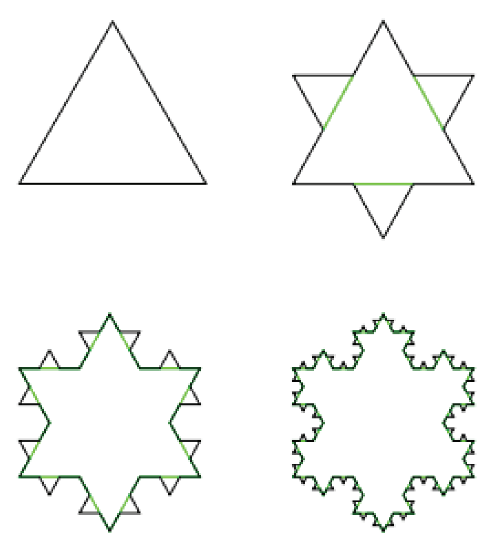


Figure 3.9.8: The first four iterations of the Koch snowflake.

The paper published by Mandelbrot was the first step in his journey to make fractals well known to the rest of the world. It was most definitely instrumental in popularizing the idea of fractals into the mathematical community because it displayed one of its many applications.

Virtual Earth Science

The ideas of fractals can also be applied to producing computer simulations of mountains (NOVA, 2004). What happens is that fractals are iterated over and over again to produce realistic-looking mountains that actually ap-pear to be rough on the computer screen (NOVA, 2004).

Figure 3.9.7: Different methods of measuring coastlines using different sized measuring sticks.

Figure 4.0.1: Chlorite in thin section, as seen through a polarizing microscope under plane polarized light.

Chapter 4: Materials and Resources

Our dynamic planet has provided us with vast amounts of natural resources and benefits. Energy, medicine, art, and technologies were all made possible from the exploitation of these resources, and it is those applications that led to the rise of civilizations.

There was a period in human history where our homes were simple stone constructions and our cities did not sprawl over the entire globe. However, changes in our environment forced us to adapt and evolve to survive our developing world. The first cities were built in locations in which natural resources could be readily accessed. Previously nomadic tribes were then able to remain in place and build villages. Water management systems were developed and allowed villages to become sprawling cities. This gave rise to the Ancient civilizations who built the foundations of the modern world: The Greeks, the Romans, the Mayans, and the Egyptians. Their city's growing populations and increasing supply demands led to the innovation of new farming, resource exploration, and sustainability. Much like today, natural resources affected the economy and socio-political interactions, which were also under the influence of different religious beliefs. This, in turn, affected the direction of scientific research. The fascination towards gold and silver drove the development of scientific processes in Greco-Roman Egypt, Medieval Islam, and Medieval Europe eras. Alchemy gained traction amongst their citizens and some began to believe pure metals were said to have divine properties.

Through the experimentation of hundreds and thousands of years, humans have improved and refined their exploration methods and uses of natural resources. The future holds many more discoveries on this topic. However, the future is also learning from the past. Many civilizations fell due to inadequate sustainability of their resources, and many suffered from wars waged over the ownership of raw materials. It is important to continue to develop an understanding on natural resources, how they form, and where they can be found. It is also very important to study the consequences of exploiting these resources on the environment, in order to continue using them into the future.

A Brief History of Mineral Classification

Among the most valuable of Earth's natural resources are its minerals. Minerals serve many practial uses, and the economy built around precious gems is an enormous one. The undertaking of systematically classifying the many minerals that compose the Earth is not one to be taken lightly. Indeed, its origins can be traced back to ancient Greece. As early as 300 B.C.E., both Aristotle and his successor Theophrastus had made observations of precious stones, categorising minerals by weight, heated behavior, and other notable properties such as magnetism (Popa, 2005). It should be noted, however, that the Aristotalean belief was that minerals were composed of the elements water, air, earth, and fire, which was reflected in these early studies. Pliny the Elder, a Roman philosopher (Figure 4.1.1), built on these studies in his *Naturalis Historia* in 77 C.E. , of which two books examined the physical properties of precious stones (Healy, 1981). The *Naturalis* even details an early measure of mineral hardness, proposing the scratching of one mineral against another to identify a fraudulent precious stone (Healy, 1981).

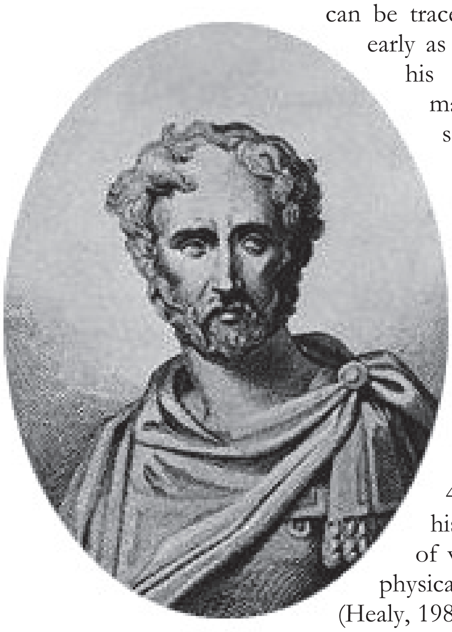


Figure 4.1.1: Plinius Maior (Pliny the Elder), the last Roman intellectual to document the study of minerals.

In western culture, the study of mineralogy was not resumed until 1546, when George Bauer published *De Natura Fossilium*, which represents the first modern scientific approach to the study of both mineralogy and geology. This, the first book on the subject of minerals in over a thousand years, opened the door for subsequent scientists to study these fields once again (Bauer, 1546). Although the oriental study of minerals had developed in the intervening time, including the discovery of deposition by evaporation, it is from an occidental background that the present study of mineralogy truly sprang. The principal characters that would shape our present understanding of minerals all came from western backgrounds, and no oriental research swayed their education.

In this chapter we will examine those pioneering men of science whose work is used today in the classification of minerals. The first portion is dedicated to the scientists most active at the beginning of the 19th century, when the techniques of chemistry had developed to the point that they could accurately examine minerals. Friedrich Mohs, Jöns Berzelius, and William Phillips are the major figures examined here. The second portion examines James D. Dana, whose mineralogical system is still used today. The conclusion of the chapter will briefly detail the modern instrumentation used to perform mineral analysis.

Pioneering Mineralogists

As was the way of science in the 19th century, the study of minerals was not isolated to one field. Rather, it was a study taken on by those naturalists who possessed an aptitude for crystallography and a mind for seeing patterns and forging new fields.

Friedrich Mohs (1773-1839) was a German geologist and mineralogist who tackled the classification of minerals by their physical properties, which continues the works of the old Greek and Roman scholars in a scientific manner. His was the first text to propose a nomenclature based on the biological and zoological developments of the time. Indeed, he discusses the orders, genera, and species of minerals much as one would discuss such aspects in any organism (Mohs, 1820). His dual texts the *Elements of Crystallography* and the *Treatise on Mineralogy* proved the foundation for much subsequent work done in the field (Phillips and Allan, 1842).

Mohs is today remembered for the Mohs hardness scale, which attributes a numerical value to different minerals' hardness based on their ability to scratch one another. In fact, his method of identifying minerals was quite comprehensive and, with expansion and minor alterations, remains generally used today for the purpose of mineral identification in the field. His criteria included the system of crystallization, cleavage, hardness (his own innovation), specific gravity, streak, colour, and lustre – though he notes that colour and lustre are minimally useful (Mohs, 1820).

The other mineralogist who held the greatest influence in shaping the mineralogy practised today was Jöns Berzelius (1779-1848). Berzelius was a highly influential Swedish chemist and mineralogist. He is notable for discovering four elements: silicon, selenium, cerium, and thorium. His analysis of minerals is noteworthy in its uniquely chemical approach to the classification of minerals. Traditional analysis of minerals, such as that which Mohs conducted, relied heavily on crystallographic analysis, which involved examining the shape that the composing elements form when bound into a lattice. Berzelius took rather the opposite approach, separating and quantifying the substituent elements (Berzelius, 1814).

Much like Mohs, Berzelius discussed the order and species of different minerals, reflecting the influence of a burgeoning system of taxonomy in biology and zoology. As might be expected given his background, Berzelius divides much of his mineral taxonomy by chemical composition. This was founded in electrochemistry (Berzelius, 1814). Berzelius understood that a positively charged atom would electrostatically draw in electronegative particles to form a mineral. He separated different species by the proportion of their chemical content, and classified the different minerals by their electro-positive base element. Though not widely adopted at the time, this represented a novel approach to the identification and classification of minerals, and would have lasting impacts on the field of mineralogy (Dana and Brush, 1885).

Foremost amongst those who united the ideas and works of other mineralogists in his time was William Phillips (1775-1878). Phillips was a geologist and mineralogist who was one of the founders of the Geological society of London. His *Mineralogy* was a text that brought together much of the work done by other mineralogists, including Mohs and Berzelius, to create a comprehensive guide for mineral identification. He gave more expansive criteria for the physical identification of minerals than did Mohs, adding such features as fracture, double refraction, flexibility, and taste (Phillips and Allan, 1842). He further elucidated methods of chemical analysis less intensive than those Berzelius used. These included methods of flame analysis, including observing flame fused minerals and the color of the flame given off by heated minerals. He also made note of chemical tests for identifying specific mineral components – for instance, using a thin wire of copper to identify the presence of phosphorous (Phillips and Allan 1842).

In application, Phillips was making strides towards uniting the numerous studies of minerals that had been done by other scientists like Mohs and Berzelius. The man to complete this work, building on the works of Mohs, Berzelius, and Phillips to construct the system of mineral identification used today, would be James D. Dana.

James D. Dana

Perhaps the most extraordinary aspect of the life of James D. Dana (1813-1895) (Figure 4.1.2) is the prolific nature of his legacy. His first and most enduring work, the *Mineralogy*, was written when he was but 24 years of age. His outpouring of literature continued nearly unto his death at the age of 82, representing almost 60 years of experimentation and ideation. He studied volcanoes and corals, proposed continental ice sheets and cephalization. In short, his contributions to the natural sciences cannot be overstated, and his impact extends far beyond the study of minerals (Gilman, 1899).


Figure 4.1.2: James D. Dana, his portrait as it first appeared in Popular Science Monthly, Volume 1, 1872.

Dana's study of the natural sciences began in the Utica high school, in the state of New York where he was born. After graduation, he attended Yale University to receive a bachelors of arts in 1833. Throughout this time it is noted that he collected those rocks and minerals that he could find in his local area. At this point in his life none of his professors saw his aptitude for observation. This was likely due to the emphasis on the study of Classics that then formed the basis for higher education. Nonetheless, Dana received good if not exemplary academic results, but with a demonstrated aptitude for mathematics and both the physical and natural sciences (Gilman, 1899).

Following his undergraduate studies, Dana became a schoolmaster for the U.S. Navy. It was customary at the time for the Navy to educate commissioned officers while on voyage, and this position afforded Dana an abundance of opportunities for academic exploration. Indeed, his new post involved travelling to the Mediterranean, and though fresh from the study of Latin and Greek classics, it was not the culture or history of these shores that excited him. No, for Dana, it was the natural world that stirred the heart, and on his Mediterranean voyage it was the phenomena of nature that he would study (Gilman, 1899).

On his voyage, when not otherwise occupied, Dana studied crystals and flies, visited Vesuvius, and otherwise found for himself the inspiration that would drive him to his future career. His mineral investigations were based in large part on Phillips work, and his results provided the outline for what would become his *Mineralogy*. It is worth noting that Dana discovered two hitherto unknown species of water mite and one new species of crustacean on his trip. Furthermore, an account of his trip to Vesuvius was published in the *American Journal of Science* after he sent these accounts to the Journal's founder, Benjamin Silliman, who had been a professor of his at Yale (Gilman, 1899).

Figure 4.1.3: A sample of sphalerite and galena from the F. John Barlow collection. sphalerite, the dark black mineral with a non-metallic or submetallic lustre, is often associated with galena, the mineral with a metallic lustre.

It is worthwhile at this point to digress into a brief mention of Benjamin Silliman, whose influence on Dana's life was monumental. Silliman taught chemistry at Yale, and after Dana's trip to the Mediterranean, accepted Dana as his laboratory assistant (Fisher, 1866). Theirs was a relationship of iron sharpening iron, and it came to pass that Dana inherited much of Silliman's life's work. Silliman gave to Dana the post of joint editor and, shortly thereafter, chief editor of the *Journal of Science*. Dana further succeeded Silliman in his professorship at Yale in 1850, with his official title being "Silliman Professor of Natural History". Moreover, Dana wed Silliman's daughter, Henrietta Silliman, forging fast the relationship between student and mentor (Gilman, 1899).

The taxonomic works of Linnaeus held sway over Dana, as they had for Mohs and Berzelius, and influenced the *Mineralogy* that he worked on while assistant to Silliman. No small part of this involved a complete overhaul of the existing mineral nomenclature. Indeed, in the first edition of the *Mineralogy*, Dana writes, "the present names, excluding those proposed by Mohs, are utterly devoid of system, unless we consider the addition of *ite* to words of various languages." It naturally followed that Dana's first proposed nomenclature for minerals followed the dual-latin plan pursued in biology and zoology. Dana's system of nomenclature was first published in a *Mineralogy,* with credit given, in 1835 by Alex Shepard, a professor at Yale. Following further refinement, the first edition of the *System of Mineralogy and Crystalography* was published in 1837 (Gilman, 1899).

Subsequent alterations to the *Mineralogy* progressed at the rate of mineralogical study. Dana corresponded with all those academics most knowledgeable about mineralogy and crystallography, including Berzelius and Silliman, and kept pace with all developments in the field. The Second Edition, released in 1844, proposed an alternate means of nomenclature, based on chemical composition, most of which was fully adopted by the third edition, released in 1850. This was expanded on and refined in later editions, with the chemistry of the minerals taking the fore (Gilman, 1899; Dana and Brush, 1885). Indeed, Dana noted in the fourth edition that one issue with classifications based on traits like lustre, hardness, or colour is that it results in unrelated minerals like diamonds and sapphires being put one alongside the other (Dana and Brush, 1885). Dana's system specifically grouped minerals by their chemical composition regardless of physical traits. For instance, Galena – a lead sulphite – and sphalerite – a zinc sulphite – are chemically similar and are often associated (Figure 4.1.3). However, sphalerite lacks the lustre of galena and the two would, under other classification systems, be separated. Not so under Dana's system, which grouped by chemical character much as Berzelius had, though with greater depth and a wider array of presented information. Dana's Mineralogy was not so much a unique undertaking as it was the aggregation and refinement of all other scientific information, from Aristotle to Bauer, Mohs to Berzeleus that had come before; the next step in the scientific process.

Analytical Mineralogy

Modern methods of analysing minerals have advanced greatly since the days when Dana and Mohs laboriously examined the crystalline character of numerous minerals. Indeed, the advantages of modern chemical analysis are perhaps best summarized by Henrich Wieland who received a Nobel prize in Chemistry, 1928, when he said of chromatography: "Up to now we have learned with much effort to distil, crystalize, and recrystallize. Now they come along and just pour the stuff through a little tube" (Gehrke *et al.*, 2001). Truly, modern methods of chemical analysis far surpass those used historically in both efficacy and expediency. Therefore, to abet the understanding of modern mineral analysis, occurring not in the field but in the lab, this section will detail but a few of the most common analytical techniques used in mineralogy.

Mass Spectroscopy

The method of perhaps greatest versatility in mineral analysis is mass spectrometry (MS). This destructive method involves the ionization of a mineral sample into gaseous ions, followed by differential diffraction of the ions by their mass: charge (m/z) ratio. Magnets diffracting the gaseous ions to a detector achieve this. Only ions with a certain m/z ratio are diffracted by the magnetic field to reach the detector. Varying the magnetic field strength alters the m/z ratio that can reach the detector. Different elements are known to have certain m/z ratios (Mukherjee, 2012).

Solid mineral samples can be converted into gaseous ions through a process called desorption – neutrons or electrons bombard the mineral surface, generating gaseous ions, which can then be diffracted for detection. Comparison of the resulting spectra to literature spectra can identify the mineral as a known compound. Alternatively, the individual fragments that appear in the mass spectra can be used for independent analysis. Evidently, this method allows for a robust analysis of mineral composition (Mukherjee, 2012).

Electron Microscopy

Microscopic methods of mineral analysis are both numerous and highly useful for qualitatively observing mineral structure. Certain techniques can even determine a crystal's elemental composition.

Electron microscopy uses an electron gun to irradiate a sample with electrons (Figure 4.1.4). The interactions can be used to form a topographic picture. Notably, the technique of scanning electron microscopy (SEM) is a non-destructive variation of the technique. This method can use the scatter of electrons as low-frequency X-rays after collision with the crystal to deduce its elemental properties from the energy dispersive spectra (EDS) given off – though elements of atomic number below 11 cannot be identified (Spence, 2013; Mukherjee, 2012). This is in addition to a high-resolution image generated by the technique (a feature as small as 50nm can be scanned).

Figure 4.1.4: A replica of the Ernst Ruska electron microscope – the first microscope to have resolution greater than a compound light microscope. The original was built in 1933.

Thermal Analysis

Thermal analysis measures either the change in a certain mineral property, such as weight, as a result of temperature changes or the change in temperature of a mineral as a result of a specific process. One example, thermogravimetric analysis, measures the change in a mineral sample's weight as a result of heating and cooling. This can be used to generate a profile specific to the mineral (Mukherjee, 2012).

Another informative thermal measurement can be gleaned from differential thermal analysis (DTA). This adjoins heating to a pan containing a mineral sample and to a reference pan. As heat is evenly applied to both pans, the heating of the mineral causes changes in the heat it evolves or absorbs. For instance, an impurity might emit extra heat at a known temperature, while crystallization might show a relative decrease in heat as chemical bonds form (Mukherjee, 2012). Spectral comparisons then elucidate the mineral composition.

Alchemy: the Origin of Chemistry

The history of human thought is one of experiencing and observing the natural world, and forging new ideas from that information. This insight developed a complex mixture of religious and scientific beliefs for the human species. Many believed that man could create mystical and divine objects such as the Philosopher's stone or the Elixir of Life, and that pure metals such gold could be artificially created. Such beliefs have been generally categorized as alchemical practices, which have been independently dabbled in by many scientists in separate civilizations. These have not been without result; the modern chemical practices that are performed today are the direct result of the evolution of alchemical experiments.

The Alchemical Background

Alchemy has played a key role in the relationship between religion and science throughout human history. It has been directly attributed to the development of modern chemistry and has led to key discoveries from some of the most well known scientists to date. One of the major issues regarding alchemy is the true definition of alchemy. Alchemy, in short, is the speculative thoughts and experiments focusing on transmuting base metals into silver or gold, determining cures for diseases, and finding a way of extending life (Zimmerman, 1984). This scientific field has been a vital force for further pursuit in scientific and medicinal practices.

Historically, alchemical practices were displayed throughout many cultures and civilizations. Although developed independently of each other, all of these cultures showed similar processes, primarily through the association of metallurgy. Metallurgy is the process of transforming minerals and metals into products that will increase one's quality of life (University of Utah, 2013). One of the most prominent historical examples involving alchemists successfully transmutating metals is the production of cinnabar. This product was achieved throughout numerous alchemical civilizations from the Greco-Romans to the Medieval Europeans. Cinnabar formed through the heating of mercury with sulphur – the final product being the red material shown in Figure 4.2.1 (Zimmerman, 1984). Although this was achieved, the major goal of alchemical metallurgy is the transformation of base metals into gold – which has historically been perceived as the pure metal. Ultimately, alchemists were individuals who manipulated natural products through imitation, replication and degradation. They had the goal of perfecting nature and employed sophisticated analytical techniques to determine the nature of matter (Newman, 2011).

Figure 4.2.1: An example of Cinnabar – the product of heating mercury with sulphur. This compound was one of the most prominent examples of a successful transmutation that was found throughout several independent alchemical civilizations.

Alchemy Throughout the Ages

Greco-Roman Egypt (332BCE-395CE)

Alchemical processes date back to the time when Egypt was under Greco-Roman rule. Laboratory-like workshops have been discovered, throughout Greece, which were used in conjunction with experimental practices. Basic alchemical practices of this era included dyeing techniques (ie. dyeing wool a purple colour), manipulating metals, and counterfeiting precious stones. Early alchemists were often very wealthy, being able to sell the manipulated stones and metals for a considerable profit. This caused the popular image of many early alchemists to be that of a greedy charlatan (Martelli, 2011), which contributed to the negative perspective commonly associated with alchemists. Although the perception of alchemy is often negative, the intrigue inherent to the field of alchemy, coupled with the financial incentive for successful work, yielded much alchemical progress.

Medieval Islamic World (700CE-1500CE)

The Islamic World from the 8th to the 10th century consisted of many scientific minds dedicated to abstract, and even apocryphal thinking. In the alchemy community, they tended to look outward at the natural world and inward at the world of psyche. Within this time frame, alchemy was looked at as a highly intellectual field. The value placed on alchemical studies at this time further transitioned alchemical studies to a more secretive field. This involved concealment of writings in the form of symbolism, allegory and allusion. This was achieved with paradoxes and puzzles that readers would have to decipher to understand the text, proving their mental capability, examples of some of the symbols are shown in Figure 4.2.2. There were key alchemy and chemistry discoveries in Medieval Islam, including the classification of bodies – substances that remain stable when exposed to fire (gold, silver, iron, copper, tin, quicksilver) – and spirits – substances that evaporate when touched by fire (sulphur, arsenic, mercury, ammonia). Furthermore, the formations of artificial substances from copper, or mercury/sulphur compounds were discovered through alchemical techniques (Ryding, 1994).

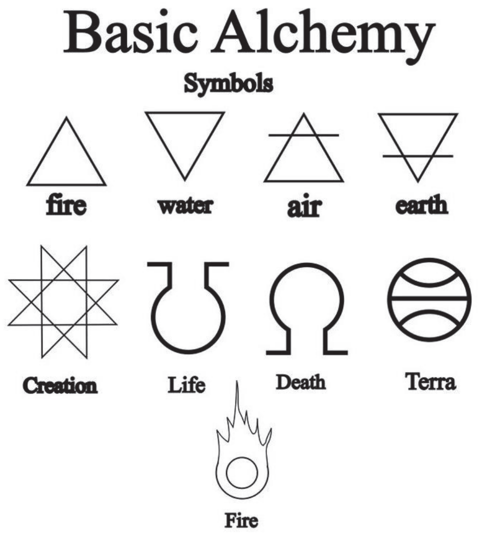


Figure 4.2.2: Visual representation of several commonly used symbols in which the medieval Islamic alchemists would use to conceal their writings away from the lesser intellectual minds of their time.

Medieval Europe (800CE-1660CE)

Alchemy in medieval Europe was driven by the goal of transmuting base metals into gold or silver, discovering of the Elixir of Life, and the creating the Philosopher's stone. However, alchemy throughout medieval Europe started to develop understanding towards the nature of matter (Newman, 2011). During the latter 16th century and early 17th century, there were key advancements in the alchemical practice. Alchemists began to record observations and write out procedures to try and understand the physical explanations to the experiments at hand. In 1619, an alchemist by the name of Daniel Sennert determined, through dissolution of a metal with an acid, that the metals were composed of smaller, minute particles. These particles helped to define the atomic theory of matter (Newman, 2011; Morris, 2011).

Alchemy and Religion

Throughout these distinct civilizations, cultures had the popular belief that there exists a relationship between the spiritual world, physical world, and the human body (Moran, 2000). Alchemy in these times was thought of as a spiritual experience. Individuals would not use scientific background to develop their experiments; rather, it would be one's knowledge of nature together with intuitions of the psyche that would dictate the experiment. Alchemists would have spiritual dreams that would inspire and direct their alchemic experimentation.

Alchemy differs from the common perception of scientific practices. This can be attributed to the lack of recording and replication of experimental procedures, but also, the strong ties that it held with religion. Christianity, in Medieval and Renaissance eras, held that God's love and divine soul could purify the soul 'of every imperfection.' This belief prompted many into believing that the same has to be done with metals. For a substance to be pure, it must be passed through fire. This can be attributed to gems, which when put through fire were cleansed, resulting in a glow of purified stone. Silver and gold were metals that remained pure after passage through fire, signifying a pure and sought after metal. This prompted the motivation to purify metals into gold or silver for they were the equivalent of the transformation into a divine soul. The lack of a concrete experimental record amongst alchemists prompted change in several scientists in the 17th century (Brann, 1985).

Figure 4.2.3: An artist's rendition of Robert Boyle: the Father of Modern Chemistry. This alchemist developed the alchemical and modern chemical procedure through his well-recorded studies.

Robert Boyle (1627-1691)

Robert Boyle (illustrated in Figure 4.2.3) was one of these key alchemists. In fact, Boyle is perceived as the Father of Modern Chemistry. Born in Lismore Castle, Ireland in 1627, he revolutionized key aspects of the chemical world; including the well-known discoveries of Boyle's gas Law (Parton, 1939). Boyle was educated at Elton College, and moved to Oxford where he would run his experiments. He kept his laboratory secluded, running studies involving metallurgy, medicine, and the manufacture of chemicals, dyes, and gases. Alchemical techniques drove Boyle to further dabble into these scientific studies. He showed a strong desire to determine the connections between alchemy and the supernatural. It was quoted that Boyle's alchemical practices were, "serious and persistent, constituting a significant and influential dimension of his life, thought, and works." (Linden, 2003) Further pursuit in alchemical studies can be attributed to the poor health of Boyle. He was shown to dose himself and his friends with recipes of miscellaneous sources (Linden, 2003).

Although Boyle had several studies and experiments with regards to the alchemical practice, he is often recognized as the father of chemistry (Chalmers, 2010). This is attributed to the high amounts of description and detail in the experiments he performed. This descriptiveness contributed to the numerous publications, distinguishing him from typical alchemists (Hunter & Principe, 2003). His descriptions involving extensive scientific methods to depict his chemical and alchemical techniques are a major contribution to the development of modern experimental chemistry (Parton, 1939).

Transition to Modern Chemistry

Although alchemy was promoted though religious and mystical beliefs, it is clear that there were key scientific processes that were developed through its application (Zimmerman, 1984). This is evident through the use of experiments and procedures, along with the reactions discovered with Earth metals. Throughout the middle ages, leading into the late 17th century, the progression of chemical knowledge was further developed through alchemical practices (Morris, 2011; Torres, 2011; Brock, 2011; Zimmerman, 1984; Linden, 2003). Alchemists were driven by the discovery of the Philosopher's stone, the Elixir of life, and the formation of artificial gold. This prompted further pursuit into the development of the equipment used and the understanding of the elements associated with that of alchemy. Furthermore, the alchemical practices performed by Boyle helped set up modern chemical practices. His extensive detail in describing his practice, discoveries and his overall focus in attempting to record information is what helped evolve the modern chemical practice (Linden, 2003). This is evident in the present chemical field, having significant emphasis on proper recording of all experimental procedures, results and analyses.

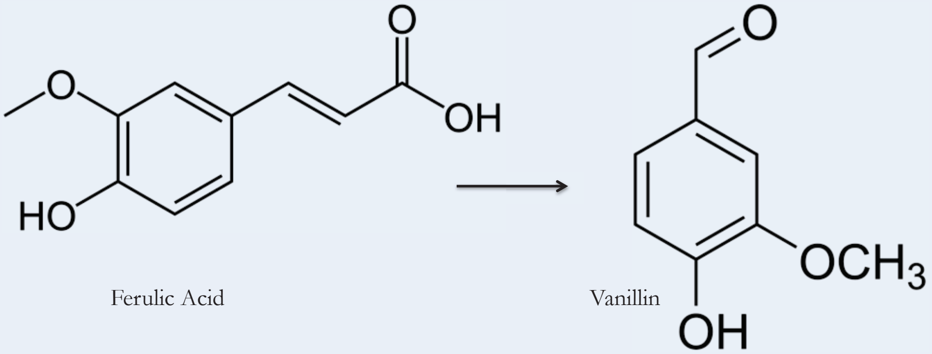
Alchemy has a significant relationship to chemistry in that it tries to gain knowledge through understanding and manipulating elements and metals through the use of experimental equipment and procedures. The inspiration in finding divine metals and potions allowed for advancement and continuation of chemical studies, and helped transition to the chemical practices of the modern world.

Biotechnology: the Modern Alchemy Perspective

Modern portrayals of alchemy depict the concept as a magical idea that is heavily reliant on the associated mythical and religious aspects. Through common understanding, one cannot fathom having eternal life or being able to create a Philosopher's stone, through discoveries made in present science. Although the formation of supernatural items is not possible, the work of the many alchemists trying to develop said items have made significant breakthroughs in experimental practices leading to further motivation in modern science.

The findings of historic alchemists have been passed on to the scientific community today. For instance, biotechnological practices closely resemble those of alchemy, in that they share similar traits. The transmutation of base metals into gold can be seen mirrored in biotechnology, which aims to create biological products from cheap, raw materials (Kirkham, 2009).

Biotechnology is defined as the processes that seek to preserve or transform biological materials of animal, vegetable, microbial or viral origin into products of commercial, economic, social and/or hygienic utility and value (Hulse, 2004). Biotechnology works through gene modifications and transgenesis of living organisms, for the eventual production of alternate biologicals. One example of this is the production of natural vanillin. Through the manipulation of ferulic acid, biotechnologists allow the acid to undergo classical fermentation, which is catalyzed by a strain of Amycolatopsis bacteria, producing vanillin (Nicholls, 2004). This technique can minimize the amount of synthetic compounds being added to our foods, while creating an economically efficient natural product. However, many European countries are against this process due to the genetically modified properties associated with the materials. There is outlook on biotechnology that is filled with heavy scepticism, having strong, negative responses (Kirkham, 2009). Having the belief that humans are performing acts of god, or having possible negative side effects that can cause harm. This is analogous to the negative perception that was associated with alchemy. But, just as alchemy showed promise in the development of our species in terms of determining pure metals, or elongated life, biotechnology shows potential in developing biological products to better the lives of the human species, although it is not a globally accepted practice. Further continuation of biotechnological research could pave the way in developing further scientific breakthroughs (Nicholls, 2004).



Ferulic Acid

Vanillin

Figure 4.2.4: The chemical reaction showing the synthesis of vanillin from ferulic acid. This is an example of Biotechnological product through chemical techniques.

The Use of Mineral Resources in Ancient Egypt

The exploitation of mineral resources is well-established throughout the history of human civilization. During a time without chemists, geologists, or mining engineers, ancient Egyptians were greatly dependent on the use of minerals to build and support their society. Much of Egypt's resources and riches came from the Nile River, an important geographical feature responsible for the development of Egyptian civilization (Christensen, 2009). The Nile River flows northward through the dry and rugged Egyptian desert and fans out into a large delta that connects with the Mediterranean Sea (Figure 4.3.1) (David, 2003).

Figure 4.3.1: Map of Ancient Egypt showing the Nile Delta connected to the Mediterranean Sea (located to the North) and the major regions of natural resources surrounding it.

Each year, the Egyptians anticipated the flooding of the Nile River, the miracle that brought life to the barren land (David, 2003). The spring rain and annual melting of snow in the Ethiopian highlands caused the Nile River to overflow its banks (Christensen, 2009). As the water flowed downstream, it transported vast amounts of volcanic silt and decayed vegetation that inundated the floodplain (Christensen, 2009). When the water level receded during the spring, black silt and organic materials were deposited on the land (Christensen, 2009). These deposits were rich in several types of minerals, such as ilmenite, hematite and magnetite (Abouzeid, 2011).

Egyptians also set out on various expeditions to exploit minerals from quarries located in remote parts of the desert (David, 2003). The vast supply of natural resources that was available to the ancient Egyptians greatly influenced the discoveries they made, such as the use of minerals in medicine, colored pigments, and cosmetics.

Medicine

The use of geological materials as therapeutic agents is as old as mankind and has been recorded in diverse forms of writing, by various cultures, for over 3,000 years (Reinbacher, 2002; Duffin, Moody, & Gardner-Thorpe, 2013). Some of the earliest accounts of the use of medicinal minerals derive from the ancient Egyptians (Duffin et al., 2013). Evidence of their medical writings is presented on clay tablets, papyri, wood, and stone blocks. One of the most significant Egyptian medical texts is the Ebers Papyrus (Figure 4.3.2). It is dated to around 1534-1536 BCE, but is believed to have been a record of treatments used much earlier (Duffin et al., 2013). This scroll is 20 meters long and contains 110 pages of both rational and magical treatments (Duffin et al., 2013). It was translated by Georg Moritz Ebers in 1872, and was found to contain 877 medical paragraphs about case studies, observed symptoms, recommended treatments, and magical formulas (Sapsford, 2009; David, 2003). A list of 98 minerals has been deciphered from the ancient medical text, which includes a variety of salts, clays, metals and stones (Sapsford, 2009). These pharmaceutical materials were administered orally, through fumigation, or applied externally as ointments by specialized doctors or priests (David, 2003). Two of the major locations from which the ancient Egyptians exploited salt were the Wadi Natrun and Oasis of Siwa (Sapsford, 2009). However, these two sites were not part of the Egyptian empire; they were both Libyan territory. As a result, much of the salt that the Egyptians used was imported from outside the country's borders and required travelling long distances through the vast and dry desert (Sapsford, 2009). According to the medical papyri, salts were used externally as an astringent to treat skin conditions such as animal bites and stings (Sapsford, 2009). However, the Egyptians often associated medicine with religion, and used salt in many of their rituals. They believed that salt had purifying properties that allowed the deceased to enter the afterlife pure and free to eat and breathe (Sapsford, 2009). With the gift of the Nile River, the ancient Egyptians also used mud and clay minerals deposited by the river banks (Reinbacher, 2002). Although these materials were mostly used for artistic purposes, they had some medicinal uses as well. Evidence from medical texts suggest that Egyptians applied clay topically onto the skin to reduce inflammation, treat rashes, and heal wounds and burns (Gomes and Silva, 2007; Sapsford, 2009). Egypt was also famous for the extensive alabaster quarries spread throughout its land. One of the primary alabaster sources was at Hat-nub. Certain details of exploratory expeditions have survived in the graffiti left by travellers in these quarries; the evidence suggests that the area had been sporadically exploited for alabaster for 3,000 years (Sapsford, 2009). The Egyptians used alabaster for the treatment of old-age problems such as wrinkles. Alabaster was often mixed with several other minerals in order to recapture youth and beauty (Sapsford, 2009). For example, one of the Ebers Papyrus prescriptions was titled "A remedy to beautify the body." In this prescription, alabaster powder was mixed with natron powder, sea salt, and honey and used as an anti-aging cream (Ebbell, 1937).

Figure 4.3.2: A Medical paragraph from the Ebers Papyrus written in black and red hieroglyphics. This prescription describes the use of herbal fumigation for the treatment of asthma.

Pigments

Colour was integral to various aspects of ancient Egyptian culture. It was used to decorate the walls of temples and tombs, to paint statues and sculptures, and express ideas through writing and illustrations.

The Egyptians began to manufacture colored pigments around 4000 BCE (Barnett, Miller and Pearce, 2006). The majority of pigments were either finely ground minerals or derived from minerals substances (David, 2003). The ones that were readily available to the Egyptians were the so-called "earth pigments." Black was one of such pigments; it was made of either soot from burning animal fat or charcoal from fire (Barnett, Miller and Pearce, 2006). Black was one of the most commonly used pigments on papyri in addition to red (David, 2003). Red and yellow pigments were made from iron oxides and ochres, which were commonly found near Aswan and in the Western Desert (Sapsford, 2009). Ochres were derived from clays containing metal oxides, hematite, and limonite, and are one of the oldest pigments used by the ancient Egyptians (Sapsford, 2009).

In addition to the naturally formed pigments, some were produced synthetically, the most famous of which is the Egyptian blue (Barnett, Miller and Pearce, 2006). It was made in around 3000 BCE by mixing calcium salt, copper compounds, and sand (Barnett, Miller and Pearce, 2006). This mixture was then heated to form colored glass or frit and crushed into a fine powder (Barnett, Miller and Pearce, 2006). Similar to all other pigments, the powder was combined with a plant or animal based glue to hold the fine grains together and adhere to surfaces more readily (Barnett, Miller and Pearce, 2006). Egyptians used this technique to create paint. Green pigment was another commonly used color that appeared in many tomb paintings. It was derived in one of two ways: as powdered malachite, which is a natural copper ore found in Sinai and the

Eastern Desert, or as an artificial frit (David, 2003). White pigment was derived from calcium carbonate, found in chalk, and calcium sulphate, found in gypsum. The Egyptians combined these pigments to form a range of colors that they used in their art. These colors were often associated with symbolic meanings, and the choice of color would usually depend on what the painter was trying to depict. In addition, some colors were used only on certain surfaces, which may have been due to practical or symbolic reasons. However, much of the color in paintings and writings have degraded over the past thousands of years, making it difficult to understand the real meaning behind certain color choices. For example, it was suggested that the green pigments in wall paintings were the result of the degradation of Egyptian blue from blue to green (Figure 4.3.3) (Pages-Camagna and Colinart, 2003). In addition, the yellow pigments may have also degraded to leave behind only the ochre (Pages-Camagna and Colinart, 2003). Many physical conditions may be responsible for the changes in the color palettes of Egyptian art, and research behind their "true" colors is still on-going (Pages-Camagna and Colinart, 2003).

Figure 4.3.3: A relief painting found in the mortuary temple of the pharaoh, Hatshepsut. Color degradation has caused physical changes to the pigments which may not be a true representation of the ancient palette.

Cosmetics

In addition to medicine and pigments, minerals were also used for adornment by the ancient Egyptians since 2000 BCE (Walter et al., 1999). One of the most common remnants of ancient Egyptian civilization is kohl tubes that contained ground minerals (Allen, 2005). Kohl is a cosmetic that both men and women applied around the eye for both adornment and health (Allen, 2005). It was primarily made from either malachite or galena (Allen, 2005). These two minerals were ground and mixed with animal fat before being applied to the eyes (Allen, 2005). Green kohl, made from malachite, appeared in 18 medical paragraphs and was used to treat eye diseases; however, it was also used because the color green held religious significance (Sapsford, 2009). It symbolized life, good health, and resurrection, and for this reason, it was placed in graves and tombs (Sapsford, 2009). Black kohl, made from galena, appeared in 48 medical paragraphs and was used to reflect the Sun's glare and repel flies (Allen, 2005). In addition, due to the lead content in galena, black kohl was used as a toxin against organisms that caused eye diseases or blindness (Allen, 2005).

The ancient Egyptian civilization lasted for more than 5,000 years, and its history is one of great interest to historians, archeologists and scholars alike. It is evident that the nature of Egypt's land and climate had profoundly influenced some of the earliest advances in art and medicine (David, 2003). The discoveries made by the ancient Egyptians certainly paved the path for later developments and still influence modern-day fashion, science, and religion (David, 2003).

Medical Geology

Medical geology is a rapidly growing scientific discipline which examines the relationship between the geological environment and public health (Gomes and Silva, 2007). The impact of natural materials on human health has been known since antiquity; our ancestors utilised rocks, minerals, soil, and water to produce therapeutic agents for thousands of years (Finkelman, Centeno and Selinus, 2005). However, during the 20th century, epidemiologists and geoscientists began to understand the many ways in which the Earth's environment can negatively affect the health of its inhabitants (Finkelman, Centeno and Selinus, 2005). Among the various health problems that have been linked to geological factors are exposure to natural dust, water contamination, and toxic levels of trace elements and minerals (Bunnell, Finkelman, Centeno and Selinus, 2007).

Within the last few decades, several health issues have arisen due to certain geological factors. For example, various types of respiratory problems can be caused by excess exposure to mineral dust (Bunnell, Finkelman, Centeno and Selinus, 2007). Dust can be generated locally by earthquakes, smoke plumes, sand blasting, and mining (Bunnell, Finkelman, Centeno and Selinus, 2007). Asbestos mining was of particular concern in the United States during the 1980s. Asbestos refers to a group of fibrous silicate minerals that was mined in commercial amounts for centuries (Komatina, 2010). Occupational exposure to large amounts of asbestos dust was discovered to be responsible for certain diseases such as lung cancer (Komatina, 2010). In 2002, asbestos mining was stopped; however, the environmental and occupational exposure to dust from mining is still a major concern today (Komatina, 2010). Earthquakes are another common source of dust. Dust particles caused by earthquakes were found to carry spores of a particular fungus called *Coccidioides immitis*. Exposure to this fungus can cause Valley Fever, a respiratory problem associated with fatigue, fever, and damage to internal organs (Bunnell, Finkelman, Centeno and Selinus, 2007). Harmful dust can also be released by volcanic eruptions. When ash is ejected from a volcanic eruption, it can be blown halfway across the world and cause a negative global impact (Figure 4.3.4) (Finkelman, Centeno and Selinus, 2005).

Health is also significantly dependent on the quality of drinking water (Selinus, 2013). Dental epidemiology has provided significant evidence of the health effects of trace elements in water (Selinus, 2013). One of the most well-known examples is the "Colorado Brown Stain" that occurred in Colorado Springs. In 1901, Frederick McKay noticed unusual discoloration in many of his patients' teeth (Komatina, 2010). With further investigation, it was found that 87.5% of school children living in the Colorado Springs region had some degree of dental fluorosis (Komatina, 2010). In 1931, US Public Health researcher Henry Dean discovered that the reason behind the "Colorado Brown Stain" was the elevated levels of fluoride in the water supply (Komatina, 2010). The Colorado Springs area had three significant natural sources of fluoride in the environment that contributed to the high fluoride levels in drinking water (Komatina, 2010). Today, the optimal fluoride concentration in drinking water is between 0.8 and 1.0 mg/L (Government of Canada, 2004). This is one of the many examples in which medical geology has influenced public health policies.

Figure 4.3.4: Volcanic ash plume after the eruption of the Cleveland Volcano, Alaska as seen from space. The eruption was photographed by an Expedition 13 crewmember on the International Space Station.

The field of medical geology has developed in many countries around the world and emphasizes the multi-disciplinary work of scientists to mitigate health problems associated with geological materials, such as chemical elements, water, and natural dust as well as geological processes such as earthquakes and volcanic eruptions (Bunnell, Finkelman, Centeno and Selinus, 2007).

Empires Built on Soil

Ever since humans learned to work the soil approximately 10 000 years ago, soil has been shaping human society (McNeill and Winiwarter, 2006). Soil science and its most important application, agricultural science, go hand in hand. The rise and fall of the greatest ancient civilizations has been shown to be in parallel to the level of soil quality and their knowledge of stewardship of the land.

The Collapse of a Civilization

Considered the cradle of civilization, (Maisels, 1998), Mesopotamia is not a culture itself, but a region which fostered a collection of the first civilizations from 7000 to 1000 BCE (Morozova, 2005). Eleven empires rose and fell on this alluvial plain, located between the Tigris and Euphrates rivers, within what is now considered Iraq (Gelburd, 1985). The name literally translates to 'between two rivers', and its location was important to the development of agricultural practices. The Sumerian civilization which began around 3500 BCE developed one of the first irrigation systems. The water used for irrigation contained salts, which were left in the soil when crops up took moisture. The arid Mesopotamian climate did not allow a sufficient amount of rainfall for soil leaching to occur causing the soils to become salinated over time(Artzy and Hillel, 1988).As a result, average barley yields fell from 29 bushels per acre in 2400 BCE to 4 bushels per acre in 1700 BCE (Gelburd, 1985). The low crop production of the Sumerians allowed the Babylonians, who were located slightly north, to gain political power in Mesopotamia (Brevik and Hartemink, 2010). However, the Babylonians cleared the forests from the surrounding hills causing erosion rates to increase upstream. Canals were created to divert water, and the silts cleaned out regularly. Even so, over 4m of sediment was deposited on the fields causing decreased yields once again and eventually the collapse of Babylonian power. War over remaining fertile land and usable water was frequent, leading to the collapse of Mesopotamia as a whole by 1000 BCE (Brevik and Hartemink, 2010). In contrast, the stability of ancient Egyptian agriculture allowed one cohesive culture to exist in the area between 3300 BCE and 332 BCE (Brevik and Hartemink, 2010). The natural periodic flooding of the Nile removed any salt accumulation as well as providingimportant minerals needed for the growth of crops (Brevik and Hartemink, 2010).

Pedology in Ancient China

Although the Mesopotamians and Egyptians knew that different crops grew best in different soils, agricultural practice was mostly a matter of trial and error. Pedology, the study of soils in their natural environment, including their classification and formation, isnow believed to have been developed by ancient China (Gong, Zhang, Chen and Zhang, 2003). By 1100 BCE, there were nine provinces of China recognized and mapped by soil type, in the ancient book of *Yugong*. This book was written about the ancient Chinese ruler Yu the Great, who was legendary for fighting floods. He was said to have left for 13 years to document and map the nine provinces based on soil type (Figure 4.4.1), and also surveyed and mapped the

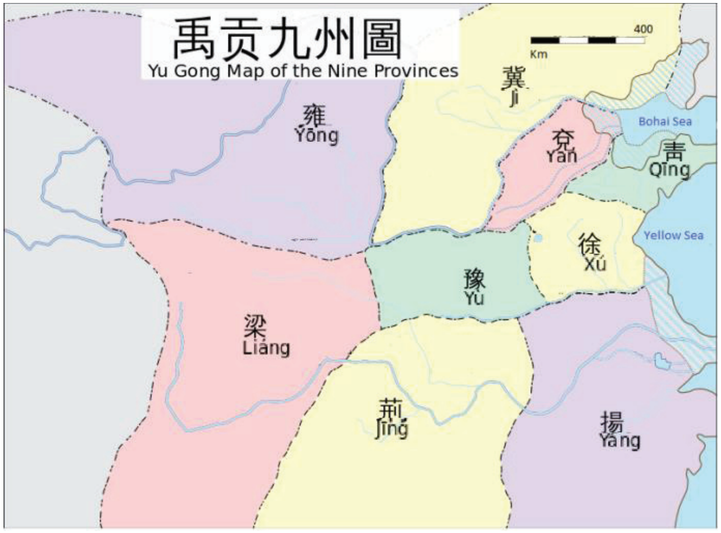


Figure 4.4.1: The 9 ancient Chinese provinces based on soil type, mapped by Yu the Great.

rivers flowing through them, and how water flows through the soils (Schafer, 2011).

Chinese soil classification methods and definitions are well documented, as the taxes a farmer paid depended on the level of soil productivity, deemed by land surveyors (Ahrens, USDA;, NRCS; and Rice, 2002). Another ancient Chinese text, *Guanzi*, meaning 'the writings of Master Guan', is an encyclopaedic collection of papers on philosophy, science, and economy (Cua, 2003).Although named after Guan Zhong, a 7th century BCE philosopher, Guan Zhong was not the author, but rather the father of the school of thought. The Jixia Academy, which was established around 400 and lasted until 206 BCE, and included some of the greatest and most famous ancient Chinese scholars, contributeda large number of papers to the text, although other schools were also involved. The papers were rewritten and more were added until 26 BCE, and the collectioncan be thought of as an economic journal of the time (Cua, 2003). A large portion of these papers are on the topic of pedology. By 206 BCE, ninety different soils were named in China, each classified by their texture, structure, porosity, organic matter, soil reaction, relief, moisture, vegetation, and fertility, and ranked in order of productivity (Gong et al., 2003).

Roman Empire

Roman knowledge of soil developed independently of the ancient Chinese. Most of Roman science, including the study of soils, was greatly influenced by the scientist-philosophers of ancient Greece between 500 and 146 BCE, as they colonized Italy before the rise and expansion of the Roman Empire in 1st century BCE. The Romans worked to systemize and test the theories of the Greeks (Egerton, 2001). The most notable ancient Greek contributors to the study of soils were Xenophon, who wrote about life as a cycle which started and ended in the soil;Plato, who observed that different soils had different tendencies to store water;and Theophrastus, who wrote of the classifications of soil and developed an idea of a soil profile (Brevik and Hartemink, 2010). The ancient Greeks were skilled at creating theories and observing nature. They saw that soils were a dynamic process, noted erosion and decreasing fertility, but did nothing to try to combat these processes, therefore the civilization only lasted 30-40 generations (Katsuyuki, 2009).

The Roman Empire was very successful in developing very systemic and efficient agricultural practices, and therefore there was much interest in soils. As trade developed, family farms grew into large scale businesses, and the occupation gained a high level of social status. Highly ranked soldiers or political figures owned and operated these farms,often given to them by the state as reward for their services, while slaves conducted the physical labour that was required (Olson, 1945). To aid these farmers, textbook-like resources were created which described every subject related to running a farming operation.

Marcus Porcius Cato, most often referred to as Cato the Elder, is famous for writing *De Agri Cultura* (On Farming) in 3rd century BCE (Egerton, 2001). He was born on a small farm in Reate (Lelle and Gold, 1994). At the age of 17, he joined the military in the fight against Hannibal. Accounts which describe him as a soldier, mention that he always picked water over wine, and his character was not particularly entertaining. However, he was respected for his discipline. His further military success in Africa and Greece granted him ownership of large farms, as well as contributed to securing him high positions in Roman government, including the position of censor in 184 BCE (Olson, 1945).

After retiring from his position as censor, Cato wrote *De Agri Cultura* with the thought that it was not the land that was degenerating, but the people who worked it (Olson, 1945). Along with a thorough description of recommended farming practices, he gave important advice on soil fertility and soil erosion (Brevik and Hartemink, 2010). Cato proposed that soil does not get 'exhausted' over time as was previously thought, but its fertility is a balance that has to be kept (Olson, 1945). He realized that adding plant matter back into the soil improves soil quality, and was the first to suggest the idea of compost, as well as advocating the use of manure and green manure on fields (Brevik and Hartemink, 2010). He also observed that certain plants, such as peas and lupines, increase a field's fertility after it has been planted with grain crops. His observations are thought to have been a basis for crop rotation techniques, which were not a known practice during the time of Cato (Olson, 1945). Terraced slopes (Figure 4.4.2) were also described by Cato, as well as suggested conditions for ploughing, in order to minimize soil erosion (Brevik and Hartemink, 2010).

Many other ancient Romans touched upon the topic of soils in their writings. Marcus Terentius Varro, who lived between 116-27 BCE, was an encyclopaedist. When asked about the topic of agriculture, he stated, "It is not only an art but... It is, as well, a science, which teaches what crops are to be planted in each kind of soil, and what operations are to be carried on in order to produce the largest crops"(Egerton, 2001). He also suggested there should be schools for farming, since there were schools for every other profession. In this frame of mind, the Romans took the Greek's philosophical approach to soils, and created theories to be tested and applied.

Lucius Julius Moderatus Columella was born into a farming family in Spain in the early 1st century CE.Columella was known to be particularly experimental with his farming practices considering the time period. He was also known to have studied soil more than any other Roman agricultural author (Olson, 1943). Columella was educated as a citizen of Rome so he knew of, and studied, previous agricultural writings, both Greek and Roman (Egerton, 2001). However, his upbringing in Spain influenced many ideas he had on soils and agriculture. At the time, black soil was valued most highly, and light coloured soil was valued the least. He proposed that grain size, structure, texture, and alkalinity were better predictors of soil productivity (Olson, 1943; Brevik and Hartemink, 2010).

In his book*De re rustica*, Columella writes of several techniques by which each soil trait can be tested (Olson, 1943). To test for structure, the soil should be moistened and rolled between fingers. He observed that plants grew best in soil which did not break apart when dropped. To test for texture, he suggested digging a hole and re-filling it with the same amount of soil. If the hole was completely re-filled and some soil was left over, it was considered fat soil, which meant it had lots of organic matter and nutrients. If the hole could not be re-filled completely, the soil was lean, with hardly any organic matter. It also did not hold moisture well. To test for acidity, the soil was mixed with water, and allowed to settle. The water was then tasted, and ashes or lime was suggested to balance out the acidity of soil (Olson, 1943). Before Columella, the general rule was to plant crops similar to those which made up the natural plant cover of the soil before it was farmed. Columella believed that soil tests such as the ones he suggested were far more relevant in determining which crops would grow best in certain locations(Agnoletti and Serneri, 2014). He also took into account annual variations in regional climate when describing the soil tests (Egerton, 2012).

Columella also wrote quite extensively about the difference between surface soil and subsoil.He mentioned in his book that in some areas the subsoil forms a hard, impermeable substance, which interfered with the processes that crops needed to grow, functioning like a layer of stone. *De re rustica* was the first time hardpan was mentioned (Olson, 1943).

The most notable quality of Columella's work was his experimental approach. He blamed nothing on faith, and only disagreed with other authors if he had practical experience that suggested otherwise(Emeritus, 2004). He experimented with his own soils, by mixing in clay, gravel, manure, or compost and recording the resulting crop yields (Egerton, 2012). Most importantly, he urged others to experiment, and record their findings. Although it may be without profit, he stated that it would be of benefit for all. In *De re rustica* he writes, "We must not be content with the authority of either former or present day husbandmen, we must hand down our experiences and set ourselves to experiments yet untried. This practice, though sometimes detrimental in part, nevertheless proves advantageous on the whole"(Olson, 1943).

Unfortunately, after the fall of the Roman Empire in 410 CE, progress in soil science and agricultural technology both declined. Columella's invitation to keep experimenting would not be fulfilled until the 1800s (Ahrens et al., 2002).

Soil as a Modern Integrated Science

The Father of Modern Soil Science

Vasily V. Dokuchaev (Figure 4.4.3) was born in 1846 in Milyukovo, Russia, a small village close to Smolensk (Daintith, 2008). He was the son of a village priest. Dokuchaev studied and graduated from the Smolensk seminary like his father. In 1867, he moved to St. Petersburg to further study theology. Between 1855 and 1881 however, Russia was in a period of great reform. Peasants were given freedom, and all people were taxed equally. This led to services such as building infrastructure, healthcare, and most importantly, educational reform. New public schools spread, and illiteracy amongst those who were previously peasants declined. Forms of higher education were institutionalized, and universities and students were given the freedom to publish (Eklof, Bushnel and Zakharova, 1994). The newfound freedom of thought influenced Dokuchaev to switch from theology to natural history within three weeks of being in St. Petersburg (Warkentin, 2006). His interest in mineralogy and crystallography led to his title as curator of the Geological Collection at the St. Petersburg University in 1870 (Warkentin, 2006). The same year, he started working with the Free Economic Society (FES), which was a collection of wealthy landowners who funded a group of great Russian scientists of the time. The FES was the first academic organization to be a separate entity from the government in Russia. They proposed funding to Dokuchaev for the study and mapping of Russian soils, and showcased his 1883 publication, *Chernozem,* as one of their main projects.

Before Dokuchaev, soils were thought to have been a dead substrate, a crumbled version of the bedrock. He integrated minerology, math, chemistry, biology, and geography in the development of a new definition of soil (McNeill and Winiwarter, 2004). He was the first to regard soils as a living entity, formed by a variety of processes, and containing a variety of biotic and abiotic elements(Ahrens et al., 2002). In 1886, he published a theory that stated that at any given location, soil is a function of the factors that dictate its formation. These factors are the content and structure of the parent material, the climate, vegetation, age, and topography of the terrain. This implies that if the factors are the same in two locations, no matter how far apart, the soils should be the same. Also, if the factors are known, the soil type can be predicted. Lastly, it implies that there is a similar relationship between each factor and the character of the soil (Florinsky, 2012).

This proposal, along with the financial support of the FES, allowed Dokuchaev to create a Special Soil Committee in 1888, which was followed with a whole school devoted to the topic of soil as a science by itself (Warkentin, 2006). His contemporaries, Kostychev and Sibertsev, were also influential in developing soil as an integrated science (Brevik and Hartemink, 2010). Kostychev was a microbiologist who worked with Dochukaev within the FES on *Chernozem*, and was co-founder of the field of soil microbiology. Sibertsev, Dokuchaev's student, was a leader in the development of genetic soil science(Brevik and Hartemink, 2010).Dokuchaev's ideas did not reach North America until the introduction of his concepts to the Bureau of Soils in the 1920s.

Figure 4.4.2 An image of Vasily V. Dokuchaev (1846-1903) at the age of 49. He is known as the father of modern soil science.

Predictive Soil Mapping

Mapping soils has been a part of history since the earliest civilizations. Modern mathematical modelling and predictive digital soil mapping (DSM) is a step further. The idea of soil as a function was developed by Dokuchaev, and DSM is now based on the factors of soil formation which he had outlined (Florinsky, 2012). Modelling and mapping of how soils change over time has very many practical uses. It is used in pedoarchaeology, and can provide insight to how the soil in a specific archaeological site was used by the people of the past (Walkington, 2010). Land degradation and the remediation of currently an important topic in soil science, and modern remediation strategies are often modelled by DSM. Modelling soils can also be applied to the study of ecosystems and environmental stressors (Boettinger et al., 2010).

Unearthing Petroleum

Petroleum is a vital natural resource as it is responsible for 70% of Canada's energy (CAPP, 2013). The petroleum industry has developed considerably since its initial discovery over four thousand years ago. More specifically, the search for petroleum, the technologies for extracting and transporting petroleum, the uses of petroleum products, and the petroleum refining process have improved remarkably. The discovery of petroleum and its impact on its associated industry has had a prominent impact on the advancement of human society. The word petroleum is derived from the Latin words *petro* and *oleum* meaning rock and oil, respectively (Klein, 2012). Petroleum encompasses both natural gas and crude oil, which are found trapped within rocks. Petroleum is composed of materials from dead organisms (Klein, 2012). It forms many years after plants and other organisms, such as plankton, have died. When the organisms are buried, all non-organic material is destroyed, leaving only the organic material, known as kerogen (Biju-Duval, 2002). As sediments build up and the kerogen gets buried deeper, the pressure and temperature increase. When the temperature of kerogen reaches between 80°C and 100°C its complex molecules begin to break down into simpler organic molecules (Hobson, 1954). The process of breaking down complex molecules is called cracking or catagenesis. Hydrocarbons are the long chains of hydrogen and carbon that are produced through catagenesis of kerogen (Hobson, 1954). At temperatures between 80°C and 100°C, the hydrocarbons are in the form of oil and at temperatures greater than 100°C, the hydrocarbons can become simpler resulting in natural gas (Biju-Duval, 2002). In order to reach such high temperatures, this process occurs kilometres below the Earth's surface.

Once oil and gas are formed, they migrate away from the source rock, in which they formed, towards Earth's surface. This allows for commercial collection of oil that has accumulated in oil pools; if hydrocarbons did not migrate, petroleum would remain dispersed throughout the source rock. The migration of oil and gas can be broken into three phases: primary, secondary, and tertiary (Biju-Duval, 2002). Primary migration involves expelling the oil and gas from the source rock (Hobson, 1954). Secondary migration is the movement of hydrocarbons from the region in which they were expelled, to the location where they accumulate (Hobson, 1954). Tertiary migration is when the hydrocarbons escape their accumulation area and travel to the surface where they become exposed in what is known as a seep (Figure 4.5.1) (Biju-Duval, 2002).

Figure 4.5.1: This picture illustrates a petroleum seep caused by tertiary migration, which is when petroleum escapes its accumulation area and rises to Earth's surface.

It was not always known what petroleum was, how it formed, where it could be found, or what it could be used for. By looking back over the past four thousand years, from the initial discovery of petroleum to the current industry, we can see the advancements that have occurred and how they have shaped society.

Greek historians, Herodotus and Diodorus Siculus, determined that the initial finding of petroleum occurred over four thousand years ago when petroleum seeps in Babylon, Iraq and Ionian Islands, Greece were discovered (Hugh, 1911). The petroleum product from these seeps was in the form of asphalt, which is a viscous type of petroleum (Totten, 2007). The asphalt was initially used to build walls and towers, and subsequently used to waterproof buckets and ships (Totten, 2007). The use of asphalt in construction became essential in increasing the quality of life at that time. It is also believed that people of higher societal classes used petroleum for medicinal uses and lighting (Heshelow, 2010).

Eventually the reserves from oil seeps in Iraq and Greece dwindled and the rate of tertiary migration was not fast enough to meet demands. This depletion of available oil caused the early industry to begin looking elsewhere for sources of oil. It was found that drilling into the surface was an alternative method of petroleum extraction. Historians believe the first time petroleum was extracted from under the surface was in China in 347 AD, 1668 years ago (Totten, 2007). In China, bamboo poles with sharp drill bits on the end were used to reach petroleum at depths up to 240 metres (Totten, 2007). The drilling techniques used by the Chinese were eventually improved upon, but the bamboo drills and pipelines provided a starting point for the drilling industry. During the early times of drilling, extracted oil was burned in order to create a heat and light source (Totten, 2007).

As the use of petroleum became more acknowledged, the search for oil expanded throughout the world. Oil seeps in Azerbaijan were exploited in the 800s (Geo Help Inc., n.d.). It was at this time that distillation of petroleum became popular as new products were discovered. Distillation involves separating the components of a substance and while the process was not documented at this time, it is believed that Persian alchemist Muhammad ibn Zakariyā Rāzī perfected the process (Sop.CO.Ltd., n.d.). Some of the products from distilled petroleum included tar, used to pave roads, kerosene, used for lighting, and many flammable products, used for military purposes. While petroleum distillation was possible, the first official oil well and refinery was not constructed until 1754, in Ukhata, Russia by Fiodor Priadunov (Sop.CO.Ltd., n.d.).

By the 1100s petroleum distillation products were being used as a medicine to treat many minor health problems. The discovery of the medicinal properties of oil came from a medieval herder who left a weak, sick camel stuck in the mud, but returned weeks later to find the camel to be cured (Zahirova, 2008). Resulting from the discoveries of distillation of oil and medicinal oil, petroleum products became a valuable resource important in trade.

The process of distillation was greatly improved upon by James Young following Priadunov's refinery. Young started a business refining crude oil in 1847 in Derbyshire, UK, eventually running into problems (SEHF, n.d.). He found that as the oil was heated it became less viscous (SEHF, n.d.). This discovery led to the theory that petroleum formed under high heat and that different types of petroleum (such as crude oil, asphalt, or natural gas) depended on the amounts of heat the kerogen was exposed to. This theory of viscosity relating to temperature is now accepted as true and is known as cracking: temperature increase causes organic matter to break down and become simpler, making it less viscous.

Young believed that the petroleum products he desired could be made artificially given the correct amount of heat and pressure (SEHF, n.d.). He started to experiment by heating coal (mineralized organic matter) at a low temperature and found he could produce a liquid resembling petroleum (SEHF, n.d.). Further experiments slowly increasing the temperature resulted in several useful products. One such product he called *paraffine oil*, which when cooled, resembled modern day paraffin wax. Young patented paraffine oil and the cooled paraffin wax derived from coal in 1850 (SEHF, n.d.). He became part of a partnership entitled E.W. Binney & Co. in Bathgate, Scotland, which became the first commercial oil refinery in 1851 (SEHF, n.d.). They focused their production on petroleum naphtha and lubricating oils. It wasn't until 1856 when paraffin wax and paraffine oils were sold for fuel (Davidson, 2014).

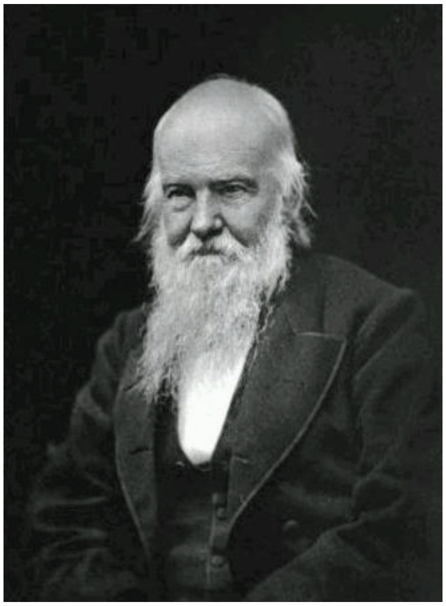


Figure 4.5.2: Portrait of James Young, who improved the distillation process and developed the idea of hydrocarbon cracking.

Canada and the Oil Industry

Canada played an important role in the development of the oil industry. The first commercial oil well was in Petrolia, Ontario in 1858 (Eyles & Miall, 2007). Furthermore, the refining process was greatly improved upon by Canadians.

Abraham Gesner was a New Brunswick Provincial Geologist in 1836; he later created the Kerosene Gaslight Co. as he distilled kerosene from coal (Eyles & Miall, 2007). Not only did Gesner play a role in developing the refining process, he also wrote a book on the geology of Nova Scotia, including information about the geology of regions in which natural petroleum resources could be found (Eyles & Miall, 2007). By studying the geology of regions is which petroleum resources were known to be, petroleum companies could get an idea of what type of environment should be explored in search of petroleum.

Native Canadians were familiar with oil and its uses even before Gesner's company and the Petrolia oil well. The natives collected oil from seeps, which they called *gum beds*. The natives used petroleum for medicinal purposes as well as for waterproofing canoes (Eyles & Miall, 2007). The gum beds were initially responsible for attracting explorers to Petrolia (Eyles & Miall, 2007). Petrolia played a very important role in the development of petroleum drilling technologies during the 1800s and onward.

The first oil wells in Petrolia involved digging rather than drilling. These wells that had been dug were known as cribbed wells (Petrolia Discovery, 2015). In order to increase oil extraction, drilling techniques were implemented, as they were more efficient than digging. The spring pole drill was most likely the first drilling method used in both China and Petrolia (Petrolia Discovery, 2015). The spring pole drill was greatly improved upon with the jerker rod system.

Petrolia advanced their techniques and began using what is now known as the Canadian Rig (Petrolia Discovery, 2015). They then introduced this drilling rig to the rest of the world, including China. They also implemented the largest pumping rig in the world, the Fitzgerald Rig (Petrolia Discovery, 2015). It has been running almost constantly for over a century. More advancement came with the three-pole derrick and wooden jerker pump lines (Petrolia Discovery, 2015). The drilling rigs, three-pole derricks, Fitzgerald Rig and the wooden jerker lines were all played an important role in the development of modern technologies in oil collection.

In 1901, the bulk of Canada's oil industry moved from Oil Springs and Petrolia to Alberta where there was an abundant supply of oil and gas due to faults caused by tectonic movement during the formation of the Rockies (Eyles & Miall, 2007).

As oil demands increased, the search for oil became critical. Early oil explorers would find oil by drilling into seeps as well as drilling into visible folds (Milligan, 2004). Once all the obvious potential petroleum reserves were drilled into, geologists began using seismic technology to find hidden petroleum accumulations. This shift in techniques coincided with the Second World War (Eyles & Miall, 2007). Seismic imaging allows the types of rocks below the surface to be determined without the need to drill down at each potential petroleum location. The technology involves producing seismic waves then recording and analyzing the movement of the waves through the Earth (Milligan, 2004). The changes in density between layers of the Earth cause the waves to reflect back to the surface at different speeds and strengths, indicating what rocks and other substances, including petroleum, lie below (Milligan, 2004). This method of finding oil revolutionized the oil industry as the search for petroleum became much more precise and effective (Chevron, 2014).

As seismic waves allowed for more thorough search for petroleum, the main issue within the industry became finding better, more efficient transportation methods to transport oil from remote areas to where it can be used. This requirement led to the CANOL project, which was the construction of Canada's first northern pipeline, which provided oil from the Northwest Territories to the United States for military uses (Barry, 1992). There were setbacks in transportation as the pipe burst due to permafrost (Eyles & Miall, 2007). The lessons learned during the CANOL project were very effective in informing us about permafrost in order for special precautions to be made for the pipelines used today.

In 1943, Canadians turned their search from exposed land to search offshore oil reserves along the Atlantic coast (Eyles & Miall, 2007). Wells were created to drill for oil in the ocean but the environment proved too difficult to work with and the technology was not advanced enough at the time causing the rigs to be abandoned (Eyles & Miall, 2007). Although the offshore efforts did not prove successful at the time, the attempt provided an opportunity to learn and led to many improvements. Several years later, drilling platforms were made to withstand the impact of icebergs as well as major storms.

Inventions such as the first coal powered steam engine, the combustion engine, and Henry Ford's first motorcar had a huge impact on the increasing demand for petroleum products. From the industrial revolution onward, the demand for petroleum products continues to rise today. The increasing demand raises concerns about the potential depletion of petroleum reserves. As oil reserves decrease, we may be required to turn to alternative energy sources.

Alternate Energy Sources

It is estimated that at a rate of production of 3.36 barrels of oil per day, Canada's oil reserves will be sufficient for 140 years (NRC, 2014b). The petroleum that is extracted today is refined into many products, the most common product being gasoline (StatCan, 2011).

Although oil is still forming today, it takes at least a million years for petroleum to form and accumulate (BP, 2014). Hence, the rate at which humans consume oil is much faster than that of petroleum formation. The slow formation rates place petroleum under the category of non-renewable energy sources. If the current reserves in Canada only last for 140 years, a new energy source must be found to decrease the amount of oil being used, particularly for transportation. There are many proposed solutions to this problem. One option could be to increase the ethanol percentage in gasoline to reduce the percentage of oil needed (NRC, 2014a). Another idea is to increase the usage of natural gas as an energy source, as it is a clean burning fuel that is plentiful, however, it is also non-renewable (NRC, 2014a). A more promising fix is the use of electricity in place of gasoline. Over the past few years, electric vehicles have become more popular. This is due to the fact that electricity can be produced from renewable resources, and electric cars do not release the pollution that gasoline vehicles do (NRC, 2014a). Another promising alternative to gasoline is biodiesel.

Biodiesel is similar to petroleum in that it is made from organic matter, however, it does not take millions of years to convert the organic matter into energy (Ma and Hanna, 1999). The organic material used can be supplied by vegetable oils, animal fats, or cellulose rich plants; vegetable oils being the most promising (Ma and Hanna, 1999). While there are four known methods of converting organic material into diesel, the most common is transesterification of vegetable oils and animal fats (Ma and Hanna, 1999).

By turning the attention to renewable sources of energy, valuable petroleum resources could be conserved.

Figure 4.5.3: An example of a vehicle powered by biodiesel.

Ancient Egyptian Gold

Figure 4.6.1: Auriferous quartz vein exhibiting green staining of the host rock in Toi gold mine, Japan.

Precious metals have always been a source of intrigue for human societies. Their purity and beauty even inspired some to believe that these elements were divine in origin. Amongst precious metals, gold has long been considered the most valuable. In empires where access to gold was available, it quickly gained significance as a status symbol and hallmark of prosperity. Ancient Egypt was renowned for its exploitation of the area's abundant gold resources. In fact, ancient Egyptian society was so deeply enamoured with the "flesh of the Gods" that the amount of gold prospection and mining can be directly linked to the economic stability of the time period in which it took place.

Geological Setting

Gold prospecting was possible even in ancient times because the geological setting of the Eastern Egyptian and Nubian Deserts was incredibly conducive to the production of shallowly concealed gold-bearing quartz veins (Botros, 2004). The Arabian-Nubian shield, where most of these deposits are located, stretches from the Arabian Peninsula to the Nile river (Klemm, Klemm and Murr, 2001). Characteristic quartz shear zones occur in the ophiolitic sequences and island arc assemblages that shaped its history (Botros, 2004). Gold ore is most commonly found within these zones and in the post-orogenic granitoids that compose large portions of the region (Azer, 2013). Continental uplift along the Red Sea rift system exposed both to the surface of the Eastern Egyptian and Nubian Deserts, making deposits shallow enough (less than 30 m deep) for ancient prospectors to mine with their poor ventilation systems (Klemm, Klemm and Murr 2001).

Figure 4.6.2: A photograph of the Pyramid of Khafre and the Great Sphinx as seen today.

Several exposed veins were superficially altered by the out-leaching of copper-sulphide minerals that were later redeposited as green secondary copper minerals (Klemm, Klemm and Murr, 2001). This visibly stained the surface host rocks (Figure 4.6.1), and guided the earliest prospectors to gold. Over time, ancient prospectors defined the 3 richest mining regions in the deserts: "gold of Koptos" is from the Hammamat to Abbad regions of the Eastern Desert, "gold of Wawat" comes from the Wadis Allaqi and Gabgaba regions, and "gold of Kush" was mined further south in the Nubian Desert (Nicholson and Shaw, 2000).

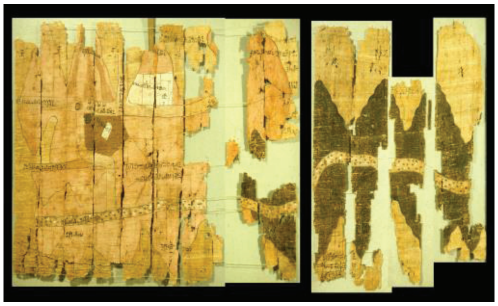
Old Kingdom (2649-2150 BCE)

The Old Kingdom was the first true peak of Egyptian civilization (Roehrig, 2000). During this time, many popular aspects of Egyptian culture were developed. The first massive stone monuments were constructed, most famously the Pyramids of Giza and the Great Sphinx (Figure 4.6.2) (Roehrig, 2000). The structure of the government became highly organized and formed the basis for the political affairs of later eras (Roehrig, 2000). The first true gold mining techniques were also developed (Roehrig, 2000). Though predynastic gold artifacts have been discovered, the base material was gathered almost exclusively through alluvial sources (Klemm, Klemm and Murr, 2001).

It was only in the beginning of the Old Kingdom that gold mining activities and tools became common (Klemm, Klemm and Murr, 2001). The prospectors of the Old Kingdom, much like their predynastic ancestors, located mining targets with characteristic green staining, but also began to take note of hematite-enriched auriferous veins with barite (Klemm, Klemm and Murr, 2001). Gold-bearing quartz was crushed in-situ with 2 types of stone hammers: an oval stone axe with a chiseled notch fitted with a forked wooden stick, and a cylindrical one-handed stone hammer with an ergonomically-formed handle (Klemm, Klemm and Murr, 2001).

Middle Kingdom (2119-1794 BCE)

A period of political upheaval and weakening pharaonic power immediately followed the dissolution of the Old Kingdom (Edwards, 2004). The reunification of Egypt marked the beginning of the Middle Kingdom, a time of prosperity and innovation (Edwards, 2004). The economy of this era stabilized alongside the political climate, giving birth to a wealth of creative pursuits including the first Egyptian literature written for informative and educative purposes (Tait, 2003). Restablization also brought about the reinstitution of the prospecting missions that had died off with the Old Kingdom. Egypt's first military campaign (1956–1911 BC) was likely launched to seize control of gold deposits in the Nubian Desert (Klemm, Klemm and Murr, 2001). Once the Egyptians gained access to gold, their mining technology began to advance. The greatest development was the introduction of stone mortars that allowed raw quartz materials to be crushed into a fine powder that eased gold extraction (Klemm, Klemm and Murr, 2001). The miners of the period had to hand-pick gold from host materials and this method vastly improved the separation of the 2, directly resulting in a spike in the amount of gold produced annually.



New Kingdom (1550-1070 BCE)

The New Kingdom was the apex of ancient Egypt's influence and prosperity, often represented today by the lavish treasures of King Tutankhamun's tomb (Figure 4.6.3). Egypt's armies swelled along with its borders, expanding far south into the Nubian Desert (Edwards, 2004). Wealthy rulers gave their thanks to the Gods with increasingly elaborate statues and temples that contributed the generation of new glazing and sculpting methods (Nicholson and Shaw, 2000). Of course, the royal treasuries also overflowed with gold. Though a portion of these supplies were generated by panning alluvial deposits, the exceptionally lucrative period between the reins of Thutmose III (1492-1479 BC) and Amenophis III (1386-1349 BC) saw a dramatic increase in gold mining activities (Klemm and Klemm, 2012). King Thutmose III actually oversaw the most intense prospecting of any ancient Egyptian ruler (Lloyd, 2010). Delivery lists from administrative and temple treasuries have provided modern researchers with a quantitative understanding of the wealth he possessed; Thutmose III donated an estimated 15000 kg of gold to the Karnak temple, an extremely powerful temple throughout most of the New Kingdom, during his reign (Lloyd, 2010). Though the majority of the donations were war spoils, further records indicate that Nubian mines produced 265 kg of gold yearly for his treasury (Klemm and Klemm, 2012). To put this value into context, most New Kingdom annual Karnak temple donations did not far exceed 230 kg of gold annually (Lloyd, 2010).

The New Kingdom gold rush gave rise to a variety of new gold prospecting, mining, and refining methods. Prospectors could now locate gold-bearing quartz veins that had none of the characteristic mineral indicators common to older finds. Instead, it is implied that the Egyptians of this era had some basic geological knowledge. The auriferous veins of the Arabian-Nubian shield tend to follow north-south east-west strike patterns that New Kingdom prospectors followed from preexisting mining sites (Klemm, Klemm and Murr, 2001). This pattern was made clearly visible to archeologists upon the discovery of the Turin Papyrus Map, one of the oldest known geological maps (Figure 4.6.4) (Harrell and Brown, 1992).

The development of wadi-working operations, the systematic removal of gold-bearing quartz from coarse valley sediments, also drastically increased the era's gold production (Klemm, Klemm and Murr, 2001). New milling technology further improved the yield of older refining techniques. Raw materials were first crushed using a double-sided stone anvil and stone pestle and then gold slivers were separated out for fine milling by hand (Klemm, Klemm and Murr, 2001). Sloped gold-washing tables began appearing during the New Kingdom, and improved the ability of ancient Egyptians to separate fine quartz and gold materials (Klemm, Klemm and Murr, 2001). Finally, the introduction of bronze chisels (Figure 4.6.5) eased the removal of raw materials from the mines and strengthened their construction, which enhanced the productivity of new mines (Klemm, Klemm and Murr, 2001).

Figure 4.6.3: King Tutankhamun's burial mask. The mask was constructed with several kilograms of gold and is opulent in comparison to burial masks recovered from other eras. This extravagance is representative of the peak of New Kingdom wealth.

Figure 4.6.4: The Turin Papyrus Map

Figure 4.6.5: A New Kingdom soft bronze chisel.

Ptolemaic Kingdom (305-30 BCE)

Figure 4.6.6: An artist's depiction of Pharos of Alexandria.

After the dissolution of the New Kingdom, Egypt became locked in a series of power struggles with various empires. This lead to 2 extended periods of Persian rule from 525-402 BCE and 343-332 BCE (James and Hill, 2003). The Persian empire was thought to be extremely oppressive, inciting rebellion, political instability, and the collapse of the Egyptian gold mining industry (James and Hill, 2003). These tumultuous relations rendered Egyptian civilians comparatively accepting of Alexander the Great's campaign into Egypt, a feeling that was extended to his succession by the Ptolemaic kings (Shaw, 2000).

Figure 4.6.7: A golden coin from the Ptolemaic Kingdom depicting Ptolemy III.

Figure 4.6.8: A placer mining sluice box, similar to those used in gold washing throughout ancient Egyptian history.

The Ptolemaic rulers were deeply influenced by Egyptian and Greek culture, bringing forth a period defined by exorbitant riches and cultural developments. The library of Alexandria was, at the time, the largest in the world and housed many of the most famous poets and scholars of the Ptolemaic Kingdom's literary golden age (Shaw, 2000). Several architectural wonders were constructed during the era, including the world's tallest lighthouse, the Pharos of Alexandria (Figure 4.6.6) (Elnashai, Sarno, and Carter, 2006). Egypt also underwent an agricultural revolution due to the Greek's advanced knowledge of irrigation and became an exporter of high-commodity crops (Shaw, 2000).

Though these developments all had an impact on Egyptian history, the most dramatic societal change was the introduction of the concept of coinage (Figure 4.6.7) to the previously trade-based Egyptian economy (Milne, 1929). Capitalistic pursuits soon became wildly popular and a luxury goods market was firmly established in around the Egyptian ports (Roy, 2011). Due to this, gold experienced a massive shift in societal value (Milne, 1929). Gold remained a status symbol, but it now had extreme monetary worth. This is likely why, though violent desert tribes caused the discontinuation of gold prospection, there was rapid progression in Egyptian gold ore processing and milling techniques (Klemm, Klemm and Murr, 2001).

Milling became a staged process: heavy (5-10 kg) semi-circular millstones were used first to crush raw materials into powder before concave millstones with parallel grooves were used to further separate the materials (Klemm, Klemm and Murr, 2001). The extra-fine produced contained more free gold than before, increasing the yield of washing procedures. The Egyptians also adapted the washing concentration plants of Greek mining districts (Springer, 2008). Egyptian plants moved water and crushed ore through a circular sluice (Oxford University Press, 2012). The heavy host rock particles would sink and become trapped in grooves along the bottom of the plant, whereas lightweight gold flakes would be carried along in the stream out of the sluice (Figure 4.6.8) (Oxford University Press, 2012). These new washing plants allowed for the processing of sulphidic ores and the extraction of previously inaccessible gold (Klemm, Klemm and Murr, 2001).

Wealth, Science, and Society

The economy is the driving force of societal development. Periods of economic stability have manifested themselves historically as the rapid advancement of technology and art. These renaissances are clearly visible throughout ancient Egyptian history. The unified Old, Middle, New, and Ptolemaic Kingdoms were defined by the progress made in architectural, literary, governmental, artistic fields. Notably, advancements of gold mining technology followed suit. Rich kings ordered prospecting missions to secure symbolic representations of their power, introducing the need to develop new gold procuring tools. Therefore, the accumulation of gold was directly proportional to the wealth of a kingdom at the time. Conclusively, it can be said that increases in gold prospection and the advancement of gold mining technology are representative of the trend linking economic stability to cultural and scientific progress.

Gold Nanoparticles in Medicine

Nowadays, gold is precious for more than aesthetic reasons. It has found use on the forefront of targeted medical research: nanomedicine. Due to their incredibly small size, nanoparticles are largely used in non-invasive medical procedures. Nanoparticles exhibit many odd size-based properties (Figure 4.6.9) that are easily manipulated for medical or imaging purposes (Daniel and Astruc, 2004). Gold nanoparticles (GNPs) are ideal for this purpose as they are chemically unreactive and form tight-knit complexes, which can travel through biological systems without impediment or risk (Daniel and Astruc, 2004). These properties, combined with several others, have made gold a popular multi-purpose medicinal tool.

Nanoparticles are currently under intense scrutiny for their ability to deliver drug doses with precision to unhealthy tissue. Nano-delivery systems can drastically reduce or even eliminate the side-effects of toxic drugs, allowing patients to receive higher doses for faster and more effective treatment (Yeo, 2006). Several steps required in the formation of these systems make gold one of the preferred delivery sources. Volatile drugs must be bound to a center or encapsulated in a compound that is stable in organic solution (De la Fuente and Elsevier, 2012). GNPs can be easily prepared to meet this requirement as they have a high affinity for thiol groups, excellent organic stabilizers, as well as almost all drug combinations (De la Fuente and Elsevier, 2012). After the complex is stable, molecular guides must be added to carry the drug to its destination and to allow it to react. Dozens of these guides and triggers, including enzymes, proteins, RNA, and DNA, can all be bound to gold complexes (Delong et al., 2010). The binding of DNA and RNA ligands is exceptionally favourable due to their potential usage as gene therapy agents (Delong et al., 2010).

A particularly interesting property of gold nanoparticles is their tendency to absorb electromagnetic radiation and release vast quantities of heat (Gannon et al., 2008). Thermal ablation, the heat-killing of malignant tissues, can be performed easily with GNP injections. Radiofrequency (RF) radiation is non-ionizing and, at low doses, can pass through biological tissues harmlessly (Cho and Krishnan, 2013). Upon collection in the desired tissues, these complexes can create isolated heat field that will not affect healthy tissues. Malignant cell DNA is vulnerable to heat damage and will be rendered nonfunctional by this method (Gonzales de Castro et al., 2013).

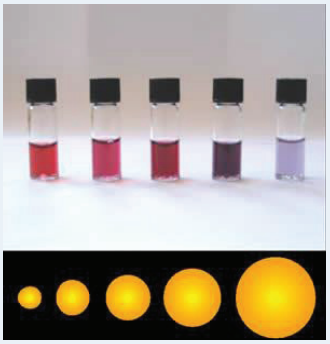
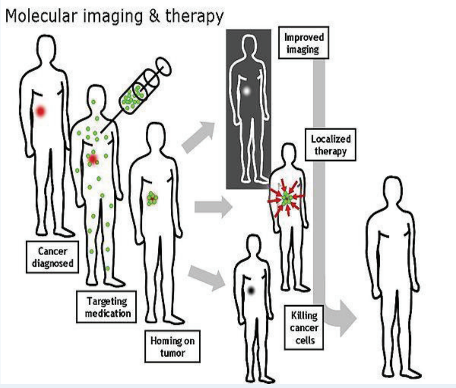


Figure 4.6.9: Various gold nanoparticle solutions. The colour of each solution is dependent on the size of the particles within. This property is linked to gold's optically reflective interactions that dictate the nanoparticles reaction to electromagnetic radiation, such as RF radiation.

Medical imaging is a vital part of the identification of disease and internal abnormalities. Many imaging methods have low specificity and, as a result, differences between tissue layers cab be difficult to detect visually (Cho and Krishnan, 2013). Nanoparticles can be manipulated to gather in sites of abnormality, which creates a stark contrast between normal and abnormal zones (Cho and Krishnan, 2013). GNPs are extremely useful visual guides due to their ability to travel through biological systems and responsiveness to several common imaging techniques. Gold nanoshells encapsulated with superparamagnetic iron oxides are currently in use as MRI specificity enhancers (Cho and Krishnan, 2013). Hollow gold nanospheres are capable of improving photoacoustic tomography imaging (Cho and Krishnan, 2013). Both of these methods are used during radiation treatments on high-risk tumours to guide thermal excision (Figure 4.6.10), which has greatly improved patient survival (Cho and Krishnan, 2013).

Medical professionals have high hopes for the future of nanomedicine. Many theorize that this new technology will drastically increase the survival rates of many illnesses. GNPs have much to contribute to this future, and as a result humanity has fallen in love with gold all over again. The ancient Egyptians, enamoured as they were, believed that gold could procure the blessings of the Gods. If nanomedicine is the miracle cure patients worldwide have been waiting for, perhaps they were right after all.

Figure 4.6.10: A schematic representation of the combination of imaging and treatment techniques for the removal of tumours in a cancer patient.



The Origins and Development of Agriculture

Until 12 000 years ago, the main source of food came from hunting and gathering. This nomadic lifestyle primarily consisted of following wild animals and gathering wild grains. The only utilization of the land consisted of gathering stone to make weapons and gathering cereal grains and plants. It was not until 10 000 to 5 000 BCE where economic and lifestyle changes were made for plant and animal domestication. People began to shift from hunter and gathering, and depend more on the cultivating the land in order to meet their food demand. Since then agriculture has been a major driving force for the development of many civilizations (Chadwick, 1996). However, what caused this shift in obtaining food?

The origins of agriculture

There were several theories behind the development of agriculture and why there was a need for food production. A popular early theory is known as the oasis hypothesis. This hypothesis stated that the beginnings of agriculture was largely influenced by environmental changes in the Earth. Pioneered by V. Gordon Childe in the 1920s, his hypothesis explained that climate change due to the last Ice Age, approximately 12 000 years ago, limited the habitable areas for humans and animals (Chadwick, 1996). As the glaciers melted, rivers ceased to flow from them and ultimately resulted in the Near East, including areas such as Iraq, Palestine, Egypt and Turkey to become deserts. Consequently, many animals and humans were forced into the limited wet areas along the Nile, Tigris, and Euphrates Rivers. Childe believed that this close proximity between humans and animals led to the domestication of livestock and encouraged settling and utilization of the land (Chadwick, 1996; Gupta, 2004). However, this theory was not enough to explain why humans would deter from their hunting and gathering, as prey would be easily accessible.

In the 1950s, Robert J. Braidwood, not convinced by the oasis hypothesis, proposed an area he called the nuclear zone as the first site of agriculture (also known as the nuclear zone hypothesis). This hypothesis stated that a “nuclear zone” which was located 300-1800m above sea level, far from ancient Egyptian and Mesopotamian river valleys, between two temperature extremities (a mountain and the desert). Braidwood and his team of professionals proposed that this area would be the first site of agriculture (Braidwood, 1960; Chadwick, 1996). Around the same time, Kathleen Kenyon, a British archaeologist, explored the ancient city of Jericho and found signs of what were thought to be pioneer farming villages (Chadwick, 1996; Kenyon, 1960). It was determined that Jericho was both an ancient trading post and an early agricultural village and since its discovery, many more farming villages have been found, most of which are located in the nuclear zone. Throughout the late 20th century, there had been a debate regarding which of the two hypotheses were correct. Braidwood and other researchers successfully discovered the first site of agriculture and animal domestication in the nuclear zone foothills in the ancient Near East. However, neither were able to explain why the shift to agriculture took place (Chadwick, 1996). In the early 80s, Canadians Philip Smith and T. Cuyler Young Jr. suggested that as a result of climate change, hunter-gather populations prospered. Consequently, population started to gradually increase and the demand for food grew. Approximately 10 000 years ago, food started to become scarce, and in order to survive, people needed to begin interacting with food and animals to increase food production (Smith and Young, 1983; Chadwick, 1996).

While research onto the origins of agriculture is relatively recent, the development has progressed over an extensive time period. While multiple theories have been proposed regarding the cause of agriculture, many researchers agree that there is no specific theory, however the culmination of all those factors that led to its development (Chadwick, 1996).

Early Development of Agriculture

The Neolithic Revolution (also known as the Agricultural Revolution) contained the first evidence of the first shift away from hunting and gathering during the Holocene in 12 000 BCE. The late Pleistocene was a time where the availability, predictability and accessibility of cereal and legume seeds could be harnessed. This congregation of resources in small areas allowed for the development of small populations in areas (Bar-Yosef, 1998a).

The first evidence of marked process in Agriculture was found in the Fertile Crescent (Figure 4.7.1, right). The Fertile Crescent, found in the Near East (now Southwest Asia; Roe, 2010), was the birthplace for systematic cultivation of cereals and 'founder crops' (Bar-Yosef, 1998b). Plants were the first to be domesticated through annual sowing of harvested and stored seeds. Thus resulted in co-evolutionary changes which affected plant germination timing and speed as a result of human harvesting and planting patterns (Zeder, 2009). Soon after, between 10000 – 9500 BCE, the first domestication of animals began. Changes in morphological records indicated that a significant drop in overall body size of prey such as sheep and goats, a key marker for domestication (Zeder, 2008). Furthermore, strategies were implemented to increase herd size. When prey were caught, males would be used for food whereas females would be kept alive for breeding (Zeder, 2008). While agriculture strategies were still primitive, between 9500 to 8800 BCE, the Sumerians had already began to use supplemental irrigation to provide moisture for plants during times of low rainfall (Lal, et al., 2007).

As agriculture began to spread, from 7000 – 5800 BCE during the Pre-Pottery Neolithic B (PPNB), farming villages across the Anatolia and neighbouring areas started arising (Bar-Yosef, 1998a). As agricultural practices became more predominant and productivity began to increase there was a need to start storing crops. Technological advances soon followed to meet the increasing yields. During 6000 BCE, the first granaries were built in Mehrgarh, a village located in the Kacchi Plain, Pakistan (Jarrige, 2008). This started the beginning of the era of abundance and agricultural efficiency.

As people grew a greater understanding of different types of plants, agricultural practices changed. Mesopotamians became one of the first to own both gardens and fields. The garden would be used for growing slips, shoots and seeds that required special care whereas the field was dedicated to bulbs, roots, and tubers which were harvested throughout the year (Reiner and Oppenheim, 1977). As fields grew, the intensity of labour resulted in significant technological advances between 5000 – 4000 BCE (Lal, et al., 2007). To cope with this increased workload, the Mesopotamians innovated the plow and harrow, similar to the dibbling stick for the garden. This technological development greatly improved field seeding and lessened worker load (Lal, et al., 2007; Reiner and Oppenheim, 1977). The Mesopotamians also investigated a new level of domestication where they utilised the wool of sheep and goat hair. On the other hand, flax was grown for its fiber medicinal properties rather than for the oily seeds (Reiner and Oppenheim, 1977). The Mesopotamians, often paralleled by the Egyptians in development at the time, often faced environmental issues. As the civilization was often plagued by salt and silt content in the alluvial soils or there would be considerable loss in harvest. As a result, between 3000 – 2000 BCE, the use of irrigation and fertilization began (Jacobsen and Thorkild, 1958; Lal, et al., 2007). During the same time, hydroagriculture, or small scale irrigation agriculture, started spreading throughout the Mediterranean and central Asia. As projects enlarged the need for a higher social structure resulted in the development of rural development (Sherratt, 1980). This rapid progression would bring about a new age in Agriculture.

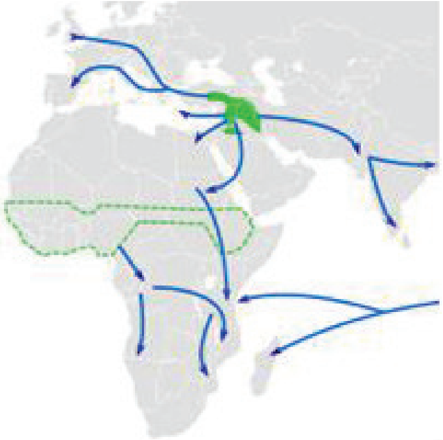


Figure 4.7.1: Birth of Agriculture: The Fertile Crescent. This area contains evidence for the first signs of agricultural development. Agriculture first started in this area and spread into surrounding regions.

Age of Antiquity

The first civilization to continue developing hydroagriculture after the Mesopotamians were the Assyrians (859 – 590 B.C.E). The Assyrians, or Urutu developed many methods of manipulating water by building dams, reservoirs and canal systems. As the Urutu were highly depended on regional agriculture, they required a large movement of water. As a result, the Assyrians developed he aqueducts, an artificial water channel, to move water into the main cities (Sparks, 2012). The aqueducts played a key role in irrigation technology during the Antiquity.

While water technology had significant improvements since the birth of irrigation, it was not until the Chinese in 400 B.C.E that soil fertilization improvements to begin. The Chinese had discovered that green-manure crops such as mung bean, red bean and flax help enrich the soil, drastically increasing yield. Furthermore, they discovered the importance of crop rotation in maintaining soil upkeep which served as benchmarks for future agricultural practices (Bin, 1983). The Chinese continued to improve technology-wise making substantial improvements innovating the iron plowshares, along with a variety of farming tools such as pointed shovels, hoes and sickles (Di Cosmo, 1994). The Chinese quickly became the leading innovators of the agricultural field during the age of Antiquity. By the end of the age, farmers had developed an annual system for agriculture (Figure 4.7.2 below; Crescenzi, 1306). As farming practices and technological advances began to become more widespread, the birth of a new agricultural era began.

Figure 4.7.2: Pietro Crescenzi's Agricultural Calander. This calendar shows the month to month activities of farmers living during the age of Antiquity.

Modern Agricultural Era

The modern agricultural advances was first sparked by the British Agricultural revolution. During this revolution, from 1760 – 1840, considerable agronomic and technological advances were being made at a remarkably swift pace. There were introductions to farming technology such as the seed drill, domestication of new crops, additional crop rotation strategies, as well as livestock breeding enhancement methods (Thomas, 2005). Furthermore, as population peaked and food demand rose rapidly, the need for more farm land was imperative. Thus began the conversion of arable and grassy areas into fertile lands for farming. By producing legumes, the soil grew richer and thus enabled the storage of larger herd of livestock. The manure of these livestock would further help to increase the field fertility (Timmer, 1969). However, technological advances were not only limited to Europe. In 1837, a blacksmith from Illinois, United States named John Deere invented the first steel plow; a plow containing wrought iron moldboards with steel shares. The invention was very effective in plowing sticky prairie soil (Rasmussen, 1962). Further development in grain drills and other planting machines had transformed agriculture from human powered to machine powered (Rasmussen, 1962).

While technological advances proved to be great assets in the improvement of agricultural production and efficiency, the pinnacle of agricultural discovery was found to be in the genetic level. Near the end of the 19th century, a German scientist, Gregor Mendel had made a discovery that revolutionized the modern approach to agriculture. Rather than increasing cultivation area, farmers began to use selection of favourable traits to increase yield. The introduction of hybrid during the 1930s, resulted in the first breakthrough in maize yields and soon followed in other crops (Ruttan, 1999). Mendel's findings opened up a new field in agriculture: biotechnology. By delving into the genome of plants, it may provide answers to problems faced by modern conventional techniques. This exploration gave birth to the current state of agriculture, The Green Revolution.

The Green Revolution

The introduction of biotechnology paved a new era of agriculture. The Green revolution involved the development of high yield crops to meet the growing food demand. The first signs of genome alteration as a method to farming appeared in during the 1940s. The development of fertilizer-containing hybrid seeds started in laboratory in the U.S and Mexico. The aim was to use these hybrid seeds for large scale, irrigated landholding projects. As a result there were significant improvements to the Mexican production in crops such as beans, sorghum, wheat and corn (Sonnenfeld, 1992). Due to the remarkable success of these modern varieties resulted into more advanced research in late 1950s and release of new crop varieties towards the 1960s and 1970s. Despite the significant improvements, there was less focus on food production in the colonies, especially in parts of Asia which were largely dependent on support from rich countries. As a result, an international agricultural program was established by the Ford and Rockefeller foundations in an attempt to promote advances in poor developing countries (Hazell, 2009). However, despite the rapid advances during the green evolution, the effects in Sub-Saharan Africa (SSA) were quite minimal compared to South and East Asia. Due to rapid population rise along with improper implementation of cultivation techniques (extensive rather than intensive) to new farming areas, productivity was rather limited. In addition, the cost of managing farmland and crops using pesticides and fertilizers was very high. Furthermore, the lack of transportation, which limited profit, greatly hampered agricultural progress in SSA (Bazuin, et al., 2011). It was not until the birth of the new millennia, with the rise of Genetically Modified Organisms (GMOs) that this issue could be tackled.

First introduced in 1994 (Ruttan, 1999), GMOs were presented to as a solution to many problems that plagued issues regarding food supply including flexibility for growth, benefits to third world countries, and cost efficiency (Spök, 2007). While at first unsuccessful, DNA marker technology was used to further track and manipulate genes to efficiently produce the desired trait. By 1998, approximately 70 million acres of herbicide or virus resistant GMO plants had been planted worldwide (Ruttan, 1999). Despite the promises GMOs hold, there is also large opposition towards the technology which hinder progress. Controversy regarding its ethics and regulations continue to be a growing spark for debate (Wynne, 2001). Currently, GMOs represent the current state of agriculture and its use continue to grow. Over the past decade, the amount of land dedicated to GMOs has risen considerably (Fafner, 2010; ISAAA, 2014; Figure 4.7.3 below) While it is unclear how much more is left to explore in genetics, it is widely accepted that modern understanding is only at the tip of the iceberg. However, it is not known if there is a level further than the genome. Most theories suggest that the development of agriculture was due to the last Ice Age. It may just be another Ice Age before the next revolution.

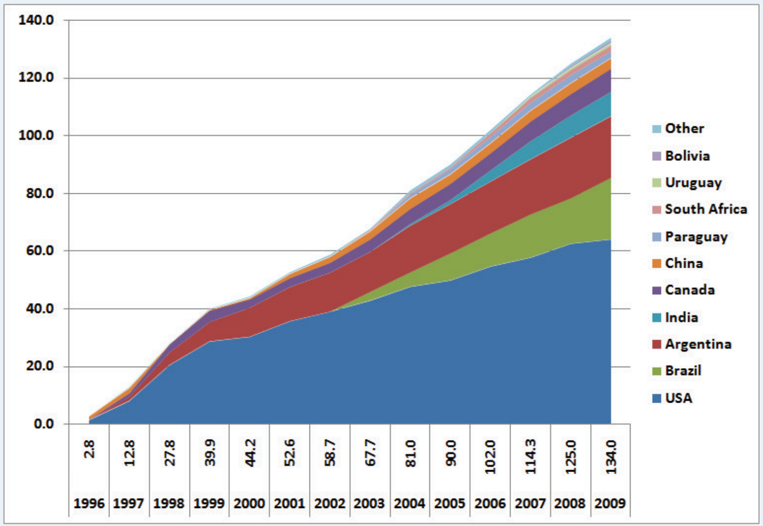


Figure 4.7.3: GMO cultivation from 1996-2009. The values on each access represent millions of hectares. Overall, the dedication of land for GMO crops has risen in the past decade.

The Maya: the Americas' First Engineers

Prior to the Spanish conquest of the 16th century, the Maya civilization was one of the most prosperous indigenous societies of Mesoamerica. Not only were they among the most prolific civilizations of the past, but they were also one of longevity. Archeologists considered the Maya a society of the "stone age"; although they developed into a scientifically advanced community as Europeans deteriorated in the Dark Ages. Establishment of the Maya occurred in the pre-classic era between 1,500 BCE and 200 BCE, originating in the Yucatan Peninsula of present day Mexico (Jarzombek & Prakash, 2011). The rapidly emerging society experienced their largest growth period during the classic era between 200 BCE and 900 CE. At the peak of their dominance around 900 CE, some urban areas had population densities exceeding 1,500 individuals per square kilometer. As such, Mayan cities were among some of the most densely populated regions in the pre-industrialized world (O'Kan, 2012). Their management of the harsh environment they inhabited led to the notable Mayan success (Jarzombek & Prakash, 2011). The eminent Mayan civilization of the past is renowned for its rich values and innovative thinking. Within a few centuries, these primitive and nomadic hunter-gatherers progressed into sophisticated city dwellers and agriculturalists. This accelerated advancement is what separates the Maya from other ancient civilizations. Although the Maya have been credited with achieving heights of scientific knowledge in fields such as astronomy, mathematics, medicine and written chronicles, their most notable of advancements is the ultimate application of science – their role as the Americas' first engineers. The Mayans used science to understand the fundamental laws of nature, and applied this knowledge to prevail as a civilization. They investigated the basic properties of various rock and soil types in order to derive engineering philosophies still used today. As such, they introduced some of the era's most prevailing technological advancements including civil engineering, hydraulics, and tools seemingly beyond their time (Fash, 1994). Mayan technicians created unique architectural monuments (Figure 4.8.1), designed an intricate water-management and infrastructure system, devised modes of land and water transportation, and developed agricultural structures. These innovations resulted in growth, trumping of their seemingly insurmountable environment, and enhancing their wealth and power. The Maya achieved scientific feats and technological advancements within the isolation of the tropical rainforests. How they accomplished this remains an enigma (O'Kan, 2012). Nonetheless, their triumph continues to inspire many of our modern-day technologies.

Figure 4.8.1: An architectural feat of the Maya. This particular structure, the Temple of the Sun stands at Palenque in Mexico.

Hydraulics and Hydrology

Water management is among the most important elements in the evolution and advancements of the Mayan population. The fundamental requirement for water and the food it allows – the preparation and maintenance of the earth – made the management of water in the fragile, water-stressed environment a primary cultural organizing force in Mayan society (Scarborough, 1998). With water came power, and with power came hierarchy. The Maya invented and reinvented their environmental parameters in order to accommodate a level of complexity unlike other better understood social organisations, and in doing so developed a political and economic cultural system driven by resources. The original Maya settled in the lowlands of the Yucatan Peninsula and the neighbouring coasts, although the environment was originally unfit to support the large populations to come (Haviland, 1972). Under this area was a karst terrain characterized by distinct topography largely shaped by the dissolution of water on carbonate bedrock (Veni, 1990). The underlying area was an extensive and porous limestone which forced the tropical rainfalls to permeate into the aquifer below. Although many regions of the Yucatan contained fertile soils and an abundance of resources, they lacked one crucial resource required for existence – water. In the Puuc region in the Southern Yucatan there was a lack of virtually all water sources such as rivers, lacustrine, or ground water sources. Instead, the Maya were forced to rely on their ingenuity and engineering skills in order to sustain their growing populations. They were dependent on the collection, control, and manipulation of rainwater. At the time, rainfall was abundant for only six months at a time followed by a drought with virtually no rainfall. To compensate, the Maya mimicked natural water storage features by engineering a number of underground caverns, or manmade cisterns termed chultuns (Pulestun, 1970). These structures were a work of sophisticated engineering carved out of limestone bedrock. They were excavated into the hard surface caprock, followed by the softer marl composed of clay and silt. Large chambers were formed underground and covered in a waterproof lining of stucco. The Maya expertly engineered the area's surrounding structures such as stairways, rooftops, and walkways, with water paths in order to capture the rainfall and collect it in these chultuns. They were often fitted with rings and caps in order to prevent large particle contamination (Figure 4.8.2). Essentially, the entire hilltops of areas functioned as extravagant rain barrels. With an average capacity of 10,000 gallons of water per chultun, these ingenious water works were capable of supporting countless individuals for several months at a time. These advanced water management infrastructures formed a liquid foundation for life in countless Mayan communities. Secondary functions of chultuns have been hypothesized, such as using their internal microclimate for the fermentation of drinks which seems particularly favourable for such processes (Scarborough, 1998). Many chultuns were located in proximity of public ceremonial areas in the Mayan lowlands which supports this notion.

Figure 4.8.2: A chultun entrance with entryway channels, a ring and a cap to prevent contamination. Any rainfall would flow through the entry channels into the chamber below to be stored until the point of usage. This particular chulun is located in Xkipché, Yucatán, Mexico.

Remarkably, this sophisticated application of water technology during antiquity occurred prior to the development of concepts such as conservation of mass, energy, and momentum used in present-day hydraulic design (Puleston, 1977). Over the past decade archaeologists have made incredible discoveries of hydraulic engineering in Mayan hilltops. The particular locations appeared to be emitting water, although they were in an area of high elevation. It appears as if these hilltops were being sourced with water from hidden reservoirs at lower grounds. By some unknown mechanism, steady streams of water flowed against the force of gravity through man-made tunnels. These channels were of decreasing cross-sectional area, an innovation prior to the creation of Bernoulli's principle – one of the fundamental concepts of fluid dynamics thought to be beyond the times of antiquity (French and Duffy, 2014). The principle states that pressure and fluid flow are inversely proportional. In other words, as cross-sectional area decreases, the pressure exerted decreases along with it, and the flow velocity of a fluid increases (Serway and Jewett, 2012). Essentially, this is the earliest known form of engineered water pressure in the new world.The Maya were using physics concepts to control nature without the explicit knowledge of notions of such sophistication. In these waterways the Maya installed hydraulic structures made of rock in order to accelerate water to a higher velocity prior to diverting a portion of it into a channel of decreasing cross-sectional area in order to supply a water reservoir at a higher elevation (Scarborough et. al., 1995). In doing so, the Maya created a water infrastructure system that transported massive amounts of water from distant locations. Interestingly, it is estimated that these enclaves had been constructed and abandoned all before 1,700 CE, the same year as the birth of Swiss mathematician and physicist Daniel Bernoulli, the founding father of the research of modern hydraulic engineering (Pincus, 2013). The intricacy involved in the Mayan hydraulic systems demonstrates that their intellect was beyond their time. This allowed them to conceptualize and engineer such complex structures.

Structural Innovations

For survival, the Maya required dependable passageways and transportation routes in order to provide an uninterrupted flow of traffic for delivery of resources such as food. In order to solve this urban transportation problem the Maya constructed numerous bridges during their existence (O'Kan, 2012). These structures included short- and medium- span bridges to cross streams and canals, and small rivers respectively. A lost landmark of bridge engineering was uncovered in the last two decades by an engineer and archaeologist John O'Kan. The bridge suspended over the Usumacinta River (Figure 4.8.3) in Yaxchilan. It was the longest bridge discovered in the ancient world, constructed in the late 7th century, although little remains today of this unique structure. The rendering bridge supported a single level deck from shore to shore. It was composed of two bridge piers located in the river with struts on each bank. The bridge extended for a total of 113 meters, trumping all other bridge structures formed, and any subsequent bridges to be constructed until 1377 (Pendergast, 1990). The design requirements of such a large bridge established by these Mayan engineers parallel those of twentieth century design. With such designs, intense mathematical computation were required, ones which we did not previously believe the Maya were capable of. Such magnificent architectural achievements led to the rapid growth, power, and success of the Maya. Present day bridges in our world were inspired by those of ancient times, such as those created by the Maya.

Figure 4.8.3: The Usumacinta River today which spans from southeastern Mexico to northwestern Guatemala.

Ancient Technologies in Modern Days

In modern times, humans rely on extensive engineering infrastructure to make the lives we live possible. We often take for granted the complex technologies which make our lives simpler. For example, our transportation techniques and infrastructure such as bridges allow us to transport resources in a similar fashion to those of the Maya in ancient times. Residents of Canada may enjoy the sweet serenity of fresh fruit in the dead of winter. Similarly, residents of southwestern areas of the U.S. are able to sustain megacities and agricultural infrastructures located in desert-like areas. This is all thanks to complex modern transportation networks which allow us to transport products from faraway places, and the technologies that allow us to transport and store massive amounts of water from distant locations. The ancient transportation and water collection and storage innovations of ancient times such as those of the Maya have served as an inspiration for the technologies that simplify our complex lives today.

Figure 6.5.4: The Grand Coulee Dam located in Washington DC. With the application of simple Mayan technologies, it may be possible to successfully downsize such power generating facilities without compromising efficiency.

Figure 4.8.4: The Grand Coulee Dam located in Washington DC. With the application of simple Mayan technologies, it may be possible to successfully downsize such power generating facilities without compromising efficiency.

Power Generation

Furthermore, the innovations of the Mayan engineers may be applicable to power generation in our modern energy dependent world. Such applications could include the generation of small-site hydroelectric power. The channels designed by Mayans which transported water in an upward direction have potential to replace free-flow kinetic turbines with water tunnels along river and oceanic channels (Pincus, 2013). Hydroelectricity is produced by the movement of water which rotates a turbine, where the movement is converted to electricity with an electrical generator. It has been proposed that a low-head turbine may be almost twice as efficient as an open steam turbine often used today. A low head turbine is one which generally utilises low dams or low height water manipulations in order to generate power. If water can be redirected to reservoirs of higher elevation, even as little as 0.7 metres above the lower reservoirs, the efficiency of hydroelectric power can be increased, changing the face of power generation. Any water manipulations such as those of the Maya could potentially lead to changes in hydroelectric power generation used in our world today (Figure 4.8.4). In particular, if predictions of the Arctic ice melting are true then Northern Canada will soon have an abundance of locations in which such low head oceanic coastal power generation could be utilized. The pioneering hydraulic engineering of the Maya may

Figure 5.0.0: An artist's depiction of the early Earth. In just over four billion years, the Earth has progressed from a hot, lifeless planet to the harbouring the abundance of life seen today.

Chapter 5: Life on Earth

Perhaps what makes the history of the Earth so unique is the development of life. Our planet is the only one on which we know life to exist. Considering the great diversity of life that exists today, it is amazing to consider that just over four billion years ago, the planet was a hot mass of barren land, devoid of life. How did life develop from these seemingly inhospitable conditions?

The origins of life have always fascinated humankind, from the Greeks in ancient times and continuing to this day. One of the key debates has always been the one on spontaneous generation: does life arise spontaneously, or must it come from previous life? And later, having disproven spontaneous generation, where did the first life come from if all life comes from other life? Today, research into abiogenesis, the creation of first life from non-life, continues.

Besides how life arose, how life developed into the forms we see today is also of great interest. Conditions on Earth have varied from the extreme heat of the early Earth to the cold of widespread glaciation. Even today, there is a wide variety of conditions on Earth. One topic of great interest in origins of life research today is extremophiles. Since conditions on Earth during the early development of life were extreme in relation to conditions today, scientists study extremophiles in an attempt to understand possible characteristics of early life. However, life today is not exclusively extremophilic. Changing conditions on Earth have led life to evolve in many ways to fill the variety of environments on Earth. The conditions on Earth affecting these environments are linked to the Earth's geological history. Understanding the origins of life on Earth is a multidisciplinary endeavor: examining everything from the chemistry of abiogenesis; to the geology of Earth's tectonic plate movements, to the biological processes involved in responding to the environments these create.

The past few hundred years have seen great advances in our understanding of life and its origins. Research into extremophiles and abiogenesis has led to useful advances in the field of biotechnology, while our increasing understanding of geology and its effects on the development of life are relevant to today's life, which exists in an environment that continues to change. Most importantly, by furthering humankind's understanding of the origins of life, we are getting closer to understanding and appreciating our place in the universe.

The Evolution of Thought on the Origins of Life

"Intelligent life on a planet comes of age when it first works out the reason for its own existence," says Richard Dawkins in *The Selfish Gene* (2006, p.1). The origins of life has always been one of the greatest mysteries that humans have ever pondered upon and the answers have evolved just as quickly as the minds of mankind. Abiogenesis is the idea that life originated by the transition of living systems from non-living systems (Oparin, 1957). It has been the most common theory of the origins of life, though rigourously studied as a science only in the 19th and 20th centuries. Studying the origins of life is heavily theory-based since no one can ever observe the exact events that led to life on Earth as we know it. However, the process of thought that has developed around this topic truly identifies humans as intellectual living beings.

Abiogenesis in the Creation Myths

The theories of the origins of life trace back to human consciousness itself. The earliest accounts of these theories are contained in ancient myths and stories passed down by cultures to explain these mysteries. From the Egyptian Khnum to the Babylonian Lullu to the Yahwist accounts from the Old Testament, myths from around the world seem to have a common theme in which mankind and life itself have arisen from clay – a non-living material (Figure 5.1.1). Interestingly, the Greek word for people is *laos,* whereas the Greek word for stone is *laas* (Abel, 1973). It is clear then that humans have always had the idea that life must have been derived from non-living sources.

Figure 5.1.1: A depiction of Prometheus, a Greek mythical Titan sculpting humans from clay on a potter's wheel. The myth says that Athena breathed life into the humans once they were sculpted from the mud.

Aristotle's theory of Spontaneous Generation

One of the most influential opinions on the scientific perspective regarding the origins of life dates back to around 400 BCE, the time of one of the greatest Greek philosophers, Aristotle. Aristotle believed strongly in the idea of rational thinking and observations to answering life's mysteries in place of irrational mythical stories. He thought about known facts of his time and explained them through logical thought processes. He accounted the theories of the origins of life at the time and based on his scientific observations he asserted the theory of spontaneous generation (Hartman, Lawless and Morrison, 1987). This theory stated that life can be spontaneously generated from nonliving material continuously – for example, flies spontaneously emerging from rotting meat. The term spontaneous generation must not be used interchangeably with abiogenesis, since the theory of spontaneous generation asserted that life can arise from nonliving material at any point in time – some may go as far as to say that spontaneous generation occurs all the time. However, abiogenesis refers to the single event of transition from nonliving to living, at which point Charles Darwin's laws of evolution by natural selection takes course thereafter. Though spontaneous generation has since been proven wrong, Aristotle provided a working philosophy that stirred the minds of the scientists after him.

Scientific Demise

Due to the fall of Alexander the Great and the rise of the Christian doctrine, ideas that supported Greek methods of rational thinking and the ideas that opposed theories from the Bible came to a halt. It was considered taboo to ponder on theories outside of the church's set of beliefs, thus those thoughts were always kept in secret and experimental studies were never released. Every scientific study was only to be studied in the context of a theological problem. For example, Thomas Aquinas (1225-1274) dealt with the mystery of the origins of life and accepted Aristotle's theory of spontaneous generation in his preaching about the Devil, whom he believed tormented people in ways including letting living pests loose (Abel, 1973). Although the context of these ideas may not be scientific, the theory of spontaneous generation was still able to live through the time of scientific demise. It was not until a couple hundred years after the Medieval Ages in the 17th century that scientific experimentation become more common and respected, and it is during these times that the study of the origins of life grew rapidly.

Disproving Spontaneous Generation in the Lab

Since the theory of spontaneous generation survived through the times when science was looked down upon, the origins of life quickly became one of the most intriguing topics of study in science. The topic of spontaneous generation as a theory of the origins of life was revived in 1668 by Francesco Redi, an Italian physician. Redi found that covering a jar of meat with a veil of muslin stopped flies from laying eggs and reproducing, thus disproving Aristotle's theory (Keosian, 1968).

However, Redi's work was still debated within the scientific community and in 1860 the French Academy of Sciences offered the Alhumbert prize that intended to award a scientist that would shed more light on the topic of the origins of life. This stirred many scientists to rigorously develop methods of investigating the mystery, but it was Louis Pasteur's work that won him the prize. Pasteur supported Redi's claim that spontaneous generation of life is false as he developed his theory of biogenesis and stated that "life must only come from life" with his swan-neck experiment (Figure 5.1.2) (Oparin, 1957).

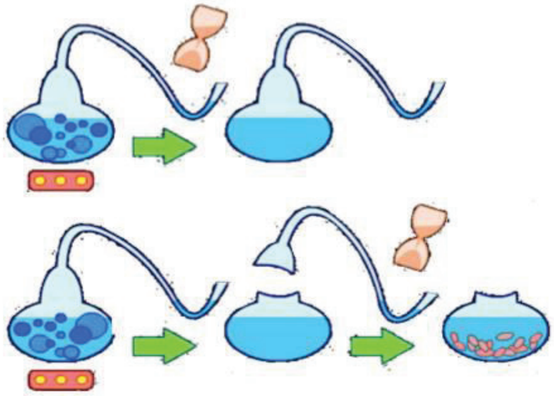


Figure 5.1.2: A schematic diagram of Louis Pasteur's experiment testing the theory of spontaneous generation using the swan-neck flask and mixtures of nutrients and water, which he called broth. He found that a flask with open access to the air grew bacteria while the untouched swan-neck flask remained sterile. This experiment provided evidence that there are invisible airborne organisms and brought Pasteur to theorize that "life must come from life".

Living versus Nonliving

The debate thus lay in the difference between the living and the nonliving. Jöns Jacob Berzelius in 1815 stated from observation that there is a clear delineation between the laws governing organic compound formation and the laws behind the formation of inorganic molecules (Hartman, Lawless and Morrison, 1987). Later in the century, Lionel Beale in 1871 took a step further and suggested that the living state is exclusive to living beings and cannot be imitated by a nonliving object. He reasoned that living beings must have been given *bioplasm* to give them living properties (Beale, 1871). More theorists throughout the years clearly rationalized that life is very different from nonliving, however it was not until the age of great biochemical discovery that the processes in living systems were revealed to be broken down into fundamental concepts in chemistry and physics.

Abiogenesis as an Integrated Science

With the scientific method becoming more organized and defined around experimental observations, the origins of life quickly became a hot topic in scientific research. The motivations of research in this field were originally for quenching the human thirst for knowledge. However, learning more about how life arose on Earth can give a better insight on how life may possibly arise on other planets. Studying the origins of life became a very interdisciplinary science, with research being done in areas including biology, chemistry, and geology. Since the theory of spontaneous generation had been disproven, the focus of studying the origins of life shifted to theorizing the pivotal moment in Earth's history – the moment when the first instance of life emerged on Earth. Therefore, learning more about the origins of life required a more detailed understanding of the history of the Earth and the conditions on Earth during the time that life first emerged. As a result, the scientific study of the origins of life progressed concurrently with the study of the history of the Earth.

The work of geologists, such as Rutten, in discovering the history of the earth was readily applied to understanding how life can emerge from it. As geological evidence of the conditions on Earth increased and as dating techniques become more advanced in the 20th century, so did the biological approach to the history of the Earth. One of the collaborative pivotal geological feats was the inference that the Earth must have been anoxic in the beginning of Earth's history. This was concluded as geologists noticed that feldspars, dark minerals, and sulphides are prominent in sedimentary layers dating back to early Earth's history. If the Earth's atmosphere contained a dominating amount of oxygen, then these materials would have been chemically weathered (Rutten, 1962). Inferences like these allowed biologists to think about what kinds of life may have formed under the conditions determined by geologists.

The work of Harold Urey and Stanley Miller in the 1950s reflects the direct application of the studies made by geologists on the history of the Earth. On the quest to learning more about how abiotic factors led to the formation of life, Urey and Miller wanted to investigate how the organic compounds necessary for life came about on Earth. They used the information that the Earth's atmosphere was made up mostly of methane, ammonia, water, and hydrogen; that the Earth was very hot; and that the Earth was subject to high amount of energy due to ultraviolet radiation from the Sun (Miller, 1954). They simulated these conditions in their chemistry laboratory at the University of Chicago (Figure 5.1.3) and successfully synthesized several amino acids – the monomers of all proteins in life on Earth. This laboratory experiment gained much interest from researchers studying the origins of life and although the experiment used wide assumptions and has various flaws, the study was very important in shedding more light to the scientific community of possible origins of life on Earth.

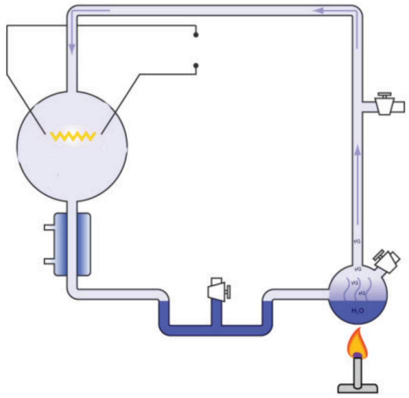


Figure 5.1.3: A schematic of the Miller-Urey apparatus used to synthesize organic compounds under primeval Earth conditions. The apparatus was anoxic, hot, exposed to radiation, and contained mixtures of methane, ammonia, water, and hydrogen.

The Symposium of the International Union of Biochemistry on the Origins of Life on Earth

Many more researchers all around the world have dedicated their careers in investigating the mystery of life in a scientific perspective. The growing community of research on this topic inspired Alexander Oparin, a leading Russian biochemist, to hold the Symposium of the International Union of Biochemistry in Moscow 1957. This symposium was introduced to get every leading researcher on the same page on the topic of origins of life. In this symposium, many topics were discussed pertaining to a wide range of topics such as the formation of the Earth, the atmospheric and other geologic conditions in the Earth's history, the formation of organic compounds, the history of photosynthesis and cellular respiration, and much more. This symposium is outlined in *Proceedings of the First International Symposium on the Origins of Life on the Earth*, a 656 page volume on the topics discussed during the symposium (Clark and Synge, 1959). Scientists from all around the world attended to share their research. The success of this conference is reflected in the amount of work that has progressed on the topic since then. Two more conferences have been held in 1963 at Wakulla Springs, Florida and in 1970 at Pont-a-Mousson, France – each with new contributions from researchers, young and old, to develop a grander understanding of the origins of life on Earth.

Future of Origins of Life Research

At the 1970 symposium, the International Society for the Study of the Origin of Life was founded by Oparin and has since then allowed for the rapid expansion of the science of the origins of life. Many theories about the origins life are openly accepted, such as the ideas of life originating from other planets or the ideas of life originating as extremophiles in deep hydrothermal vents. The true origins of life as we know it today can never be revealed, however as more information from every discipline of science grows, so does the capacities of the minds of humankind. The age old mystery of the origins of life continues to be a both a philosophical and scientific question, and no matter the perspective of the individual, mankind can continues to prove their intelligence as they develop a deeper understanding of their own origins.

Synthetic Biology: Human-made Organisms

The study of the origins of life has thus far been considered a study of the life on Earth that has already existed – an analytic approach to biology. The next step upon learning the history of life on Earth is in the investigation of the conditions that could give rise to any life in general – a synthetic approach to biology. Synthetic biology helps mankind understand how biology works by investigating the manipulation of life and the conditions by which life can remain extant. "The creation of small artificial [genetic] networks helps to analyse hypotheses on the function of natural ones," as Ron Weiss says in a Viewpoint article in Nature (Church et al., 2014, p.289).

Synthetic biology is the design or redesign of biological components such as enzymes, entire cells, and even entire organisms (Synthetic Biology Project, 2014). This designing and redesigning is done by manipulating the code that facilitates all life processes – the genetic code. The field of synthetic biology is a very hot topic in not only the scientific community, but also in humanities, social science, and in the general community. The study of how to manipulate the genetic code for human purposes raises countless debates in bioethics(Kaebnick and Murray, 2013).

It is a truly integrated science in the 20th century that requires concepts from all of engineering, biology, chemistry, physics, and even computer science. Upon developing a deeper understanding of the roles of genetics in the processes of life, synthetic biology is a logical next step in science.

Synthetic biology is analogous to computer programming. Much like how computer programmers compose code to be processed by a computer that will perform desired tasks, so does the synthetic biologist with DNA as the program language and the cell as the computer (Ginsberg, 2014). DNA is the genetic code by which all life as we know it functions. The code is simply composed of four nucleotide bases: adenine, thymine, cytosine, and guanine (Figure 5.1.4). Sequences of these four bases give rise to sequences of amino acids that eventually lead to functioning proteins that facilitate life – as outlined in the central dogma for molecular biology (Crick, 1970). By changing the sequences of DNA in certain genomes using modern bioological engineering technology, synthetic biologists are able to program the proteins expressed by a cell and ultimately control the living processes carried out by the organism.

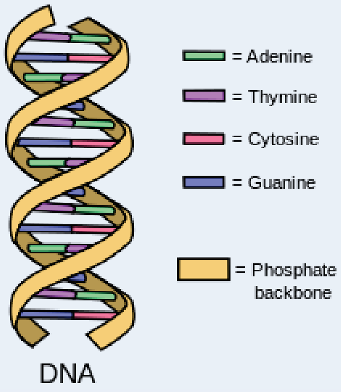


Figure 5.1.4: The double helix structure of DNA. The four bases are composed in varying sequences to give rise to various products upon transcription.

The manipulation of organisms can be applied in a variety of ways. Humankind has advanced science so much, however it is difficult to foresee the repercussions of our discoveries. A prime example is the discovery of the splitting of the atom. Companies in the synthetic biology industry such as the J. Craig Venter Institute advertise that their research is geared towards developing new medical solutions, solutions in food supply, and in engineering bioenergy – a possible new source of energy (JCVI, 2014). Though the prospects seem promising, there are many debates on topics such as possible escape of these synthetic organisms that can pose threats to public health and environmental issues due to the production and maintenance of these organisms. Further ethical issues include the manipulation of synthetic biology to create biological weapons in warfare – in fear that this will reflect the advent of nuclear chemistry and the atomic bomb in the early 1900s (Kaebnick and Murray, 2013). Synthetic biology is a very new discipline in science which means that humankind does not know what to expect from the future of this research. All that we know is that humankind once again has expanded their knowledge of the universe.

The History of Research on Thermophilic Microorganisms

It is almost universally understood that where water exists there will be bacteria; that extreme temperatures, acidity, and pressure is no barrier to bacterial life. However, this understanding is relatively recent. Less than 50 years ago it was still believed that temperature was an enormous barrier to bacterial life. In numerous publications Dr. Thomas Brock, a microbiologist, is credited with the discovery of thermophiles (Beal, 2014; Todar, 2012). Thermophiles are heat loving organisms, and interest in such organisms predated the research of Brock. Contrary to popular belief, the study of thermophilic organisms was already well established prior to Brock's research. This misunderstanding can be traced back to several elements. The first is that a well-established definition of a thermophile was not determined until much later and this definition still varies in literature today. Due to this controversy, early discoveries were classified as thermophilic, but were not necessarily thermophiles since the lack of a definition skewed early biological classifications. Additionally, Brock's research unveiled temperature records of life, which delineated a more specific temperature range and classification system of thermophiles. Thus, his research played an instrumental role in the development of today understanding and application of thermophilic bacteria.

Figure 5.2.1: View of Yellowstone hydrothermal features. Early explorers describe the scene as "the springs themselves were as diabolical in appearance as the witches cauldron in Macbeth, and need but the presence of Hecate and her weird bard to realize that horrible creation of poetic fancy" –Nathaniel Pitt Langford, 1871

Early Research

In the 1800s microbiology research was centred on the characterization and pathogenic nature of bacteria (Vinay, 1890). Sterilization techniques were of importance for both food and medical industries. In 1879 Pierre Miquel, a doctor of physical science and medicine, the head of micrographic services at the Montsouris observatory, and director of the bacteriology laboratory in Paris, was the first to publish work on thermophilic bacteria, (Bibliothèque nationale de France, 2014; Miquel, 1879). He reported cultivating the bacteria *Bascillus thermophiles* in broth at 74°C. He also reported findings on spores that could persist in temperatures up to 105°C. His research concentrated on the survival of bacteria at high temperatures, not continued habitation. Nonetheless, foundations of research on thermophilic bacteria were set. Laboratory based research in the late 1800s to 1900s was performed almost exclusively by food bacteriologists (Reysenbach, Voytek and Mancinelli, 2001; Gaughran, 1947). The result was the discovery of many species now classified as facultative thermophilic species. Meaning these organisms are able to sustain life at high temperatures and below the thermophilic range. The research determined 50°C being selected as the standard lower boundary for thermophiles which is consistent with the definition today.

This early research is often ignored in relation to ecological studies in geothermal environments that began in the late 1800s (Reysenbach, Voytek and Mancinelli, 2001). Yellowstone National Park became the epicentre for this research, with the highest concentration of geothermal features in the world. The source of Yellowstones geothermal energy is still debated (Fouch, 2012). However, it is generally accepted that Yellowstone is on a hot spot located over a mantle plume that formed approximately 16 Ma ago (Pierce, et al., 2007). This hotspot has shaped the geography of Yellowstone with volcanism, hot springs, active faulting, and uplift followed by subsidence (Figure 5.2.1). Hotspot volcanism produced rhyolitic lava creating the Yellowstone plateau. The hydrothermal features are formed by surface water flowing through the cracks and faults in the Earth's surface (Thermal Biology Institute, 1978). The magma chamber then super-heats the water, and convection currents return the water to the surface (Thermal Biology Institute, 1978; Kristjansson, 1991). The water dissolves minerals from the surrounding rock, such as rhyolite, which gives the thermal water a high silica content (Thermal Biology Institute, 1978).

Figure 5.2.2: Hot spring in Yellowstone (left). "Around the border of these springs, there is a striking variety of colors. I can only compare them to our most brilliant aniline dyes. Various shades of red, from the most brilliant scarlet to the light purple; also yellow, from deep sulfur through all the shades to light cream color; then also various shades of green." - Ferdinand Vandiveer Hayden, 1872

It was these geothermal features that interested early explorers in the late 1900s (Wylie, 1882; Langford, 1871; Tweedy, 1886; Hayden, 1872). Yellowstone was an area of mystery and wonder, with strange phenomena only found in geothermal regions. Most renditions of early explorations were extremely detailed and written rather poetically. Descriptions from early explorations noted the brilliant colours that cover the floor of the hot springs (Figure 5.2.2). Although most only captured the magnificence of the colours in their observations, others offered explanations for their presence. Explorers Langford and William Wallae Wylie suggested that different colours were different types of sediment (Langford, 1871; Wylie, 1882). Biologist Frank Tweedy noted that the geyser and hot spring environments have unique flora (Tweedy, 1886). It was Walter Harvey Weed who first remarked that the coloured "sediment" was algae capable of surviving in the hot mineralized waters (Weed, 1889). From the 1880s to 1950s research progressed in laboratory and field settings without spectacular results. Research in the 1960s presented a maximum temperature for thermophilic microorganisms of 73°C (Brock, 1967). It was at this time that Brock began his work in Yellowstone.

Thomas D. Brock

Brock began his scientific career in 1951 as a microbial physiologist, and did extensive work in molecular biology and microbial genetics through the 1960s (Brock, 1995). However, he had always been interested in exploring microbes in outdoor environments. In 1963 he began his work in microbial ecology, the study of microbes in their natural environments. For approximately 10 years Brock concentrated on hot springs and geyser environments in Yellowstone National Park. When he began his work thermophilic bacteria were thought to live at an optimum temperature of 55°C and the maximum temperature for life was thought to be 73°C.

Brock's research was originally centred on the distribution of photosynthetic microorganisms along thermal gradients, looking at their distribution according to niche spaces. The discovery of "extreme thermophiles" was unexpected. While well examining the distribution of photosynthetic life, Brock discovered large amounts of pink filamentous bacteria at temperatures of 82°C–88°C (Figure 5.2.3). He observed and characterized these bacteria in their natural habitats; however, was unable to cultivate them in laboratory conditions. For this reason Brock concentrated his work on the bacteria *Thermus aquaticus* which was found at temperatures between 70–73°C.

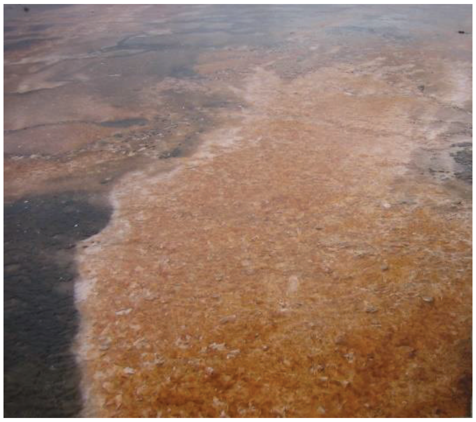


Figure 5.2.3: Bacterial mat in Yellowstone National Park. These bacteria would appear similar to the pink thermophilic bacteria Brock discovered.

His research with Dr. Hudson Freeze on *T. aquaticus* demonstrated optimum growth temperatures at 70°C and the ability to grow at temperatures up to 79°C (Brock, 1995).

T. aquaticus is the source of *taq* polymerase applied in polymerase chain reaction (PCR) a technique used to amplify genes (van den Burg, 2003; Gomes and Steiner, 2004). *Taq* polymerase allows for a cycle to be developed that alternates steps of DNA denaturation and DNA synthesis to amplify a specific gene. This process is possible as DNA denatures at temperatures at which *taq* polymerase is still stable. This application promoted thermophilic research.

Near the end of 1967 Brock began using a sensitive immersion slide technique to demonstrate the presence of bacteria in boiling water (Brock, 1995). He discovered that although there were not bacteria present in macroscopic quantities, there were bacteria living in boiling water in every hot spring he tested. In 1969 Brock measured the growth rates of these bacteria proving they were growing at such temperatures (Bott and

Brock, 1969). In Yellowstone water boils at temperatures of about 92.5°C due to altitude limiting explorations for a maximum temperature in this location. Brock's discoveries were classified as hyperthermophiles in later papers, organisms that can thrive at temperatures of 80°C. However, his discoveries are not considered to be hyperthermophiles by the temperature standards applied today which require temperatures of 90°C (Reysenbach, Voytek and Mancinelli, 2001). Brock's initial findings sparked the beginning of hyperthermophile research. The discovery of hydrothermal vents in the 1970s confirmed many of Brock's hypotheses. It was Karl O. Stetter's work with hot springs in Iceland in 1981 that is today credited with the discovery of the first hyperthermophile as the bacteria Brock found in boiling water remained uncategorized (Stetter, 2006; Clarke, 2014).

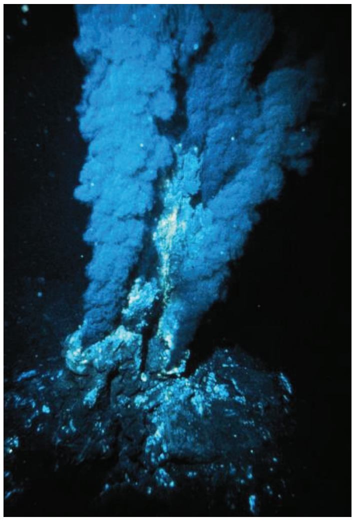


Figure 5.2.4: Image of deep-sea hydrothermal vents. The clouds in the water are minerals precipitating due to the change in temperature.

Hydrothermal Vents

Hydrothermal vents were discovered by a group of scientists from Oregon University and published in 1977, noting life in these extreme environments (Lonsdale, 1977). Deep-sea hydrothermal vents form along divergent boundaries producing new seafloor crust or as a plate moves over a hot spot. Faults or fissures in the crust permit water to permeate into the rock. The magma chamber and heated rock heats the water, which can then react with the rock adding minerals and gases (iron, manganese, carbon dioxide, hydrogen and hydrogen sulfide) and removing sulfate and magnesium (Kristjansson, 1991). The water is then forced to the surface. Temperatures at hydrothermal vents temperatures can reach over 400°C due to the pressure at these depths. The mixture of hot water and cold ocean water results in the precipitation of minerals out of the water (Figure 5.2.4). *Methanococcus jannaschii* was the first thermophilic microorganisms characterized from hydrothermal vents in 1983 (Clarke, 2014). Research on these unique life forms has now discovered thermophilic Achaeans that can grow at temperatures of 122°C, the current maximum for life forms.

Discovery of Archaea

In 1977, research on thermophiles overturned a major dogma of biology. Dr. Carl Woese discovered that there are three domains of early life, not just eukaryotes and prokaryotes, through sequencing of ribosomal RNA. This research led to the current classification system of: Eukarya, Bacteria and Archaea. Archaea were originally thought to only exist in extreme environments, as the first members of the domain were found in hyperthermophilic conditions (Woese, 1977).

Woese's discovery of Archaea sparked many new theories on the origin of life. Through ribosomal RNA sequencing it was determined that hyperthermophiles are the oldest extant organisms found on Earth (Frock and Kelly, 2012; Miller and Lazcano, 1995). This relationship resulted in many speculations about early Earth conditions and the types of metabolisms and physiologies present (Forterre, 1996; Frock and Kelly, 2012). This was not the first proposed thermophilic origin for life, in 1924 Harvey similarly proposed thermophilic origins of life (Harvey, 1924; Miller and Lazcano, 1995). Theories on the origin of life are still disputed today. Hyperthermophile research provides a look at Earth's past and is also being applied for a better future in industrial applications today.

Bioapplications of Thermophilic Enzymes

The discovery and application of *taq* DNA polymerase in PCR sparked an interest inthermophilc bacteria in the field of enzymology (Adams, Perler and Kelly, 1995; Niehaus, et al., 1999). The study of extremophile enzymes has various plausible bioapplications in extreme industrial conditions. The biocatalysts that function in these conditions have been labelled extremozymes. (Adams, Perler and Kelly, 1995). The study of extremozymes is a rapidly expanding field (Adams, Perler and Kelly, 1995; van den Burg, 2003; Gomes and Steiner, 2004; Niehaus, et al., 1999). Thermophilic extremozymes have attracted significant attention due to the advantages of conducting industrial processes at high temperatures.

High temperatures are associated with increased solubility, increased bioavailability, faster rates of reactions, and decreased risk of microbial contamination (Danson and Hough, 2000). The market for thermostable enzymes in the USA was approximately 250 million dollars annually in 2010 and expanding (Prakash and Jaiswal, 2010). Enzyme biotechnologies provide an opportunity to create more efficient industrial processes and replace processes with high environmental impacts (Ahuja, Ferreira and Moreira, 2004).

Thermophiles live in environments where regular enzymes would denature and be non-functional (Adams, Perler and Kelly, 1995; van den Burg, 2003; Gomes and Steiner, 2004; Niehaus, et al., 1999). As a result their enzymes are hyperstable (Danson and Hough, 2000; Synnes, 2007). Some structural features explaining this are: increased surface charge, increased protein core hydrophobicity, decreased flexibility, and smaller surface loops. For processes such as the degradation of starch and cellulose to glucose, high temperature conditions are preferred (Adams, Perler and Kelly, 1995; Bertoldo and Antranikian, 2002; Gomes and Steiner, 2004; Niehaus, et al., 1999; Prakash and Jaiswal, 2010). Enzymes are also applied in detergents, brewing, baking, chitin modification, and oxidation reactions.

Industrial Applications

Starch industries are a major consumer of thermostable enzymes. (Bertoldo and Antranikian, 2002; Prakash and Jaiswal, 2010). Starch is composed of α-glucose units connected by 1-4 or 1-6 glycosidic bonds. Depending on the linkage type this can be divided into polymers of amylose and of amylopectin correspondingly. There are many types of enzymes that can hydrolyse these linkages into oligo and/or monosaccharides. Among these enzymes is α-amylase. α-amylase hydrolyses linkages randomly in the starch forming linear and branched oligosaccharides. α-amylase is found in many bacteria, fungi and Achaea (Bertoldo and Antranikian, 2002). Thermostable α-amylases have been characterized in the hyperthermophile *Pyrococcus woesei* with optimal activity ranges at 100°C. The process of the conversion of starch to glucose gelatinizes and liquefies at temperatures of, 110°C and 95°C respectively. α-amylase and other thermostable starch hydrolysing enzymes complete this process using enzymatic catalyzation (Bertoldo and Antranikian, 2002; Prakash and Jaiswal, 2010). The glucose can be used in multiple processes afterwards such as fermentation in biorefineries. Prior to the discovery of thermostable enzymes this process was completed using acid hydrolysis (Prakash and Jaiswal, 2010). The replacement has alleviated the need for corrosion resistant materials, the necessity of removing salts, higher energy consumption, and is easier to control.

Amylolytic enzymes are also being used in the textile, paper and baking industries (Adams, Perler and Kelly, 1995; van den Burg, 2003; Gomes and Steiner, 2004; Niehaus, et al., 1999). Cellulolytic enzymes are used in brightening detergents, bio-stoning of jeans, and pretreatment of plant biomass. Other enzymes such as xylanases have greatly reduced pollution in the bleaching of pulp and paper by replacing halogen use.

Environmental Considerations

Enzyme technologies offer industrial alternatives that reduce the use of toxic chemicals, can enhance the efficiency of waste treatment, and can be used as tools in environmental monitoring (Ahuja, Ferreira and Moreira, 2004). The advantages to using enzymes include: their high specificity, reducing by-products, and their biodegradability. It has been suggested that enzymes could be used to remediate environments with high levels of pollution.

The applications of thermostable enzymes are extensive and have the capability to reduce the environmental impacts of many industrial processes (Ahuja, Ferreira and Moreira, 2004). However, these enzymes are harvested from organisms living in delicate geothermal environments (Synnes, 2007). Hot springs and deep sea hydrothermal vents are explored for research activity and bio prospecting. The microorganisms found in these regions are often unique and have evolved to specific environments. Extensive sampling of these regions could easily disturb or destroy these ecosystems. Advancements in molecular biology alternatively allow genes to be spliced into alternate microorganisms for expression. Sustainable techniques are necessary to maintain the ecosystems of thermophiles.

From Hutton to Wilson

Richard Feynman, a world renowned theoretical physicist, probably put it best when describing the knowledge we hold about what happens beneath our feet, "strange as it may seem," he wrote, "we understand the distribution of matter in the interior of the Sun far better than we understand the interior of the Earth" (Feynman, Leighton and Sands, 1995). Until very recently, we understood little about plate tectonics. The idea that continents move about, collide, and retract on Earth's surface, known as the super continental cycle, has become common knowledge for just about half a century. To understand the birth of the super continental cycle, one must examine the geologic theories that predated it.

Figure 5.3.1: A portrait of the famous geologist Charles Lyell (Wikimedia Commons, 2015)

Geology is a relatively new discipline of science, tracing its roots back to the turn of the seventeenth century with the work of James Hutton (Former Fellows of the Royal Society of Edinburgh, 2006). He almost singlehandedly created the science of geology with his 1795 masterwork titled, *A Theory of the Earth with Proofs and Illustrations* (Royal Society of Edinburgh, 2006). Soon after the simplified exposition of the Huttonian principals were published by John Playfair in 1802 (Geologic Archive, 2015), geology began to gain popularity. The Geological Society was born in 1807 out of the Freemasons Tavern at Long Acre in Covent Garden as a dining club where like-minded individuals could share geological findings and theories (Woodward, 1907). Geology positively gripped the nineteenth century, and grew in ways never before seen in any scientific discipline. To gain perspective of the geological fervor of the time, in nearly a decade of existence, the membership of the Society grew from thirteen to four hundred, and by 1830, and rose to a staggering 745 (Woodward, 1907; Bryson, 2003). The growth of the field was predominantly due to gentlemen with wealth looking for a professional hobby, rather than particular scientists interested in geologic theories and minerals.

A particularly influential man who also succumbed to the geological enthusiasm of the time was Charles Lyell. Lyell was born in 1797 in the village of Kinnordy, Scotland (Bailey, 1962). His father first introduced him to natural history through his study of botany (Bailey, 1962). His devotion to geology however began during his enrolment in Oxford, where he was introduced to Reverend William Buckland (Bailey, 1962). Lyell decided to accompany the Reverend on a tour of Scotland in 1824, and reportedly decided to abandon his previous career in law soon after the trip to study geology. His most revered work was his paper titled *The Principles of Geology*, published in 1830 (Public Broadcast Serive, 2015). The volume concisely elaborated on Playfair's and Hutton's original ideas of uniformitarianism. During the time that the volume was published there existed a long running dispute between two schools of thought, namely uniformitarianism and catastrophism. Catastrophists believed that the Earth was shaped by a myriad of catastrophic events such as floods (Cannon, 1960). Catastrophism was popular since it allowed religious scientists to provide scientific evidence for certain biblical events, such as Noah's flood. Uniformitarians believed that the processes that formed Earth occurred gradually and slowly, over immense spans of geologic time (Cannon, 1960). In other words, uniformitarians believed events that occurred in the past could be explained by the events occurring present day. Lyell's work was a step forward in the uniformitarian direction. It suggested that the Earth must be much older than originally thought (most believed it to be in the tens to hundreds of millions) in order for the geologic timescale to conform to the theory, which would ultimately prove to be correct (Cannon, 1960).

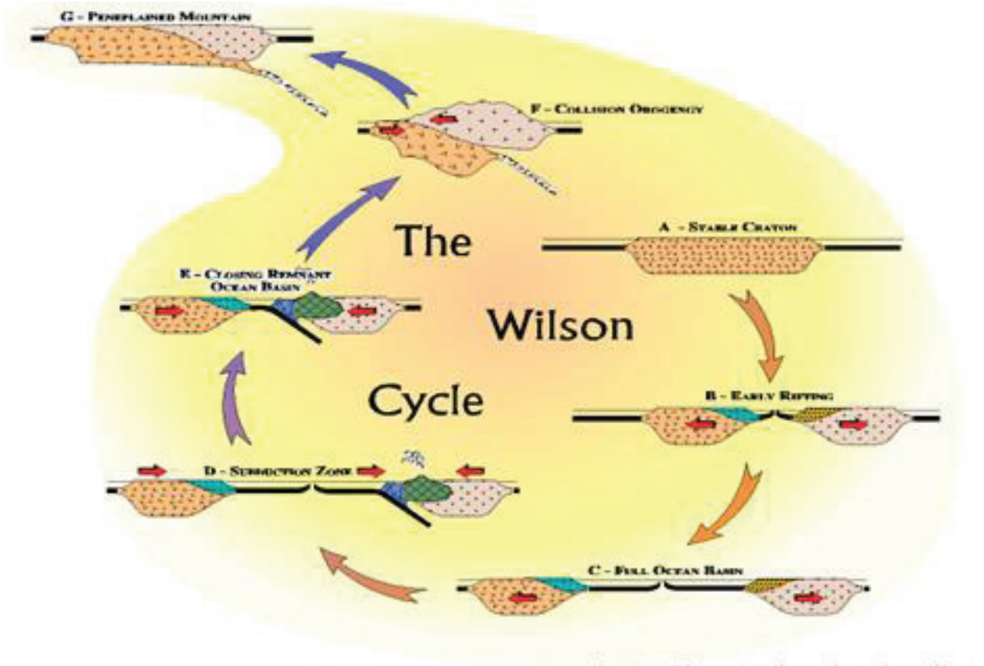
Following alongside the geological craze of the late eighteenth century and early nineteenth century was a paleontological revolution. Unknown to the geologists of the time, fossils held more clues about the geologic past than the mere anatomical make-up of the creatures that once roamed its surface. A particular Englishman named

William Smith was able to decipher the obscure clues fossils withheld. Although geologists at the time were becoming more accurate at classifying rock strata, the technological limits of the time hindered the geologists in their ability to tell which rock strata were younger than one another. Smith ingeniously theorized that there must be a means of correlation, a way to tell that the rocks from the Devonian are younger than the rocks from the Cambrian (Bath Royal Literary and Scientific Institution, 2015). He noticed that at every change in rock strata certain fossilized species became extinct, while other lived on into upper layers of the stratigraphy (Bath Royal Literary and Scientific Institution, 2015). One could work out the relative age of the geologic strata by investigating the fossils within. Smith, using his newly discovered technique, published a map of Britain's rock strata in 1815, which would become historically revered and solidify his place as one of the founders of modern geology (Bath Royal Literary and Scientific Institution, 2015). Smith's discovery would become another cornerstone of the super continental cycle, as one could now examine the rock strata of locations around the world and know their relative age and position within the geologic timespan, which is particularly useful when examining the geologic relatedness of two locations.

During the nineteenth century contractionism was the prevailing fixist geologic theory on the creation of Earth and its landmasses (Solomon, 1992). Fixism was the prominent school of thought in terms geologic continents, maintaining in the belief that Earth's continents remained fixed in relatively the same place since their formation (Engelhardt and Zimmermann, 1988). Contractionism conformed within the bounds of fixism (Engelhardt and Zimmermann, 1988). It was made famous by an influential European geologist named Eduard Suess, and his ideas contained many elements of the modern super continental cycle (Solomon, 1992). Contractionism is the belief that the Earth is constantly cooling down, causing contraction (Frankel, 2012). The process can be visualized by the "baked apple" analogy; if one were to bake an apple then let it cool, it would wrinkle. Many geologists such as Suess believed that as the molten Earth cooled, it created ocean basins and mountain ranges. However, the theory, albeit a good one for the time, was highly debated. Suess failed to take into account the work Rutherford and Soddy had done discovering and classifying the elements that existed on the Earth and understanding how some were capable of holding large reservoirs of heat from escaping into space (Wilson, 1983; Frankel, 2012). Another opposing point is that mountains were not evenly distributed of the Earth's surface as they should have been according to Suess' theory (Frankel, 2012). In the early nineteen hundreds there existed evidence that the age of mountain ranges differed by millions of years, which contradicted Suess' theory as the mountain ranges that were believed to have formed by contraction should have all been the same age (Frankel, 2012). Nevertheless, some of his ideas persisted into modern geology. He postulated the existence of the Tethys Ocean, which once existed between India and Asia (Judd, 1914). He was also the first to (unknowingly) name the first super continent, Gondwanaland, comprised of Africa, Madagascar, Arabia, India, New Guinea, Australia, and part of South America (Frankel, 2012). His postulation was based of the existence of disjunctive biota; the presence of similar fossilized species on different landmasses separated by oceans, a key idea in the growing mobilization movement (Frankel, 2012). His ideas laid down the framework by which the super continental cycle would soon be born.

Figure 5.3.2: A portrait of the famous fixist geologist Eduard Suess (Wikimedia Commons, 2015).

Mobilism is the view that the continents are gradually moving along the Earth's surface. It is the theory that now holds today, and was first presented in the nineteenth century. However, without the existence of scientific evidence, it was hardly supported compared to the theory of contractionism. The first real proposition of mobilism came in 1908 by an American geologist named Frank Bursley Taylor (Miller, 1983). He proposed to the Geological Society of America that year that continents move on the Earth's surface, analogous to how ice moves on the surface of



http://geollab.jmu.edu/Fichter/Wilson/wilsoncircl.html

Figure 5.3.3: An illustrati the retraction and collision of contienents, named the Wilson cycle after the geologist J. Tuzo Wilson (James Madison University Geology, 2015).

water (Miller, 1983). He also suggested that such movements and collisions produced the world's mountain chains (Miller, 1983). He was struck by the similarity in shape between the opposing coastlines of South America and Africa, however lacked the evidence to support his claims. Taylor's theory had an impact on the mind of a certain meteorologist at the University of Marburg, Alfred Wegener. Wegener was also interested in the shape of Africa and South America, specifically how they seemingly fit like a geologic jigsaw puzzle (Wegener, 1966; Pangaea.org, 2015). He also realized that fossil evidence seemed to favour a mobilist theory, as similar species appeared in the strata of both continents, much too far to swim (Pangaea.org, 2015; Wegener, 1966). He was also puzzled by the fact that marsupials existed in the geologic record on both South American and Australian continents, as well as identical snails inhabiting Scandinavia and New England (Wegener, 1966). During the time many geologists dismissed such evidence through the fixist idea of intercontinental land bridges where species could have travelled between continents before the bridge was once again engulfed by the ocean (Frankel, 2012). In 1912 Wegener proposed that the continents had once existed as a single landmass called Pangaea, where flora and fauna could intermingle on each continent (Frankel, 2012; Wegener, 1966). Wegener's theory sparked debate, as not only did the tide turn in favour of the mobilists, he also proposed that the continents could move sideways not only up and down as precious mobilists had believed (Wegener, 1966). However he had difficultly providing an ample explanation for how the continents could move so readily across the surface. Arthur Holmes, an English geologist, insightfully proposed that radioactive warming could produce convection currents in the Earth strong enough to move continental crust (American Museum of Natural History, 2015). He published the textbook *Principles of Physical Geology* in 1944, which contained the theories for continental drift more or less that prevail today (American Museum of Natural History, 2015).

Despite the progress, scientists still had to answer the looming question of where all the sediments went after being deposited in the oceans. Harry Hess was the first to discover that the sea floor was not covered in sediments, but was rather a string of canyons and trenches (Geologic Society, 2015). He was also the first to discover the presence of Mid Ocean Ridges, publishing his findings in *The History of Ocean Basins* in 1962, outlining the theory of sea floor spreading. A few years later the debate between fixism and mobilism came to an end with a symposium in 1964 under the auspices of the Royal Society, in which mobilism was declared the victor. A Canadian geologist named John Tuzo Wilson proposed the supercontintal cycle, also named the Wilson cycle. He was a key proponent of plate tectonics, introducing hotspots when fixists argued the existence of volcanoes in the middle of a plate rather than a subduction zone (College of Earth and Mineral Sciences, 2015). In his paper, *Did the Atlantic Close and then Re-open?* published in 1966, Wilson indicated the presence of an earlier Atlantic ocean that was closed by continental drift then re-opened (Wilson, 1966: Damian Nance and Brendan Murphy, 2013). His work was used to categorize the world's oceans in terms of a cycle where supercontinents are formed, break up, and then are reformed (Wilson, 1966). Therefore the super continental cycle was born using evidence and theories proposed since the study of geology was pioneered by James Hutton in the seventeenth century. Today the cycle is well supported, and geologists are creating models that predict the supercontinents that will form in Earth's future (Damian Nance and Brendan Murphy, 2013).

The Return of the Supercontinents

Geoscientists have predicted that within the next 50 to 200 million years all of Earth's landmasses will reform into a supercontinent named Amasia (Mitchell, et al., 2014). There exist multiple models that predict the way in which Amasia will amalgamate; the introversion model, the extroversion model, and the relatively new orthoversion model (Murphy, et al., 2003; Mitchell, et al., 2013).

The extroversion model predicts that the continents that broke apart after the separation of Pangaea will continue to drift apart until they collide on the opposite side of the globe (Hartnady, 1991). This is caused by the subduction of oceanic lithosphere surrounding the supercontinent (Murphy, et al., 2013). Murphy describes this process as "top-down" geodynamics, where a supercontinent breaks up over a geoid high, and reforms above a geoid low (Murphey, et al., 2013). The introversion model predicts that the continents that split apart after the separation of Pangaea will not continue to drift apart, but rather amalgamate where Pangaea rifted (Nance, et al., 1988). This is because the oceanic lithosphere formed between dispersing continents, forming an interior ocean, is preferentially subducted (Murphy, et al., 2013). Introversion requires that slab-pull and ridge push, forces which act in concert during the break up of a supercontinent, must be overcome. Slab pull occurs when the cooling oceanic crust is subducted beneath the continental crust and begins to sink, causing it to pull the continental crust downwards as well (University of Guelph, 2015). Ridge push is the gravitational force that causes a plate to move away from the crest of an ocean rideg into a subduction zone (University of Guelph, 2015). Murphy and his team speculate that continental reversal required for introversion can be induced by slab avalanches (Murphy, et al., 2013). The slab avalanches trigger the rise of superplumes of magma from the core-mantle boundary (Murphy, et al., 2013). The orthoversion model predicts that Amasia will form 90^0 away from where Pangaea was formed, within the circle of subduction surrounding the rift locations of Pangaea, illustrated by Figure 5.3.4 (Mitchell, et al., 2012). The team calculated the minimum moment of inertia about which oscillatory true polar wander occurs, and by fitting great circles to each of the past supercontinent's true polar wander legacy, the team was able to determine the arc distances between subsequent supercontinent centers (Mitchell, et al., 2012). The arc distance between Rodinia to Pangaea was 87^0, and the arc distance between Nuna and Rodinia was 88^0, consistent with the hypothesis offered by the orthoversion model (Mitchell, et al., 2012). The introversion and extroversion models simply forecast the closures of either the Pacific or Atlantic oceans, with the continent remaining relatively within the same hemisphere (Mitchell, et al., 2012). The orthoversion model predicts that the Americas will amalgamate with Asia, which will remain within the Pacific ring of fire while the Caribbean and Artic oceans are closed off (Mitchell, et al., 2012). The orthoversion model is important as it proposes a structure to the super continental cycle, as it is often assumed that it operates randomly.

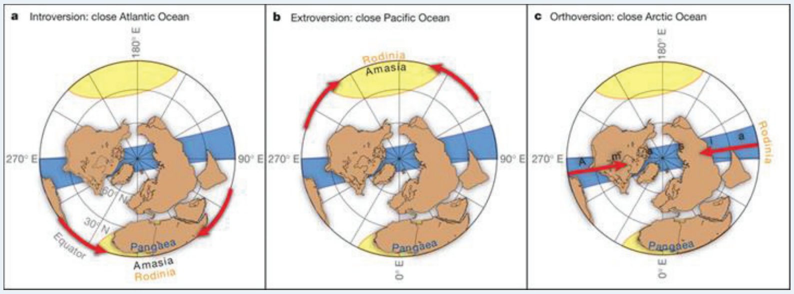


Figure 5.3.4: A comparison of the three models predicting the location of Amasia. Left) Introversion model, Center) Extroversion model, Right) Orthoversion model (Mitchell, et al, 2012).

The Separation of Pangaea: Theories and Influences on Evolution

Over 200 million years ago, the surface of the Earth looked much different than it does today. Generally, the idea of changing conditions on Earth has been present within the scientific community since the 16th century; however, there was great debate over the mechanisms by which Earth's current appearance came to be. Additionally, the theories that account for the changing form of the Earth's surface have been extended and elaborated to include and explain the potential mechanisms by which species have developed and evolved.

Early Hypotheses

Abraham Ortelius, a Dutch cartographer, was the first to notice and publish on the existence of homologous coastlines of South America and Africa in *Thesaurus Geographicus* in 1596 (Smith, 2011). Over the course of the following 300 years, other scientists made similar observations, but it was not until 1912 that this observation became the foundation of the "theory of continental drift," courtesy of Alfred Wegener (Figure 5.4.1) (Marvin, 1973). Wegener and his predecessors suggested that the South American and African continents had previously been connected due to the similarities in their coastlines (Marvin, 1973).

Figure 5.4.1: A portrait of Alfred Wegener (1880-1830) in 1910, the father of the Theory of Continental Drift (Marvin, 1973).

During these same 300 years, other scientists were proposing alternative theories as to how the Earth's current layout came to be. One of these scientists, James D. Dana, proposed continental evolution in accordance with the belief that Earth's surface structures formed as a result of cooling the once molten Earth (Dott, 1997). Dana's theory also encompassed the idea of the divine creation of Earth's structures, opposing the ideas previously described by Ortelius and others (Dott, 1997).

The theory hypothesized by Wegener was supported by evidence from various scientific disciplines, ranging from geology and climate reconstruction to biology and paleontology (Marvin, 1973). The publication of Wegener's hypothesis occurred at a time when other geologists were beginning to question previous theories of the evolution of Earth's surface as a result of new scientific findings (Marvin, 1973). However, Wegener's ideas were not widely distributed due to the publication and distribution restrictions of the First World War and also as a result of their criticisms within the scientific community (Newman, 1995).

Wegener's rejection of previous theories of vast "land bridges" and sinking continents caused much controversy (Newman, 1995). At various geologic conferences, experts of the time refuted Wegener's proposal on the basis that he hadn't presented a mechanism of adequate strength by which these events could have occurred (Du Toit, 1937). Thus, publications by Wegener's rivals continued citing the works of Dana and other accepted theorists to promote their argument (Newman, 1995).

Despite the unrest caused by his publication, Wegener persisted and continued to publish revisions of *The Origin of Continents and Oceans* (Du Toit, 1937). Each edition addressed the most recent controversies surrounding his theories in attempt to clarify them and convince the scientific community of the plausibility of his hypotheses (Du Toit, 1937). Wegener's theories were greatly debated and questioned until the mid-1960s, at which time enough additional evidence had been collected through the study of stratigraphy, seismic activity, paleomagnetism, and deep ocean geology to convince the scientific community to support Wegener's hypothesis (Marvin, 1973).

Although Wegener's hypothesis was

eventually accepted, its title has since been altered to more accurately describe the movement of continents (Marvin, 1973). The term “continental drift” suggests that continents move gradually by their own free will; however, their displacement along Earth’s crust is actually a result of active tectonic plate movement (Marvin, 1973). Thus, the theory has been deemed “plate tectonics” (Marvin, 1973).

Evidence of Pangaea

After establishing a theory to explain the mechanism of formation of the current continents, it is possible to reconstruct previous versions of the Earth’s surface. This is the basis by which geologists, including Wegener, were able to fuse the current continents together, forming the most recent supercontinent to exist on planet Earth, Pangaea (Marvin, 1973). Pangaea is proposed to have existed from the Late Permian period at the end of the Paleozoic era through to the Triassic period at the beginning of the Mesozoic (Collins, 2003; Fooden, 1972). It was composed of two sub-continents, Laurasia and Gondwana, from which the current continents were derived (Hallam, 1983).

Wegener’s theories, which were further supported by Alex L. Du Toit and others, proposed a reconstruction of Pangaea based upon geologic evidence (Du Toit, 1937). In his publication entitled *Our Wandering Continents*, Du Toit proposed that different climatic zones existed within Laurasia and Gondwana, and the climates cycled differently to produce different stratigraphy within each land mass (Du Toit, 1937). Using this idea and the concept of polar wandering set forth by Wegener, Du Toit was able to trace the stratigraphy across the continents (Du Toit, 1937). In doing so, Du Toit deduced that each continent’s distance from the poles must have varied over time in order to account for the changes in stratigraphy (Du Toit, 1937). Thus, Du Toit concluded that the positions of continents are not fixed.

A significant difference between the theories proposed by Wegener and Du Toit surrounds each scientist’s proposed direction of separation of Pangaea. Wegener proposed that the continents first split to form what is now the Atlantic Ocean, whereas Du Toit put forth the idea that Laurasia had drifted northward and Gondwana southward (Figure 5.4.2) (Du Toit, 1937). Regardless of this discrepancy, Du Toit’s research further supported the idea of “mobile continents” and continued to oppose the theories set out previously.

Promoting Speciation

In *The Origin of Continents and Oceans*, Wegener did not offer much biological evidence to support his theory of continental drift.

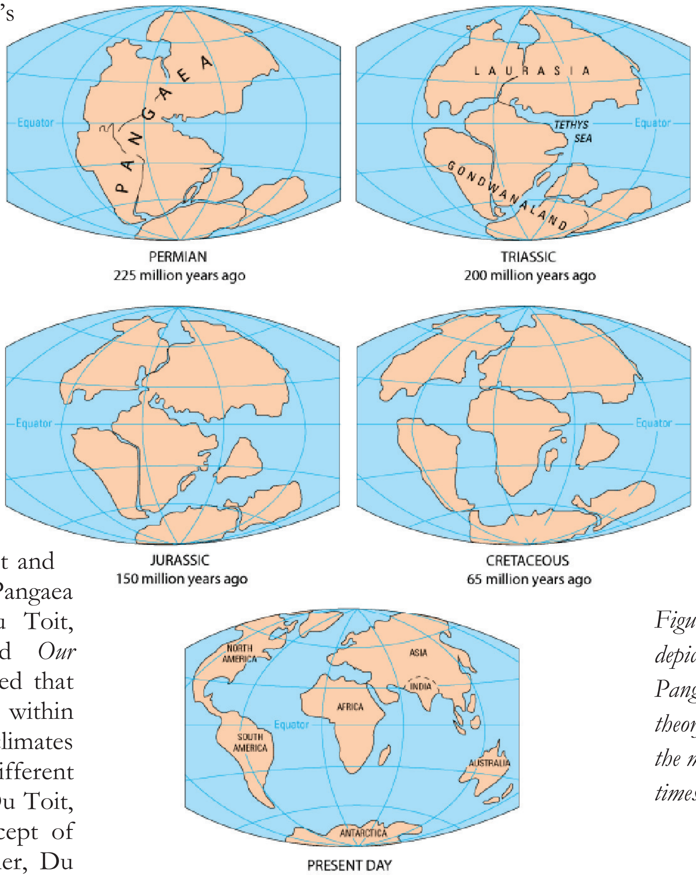


Figure 5.4.2: A graphical depiction of the separation of Pangaea, based upon the theory set out by Du Toit and the modern proposed timescale.

However, other scientists of the time were making observations that would have aided in his argument. Although his observations were made prior to the publication of *The Origin of Continents and Oceans*, Charles Darwin was the first to document biologic evidence to support the theory of plate tectonics (Darwin, 1836-1844). Though very primitive, Darwin’s observations provide supportive evidence and serve as a foundation for divergent evolution and speciation as a result of shifting continents (Darwin, 1836-1844).

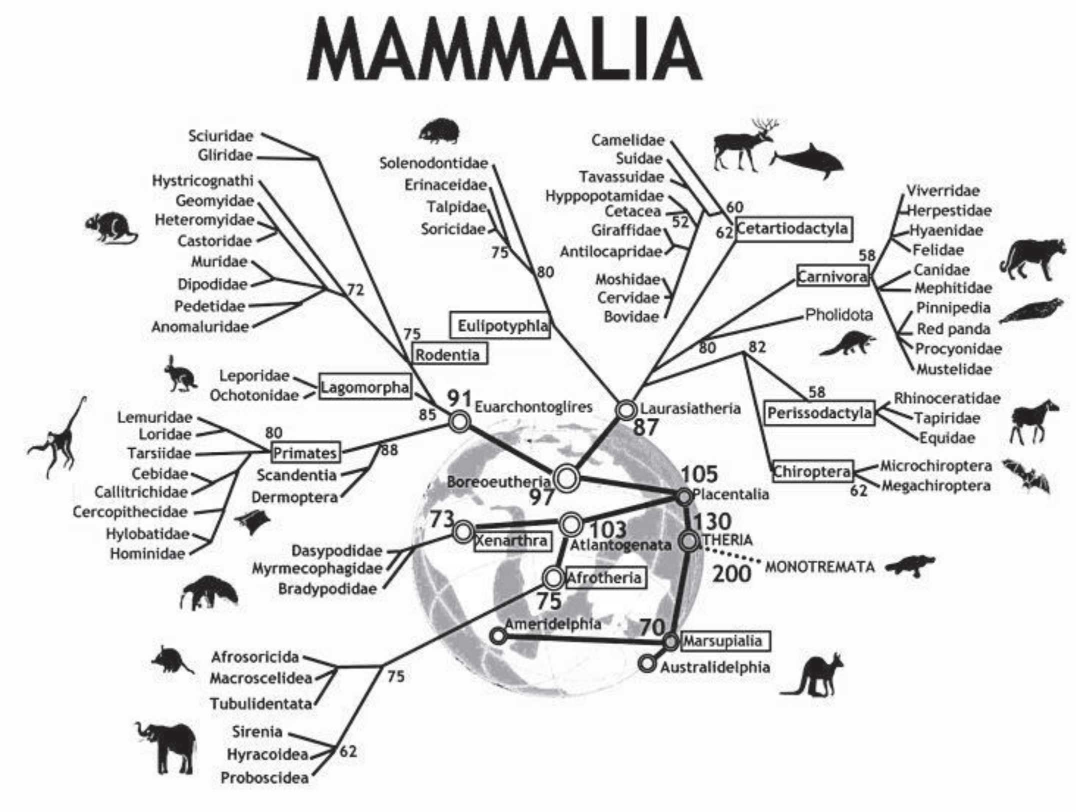


Figure 5.4.3: An example of a phylogenetic tree distribution map of mammalian species, similar to those cited in Our Wandering Continents. *The numbers indicate the estimated year of divergence from the common ancestor.*

Darwin's notebooks included the observation of similarities between species of island ecosystems and those of the continents in closest proximity (Darwin, 1836-1844). In addition, Darwin documented the existence of a fossilized horse found in South America, and hypothesized it to be related to the zebra in South Africa (Darwin, 1836-1844). He then proposed his theory that all organisms originated from pre-existing ones, and they likely diverged when they became geographically separated since it was unlikely they were able to traverse the ocean (Darwin, 1836-1844). Lastly, Darwin put forth the idea that it is not correct for humans to assume that one species is more highly evolved or developed than another, further solidifying the concept of divergent evolution (Darwin, 1836-1844).

Moreover, Du Toit published biologic evidence supporting Wegener's theories in *Our Wandering Continents*. Du Toit discussed the similarities of marine fossils located on opposite sides of the ocean and, similar to Darwin, determined that the ocean was too vast for the species to have survived its crossing (Du Toit, 1937). Furthermore, Du Toit cites distribution maps created by biologists of the time which identify various related species on different continents, providing additional evidence to support the idea that the continents were previously connected (Figure 5.4.3) (Du Toit, 1937). Finally, Du Toit combined his idea of changing climate with speciation. He noted that the climate present in a particular region at the time of his observation could not have permitted the survival of a species had it migrated there more recently (Du Toit, 1937). Thus, Du Toit's research further supports both plate tectonics and the divergent evolution of species.

In general, the postulates put forward by Darwin and Du Toit support the existence of Pangaea and its subsequent separation. Their ideas also promoted the concept of the divergence of species through climatic and geographic separation giving rise, through evolution, to the many species seen on Earth today.

Current Impacts on Speciation

While the geologic history of the Earth has had tremendous impacts on the speciation and evolution of organisms, there are other processes occurring that continue to affect speciation and biodiversity in the modern world. Currently, anthropogenic factors have a major influence on speciation (Palumbi, 2001).

One such factor causing the reversal of speciation is the introduction of invasive species into ecosystems. This phenomenon is largely a result of the increases in global infrastructure implemented for human benefit (Hulme, 2009). The increase in trade routes via water, air, or land has provided new pathways for species to travel to new environments (Hulme, 2009). The invasive species often out-compete native species and are usually less predated (Lee, 2002). This reduces the potential for the evolution of native species, but allows the new species to become better established in the ecosystem (Lee, 2002). Thus, the speciation of native species is reduced.

An example of the unwanted speciation of invaders occurs in bacterial and viral diseases. Again, human movement is a major contributor to disease propagation and speciation. Humans are able to medically treat infections and diseases, rather than waiting for the body's natural defense mechanisms to fight off the disease. This reduces natural human immune defenses and promotes the resistance of the disease to treatment (Wilson, 1995). Additionally, humans have the ability to transport diseases farther and faster than ever before, promoting their diversification (Wilson, 1995). The diseases transported by humans can be transferred interspecifically, suggesting that the impacts of increased disease could cause significant ecological impacts (Daszak, 2000). Therefore, disease has the potential to cause detrimental effects to many populations, leading to a decrease in biodiversity and speciation.

Furthermore, human environmental impacts have significantly altered the rates of speciation. At the present time, humans are the main cause of environmental alteration by means of carbon emissions and deforestation, both of which contribute to the warming of the planet (Figure 5.4.4) (Maslin, 2004). Changing climates have positively impacted speciation in the past, however current climate change is doing the opposite (Mittelbach, et al., 2007). Climate change at the present time is occurring more quickly, pressuring species into faster adaptation and evolution (Visser, 2008). Evidently, if a species is unable to adapt to rapid climatic changes, it is less likely to become ecologically fit and this decreases its chance of diversification (Visser, 2008). Thus, human expansion and resource exploitation are negatively contributing to speciation.

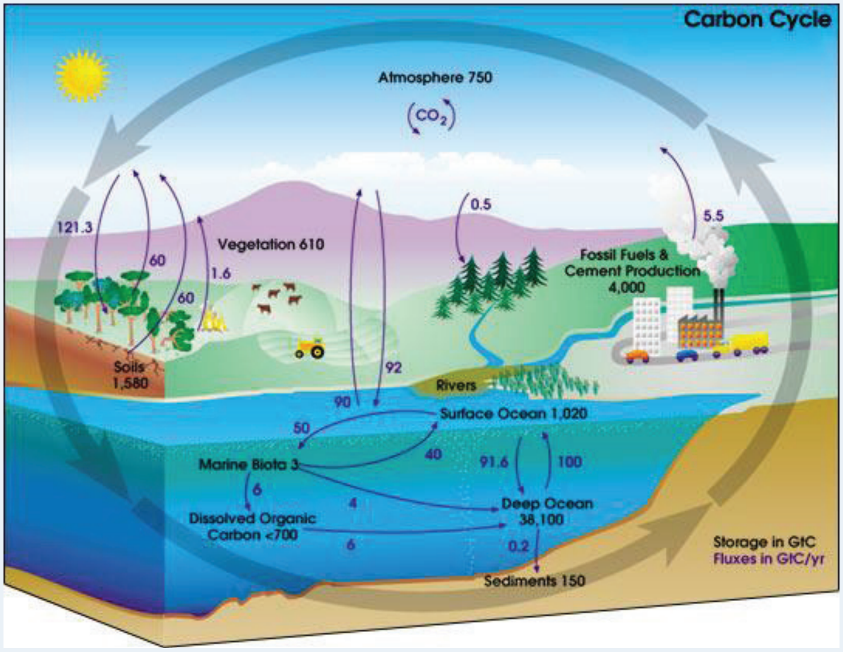


Figure 5.4.4: An illustration of the carbon cycle. Notice the imbalance between carbon flux due to fossil fuel consumption and carbon fixation by the environment. Values presented are in gigatons of carbon (GtC).

Overall, the current human impact on speciation is largely due to the ease of travel and increased distribution of invasive species, disease, and the exploitation of resources. At the current rate, humans have the potential to cause the extinction of 12% of species and threaten over 30% more (Maclean and Wilson, 2011). Thus, it is imperative to reduce human environmental impacts in order to preserve biodiversity and promote positive speciation.

School of Athens (Scoula di Atene) *a fresco painted by the Italian artist Raphael in 1505. The scene depicts some of history's greatest philosophers, and it exemplifies the importance of communication in scientific growth and development.*

Conclusion

Our current understanding of the Earth and its inhabitants is the product of years of scientific discovery and refinement. Throughout history, scientists from all different fields of study have contributed to different aspects of Earth science, slowly constructing the foundation of knowledge from which future discoveries and advancements can be made. No single individual can be accredited with the development of the current theories that prevail within the scientific community; rather, the amalgamation of centuries of scientific discourse and the desire to know has brought us to our current point in history. *History of the Earth V — An Integrated and Historical Perspective* brings light to notable figures and theories throughout history. However, it also describes the evolution of scientific thought alongside the maturation of theory. Through this introspective journey of failure and success, we can develop a new perspective from which to view human progress.

Chapter 1: Paleontology began the anthology with a discussion of our most ancient pieces of geological and biological evidence. It showcased how scientific inquiry and analysis could provide information about an ancient Earth that was much different than the planet that we call home today. From fossil excavation to the birth of stratigraphy, this chapter showed us how reconstructing the past can give valuable information about the future of life and scientific evolution.

Chapter 2: Beyond the Globe showcased how observing the planet beneath our feet could not satiate human curiosity. It began with an overview of the paradigm shift from geocentrism to heliocentrism, detailing the incredible nature of the human populous to grow alongside scientific thought. It tackled such complex issues as religion and the noosphere before discussing the rapidly growing fields of space exploration and astrobiology. Overall, it gave an insight into the individuals that strove to expand the world in ways that a chart and a compass never could.

Chapter 3: Charting, Mapping & Exploring detailed some of the first instances of human inquisition and exploration. It showed that the capacity of the human mind to wonder is surpassed only by our innate desire to discover what lies ahead. From the bottom of the ocean to the edge of the New World, humans throughout history have challenged the frontiers of possibility in the quest for understanding. By reflecting upon the obstacles and barriers that these individuals faced as well as the outcomes of their endeavours, humankind can delve deeper into the unknown in search of more answers about the fundamental nature of our planet.

Chapter 4: Materials and Resources overviewed the capacity to which humans have been able to use the materials of the Earth in the development of modern society. It described modern applications of minerals and other substances, while concurrently detailing the history through which humans have utilized and classified these materials. By highlighting the practical side of Earth science, this chapter showcased how the human drive to discover can have real and lasting implications for society at large.

Chapter 5: Life on Earth delved into how the study of geology could provide insight into the development of life. Starting with the origins of life itself, it progressed into more specific instances of this important interconnection. It ended with a discussion of how geological change has affected life on the planet, displaying the beautiful co-evolution of this planet and the organisms that inhabit it. This encompassing description of the fundamentals of life presented a platform upon which we can ponder both our origins and our future.

Although this book may appear to be just a commentary about the development of sophisticated ideas within the field of Earth science, it also serves as an exemplar of human achievement. The innate desire to discover has driven humans into deeper understanding with each successive generation. The same species that once trembled as their gods shook the Earth or conjured lightning can now draw upon years of scientific development to explain these phenomena as faults within subsurface rock or the release of static electricity. The evolution of scientific thought showcases some of the most fundamental aspects of the human condition. The vicarious benefit of retracing the steps of these great minds provides a sort of intellectual catharsis that transcends the barriers of gender, race, culture, and class. It is through the internalization of these experiences that we can progress scientifically and culturally; individually and communally; as a civilization and as a species.

Black Marble, a photo taken by NASA in 2012. The juxtaposition of the vastness of the Earth and the shining lights of humanity shows that history of the Earth cannot be written without also writing of human exploration, advancement, and discovery.

Index

References

ABC News, 2014. Thieves chisel off part of Pompeii fresco. ABC News, [online] 18 Mar. Available at: <http://www.abc.net.au/news/2014-03-19/thieves-steal-part-of-pompeii-fresco/5330072> [Accessed 24 Nov. 2014].

Abel, E., 1973. *Ancient views on the origins of life*. Rutherford: Fairleigh Dickinson University Press.

Abouzeid, A. and Khalid, A., 2011. Mineral industry in Egypt-part I: metallic mineral commodities. *Natural Resources*, 2(1), pp.35-53.

Abrahamsen, N., 1992. Evidence for church orientation by magnetic compass in twelfth-century Denmark. *Archaeometry,* 34(2), pp.293-303.

Adams, M., Perler, F. and Kelly, R., 1995. Extremozymes: expanding the limits of biocatalysis. *Nature Biotechnology*, 13, pp.662-668.

Adams, R. and Ware, D., 1977. Subcrustal earthquakes beneath New Zealand; locations determined with a laterally inhomogeneous velocity model. *New Zealand Journal of Geology Geophysics*, 20, pp.59-83.

Ager, D., 1993. *The new catastrophism: the importance of the rare event in geological history*. Cambridge: Cambridge University Press.

Agnoletti, M. and Serneri, S. eds., 2014. *The basic environmental history*. 4th ed. New York: Springer.

Ahrens, R., Rice, T. and Eswaran, H., 2002. Soil classification: past and present. *National Cooperative Soil Survey Newsletter*, 19, pp.1-10.

Ahuja, S., Ferreira, G. and Moreira, A., 2004. Utilization of enzymes for environmental applications. *Critical Reviews in Biotechnology*, 24(2-3), pp.125-54.

Akim, E., 1966. Determination of the gravitational field of the moon by the movement of the artificial satellite luna-10. *Academy of Sciences of the USSR Reports*, 170(4), pp.799-802.

Allaby, M., 2009. Oceans: a scientific history of oceans and marine life. New York: Infobase Publishing.

Allen Institute for Brain Science, 2014. *Allen brain atlas: data portal*. [online] Available at: <http://casestudies.brain-map.org/ggb#section1a> [Accessed 19 December 2014].

Allen, A. and Briggs, D. eds., 1990. *Evolution and the fossil record*. Washington, DC: Smithsonian Institution Press.

Allen, J., 2005. *The art of medicine in Ancient Egypt*. New York: Metropolitan Museum of Art.

Amato, C., 2002. Digging sacred ground: burial site disturbances and the loss of New York's Native American heritage. *Columbia Journal of Environmental Law*, 1(27).

American Museum of Natural History, 2015. Arthur Holmes: harnessing the mechanics of mantle convection to the theory of continental drift. [online] Available at: <http://www.amnh.org/education/resources/rfl/web/essaybooks/earth/p_holmes.html> [Accessed 24 Jan. 2015].

Anderson, D. and Natland, J., 2005. A brief history of the plume hypothesis and its competitors : concept and controversy. *Geological Society of America Special Paper*, 388, pp.119-145.

Anderson, D., 2004. A short history of the plume hypothesis: the inside story. *Plume IV: Beyond the Plume Hypothesis*.

Anesi, C., 1997. Titanic disaster: official casualty figures and commentary. [Online] Available at: <http://www.anesi.com/titanic.htm> [Accessed 4 Dec. 2014].

Angrove, D., 2011. *Magnetite: structure, properties, and applications*. New York: Nova Science Publishers.

Anton, H., and Rorres, C., 2010. *Elementary Linear Algebra: Applications Version*. 10th ed. New York: Wiley.

Arabia, S., 1987. Cartography in the Ancient Near East. In: D. Woodward, J.B. Harley, ed. 1987. *History of Cartography: Volume One*. Chicago: University of Chicago Press.

Artzy, M. and Hillel, D., 1988. A defense of the theory of progressive soil salinization in ancient southern Mesopotamia. *Geoarchaeology*, 3(3), pp.235-238.

Ashford, O., 1985. *Prophet, or, professor?: the life and work of Lewis Fry Richardson*. Bristol: CRC Press.

Atkinson, D., 1998. *Scientific discourse in sociohistorical context: the philosophical transactions of the Royal Society of London, 1675-1975*. Abingdon: Routledge.

Aujac, G., 1987a. Greek cartography in the Early Roman world. In: D. Woodward, J.B. Harley, ed. 1987. *History of Cartography: Volume One*. Chicago: University of Chicago Press.

Aujac, G., 1987b. The growth of an empirical cartography in Hellenistic Greece. In: D. Woodward, J.B. Harley, ed. 1987. *History of Cartography: Volume One*. Chicago: University of Chicago Press.

Aujae, B., 1987. The foundations of theoretical cartography in Archaic and Classical Greece. In: D. Woodward, J.B. Harley, ed. 1987. *History of Cartography: Volume One*. Chicago: University of Chicago Press.

Australian Centre for Astrobiology, n.d. *About the ACA*. [online] Available at: < http://aca.unsw.edu.au/content/about-aca> [Accessed 3 Dec. 2014].

Azer, M., 2013. Evolution and economic significance of listwaenites associated with Neoproterozoic ophiolites in South Eastern Desert, Egypt. *Geologica Acta,* 1, pp.113-128.

Bailey, E., 1962. *Charles Lyell*. London: Nelson.

Bains, W., 2004. Many chemistries could be used to build living systems. *Astrobiology*, 4(2). pp. 137-167.

Baldwin, R., 1949. *The Face of the Moon*. Chicago: The University of Chicago Press.

Barnett, J., Miller, S. and Pearce, E., 2006. Colour and art: a brief history of pigments. *Optics & Laser Technology*, 38(4-6), pp.445-453.

Barnosky, A., et al., 2011. Has the Earth's sixth mass extinction already arrived? *Nature*, 471(7336), pp.51-57.

Barry, P., 1992. The canol project, 1942-1945. *Arctic Institute of North America,* 45(4), pp.401-403.

Bar-Yosef, O., 1998a. On the nature of transitions: the middle to upper palaeolithic and the neolithic revolution. *Cambridge Archaeological Journal*, 8(2), pp.141-163.

Bar-Yosef, O., 1998b. The natufian culture in the Levant, threshold to the origins of agriculture. *Evolutionary Anthropology: Issues, News, and Reviews*, 6(5), pp.159-177.

Bath Royal Literary and Scientific Institution, 2015. William Smith: Father of English Geology. [online] Available at: <http://www.brlsi.org/node/18152> [Accessed 24 Jan. 2015].

Bauer, G., 1546. *De Natura Fossilium*. Translated from Latin by M.C. Bandy and J.A. Bandy. New York: Dover Publications.

Baxter, M., 1999. Dancing with the dead in a mass grave. *British Archaeology,* 50.

Bazuin, S., Azadi, H. and Witlox, F., 2011. Application of GM crops in Sub-Saharan Africa: lessons learned from green revolution. *Biotechnology Advances*, 29(6), pp. 908-912.

BBC News, 2014. *Rocks stolen from Portrush national nature reserve*. [online] Available at: <http://www.bbc.com/news/uk-northern-ireland-28290468> [Accessed 25 Nov. 2014].

Beal, H., 2014. *Microbial life in extremely hot environments.* [online] Available at: <http://serc.carleton.edu/microbelife/extreme/extremeheat/index.html> [Accessed 24 Jan. 2015].

Beale, L., 1871. Life theories, their influence upon religious thought. London: J. & A. Churchill.

Beatty, R., et al., 2008. *Inventors and Inventions*. Tarrytown: Marshall Cavendish.

Becquerel, H., 1896. Sur les radiations émises par phosphorescence. *Comptes Rendus*, 122, pp.420-421.

Bell, P., 2012. *"Irreplaceable" dinosaur fossil destroyed at Alberta dig site*. CBC News. [online] Available at: <http://www.cbc.ca/news/canada/edmonton/irreplaceable-dinosaur-fossil-destroyed-at-alberta-dig-site-1.1181588> [Accessed 23 Nov. 2014].

Bertoldo, C. and Antranikian, G., 2002. Starch-hydrolyzing enzymes from thermophilic archaea and bacteria. *Current Opinion in Chemical Biology*, 6(2), pp.151-160.

Berzelius, J., 1814. *An attempt to establish a pure scientific system of mineralogy by the application of the electro-chemical theory and the chemical proportions*. Translated from Swedish by J. Black. London: Printed for R. Baldwin and W. Blackwood.

Bethel, I., Perera, V., Nimmo, F. and Zuber, M., 2014. The tidal-rotational shape of the Moon and evidence for polar wander. *Nature*, 512, pp.181-184.

Bibliothèque nationale de France, 2014. *Pierre Miquel (1850-1922).* [online] Available at: <http://data.bnf.fr/13482017/pierre_miquel/> [Accessed 3 Dec. 2014].

Biju-Duval, B., 2002. Petroleum systems. In: *Sedimentary geology.* Translated by Swezey, J.E. and Traduclair Translation Company. Paris: Editions Techip.

Bin, J., 1983. Utilization of green manure for raising soil fertility in China. *Soil Science*, 135(1), p. 65.

Bingham, J., Chandler, F. and Taplin, S., 2000. *The Usborne internet-linked encyclopedia of world history,* London: Usborne Publishing.

Boettinger, J., Howell, D., Moore, A., Hartemink, A. and Kienast-Brown, S. eds., 2010. *Digital Soil Mapping*. Dordrecht: Springer Netherlands.

Boltwood, B., 1907. Ultimate disintegration products of the radio-active elements; Part II, Disintegration Products of Uranium. *American Journal of Science*, 4(23), p.77-88.

Bos, A., 1973. *On the elements: Aristotle's early cosmology.* Assen: Van Gorcum.

Botros, N., 2004. A new classification of the gold deposits of Egypt. *Ore Geology Reviews,* 25, pp.1-37.

Bott, T. and Brock, T., 1969. Bacterial Growth Rates above 90°C in Yellowstone Hot Springs. *Science*, 164(3886), pp.1411-1412.

Braidwood, R., 1960. *The Agricultural Revolution.* New York: Springer.

Brann, N., 1985. Alchemy and melancholy in medieval and renaissance thought: a query into the mystical basis of their relationship. *Ambix*, 32(3), pp.127-148.

Bressan, D., 2013. July 30, 1920: Marie Tharp, the woman who discovered the backbone of Earth [Online] Available at: <http://blogs.scientificamerican.com/history-of-geology/2013/07/30/july-30-1920-marie-tharp-the-women-who-discovered-the-backbone-of-earth/> [Accessed 26 Nov. 2014].

Brevik, E. and Hartemink, A., 2010. Early soil knowledge and the birth and development of soil science. *Catena*, 83, pp.23-33.

Bristow, W., 2011. *Enlightenment.* [online] The Stanford Encyclopedia of Philosophy. Available at: <http://plato.stanford.edu/archives/sum2011/entries/enlightenment/> [Accessed 20 Jan. 2015].

British Petroleum, 2014. *How oil and gas form.* [online] Available at: <http://www.bp.com/en/global/corporate/about-bp/what-we-do/finding-oil-and-gas/how-oil-and-gas-form.html> [Accessed 30 Nov. 2014].

Brock, T., 1967. Life at High Temperatures. *Science*, 158(13), pp.1012-1019.

Brock, T., 1995. The Road to Yellowstone-and beyond. *Annual Reviews Microbiology*, 49, pp.1-288.

Brock, W., 2011. Exploring early modern chemistry: the first twenty-five years of the society for the study of alchemy and early modern chemistry 1935-1960. *Ambix*, 58(3), pp.191-214.

Bryson, B., 2003. *A short history of nearly everything*. New York: Broadway Books.

Bunnell, J., Finkelman, R., Centeno, J. and Selinus, O., 2007. Medical geology: a globally emerging discipline. *Geologica Acta*, [online]. Available at: <http://revistes.ub.edu/index.php/GEOACTA/article/view/1908> [Accessed 6 Dec. 2014].

Burger, P., 2006. *Cave exploring: the definitive guide to caving technique, safety, gear, and trip leadership*. Guilford: FalconGuide.

Burroughs, W., 2003. *Climate into the 21st Century*. Cambridge: University of Cambridge.

California Department of Parks and Recreation, 2014. *Impacts to Archaeological Sites.* [online] Available at: <http://www.parks.ca.gov/?page_id=24533> [Accessed 25 Nov. 2014].

Campbell, I., 2005. Large igneous provinces and the mantle plume hypothesis. *Elements*, 1, pp.265-270.

Campbell, W., 2001. *Earth magnetism: a guided tour through magnetic fields*. Waltham: Academic Press.

Campbell, W., 2003. *Introduction to geomagnetic fields*. Cambridge: Cambridge University Press.

Canadian Association of Petroleum Producers, 2013. *Basic statistics*. [online] Available at: <http://www.capp.ca/library/statistics/basic/Pages/default.aspx> [Accessed 30 Nov. 2014].

Cannon, W., 1960. The Uniformitarian-Catastrophist Debate. Isis, 51(1), p.38.

Canup, R. and Asphaug, E., 2001. Origin of the Moon in a giant impact near the end of the Earth's formation. *Nature*, 412(6848), pp.708-712.

Carlson, J., 1975. Lodestone compass: Chinese or Olmec primacy? *Science,* 189, pp.753-760.

Castro, D., Clarke, P., Al-Lazikani, B. and Workman, P., 2012. Personalized cancer medicine: molecular diagnostics, predictive biomarkers, and drug markers. *Clinical pharmacology and therapeutics*, 93(3), pp.252-259.

Central Federal Lands Highway Division, 2011. Advanced InSAR Technology (SqueeSAR*TM)*, p.2.

Centro de Astrobiología, 2012. *Centro de Astrobiología*. [online] Available at: < https://cab.inta-csic.es/es/cab> [Accessed 3 Dec. 2014].

CGG, 2015. What is InSAR? [online] Available at: http://www.cgg.com/default.aspx?cid=7641 [Accessed 23 Jan. 2015].

Chadwick, R., 1996. *First civilizations: ancient Mesopotamia and ancient Egypt.* Ayers Cliff: Éditions Champ Fleury.

Chalmers, A., 2010. Boyle and the origins of modern chemistry: Newman tried in the fire. *Studies in History and Philosophy of Science*, 41(1), pp.1-10.

Charvatova, I., Klokonik, J., Klomas, J., Kostelecky, J., 2010. Chinese tombs oriented by a compass: evidence from paleomagnetic changes versus the age of tombs. *Studia Geophysica et Geodaetica,* 55, pp.159-174.

Chevron, 2014. *Seismic imaging.* [online] Available at: <http://www.chevron.com/deliveringenergy/oil/seismicimaging/> [Accessed 25 Jan. 2015].

Cho, S. and Krishnan, S., *Cancer Nanotechnology: Principles and Applications in Radiation Oncology*. London: CRC Press.

Christensen, W., 2009. *Empire of Ancient Egypt*. New York: Infobase Publishing.

Church G., Elowitz, M., Smolke, C., Voigt, C. and Weiss, R., 2014. Realizing the potential of synthetic biology. *Nature Reviews Molecular Cell Biology*, 15(4), pp.289-294.

CIBA Foundation Symposium, 2008. *Evolution of Hydrothermal Ecosystems on Earth and Mars*. Etobicoke: John Wiley and Sons, p.346.

Clague, D. and Dalrymple, G., 1994. Early work: legends and degree of erosion. In A. Kay, ed. *A Natural History of the Hawaiian Islands: Selected Readings II*. Honolulu, Ha: University of Hawai'i Press, pp.13-14.

Clark, F., Synge, R., eds. 1957. *Proceedings of the first international symposium on the origin of life on the Earth, held at Moscow*. New York: Pergamon.

Clarke, A., 2014. The thermal limits to life on Earth. *International Journal of Astrobiology*, 13(2), pp.141-154.

Cleeves, L., Bergin, E., Alexander, C., Du, F., Graninger, D., Öberg, K. and Harries T., 2014. The ancient heritage of water ice in the solar system. *Science*, 345(6204), pp.1590-1593.

Cobb, M., 2006. *Generation: The Seventeenth-Century Scientists Who Unraveled the Secrets of Sex, Life, and Growth*. New York: Bloomsbury Publishing.

Collins, W., 2003. Slab pull, mantle convection, and Pangaean assembly and dispersal. *Earth and Planetary Science Letters*, 205(3-4), pp.225-237.

Common-place, 2015. Common-place: Peale's Mastodon. [online] Available at: <http://www.common-place.org/vol-04/no-02/semonin/> [Accessed 24 Jan. 2015].

Conyers, B., 2006. Ground-Penetrating Radar Techniques to Discover and Map Historic Graves. *Historical Archaeology*, 40(3), pp.64-73.

Copi, I., 2011. *The theory of logical types (Routledge Revivals)*. Abingdon: Routledge.

Copley, J., 2014. Just How Little Do We Know about the Ocean Floor? *Scientific American*.

Cortright, E. ed., 1975. *Apollo Expeditions to the Moon*. Washington, DC: National Aeronautics and Space Administration.

Courtillot, V., 1999. *Evolutionary Catastrophes*. Translated by J. Courtillot. Cambridge: Cambridge University Press.

Creno, G., 2010. *Arizona archaeology sites under attack by vandals*. Phoenix: The Arizona Republic.

Crick, F., 1970. Central Dogma of Molecular Biology. *Nature*, 227(5258), pp.561-563.

Cua, A., 2003. *Encyclopedia of Chinese Philosophy*. 1st ed. New York: Routledge.

Cunningham, A. and Williams, P., 2009. De-centring the "big picture": The origins of modern science and the modern origins of science. *The British Journal for the History of Science*, 26(4), p.407.

Curie, M., 1903. *Rèserches sur les substances radioactivity*. L'Êcole Polytechnique.

Cuvier, G. and Brongniart, A., 1822. *Description geologique des environs de Paris*. Paris.

Cuvier, G., 1825. *Discours sur les révolutions de la surface du globe*. 3rd ed. Paris.

Daintith, J., 2008. *Biographical Encyclopedia of Scientists*. 3rd ed. London: CRC Press.

Dalrymple, G., 1994. *The age of the Earth*. Stanford: Stanford University Press.

Damian, R. and Brendan Murphy, J., 2013. Origins of the supercontinent cycle. *Geoscience Frontiers*, 4(4), pp.439-448.

Dana, J. and Brush, J., 1885. *A System of Mineralogy: Descriptive Mineralogy Comprising the Most Recent Discoveries*. 7th ed. New York: John Wiley and Sons.

Daniel M. and Astruc D., 2004. Nanoparticles: assembly, supramolecular chemistry, quantum-size-related properties, and applications toward biology, catalysis, and nanotechnology. *American Chemical Society,* 104, pp.293-346.

Danson, M. and Hough, D., 2000. Thermostability and thermoactivity of extremozymes. *Extremophiles*, 1.

Darwin, C., 1987. *Charles Darwin's notebooks, 1836-1844 : geology, transmutation of species, metaphysical enquiries*. Transcribed by P.H. Barrett, P.J. Gautrey, S. Herbert, D, Kohn, S. Smith., 1987. Ithaca: Cornell University Press.

Daszak, P., 2000. Emerging infectious diseases of wildlife - threats to biodiversity and human health. *Science*, 287(5452), pp.443-449.

David, A., 2003. *Handbook to life in ancient Egypt*. New York: Facts on File.

Davidson, G., 2014. Looking back at the glory days of shale oil mining. [online] Available at: <http://www.edinburghnews.scotsman.com/life-style/looking-back-at-glory-days-of-shale-oil-mining-1-3472222> [Accessed 25 Jan. 2015].

Dawkins, R., 2006. *The God delusion*. Boston: Houghton Mifflin Co.

Dawkins, R., 2006. *The selfish gene*. Oxford: Oxford University Press.

De Boer, P. and Smith, D., 1994. Orbital forcing and cyclic sequences. In: *Orbital Forcing and Cyclic Sequences*. New York: Blackwell Publishing Ltd.

De Chardin, P., 1955. The ramifying phase of the pre-hominids. In: *Phenomenon of Man*, 1st ed. New York: Harper and Row Publishers.

Dean, D., 1975. James Hutton on religion and geology: the unpublished preface to his theory of the Earth. *Annals of Science*, 32(3), pp.187-193.

Decker, R. and Decker, B., 1991. Volcanoes and plate tectonics. In *Mountains of fire: the nature of volcanoes*. New York: Cambridge University Press.

Di Cosmo, N., 1994. Ancient inner Asian nomads: their economic basis and its significance in Chinese history. *The Journal of Asian Studies*, 53(4), pp.1092-1126.

Dick, S. and Strick J., 2004. *The living universe: NASA and the development of astrobiology*. New Brunswick: Rutgers University Press.

Dick, S., 2007. From exobiology to astrobiology. In: W. T. Sullivan III and J. A. Baross, eds. 2007. *Planets and Life: The Emerging Science of Astrobiology*. Cambridge: Cambridge University Press.

Dickson, P., 2009. *Sputnik: the shock of the century*. New York: Bloomsbury Publishing.

Dilke, O., 1987a. Cartography in the Byzantine Empire. In: D. Woodward, J.B. Harley, ed. 1987. *History of Cartography: Volume One*. Chicago: University of Chicago Press.

Dilke, O., 1987b. The culmination of Greek cartography in Ptolemy. In: D. Woodward, J.B. Harley, ed. 1987. *History of Cartography: Volume One*. Chicago: University of Chicago Press.

Dott, R., 1997. James Dwight Dana's old tectonics; global contraction under divine direction. *American Journal of Science*, 297(3), pp.283-311.

Drake, S., 1957. *Discoveries and opinions of Galileo: including the starry messenger (1610), letter to the Grand Duchess Christina (1615), and excerpts from letters on sunspots (1613), The assayer (1623)*. Toronto: Anchor Books.

Draper, J., 1889. *History of the conflict between religion and science*. New York: Appleton.

Du Toit, A., 1937. *Our wandering continents : a hypothesis of continental drifting.* Edinburgh: Oliver and Boyd.

Duffin, C., Moody, R. and Gardner-Thorpe, C., 2013. *A history of geology and medicine*. London: Geological Society.

Ebbell, B., 1937. *The papyrus ebers: The greatest Egyptian medical document*. Oxford: Oxford University Press.

Egerton, F., 2001. A history of the ecological sciences, Part 4. Roman natural history. *Bulletin of the Ecological Society of America*, 82(4), pp.243-246.

Egerton, F., 2012. *Roots of ecology: antiquity to haeckel*. Los Angeles: University of California Press, p.288.

Ehrenfeld, D., 1978. *The arrogance of humanism*. New York: Oxford University Press Inc.

Ehrenfeld, D., 1993. *Beginning again: people and nature in the new millennium*. New York: Oxford University Press Inc.

Eklof, B., Bushnel, J. and Zakharova, L., 1994. *Russia's great reforms, 1855-1881*. Indiana: Indiana University Press.

Emeritus, G., 2004. *The world's greatest fix : a history of nitrogen and agriculture: a history of nitrogen and agriculture*. Oxford: Oxford University Press.

Émile Durkeim (1858-1917). [online] Internet encyclopedia of philosophy. Available at: <http://www.iep.utm.edu/durkheim/> [Accessed 3 Dec. 2014].

Encyclopaedia of the history of science, technology, and medicine in mon-Western cultures. New York: Springer Science & Business Media.

Enge, P., and Pratap, M., 1999. Scanning the issue/technology: special issue on global positioning system. *Proceedings of the IEEE,* 87(1), pp.3-15.

Engelhardt, W. and Zimmermann, J., 1988. *Theory of earth science*. Cambridge: Cambridge University Press.

European astrobiology network association, n.d. *European Astrobiology Network Association (EANA)*. [online] Available at: < http://www.astrobiologia.pl/eana/abouteana.html> [Accessed 3 Dec. 2014].

European Space Agency, 2014. *The ExoMars programme 2016-2018*. [online] Available at: <http://exploration.esa.int/mars/46048-programme-overview> [Accessed 3 Dec. 2014].

Eve and Arthur, S., 1945. *Life and work of John Tyndall*. London: Macmillan and co. ltd.

Eyles, N. and Miall, A., 2007. Canada rocks: the geologic journey. Markham: Fitzhenry and Whiteside.

Falconer, 1990. *Fractal Geometry: Mathematical Foundations and Applications*. New York: Wiley.

Fash, W., 1994. Changing perspectives on Maya civilization. *Annual Review of Anthropology*, 23, pp.181-208.

Feingold, M., 2004. *The Newtonian moment - Isaac Newton and the making of modern culture*. New York/Oxford: The New York Public Library/Oxford University Press.

Feynman, R., Leighton, R. and Sands, M., 1995. *Six easy pieces*. Reading: Addison-Wesley.

Finkelman, R., Centeno, J. and Selinus, O., 2005. The emerging medical and geological association. *Transactions of the American Clinical and Climatological Association*, 116, pp.155-165.

Finocchiaro, M., 1989. *The Galileo affair : a documentary history*. Berkeley: University of California Press.

Fisher, G., 1866. *Life of Benjamin Silliman, MD., LL.D., late professor of chemistry, mineralogy, and geology in Yale College*. New York: Charles Scribner and Company.

Fleming, J., 2007. *The life and work of Guy Stweard Callendar (1898-1964), the scientist who established the carbon dioxide theory of climate change*. Boston: American Meteorological Society.

Florinsky, I., 2012. The Dokuchaev Hypothesis as a basis for predictive digital soil mapping (On the 125th Anniversary of Its Publication). *Eurasian Soil Science*, 45(4), pp.445-451.

Fooden, J., 1972. Breakup of pangaea and isolation of relict mammals in Australia, South america, and madagascar. *Science*, 175(4024), pp.894-898.

Former Fellows of the Royal Society of Edinburgh, 2006. Available at: <http://www.royalsoced.org.uk/cms/files/fellows/biographical_index/fells_indexp1.pdf> [Accessed 18 Jan. 2015].

Forterre, P., 1996. A Hot Topic : The origin of hyperthermophiles. *Cell*, 85(1996), pp.789-792.

Fouch, M., 2012. The Yellowstone hotspot : plume or not ? *Geological Society of America*, 40(5), pp.479-480.

Foulger, G. and Natland, J., 2003. Is “hotspot” volcanism a consequence of plate tectonics? *Science*, 300, pp.921-922.

Fraczek, W., 2003. *Mean sea level, GPS, and the geoid.* [online] Available at: <https://www.wou.edu/las/physci/taylor/g492/geoid.pdf> [Accessed 3 Dec. 2014].

Frankel, H., 2012. *The continental drift controversy*. Cambridge: Cambridge University Press.

Fraser, C., 2006. *The cosmos: a historical perspective*. London: Greenwood Press.

French, K. and Duffy, C., 2014. Understanding ancient Maya water resources and the implications for a more sustainable future. *Wiley Periodicals*, 2, pp.305-313.

Friedman, R., 1989. *Appropriating the weather- Vilhelm Bjerknes and the construction of a modern meterology*. New York: Cornell University Press.

Frisinger, H., 1977. *The history of meteorology: to 1800*. New York: Science History Publications.

Frock, A. and Kelly, R., 2012. Extreme thermophiles: moving beyond single-enzyme biocatalysis. *Current opinion in chemical engineering*, 1(4), pp.363-372.

Fuson, R., 1969. The orientation of Mayan ceremonial centers. *Annals of the Association of American Geographers,* 59, pp. 494-511.

Gale, J., 2009. *Astrobiology of Earth: the emergence, evolution, and future of life on a planet in turmoil*. Oxford: Oxford University Press.

Galilei, G. and Drake, S., 1957. *Discoveries and opinions of Galileo.* Garden: Doubleday.

Gannon, C., Patra, C., Bhattacharya, R., Mukhherjee, P. and Curley, S., 2008. Intracellular gold nanoparticles enhance non-invasive radiofrequency thermal destruction of human gastrointestinal cancer cells. *Journal of Nanobiotechnology,* 6(2).

Garrick-Bethell, I. and Zuber, M., 2009. Elliptical structure of the lunar South Pole-Aitken basin. *Icarus*, 204(2), pp.399-408.

Gaughran, E., 1947. The thermophilic microorganisms. *Bacteriological reviews*, 11(3), p.189.

Gaukroger, S., 2008. *The emergence of a scientific culture: science and the shaping of modernity 1210-1685.* Oxford: Oxford University Press.

Gehrke, C., Wixom, R. and Bayer, E., 2001. *Chromatography: a century of discovery 1900-2000*. New York: Elsevier.

Gelburd, D., 1985. Managing salinity: lessons from the past. *Journal of Soil and Water Conservation*, 40(4), pp.329-331.

Geo Help Inc., n.d. History of the world petroleum industry (key dates). [online] Available at: <http://www.geohelp.net/world.html> [Accessed 10 Jan. 2015].

Geospatial Information Authority of Japan, 2004. How to make out the SAR interferogram? *Synthetic Aperture Radar Interferometry*. [online] Available at: <http://vldb.gsi.go.jp/sokuchi/sar/mechanism/mechanism04-e.html> [Accessed 23 Jan. 2015].

Getting, I., 1993. Perspective/navigation – the global positioning system. *IEEE Spectrum,* 30(12), pp.36-38.

Gilbert, G., 1893. *The Moon's face: a study of the origin of its features*. Washington: Philosophical Society of Washington.

Gilbert, W., 1600. *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure*.

Gilder, J., 2005. *Heavenly intrigue : Johannes Kepler, Tycho Brahe, and the murder behind one of history's greatest scientific discoveries*. New York: Anchor Books.

Gilman, D., 1899. *The life of James Dwight Dana: scientific explorer, mineralogist, geologist, zoologist, professor at Yale University*. New York and London: Harper and Brothers Publishers.

Ginsberg, A., 2014. *Synthetic aesthetics : investigating synthetic biology's designs on nature*. Massachusetts: The MIT Press.

Glasscoe, M., 1998. *History of plate tectonics*. [online] Available at: <http://www.scec.org/education/k12/learn/plate2.htm> [Accessed 3 Dec. 2014].

Global Policy Forum, 2014. *Globalization*. [online] Global Policy Forum. Available at: <https://www.globalpolicy.org/globalization.html> [Accessed 3 Dec. 2014].

Gomes, C. and Silva, J., 2007. Minerals and clay minerals in Medical geology. *Applied Clay Science*, 36(1-3), pp.4-21.

Gomes, J. and Steiner, W., 2004. The biocatalytic potential of extremophiles and extremozymes. *Food Technology and Biotechnology,* 42(4), pp.223-235.

Gomez, A., 2014. *Biruni's measurement of Earth*. [online] Available at: <http://www.jscimath.org/uploads/J2011172AG.pdf> [Accessed 28 November 2014]

Gong, Z., Zhang, X., Chen, J. and Zhang, G., 2003. Origin and development of soil science in ancient China. *Geoderma*, 115, pp.3-13.

Gould, J., 1984. Magnetic field sensitivity in animals. *Annual review of physiology*, 46, pp.585-98.

Government of Canada, H.C.H.E. and C.S.B.S.E.P.W.Q. and H.B., 2004. *Canadian drinking water guidelines*. Available at: <http://www.hc-sc.gc.ca/ewh-semt/water-eau/drink-potab/guide/index-eng.php> [Accessed 6 Dec. 2014].

Grafen, A., and Ridley, M., 2006. *Richard Dawkins: how a scientist changed the way we think : reflections by scientists, writers, and philosophers.* Oxford: Oxford University Press.

Grant, R., 1852. *History of physical astronomy: from the earliest ages to the middle of the nineteenth century*. London: Henry G. Bohn.

Gray, M., 2013. *Geodiversity: valuing and conserving abiotic nature*. 2nd ed. Chichester: John Wiley and Sons, Ltd.

Greenberg, J., 1995. Isaac Newton and the problem of the Earth's shape. *Archive for History of Exact Sciences*, 49(4), pp.371-391.

Grenet, P., 1960. *Teilhard de Chardin*. Paris: Editions Seghers.

Griffin, D., 2013. The quest for extraterrestrial life: what about the viruses? *Astrobiology*, 13(8). pp.774-783.

Grinevald, J. and Vernadsky, V., 1998. Introduction. In: *La biosphere*. New York: Copernicus.

Gubbins, D. and Herrero-Bervera, E., 2007. *Encyclopedia of geomagnetism and paleomagnetism*. New York: Springer Science & Business Media.

Gupta, A., 2004. Origin of agriculture and domestication of plants and animals linked to early Holocene climate amelioration. *Current Science*, 87(1), pp. 54-59.

Haldane, J., 1929. The origin of life. *Rationalist Annual,* 148, pp.3-10.

Hallam, A. and Wignall, P., 1997. *Mass extinctions and their aftermath*. New York: Oxford University Press.

Hallam, A., 1983. Supposed Permo-Triassic megashear between Laurasia and Gondwana. *Nature,* 301(5900), pp.499-502.

Halley, E., 1692. An account of the cause of the change of the variation of the magnetical needle; with an hypothesis of the structure of the internal parts of the Earth: as it was proposed to the Royal Society in one of their late meetings. London: Royal Society of London.

Harman, P. and DeVore, E., 2009. Astrobiology as a context for high school science: teachers' professional development. In: K. Meech, J. Keane, M. Mumma, J. Siefert and D. Werthimer, eds. *Bioastronomy 2007: Molecules Microbes and Extraterrestrial Life*. San Juan, Puerto Rico, July 16-20, 2007. Orem: Astronomical Society of the Pacific

Harrell A. and Brown M., 1992. The oldest surviving topographical map from Ancient Egypt: (Turin Papyri 1879, 1899, and 1969). *Journal of American Research Center in Egypt,* 29, pp.81-105.

Harrell, J., Turin Papyrus map from Ancient Egypt. Available at: <http://www.eeescience.utoledo.edu/faculty/harrell/egypt/Turin Papyrus/Harrell_Papyrus_Map_text.htm> [Accessed December 18, 2014].

Hartman, H., Lawless, J., Morrison, P. eds., 1987. *Search for the universal ancestors : the origins of life*. Oxford: Blackwell Scientific Publications.

Hartnady, C., 1991. About turn for supercontinents. *Nature*, 352(6335), pp.476-478.

Harvey, R., 1924. Enzymes of thermal algae. *Science* 60, pp.481-482.

Haviland, W., 1972. Family size, prehistoric population estimates, and the Ancient Maya. *Society for American Archaeology*, 37(1), pp.135-139.

Hayden, F., 1872. The hot springs and geysers of the Yellowstone and Firehole rivers. *American Journal of Science*, 3(14), pp.105-115.

Hazell, P., 2009. *The Asian green revolution.* International Food Policy Research Institute Available at: < http://www.ifpri.org/sites/default/files/publications/ifpridp00911.pdf > [accessed 6 December, 2014].

Head, J., Fassett, C., Kadish, S., Smith, D., Zuber, M., Neumann, G. and Mazarico, E., 2010. Global distribution of large lunar craters: implications for resurfacing and impactor populations. *Science (New York, N.Y.)*, 329(5998), pp.1504-1507.

Healy, J., 1981. Pliny the elder and ancient mineralogy. *Interdisciplinary Science Reviews*, 6(2), pp.166-180.

Henderson, S. and Pritchard, M., 2013. Decadal volcanic deformation in the Central Andes volcanic zone revealed by InSAR time series. *Geochemistry Geophysics Geosystems*, 14(5), pp.1358-1374.

Heshelow, K., 2010. History of oil and gas. In: *Investing in oil and gas: the ABC's of Dpps.* 2nd ed. Bloomington: iUniverse Inc.

Hesketh, I., 2009. *Of apes and ancestors: evolution, Christianity, and the Oxford debate*. Toronto: University of Toronto Press.

Heylighen, F. and Bollen, J., 1996. The world-wide web as a super-brain : from metaphor to model the web as an associative memory. *Cybernetics and Systems*, pp.917-922.

Hill, M. and James, A., 2000. Egypt in the late period (712-332 B.C.). *The Metropolitan Museum of Art,* [online] Available at: < http://www.metmuseum.org/toah/hd/lapd/hd_lapd.htm> [Accessed 3 Dec. 2014].

Hitchens, C., 2007. *God is not great: how religion poisons everything.* Toronto: McClelland and Stewart.

Hobson, G., 1954. *Some fundamentals of petroleum geology*. London: Oxford University Press.

Hooke, R., 1667. *Micrographia: or some physiological descriptions of minute bodies made by magnifying glasses, with observations and inquiries thereupon*. London: Royal Society.

Hotspot Ecosystem Research and Man's Impact on European Seas, 2009. *Early ocean exploration*. [Online] Available at: <http://www.eu-hermione.net/learning/early-ocean-exploration> [Accessed 1 Dec. 2014].

Huffman, C., 1993. *Philolaus of Croton : Pythagorean and presocratic : a commentary on the fragments and testimonia with interpretive essays*. Cambridge: Cambridge University Press.

Huggett, R., 1990. *Catastrophism: systems of Earth history*. London: Hodder and Stoughton.

Huggett, R., 1995. *Geoecology: an evolutionary approach*. New York: Routledge.

Hugh, C., 1911. Petroleum. In: *Encyclopaedia Britanica Online.* [online] Available at: <http://encyclopedia.jrank.org/PER_PIG/PETROLEUM_Lat_Petra_rock_and_ol.htm> [Accessed 25 Jan. 2015].

Hulme, P., 2009. Trade, transport and trouble: managing invasive species pathways in an era of globalization. *Journal of Applied Ecology*, 46(1), pp.10-18.

Hulse, J., 2004. Biotechnologies: past history, present state and future prospects. *Trends in Food Science and Technology*, 15(1), pp.3-18.

Hung, E., 2014. *Philosophy of science complete: a text on traditional problems and schools of thought*. 2nd ed. Boston: Wadsworth.

Hunter, M. and Principe, L., 2003. The Lost Papers of Robert Boyle. *Annals of Science*, 60(3), pp.269-311.

Hutchinson, E., 1970. The biosphere. In: *Scientific American Inc.*, ed., *The biosphere*, 1st ed. San Francisco: W.H. Freeman and Company.

Huurdeman, A., 2003. *The worldwide history of telecommunications*. New York: John Wiley and Sons.

Incorporated Research Institutions for Seismology, 2014. Seismic tomography. *Earth Scope*. *International Journal of Nonlinear Sciences and Numerical Simulation*, 7(2), pp.137-148.

Internet Archive, 2015. *Illustrations of the Huttonian theory of the earth*. Edinbourgh: Cadell and Havies.

ISAAA, 2014. *Global status of commercialized biotech/GM crops: 2011.* [online] Available at: <http://www.isaaa.org/resources/publications/briefs/43/executivesummary/default.asp> [Accessed 6 Dec. 2014].

Iz, H., Shum, C., Ding, X. and Dai, C., 2011. Orientation of the geometrically best fitting triaxial lunar ellipsoid with respect to the mean Earth/polar axis reference frame. *Journal of Geodetic Science*, 1(1), pp.52-58

J. Craig Venter Institute, n.d. *Synthetic Biology and Bioenergy*. [online] Available at: <http://www.jcvi.org/cms/research/groups/synthetic-biology-bioenergy/> [Accessed 1 Dec. 2014].

Jacobsen, T. and Adams, R., 1958. Salt and silt in Ancient Mesopotamian agriculture. *Science*, 128(3334), pp.1251-1258.

James Hutton, 1795. *Theory of the Earth*. 2nd ed. Edinburgh.

Jarrige, J., 2008. Mehrgarh Neolithic. *Pragdhara*, 18, pp.135-154.

Jarzombek, M. and Kramaditya, P., 2011. *A global history of architecture*. Second Edition. Hoboken: John Wiley and Sons Inc.

Jay, J., Welch, M., Pritchard, M., Mares, P., Mnich, M., Melkonian, A., Aguilera, F., Naranjo, J. A., Sunagua, M. and Clavero, J., 2013. Volcanic hotspots of the central and southern Andes as seen from space by ASTER and MODVOLC between the years 2000 and 2010. *Geological Society*, 380, pp.161-185.

Jekeli, C., 2000. *Heights, the geopotential, and vertical datums*. [online] Available at: <http://www.fgg.uni-lj.si/~/mkuhar/Zalozba/Heights_Jekeli.pdf> [Accessed 3 Dec. 2014].

Job, K., 1994. *The discovery of Kepler's laws : the interaction of science, philosophy, and religion*. Notre Dame: University of Notre Dame Press.

Jones, A., 2011. *A Survey of the Almagest*. New York: Springer.

Jones, W., 2012. Introduction. In: *The Transition from the Biosphere to the Noosphere*. [online] 21st Century, pp.11-15. Available at: <http://www.21stcenturysciencetech.com/Articles_2012/Spring-Summer_2012/04_Biospere_Noosphere.pdf> [Accessed 6 Dec. 2014].

Judd, J., 1914. Prof. Eduard Suess, For. Mem. R. S. *Nature*, 93(2323), pp.245-246.

Jung, C., 1981. The concept of the collective unconscious. In: F. Hull, ed., *The archetypes and the collective unconscious*. Princeton: Princeton University Press.

Kaebnick, G., Murray, T., eds. *Synthetic biology and morality : artificial life and the bounds of nature*. Massachusetts: The MIT Press: 2013.

Kahn, C., 1994. *Anaximander and the origins of Greek cosmology*. Indianapolis: Hackett.

Kamiar, M., 2006. *A bio-bibliography for Biruni*. Maryland: Scarecrow Press Inc.

Kardel, T. and Maquet, P., eds., 2013. *Nicolaus Steno: biography and original papers of a 17th century scientist*. Heidelberg: Springer Science and Business Media.

Katsuyuki, M., 2009. Soil and humanity: culture, civilization, livelyhood, and health. *Soil Science and Plant Nutrition*, 55, pp.603-615.

Kenyon, K., 1960. Excavations at Jericho, 1957-58. *Palestine Exploration Quarterly*, 92(2), pp. 88-113.

Keosian, J. The origin of life. New York: Reinhold Book Corp.

Kermit, H., 2003. *Niels Stensen, 1638-1686: The Scientist who was Beatified*. Leominster: Gracewing Publishing.

Kirkham, G., 2009. Is biotechnology the new alchemy? *Studies in history and philosophy of science part A*, 40(1), pp.70-80.

Klein, D., 2012. Alkanes and cycloalkanes. In: *Organic chemistry*. Hoboken: John Wiley and Sons.

Klemm D., Klemm R. and Murr A., 2001. Gold of the Pharaohs – 6000 years of gold mining in Egypt and Nubia. *African Earth Science,* 33, pp. 643-659.

Klemm, R. and Klemm, D., 2012. *Gold and gold mining in Ancient Egypt and Nubia: geoarchaeology of the Aacient gold mining sites in the Egyptian and Sudanese Eastern deserts*. New York: Springer Science & Business Media.

Klokocnik, J., Kostelecky, J., Vitek, F., 2007. Pyramids and ceremonial centers in Mesoamerica: were they oriented using a magnetic compass? *Studia Geophysica et Geodaetica,* 51, pp.515-533.

Knowles, E., 1999. *The Oxford Dictionary of Quotations*. Revised ed. Oxford: Oxford University Press.

Koch, D., Borucki, W., Basri, G., Batalha, N., Brown, T., Caldwell, D., Christensen-Dalsgaard, J., Cochran, W., DeVore, E. and Dunham, E., 2010. Kepler mission design, realized photometric performance, and early science. *The Astrophysical Journal Letters*, 713(2), p.L79.

Kolbert, E., 2014. *The Sixth Extinction*. New York: Henry Holt and Company.

Kölbl-Ebert, M., Geological Society of London, International Union of Geological Sciences and I.C. on the H. of the G.S., 2009. *Geology and religion: a history of harmony and hostility*. London: Geological Society.

Komatina, M., 2010. *Medical geology: a regional synthesis*. Netherlands: Springer.

Kollerstrom, N., 1992. *The hollow world of Edmond Halley*. Journal for History of Astronomy, 23, p.185-192.

Kristjansson, J., 1991. *Thermophilic Bacteria*. p.240.

Lal, R., Reicosky, D. and Hanson, J., 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. *Soil and Tillage Research*, 93(1), pp.1-12.

Langford, N., 1871. *The wonders of the Yellowstone*. p.38.

Langermann, Y., 1985. The book of bodies and distances of Habash al-Hāsīb. *Centaurus*, 28(2), pp.108-128.

Langmuir, C. and Broecker, W., 2012. *How to build a habitable planet: the Story of Earth from the big bang to humankind*. Princeton: Princeton University Press.

Laughton, 1959. *New Scientist - The Sea Floor*. London: Reed Business Information.

Launius, R., Logsdon, J. and Smith, R., eds., 2013. *Reconsidering Sputnik: forty years since the Soviet satellite*. Cornwall: Routledge.

Le Roy, E., 1928. *Les origines humaines et l'évolution d'intelligence*. Paris: Boivin.

Lee, C., 2002. Evolutionary genetics of invasive species. *Trends in Ecology and Evolution*, 17(8), pp.386-391.

Lee, S., 1833. *Memoirs of Baron Cuvier*. New York: Harper.

Lelle, M. and Gold, M., 1994. Agroforestry systems for temperate climates: Lessons from Roman Italy. *Forest and Conservation History*, 38(3), pp.118-126.

Leiter, D., Ward, P., PED and Leiter, S., 2009. *A to Z of physicists*. New York: Infobase Publishing.

Lienhard, J., 1997. No. 363: Sub-Ocean Maps. [Online] Available at: <http://www.uh.edu/engines/epi363.htm> [Accessed 26 Nov. 2014].

Lindberg, D. and Numbers, R., 2009. Beyond war and peace: a reappraisal of the encounter between Christianity and science. *Church History*, 55(03), p.338.

Linden, S., 2003. *The Alchemy Reader*. Cambridge: Cambridge University Press.

Lloyd, B., 2010. *A companion to Ancient Egypt*. Etobicoke: John Wiley & Sons.

Lockwood, M., Worboys, G. and Kothari, A., 2012. *Managing protected areas: a global guide*. Trowbridge: Cromwell Press.

Lonsdale, P., 1977. Clustering of suspension-feeding macrobenthos near abyssal hydrothermal vents at oceanic spreading centers. *Deep Sea Research*, 24(9), pp.857-863.

Lowrie, W., 2007. *Fundamentals of Geophysics*. Cambridge: Cambridge University Press.

Lyell, C., 1833. *Principles of geology*. New York: D. Appleton and Co.

Lyell, C., 1970. *Principles of Geology*. Lehre: Cramer, J.

Lynch, P., 2008. The origins of computer weather prediction and climate modeling. *Journal of Computational Physics*, 227(7), pp.3431-3444.

Ma, F. and Hanna, M., 1999. Biodiesel production: a review. *Bioresource Technology*, 70(1), pp.1-15.

Maclean, I. and Wilson, R., 2011. Recent ecological responses to climate change support predictions of high extinction risk. *Proceedings of the National Academy of Sciences of the United States of America*, 108(30), pp.12337-12342.

Magner, L., 2002. *A history of the life sciences*. 3rd ed. New York: Marcel Dekker, Inc.

Maisels, C., 1998. *The Near East*. New York: Routledge.

Mandelbrot, B.B., 2004. *Fractals and Chaos: The Mandelbrot Set and Beyond*. New York: Springer.

Mandelbrot, B.B., 1967. *How Long is the Coast of Britain?* Science, [online] Available at: <http://www.jstor.org/discover/10.2307/1721427?uid=2&uid=4&sid=21104786204581> [Accessed 01 December 2014].

Mandelbrot, B.B., 1983. *The Fractal Geometry of Nature*. New York: Freeman.

Marcus, G., 1956. The mariner's compass: its influence upon navigation in the later middle ages. *History,* 41(141-143), pp.16-24.

Martelli, M., 2011. Greek alchemists at work: "alchemical laboratory" in the Greco-Roman Egypt. *Nuncius / Istituto e museo di storia della scienza*, 26(2), pp.271-311.

Martinón-Torres, M., 2011. Some recent developments in the historiography of alchemy. *Ambix*, 58(3), pp.215-237.

Marvin, U., 1973. *Continental drift: the evolution of a concept.* Washington: Smithsonian Institution Press.

Maslin, M., 2004. *Global warming: a very short introduction.* New York: Oxford University Press.

Mathiesen, K., 2005. Collective consciousness. In: D. Woodruff Smith and A. Thomasson, eds., *Phenomenology and Philosophy of the Mind*, 1st ed. New York: Oxford University Press Inc.

Mayor, M. and Queloz, D., 1995. A Jupiter-mass companion to a solar-type star. *Nature*, 378(6555), p. 355.

McCarthy, D., Petit, G., 2003. *IERS Conventions*. [online] Available at: <http://www.iers.org/SharedDocs/Publikationen/EN/IERS/Publications/tn/TechnNote32/tn32.pdf?__blob=publicationFile&v=1> [Accessed 1 Dec. 2014].

McGuffie, K. and Henderson-Sellers, A., 2001. Forty years of numerical climate modelling. *International Journal of Climatology*, 21(9), pp.1067-1109.

McKay, D., Gibson, E., Thomas-Keprta, K., Vali, H., Romanek, C., Clemett, S., Chillier, X., Maechling, C. and Zare, R., 1996. Search for past life on Mars: possible relic biogenic activity in Martian meteorite ALH84001. *Science*, 273(5277), pp.924-930.

McNeill, J. and Winiwarter, V., 2004. Breaking the sod: humankind, history, and soil. *Science*, 304, pp.1627-1628.

McNeill, J. and Winiwarter, V., 2006. *Soils and Societies*. Strond, Isle of Harris: The White Horse Press.

Medawar, P., 1982. *Pluto's Republic*. New York: Oxford University Press Inc.

Meng, W. and Higgs, P., 2012. The origin of life is a spatially localized stochastic transition. *Biology Direct*, 7(42).

Merril, R., 1984. *The earth's magnetic field : its history, origin, and planetary perspective: its history, origin, and planetary perspective*. New York: Academic Press.

Merrill, R. and McElhinny, M., 1998. *The magnetic field of the Earth: paleomagnetism, the core, and the deep mantle*. New York: Academic Press.

Miller, S., 1995. Production of some organic compounds under possible primitive Earth conditions. *Journal of the American Chemical Society*, 77(9), pp.2351-2361.

Miller, R., 1983. Continents in collision. Alexandria: Time-Life Books.

Miller, S. and Lazcano, A., 1995. The origin of life—did it occur at high temperatures? *Journal of molecular evolution*, 41, pp.689-692.

Milligan, M., 2004. *What are seismic surveys and how much "shaking" do they create?* [online] Available at: <http://geology.utah.gov/surveynotes/gladasked/gladseismicsurveys.htm> [Accessed 25 Jan. 2015].

Milne, J., 1929. Ptolemaic coinage in Egypt. *The Journal of Egyptian Archaeology,* 15(3/4), pp.150-153.

Miniati, S., 2009. *Nicholas Steno's challenge for thruth. Reconciling Science and Faith*. Siena: FrancoAngeli.

Misra, R. and Ramesh, A., 1989. *Fundamentals of Cartography*. New Delhi: Concept Publishing Company.

Mitchell, R., 2014. Supercontinent cycles and the calculation of absolute palaeolongitude in deep time. *Nature*, 482(7384), pp.208-211.

Mittelbach, G., et al., 2007. Evolution and the latitudinal diversity gradient: speciation, extinction and biogeography. *Ecology letters*, 10(4), pp.315-331.

Miquel, M., 1879. Bulletin de la statistique municipale de la ville de Paris. *Annuaire de l'observatoire de Montsouris pour 1881*. p. 464.

Mohs, F., 1820. *The characters of the classes, order, genera, and species; or the characteristic of the natural history system of mineralogy*. Edinburgh: Printed for W. and C. Tait.

Moran, B., 2000. Alchemy, chemistry and the history of science. [Review of: Priesner, C; Figala, K. Alchemie: Lexikon einer hermetischen Wissenchaft. Verlag C.H. Beck, 1998]. *Studies in history and philosophy of science*, 21(4), pp.711-720.

Morris, P., 2011. The fall and rise of the history of recent chemistry. *Ambix*, 58(3), pp.238-256.

Morozova, G., 2005. A review of Holocene avulsions of the Tigris and Euphrates Rivers and possible effects on the evolution of civilizations in Lower Mesopotamia. *Geoarcheology: An International Journal*, 20(4), pp.401-423.

Mukherjee, S., 2012. *Applied mineralogy: applications in industry and environment*. New York: Springer.

Murphy, J. and Nance, R., 2003. Do supercontinents introvert or extrovert?: Sm-Nd isotope evidence. *Geology*, 31(10), p.873.

Murphy, J. and Nance, R., 2013. Speculations on the mechanisms for the formation and breakup of supercontinents. *Geoscience Frontiers*, 4(2), pp.185-194.

Nairn, A., 1965. Uniformitarianism and environment. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 1, pp.5-11.

Nance, R., Worsley, T. and Moody, J., 1988. The Supercontinent Cycle. *Scientific American*, 259(1), pp.72-79.

Nanobiotechnology: Concepts, Applications and Perspectives. New York: John Wiley and Sons.

Nanobiotechnology: Inorganic Nanoparticles Vs Organic Nanoparticles. New York: Elsevier.

Nanoparticulate Drug Delivery Systems: Strategies, Technologies, and Applications. New York: John Wiley and Sons.

Nanotechnology, science and applications, 3, pp.53-63.

NASA, n.d. *Solar System Exploration*. [online] Available at: <http://solarsystem.nasa.gov/planets/profile.cfm?Display=Facts&Object=Earth> [Accessed 29 Nov. 2014].

National Aeronautics and Space Administration, 2010a. *Luna 15*. [online] Available at: <http://solarsystem.nasa.gov/moon/missionsFeed.cfm?Sort=Target&Target=Moon&MCode=Luna_15> [Accessed 1 Dec. 2014].

National Aeronautics and Space Administration, 2010b. *Luna 2*. [online] Available at: <http://solarsystem.nasa.gov/moon/missionsFeed.cfm?Sort=Target&Target=Moon&MCode=Luna_02> [Accessed 30 Nov. 2014].

National Aeronautics and Space Administration, 2010c. *Luna 9*. [online] Available at: <http://solarsystem.nasa.gov/moon/missionsFeed.cfm?Sort=Target&Target=Moon&MCode=Luna_09> [Accessed 1 Dec. 2014].

National Aeronautics and Space Administration, 2011. *Luna 1*. [online] Available at: <http://solarsystem.nasa.gov/moon/missionsFeed.cfm?Sort=Target&Target=Moon&MCode=Luna_01> [Accessed 30 Nov. 2014].

National Aeronautics and Space Administration, 2012. *Evolution of the Moon*. [online] Available at: <http://en.wikipedia.org/wiki/File:Evolution_of_the_Moon.ogv> [Accessed 3 Dec. 2014].

National Aeronautics and Space Administration, 2013a. *About the Moon*. [online] Available at: <http://solarsystem.nasa.gov/moon/about.cfm> [Accessed 2 Dec. 2014].

National Aeronautics and Space Administration, 2013b. *Apollo 11*. [online] Available at: <http://solarsystem.nasa.gov/moon/missionsFeed.cfm?Sort=Target&Target=Moon&MCode=Apollo_11> [Accessed 1 Dec. 2014].

National Aeronautics and Space Administration, 2013c. *Luna 3*. [online] Available at: <http://solarsystem.nasa.gov/moon/missionsFeed.cfm?Sort=Target&Target=Moon&MCode=Luna_03> [Accessed 1 Dec. 2014].

National Aeronautics and Space Administration, 2014. *About NAI*. [online] (December 2, 2014) Available at: < https://astrobiology.nasa.gov/nai/about/> [Accessed 2 Dec. 2014].

National Aeronautics and Space Adminsitration, n.d. *Habitability, survivability, detectability*. [online] Available at: <http://icyworlds.jpl.nasa.gov/habitability> [Accessed 3 Dec. 2014]

Natland, J., 2003. James Dwight Dana (1813-1895): Mineralogist, Zoologist, Geologist, Explorer. *GSA TODAY*, February Issue, pp.20-21.

Natural Resources Canada, 2014a. *Alternative fuels*. [online] Available at: <http://www.nrcan.gc.ca/energy/alternative-fuels/3487> [Accessed 1 Dec. 2014].

Natural Resources Canada, 2014b. *Proven oil reserves*. [online] Available at: <http://www.nrcan.gc.ca/energy/crude-petroleum/4543> [Accessed 30 Nov. 2014].

Natural Resources Canada, 2014. *GPS-H*. [online] Available at: <http://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/tools-applications/9070> [Accessed 3 Dec. 2014]

Neckam, A., 1863. *De Naturis Rerum*. London: Longman, Roberts, and Green.

Newman, R., 1995. American intransigence : the rejection of continental drift in the great debates of the 1920s. In: *H. Krips, J.E. McGuire, T. Melia* eds. 1995. *Science, reason, and rhetoric*. Pittsburgh: University of Pittsburgh Press.

Newman, W., 2011. What have we learned from the recent historiography of alchemy? *Isis*, 102(2), pp.313-321.

National Geographic, 2014. *Supercontinent Pangaea pushed, not sucked, into place*. [online] Available at: <http://news.nationalgeographic.com/news/2008/09/080905-pangaea-suction_2.html> [Accessed 4 Dec. 2014].

Newton, I. *et al,* 1833. *Philosophiae naturalis principia mathematica. Vol. 1*. Glasgow: George Brookman. *"Never Had the Like Occurred": Egypt's View of Its Past*. London: University College London.

Nicholls, H., 2004. Biotech is the new alchemy. *Drug Discovery Today*, 9(3), p.103.

Nicholson, P. and Shaw, I., 2000. *Ancient Egyptian materials and technology*. Cambridge: Cambridge University Press.

Niehaus, F., Bertoldo, C., Kahler, M. and Antranikian, G., 1999. Extremophiles as a source of novel enzymes for industrial application. *Applied Microbiology and Biotechnology*, 51, pp.6711-6729.

NOAA, 2008. *Geodesy*. [online] Available at: <http://oceanservice.noaa.gov/education/kits/geodesy/geo02_histr.html> [Accessed 29 Nov. 2014].

Norn, S., Permin, H., Kruse, E. and Kruse, P., 2008. Kviksolv--et centralt stof i medicinens og alkymiens historie. *Dansk medicinhistorisk arbog*, 36, pp.21-40.

Nubian past: an archaeology of the Sudan. Oxon: Routledge.

O'Kan, J., 2012. *The lost secrets of Maya technology.* Pompton Plains: Career Press.

Odum, E., 1959. *Fundamentals of ecology*. Philadelphia: W. B. Saunders Company.

Odum, E., 1993. *Ecology and our endangered life-support systems*. Sunderland: Sinauer Associates.

Olson, L., 1943. Columella and the beginning of soil science. *Agricultural History*, 17(2), pp.65-72.

Olson, L., 1945. Cato's views on the farmer's obligation to the land. *Agricultural History*, 19(3), pp.129-132.

Olson, L., 2009. *Modernism and the ordinary*. Oxford: Oxford University Press.

Oparin, A., 1957. The origin of life on the earth. Edinburgh: Oliver and Boyd.

Oparin, A., 1938. *The origins of life*. Translated by S. Morgulis. Mineola: Dover Publications, Inc.

Origins Institute, n.d. *How our program works*. [online] Available at: <http://origins.mcmaster.ca/academic/graduate/how-our-program-works> [Accessed 3 Dec. 2014].

Orloff, R. and Hartland, D., 2006. *Apollo: the definitive sourcebook*. Herfordshire: Praxis Publishing Ltd.

Ortiz, E., 2014. *Fossil theft raises concerns about bustling black market.* [online] 21 Feb. Available at: <http://www.nbcnews.com/news/crime-courts/fossil-theft-raises-concerns-about-bustling-black-market-n35846> [Accessed 25 Nov. 2014].

Osman, A., 2013. *Antinoupolis archaeological site being "destroyed systematically." Egypt Independent.* [online] 9 Mar. Available at: <http://www.egyptindependent.com/news/antinoupolis-archaeological-site-being-destroyed-systematically> [Accessed 23 Nov. 2014].

Pace, S., Frost, G., Lachow, I., Frelinger, D., Fossum, D., Wassem, D. and Pinto, M., 1995. *The global positioning system: assessing national policies.* California: RAND Coperation.

Pagan, D., 2008. *Stolen fossils returned thanks to U of C prof.* The Gauntlet. 19 Jun.

Pages-Camagna, S. and Colinart, S., 2003. The Egyptian green pigment: its manufacturing process and links to Egyptian blue. *Archaeometry*, 45(4), pp.637-658.

Palumbi, Stephen R., 2001. Humans as the World's greatest evolutionary force. *Science.* 293(5536), pp. 1796-1890.

Pangaea.org, 2015. Wegener, Alfred. [online] Available at: <http://pangaea.org/wegener.htm> [Accessed 24 Jan. 2015].

Papadimitriou, F. et al., 2010. Ancient Greek cartography and its relevance for modern geographical education : from geodesy to networks. pp. 15-17.

Papike, J., Karner, J. and Shearer, C., 2003. Determination of planetary basalt parentage: a simple technique using the electron microprobe. *American Mineralogist*, 88(2-3), pp.469-472.

Parrish, R. and Noble, S., 2003. Zircon U-Th-Pb geochronology by isotope dilution—thermal ionization mass spectrometry (ID-TIMS). *Reviews in Mineralogy and Geochemistry,* 53(1), pp.183-213.

Parton, J., 1939. *Short history of chemistry*. Great Britain, pp.66-77.

Pasteur, L., 1861. On the organized bodies which exist in the atmosphere. Translated by T. D. Brock. In: L. Otis, ed. 2002. *Literature and Science in the Nineteenth Century: An Anthology*. Oxford: Oxford University Press.

PBS, 2015. Charles Lyell: principles of geology. [online] Available at: <http://www.pbs.org/wgbh/evolution/library/02/4/l_024_01.html> [Accessed 18 Jan. 2015].

Peat, F., 2002. *From certainty to uncertainty: the story of science and ideas in the twentieth century*. Washington: Joseph Henry Press, National Academies Press.

Pendergast, D., 1990. Engineering problems in Ancient Maya architecture: past, present, and future. *Environmental Geology Water Science*, 16(1), pp.67-73.

Penn State Astrobiology Research Centre, n.d. *Higher education programs*. [online] Available at: <http://psarc.weebly.com/higher-education.html> [Accessed 3 Dec. 2014].

Penn State, 2015. John Tuzo Wilson. [online] Available at: <https://www.e-education.psu.edu/earth520/content/l2_p7.html> [Accessed 24 Jan. 2015].

Peregrinus de Maricourt, P., 1269. *Epistola de Magnete*.

Peregrinus, P., 1269. *The letter of Petrus Peregrinus on the magnet*. Translated by Brother Arnold., 1868. New York: McGraw Publishing Company.

Peter Slevin, 2005. Kansas education board first to back ‘intelligent design’. *The Washington Post*. [online] 9 Nov. Available at: <http://www.washingtonpost.com/wp-dyn/content/article/2005/11/08/AR2005110801211.html> [Accessed 4 Dec. 2014].

Petrolia Discovery, 2015. *Petrolia Discovery Locations and Tour Overview*. [online] Available at: < http://petroliadiscovery.com/education/#top> [Accessed 14 Jan. 2015].

Phillips, C. and Pappalardo, R., 2014. Europa Clipper mission concept: exploring Jupiter's ocean moon. *Eos, Transactions, American Geophysical Union*, 95(20), pp.165-167.

Phillips, W. and Allan R., 1842. *An elementary introduction to mineralogy*. 4th ed. Edinburgh: Thomas Allan and Co.

Piepmeyer, A., 2007. *Collective consciousness*. [online] University of Chicago. Available at: <http://csmt.uchicago.edu/glossary2004/collectiveconsciousness.htm> [Accessed 2 Dec. 2014].

Pierce, K., Despain, D., Morgan, L. and Good, J., 2007. The Yellowstone hotspot, greater Yellowstone ecosystem, and human geography. In: L.A. Morgan, ed., *Integrated Geoscience Studies in the Greater Yellowstone Area - Volcanic, Tectonic, and Hydrothermal Processes in the Yellowstone Geosystem*. pp.5-39.

Pieters, C., Head, J., Gaddis, L., Jolliff, B. and Duke, M., 2001. Rock types of South Pole-Aitken basin and extent of basaltic volcanism. *Journal of Geophysical Research*, 106(E11), p.28001.

Pincus, G., 2013. *Adapting a Mayan hydraulic concept*. Georgetown: University of Georgetown.

Puleston, D., 1970. An experimental approach to the function of classic Maya chultuns. *American Antiquity*, 36(3), pp.322-335.

Pirsson, L. V, 1919. Biographical Memoir of James Dwight Dana 1813-1895. *National Academy of Sciences*, 9.

Plummer, C., Carlson, D., McGeary, D., Eyles, C. and Eyles, N., 2007. *Physical Geology & the Environment*. 2nd ed. ed. North York: McGraw-Hill Ryerson.

Plummer, C., McGeary, D., Carlson, D., Eyles, C. and Eyles, N., 2004. *Physical Geology & the Enviornment*. First Cana ed. Toronto: McGraw-Hill Ryerson.

Popa, T.M., 2005. *Aristotle on Material Depositions in Meteorology IV*. Ph. D. University of Pittsburgh.

Porter, R., 1999. *The Greatest Benefit to Mankind: A Medical History of Humanity*. New York: W. W. Norton.

Prakash, O. and Jaiswal, N., 2010. α-amylase : An ideal representative of thermostable eenzymes. *Applied Biochemistry and Biotechnology*, 160(8), pp.2401–2414.

PRC, 2015. *Faith on the Hill: The Religious Composition of the 114th Congress*. [online] Pew Research Center. Available at: <http://www.pewforum.org/2015/01/05/faith-on-the-hill/>.

Price, B., 1889. *A Treatise on Infinitesimal Calculus: The Dyanmics of Material…* 2nd ed. Oxford: Clarendon Press.

Pritchard, M.E., 2006. InSAR, a tool for measuring Earth's surface deformation. *Physics Today*, pp.68–69.

Puleston, D., 1977. The Art and Archaeology of Hydraulic Agriculture in the Maya Lowlands. *Social Processes in Maya Prehistory*, 4, p.449-467.

Quintana, E. V, Barclay, T., Raymond, S.N., Rowe, J.F., Bolmont, E., Caldwell, D.A., Howell, S.B., Kane, S.R., Huber, D., Crepp, J.R., Lissauer, J.J., Ciardi, D.R., Coughlin, J.L., Everett, M.E., Henze, C.E., Horch, E., Isaacson, H., Ford, E.B., Adams, F.C., Still, M., Hunter, R.C., Quarles, B. and Selsis, F., 2014. An Earth-Sized Planet in the Habitable Zone of a Cool Star. *Science* , [online] 344 (6181), pp.277–280. Available at: <http://www.sciencemag.org/content/344/6181/277.abstract>.

Rasmussen, W.D., 1962. The Impact of Technological Change on American Agriculture, 1862–1962. *The Journal of Economic History*, vol. 22, no. 04 [accessed 5 December, 2014], pp. 578-591.

Reiner, E. and Oppenheim, A.L., 1977. *Ancient Mesopotamia: Portrait of a Dead Civilization.* University of Chicago Press [accessed 7 December, 2014].

Reinbacher, W.R., 2002. *Healing earths: The Third Leg of Medicine : a history of minerals in medicine with rare illustrations from 300 to 1000 years ago*. W. Rudolph Reinbacher.

Reinhardt, E., 2014. Exploring Underwater Caves. *Integrated Science 2A18 History of the Earth*. [lecture] 28 Nov.

Reysenbach, A. and Rising, M.L., 2001. Thermophiles, origin of. *Encyclopedia of Biodiversity*, [online] 5, pp.647–654. Available at: <http://enviro.doe.gov.my/lib/digital/1385557763-3-s2.0-B0122268652002704-main.pdf>.

Reysenbach, A.-L., Voytek, M. and Mancinelli, R., 2001. *Thermophiles: Biodiversity, Ecology, and Evolution*. Springer, p.205.

Rezneck, S., 1962. Notes on a Correspondence between Charles Darwin and James Dwight Dana. *The Yale Univeristy Library Gazette*, 36(4), pp.176–183.

Richardson, L.F., 1922. Weather prediction by numerical process. *Cambridge University Press*, [online] 48(203), pp.282–284. Available at: <http://doi.wiley.com/10.1002/qj.49704820311> [Accessed 7 Dec. 2014].

Ringel, F., 1995. *New England's Gothic literature: history and folklore of the supernatural from the seventeenth through the twentieth centuries*. Lewiston: E. Mellen Press, p.266.

Rittner, D., 2009. *A to Z of Scientists in Weather and Climate*. [online] Infobase Publishing, p.273. Available at: <http://books.google.com/books?id=nU_jIyhvKOUC&pgis=1> [Accessed 6 Dec. 2014].

Roberts, M.B., 1998. Geology and Genesis Unearthed. *The Churchman*, 112(3).

Robertson, R., 2003. *The Three Waves of Globalization*. 1st ed. Nova Scotia: Fernwood Publishing, pp.3–4.

Rodhe, H., Charlson, R. and Crawford, E., 1997. Svante Arrhenius and the Greenhouse Effect. *Royal Swedish Academy of Sciences*, 26(1), pp.2–5.

Roehrig, C., 2000. Egypt in the Old Kingdom (ca. 2649–2150 B.C.). *The Metropolitan Museum of Art*, [online] Available at: <http://www.metmuseum.org/toah/hd/oking/hd_oking.htm> [Accessed 3 Dec. 2014].

Roller, D. W., 2010. *Eratosthenes' Geography*. Princeton: Princeton University Press.

Roth, E., 1989. Dating methods using natural radioactive phenomena: principles and general aspects. In: E. Roth and B. Poty, eds., *Nuclear Methods of Dating*. Dordrecht: Kluwer Academic Publishers.

Royal Society in one of their late meetings. *Phil. Trans. (1683–1775)*, 16(1686–1692), pp.563–578.

Rüdiger, G. and Hollerbach, R., 2006. *The Magnetic Universe: Geophysical and Astrophysical Dynamo Theory*John Wiley & Sons.

Rudwick, M.J.S., 1997. *Georges Cuvier, Fossil Bones, and Geological Catastrophes: New Translations & Interpretations of the Primary Texts*. Chicago: The University of Chicago Press.

Russell, B., 2008. *History of Western Philosophy*. New York: Simon and Schuster.

Rutherford, E., 1905. *Radio-activity*. 2nd ed. Cambridge: Cambridge University Press.

Ruttan, V.W., 1999. Biotechnology and Agriculture: A Skeptical Perspective. *The Journal of Agrobiotechnology Management and Economics*. 2(1) pp1107-9.

Rutten M.G., 1962. The geological aspects of the origin of life on earth. Elsevier Pub. Co.

Ryding, K., 1994. Islamic alchemy according to al-Khwarizmi. *Ambix*, 41(3), pp.121–34.

Safdie, M., 1975. Collective consciousness in making environment. In: *The Frontiers of Knowledge*, 1st ed. New York: Doubleday.

Samson, P. and Pitt, D., 1999a. A world of spheres. In: P. Samson and D. Pitt, eds., *The Biosphere and Noosphere Reader: Global Environment, Society and Change*, 1st ed. New York: Routledge, pp.11–16.

Samson, P. and Pitt, D., 1999b. Introduction: Sketching the Noosphere. In: P. Samson and D. Pitt, eds., *The biosphere and noospherer reader: global environment, society and change*, 1st ed. New York: Routledge, pp.1–10.

Samson, P. and Pitt, D., 1999c. Potential: The future of the Noosphere. In: P. Samson and D. Pitt, eds., *The Biosphere and Noosphere Reader: Global Environment, Society and Change*. New York: Routledge, pp.142–146.

Samson, P. and Pitt, D., 1999d. Theories: The evolution of the concept "Noosphere." In: *The Biosphere and Noosphere Reader: Global Environment, Society and Change*. New York: Routledge, pp.50–71.

Sandwell, D.T., n.d. Estimated and Predicted Sea Floor Topography from Satellite Altimetry. [Online] Available at: <http://www.ngdc.noaa.gov/mgg/bathymetry/predicted/explore.HTML#sat_alt> [Accessed 6 Dec. 2014].

Sant, J., 2014. Wegener and Continental Drift Theory. [Online] Available at: <http://www.scientus.org/Wegener-Continental-Drift.html> [Accessed 26 Nov. 2014].

Sapsford, M., 2009. *The Use of Sodium Salt Deposits in Medical and Medically Associated Industries in Ancient Egypt*. Ph. D. Cranfield University. Available at: <https://dspace.lib.cranfield.ac.uk/handle/1826/4009> [Accessed 3 Dec. 2014].

Scarborough, V., 1998. Ecology and Ritual: Water Management and the Maya. *Society for American Archaeology*, 9(2), p. 135-159.

Scarborough, et al., 1995. Water and Land at the Ancient Maya Community of La Milpa. *Latin American Antiquity*, 6(2), p.98-119.

Schaffer, W.M., 2009. Darwin's Theory of Coral Atoll Formation. *University of Arizona*. [online] Available at: http://www.blc.arizona.edu/courses/schaffer/182/DarwinReef.htm [Accessed January 15, 2015].

Schafer, D., 2011. *Cultures of Knowledge: Technology in Chinese History*. Leiden: BRILL, pp.390–395.

Schellen, H., 1884. *Magneto-electric and Dynamo-electric Machines: Their Construction and Practical Application to Electric Lighting and the Transmission of Power, Volume 1*. D. Van Nostrand.

Scheppler, B., 2006. *Al-Biruni*. New York: The Rosen Publishing Group, Inc.

Schmidt, M., 2010. Xenobiology: a new form of life as the ultimate biosafety tool. *BioEssays*, 32(4). pp. 322-331.

Schwarz, M., and Jersey, B., 2008. *Hunting the Hidden Dimension*. [video] New York: NOVA.

Scottish Engineering Hall of Fame (SEHF), n.d.. *James Young (1811-1883), engineer, founder of first commercial oil-works in the world and the father of the petrochemical industry.* [online] Available at: <http://www.engineeringhalloffame.org/profile-young.html> [Accessed 10 Jan. 2015].

Selinus, O., 2013. *Essentials of Medical Geology.* [online] Springer.

Serway, J., Serway, R., 2010. *Physics for Scientists and Engineers with Modern Physics*. Eighth Edition. Los Angeles, CA. Brooks Learning.

Serway, R. and Jewitt, J., 2010. *Physics For Scientists and Engineers with Modern Physics - Eighth Edition*.

Sharples, R. and Sheppard, A., 2003. *Ancient approaches to Plato's Timaeus*. London: Institute of Classical Studies School of Advanced Study University of London.

Sherratt, A., 1980. Water, Soil and Seasonality in Early Cereal Cultivation. *World Archaeology*, 11(3) pp. 313-330.

Shirley, D.N., 1983. A partially molten magma ocean model. *Journal of Geophysical Research*, 88(S02), pp.A519–A527.

Shore, A.F., 1987. Egyptian Cartography. In: D. Woodward, J.B. Harley, ed. 1987. *History of Cartography: Volume One*. Chicago: University of Chicago Press.

Simpson, G., 1964. The nonprevalence of humanoids. *Science,* 143(3608). pp. 769-775

Singer, S., 1970. Human energy production as a process in the biosphere. In: Scientific American Inc., ed., *The Biosphere*, 1st ed. San Francisco: W.H. Freeman and Company, p.107.

Sleep, H., 1992. Hotspot Volcanism and Mantle Plumes. *Annual Review of Earth and Planetary Sciences*, 20, pp.19–43.

Smith, C.D., 1987. Cartography in the prehistoric period in the old world : Europe, the Middle East, and North Africa. In *History of Cartography: Volume One*. Chicago: University of Chicago Press.

Smith, A.G., 2011. *Encyclopedia of Solid Earth Geophysics. Encyclopedia of Earth Sciences Series.* Dordrecht: Springer Netherlands, pp.40-41.

Smith, D. H., 2004. Astrobiology in the United States: a policy perpsective. In: P. Ehrenfreund, *et al.*, eds. 2004. *Astrobiology: Future Perspectives* Dordrecht: Springer.

Smith, J., 1992. Precursors to Peregrinus: the early history of magnetism and the mariner's compass in Europe. *Journal of Medieval History,* 18, pp.21-27.

Smith, P.E. and Young, T., 1983. The Force of Numbers: Population Pressure in the Central Western Zagros 12,000–4500 BC. *The Hilly Flanks.Essays on the Prehistory of Southwestern Asia*, pp. 141-161.

Smith, R.B.,et al., 2009. Geodynamics of the Yellowstone hotspot and mantle plume: Seismic and GPS imaging, kinematics, and mantle flow. *Journal of Volcanology and Geothermal Research*, 188, pp.26–56.

Solomon, M. (1992). Scientific Rationality and Human Reasoning. Philosophy of Science, 59(3), p.439.

Somerville, M., 1874. *Personal recollections, from early life to old age, of Mary Somerville. With selections from her correspondence*. London: J. Murray, p.377.

Sommerville, J., 1990. Religious Faith, Doubt and Atheism. *The Past and Present Society*.

Sonnenfeld, D.A., 1992. Mexico's" Green Revolution," 1940-1980: Towards an Environmental History. *Environmental History Review*, pp. 29-52.

Sop.Co.Ltd., n.d.. *Black gold.* [online] Available at: <http://www.sopcoltd.com/> [Accessed 25 Jan. 2015].

Sparks, J., 2012. Urartu: Irrigation and Water Management in the Armenian Highland. *Graduate Student Journal of Anthropology* pp. 41.

Spence, J.H.E., 2013. *High-Resolution Electron Microscopy*. 4th ed. Oxford: Oxford University press.

Spök, A., 2007. Molecular Farming on the rise–GMO Regulators Still Walking a Tightrope. *Trends in Biotechnology*, 25(2) pp. 74-82.

Stanford University, 2012. Darwin's Volcano. *microdocs*. [online] Available at: http://web.stanford.edu/group/microdocs/darwinvolcano.html [Accessed January 15, 2015].

Stanley, S.M., 2005. *Earth Systems History*. 2nd ed. New York: W. H. Freeman and Company.

Statistics Canada (StatCan), 2011. *Energy: crude oil and natural gas*. [online] Available at: <http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/prim71-eng.htm> [Accessed 3 Dec. 2014].

Stein, J.K., 2014. Earthworm Activity: A Source of Potential Disturbance of Archaeological Sediments. *American Antiquity*, 48(2), pp.277–289.

Stenonis, N., 1669. *The Prodromus of Nicolaus Steno's Dissertation Concerning a Solid Body Enclosed by Process of Nature Within a Solid*. Translated from Latin by L. G. Winter in 1916. London: The Macmillan Company.

Stetter, K.O., 2006. History of discovery of the first hyperthermophiles. *Extremophiles*, 10, pp.357–362.

Strom et al., 2005. The Origin of Planetary Impactors in the Inner Solar System. *Science*, 309(5742), pp.1847–1850.

Suess, E., 1924. *The Face of the Earth*. Oxford: Clarendon Press.

Sullivan, W. T. III and Carney D., 2007. History of astrobiological ideas. In: W. T. Sullivan III and J. A. Baross, eds. 2007. *Planets and Life: The Emerging Science of Astrobiology*. Cambridge: Cambridge University Press. Ch. 1.

Swerdlow, N. and Neugebauer, O., 1984. *Mathematical astronomy in Copernicus's De revolutionibus*. New York: Springer-Verlag.

Synthetic Biology Project, 2014.Synthetic Biology 101: What is Synthetic Biology? [online] Available at: <http://www.synbioproject.org/topics/synbio101/definition/> [Accessed 1 December 2014].

Synnes, M., 2007. Bioprospecting of organisms from the deep sea: scientific and environmental aspects. *Clean Technologies and Environmental Policy*, 9, pp.53–59.

Tarduno, et al., 2003. The Emperor Seamounts: Southward Motion of the Hawaiian Hotspot Plume in Earth's Mantle. *Science*, 301, pp.1064–1070.

Taylor, S. R.; Bonner, B. P.; Zandt, G., 1986. Attenuation and Scattering of Broadband P and S Waves across North America. *J. Geophys. Res.*, 91, 7309–7325.

Texas Archaeological Research Laboratory (TARL), 2009. *Mitchell Ridge*. [online] Texas Beyond History. Available at: <http://www.texasbeyondhistory.net/mitchell/mortuary.html> [Accessed 23 Nov.

The Geological Society, 2015. *Plate Tectonics*. [online] Available at: <https://www.geolsoc.org.uk/Plate-Tectonics/Chap1-Pioneers-of-Plate-Tectonics/Harry-Hess> [Accessed 24 Jan. 2015].

The Oxford Classical Dictionary. Oxford University Press, p.1592.

The Oxford History of Ancient Egypt. [online] Oxford University Press, p.544.

Thermal Biology Institute, 1978. *An Overview of Yellowstone Geologic History*. [online] p.10. Available at: <http://tbi.montana.edu/outreach/hotscience/materials/resources/ynp geology.pdf>.

Thomas, O.C., 2010. The Atheist Surge: Faith in Science, Secularism, and Atheism. *Theology and Science*, 8(2), pp.195–210.

Thomas, R., 2005. Zooarchaeology, Improvement and the British Agricultural Revolution. *International Journal of Historical Archaeology*, 9(2) pp. 71-88.

Tilling, R., Heliker, C. and Swanson, D., 2010. Eruptions of Hawaiian Volcanoes - Past, Present, and Future. *U.S. Geological Survey General Information Product 117*. [online] Available at: <http://geology.com/usgs/hawaiian-hot-spot/> [Accessed 2 December 2014].

Timmer, C.P., 1969. The Turnip, the New Husbandry, and the English Agricultural Revolution. *The Quarterly Journal of Economics* pp. 375-395.

Todar, K., 2012. *Textbook of Bacteriology*.

Tohge, M. et al., 1998. The use of ground-penetrating radar to map an ancient village buried by volcanic eruptions. *Journal of Applied Geophysics*, (40), pp.49–58.

Tomkeieff, S.I., 1946. James Hutton's "Theory of the Earth," 1795. *Proceedings of the Geologists' Association*, 57(4), pp.322–328.

Torge, W., 2001. *Geodesy*. 3rd ed. Berlin: Walter de Gruyter.

Totten, G.E., 2007. *A timeline of highlights from the histories of ASTM committee D02 and the petroleum industry*. [online] Available at: <http://www.astm.org/COMMIT/D02/to1899_index.html> [Accessed 23 Jan. 2015].

Tucker, A., 2012. *The Great New England Vampire Panic*. Smithsonian Magazine.

Tweedy, F., 1886. *Flora of the Yellowstone National Park*. Nabu Press, p.82.

University of Washington Astrobiology, 2012. *Courses*. [online] Available at: <http://depts.washington.edu/astrobio/drupal/content/courses> [Accessed December 3, 2014].

Uoguelph.ca, 2015. Ridge Push. [online] Available at: http://www.uoguelph.ca/geology/geol2250/glossary/HTML%20files/ridgepush.html [Accessed 27 Jan. 2015].

Uoguelph.ca, 2015. Slab Pull. [online] Available at: http://www.uoguelph.ca/geology/geol2250/glossary/HTML%20files/slabpull.html [Accessed 27 Jan. 2015].

University of Utah, 2013. *Metallurgical Engineering - Metallurgical Engineering - The University of Utah*. [online] The University of Utah. Available at: <http://www.metallurgy.utah.edu/about/index.php> [Accessed 4 Dec. 2014].

Vago, et al., 2006. ExoMars: searching for life on the Red Planet. *ESA Bulletin*, 126, pp. 17-23.

Van den Burg, B., 2003. Extremophiles as a source for novel enzymes. *Current Opinion in Microbiology*, 6(3), pp.213-218.

Vázquez, M., Pallé, E. and Rodríguez, P.M., 2010. *The Earth as a Distant Planet: A Rosetta Stone for the Search of Earth-Like Worlds*. Springer Science & Business Media, p.437.

Veni, G., 1990. Maya utilization of karst groundwater resources. *Environmental Geology,* 16(1), p.63.

Visser, M.E., 2008. Keeping up with a warming world; assessing the rate of adaptation to climate change. *Proceedings. Biological sciences* 275(1635), pp.649–59.

Virga, V., Grim, R.E. & Billington, J.H., 2007. *Cartographia: Mapping Civilizations*, New York: Little, Brown and Company.

Vitry, J., 1459. *Historia Hierosolymitana*. Milan.

Wagner, C. H., 1983. Uncertainty in science and statistics. *The Two-Year College Mathematics Journal*, 14(4), 360–363.

Wallace, W.A., 1981. *Prelude to Galileo: Essays on medieval and sixteenth-century sources of Galileo's thought*. Boston, MA: D. Reidel Pub. Co.

Walter, ed. 1951. *Encyclopedia Britannica.* Chicago: Encyclopedia Britannica Inc.

Walkington, H., 2010. Soil science applications in archaeological contexts: A review of key challenges. *Earth-Science Reviews*, 103(3-4), pp.122–134.

Watson, J., 1999a. "Hotspots": Mantle thermal plumes. *U.S. Geological Survey*. [online] Available at: http://pubs.usgs.gov/gip/dynamic/hotspots.html [Accessed November 28, 2015].

Watson, J., 1999b. J. Tuzo Wilson: Discovering transforms and hotspots. *U.S. Geological Survey*. [online] Available at: http://pubs.usgs.gov/gip/dynamic/Wilson.html [Accessed January 10, 2015].

Warkentin, B., 2006. *Footprints in the Soil: People and Ideas in Soil History*. Amsterdam: Elsevier, p.572.

Wegener, A., 1966. The origin of continents and oceans. New York: Dover Publications.

Wegener, A., 1966. *The Origin of Continents and Oceans*, Mineola, N.Y. Dover Publications.

Wells, C., 1968. Dental Pathology from a Norwich, Norfolk, Burial Ground. *Journal of the History of Medicine and Allied Sciences*, 4(23), pp.372–379.

Walter, P, et al., 1999. Making Make-up in Ancient Egypt. *Nature*, 397(6719), pp.483–484.

Wells, L., Armstrong, J. and Huber, J. A., 2007. Disciplinary aspirations and educational opportunities. In: W. T. Sullivan III and J. A. Baross, eds. 2007. *Planets and Life: The Emerging Science of Astrobiology*. Cambridge: Cambridge University Press.

White, A.D., 1955. *A history of the warfare of science with theology in Christendom*. New York, NY: G. Braziller.

White, G.W. ed., 1968. Contributions to the History of Geology Volume 4: Nicolaus Steno The Promodus of a Dissertation Concerning a Solid Body. New York: Hafner Publishing Company, Inc.

Whitley, D.S., 1996. *A Guide to Rock Art Sites: Southern California and Southern Nevada*. Missoula: Mountain Press Publishing, p.218.

Wiechert, U, et al., D., 2001. Oxygen isotopes and the moon-forming giant impact. *Science*, 294(5541), pp.345–8.

Wilhelms, D.E., 1993. *To a Rocky Moon: a Geologist's History of Lunar Exploration*. Tucson, AZ: University of Arizona Press.

Wille, P., 2005. Sound Images of the Ocean: In Research and Monitoring. [Online] Springer Science & Business Media, p.471. Available at: <http://books.google.com/books?id=r5CUczPBlp0C&pgis=1> [Accessed 4 Dec. 2014].

Wilson, D., 1983. Rutherford - simple genius. [online] Inis.iaea.org. Available at: https://inis.iaea.org/search/search.aspx?orig_q=RN:15039499 [Accessed 24 Jan. 2015].

Wilson, D.B., 2014a. Galileo's Religion Versus the Church's Science? Rethinking the History of Science and Religion. *Physics in Perspective*, 1(1), pp.65–84.

Wilson, D.B., 2014b. Galileo's Religion Versus the Church's Science? Rethinking the History of Science and Religion. *Physics in Perspective*,1(1), pp.65–84

Wilson, J. (1966). Did the Atlantic Close and then Re-Open?. *Nature*, 211(5050), pp.676-681.

Wilson, J.T., 1963. A possible origin of the Hawaiian Islands. *Canadian Journal of Physics*, 41, pp.863–870.

Wilson, L., 2011. The role of geoarchaeology in extending our perspective. In: L. Wilson, ed., *Human interactions with the Geosphere*, 352nd ed. London: Geological Society, p.1.

Wilson, M.E., 1995. Travel and the emergence of infectious diseases. *Emerging infectious diseases,*1(2), pp.39–46.

Wolfram Alpha, 2014. *Fractals*. [online] Available at: <http://www.wolframalpha.com/input/?i=fractals> [Accessed 01 December 2014].

Woods Hole Oceanographic Institution, 2006. Marie Tharp Bio : Mary Sears Woman Pioneer in Oceanography Award : Woods Hole Oceanographic Institution (WHOI). [Online] Available at: <http://www.whoi.edu/sbl/liteSite.do?litesiteid=9092&articleId=13407> [Accessed 26 Nov. 2014].

Woods Hole Oceanographic Institution, 2012. Ships & Technology used during the Titanic Expeditions : Woods Hole Oceanographic Institution. [Online] Available at: <http://www.whoi.edu/page.do?pid=83577&tid=3622&cid=130989> [Accessed 6 Dec. 2014].

Woodward, H., 1907. The history of the Geological society of London. London: Geological Society.

Woese, C.R. and Fox, G.E., 1977. Phylogenetic structure of the prokaryotic domain: The primary kingdoms. *Proceedings of the National Academy of Sciences of the United States of America*, 74(11), pp.5088–5090.

Wynne, B., 2001. Creating Public Alienation: Expert Cultures of Risk and Ethics on GMOs. *Science as Culture*, 10(4)pp. 445-481.

Xu, Y., 2007. Identification of mantle plumes in the Emeishan Large Igneous Province. *Episodes*, 30(1), pp.32–42.

Youmans, E.L., 1875. Editor's Table. *Popular Science*, 6(17), pp.361–364.

Zahirova, V., 2008. Not just energy - Azerbaijan's medicinal oil. *Visions of Azerbaijan,* 3.2, pp.66-71.

Wylie, W.W., 1882. *Yellowstone National Park, Or, The Great American Wonderland: A Complete Description of All the Wonders of the Park, Together with Distances, Altitudes, and Such Other Information as the Tourist Or General Reader Desires : a Complete Hand, Or Guide Book.* House of Ramsey, Millett & Hudson, p.99.

Zeder, M.A., 2008. Domestication and Early Agriculture in the Mediterranean Basin: Origins, Diffusion, and Impact. *Proceedings of the National Academy of Sciences of the United States of America*, 19(105) pp. 11597-11604.

Zeder, M.A., 2009. The Neolithic Macro-(r) Evolution: Macroevolutionary Theory and the Study of Culture Change. *Journal of Archaeological Research*, 17(1)pp. 1-63.

Zhdanov, M.S., 2009. *Geophysical Electromagnetic Theory and Methods*. Elsevier, p.868.

Zimmer, C., 2014. Secrets of the Brain. *National Geographic*, pp.26–56.

Zimmerman, R., 1984. The structure of mythos: on the cultural stability of alchemy. *Ambix*, 31(3), pp.125–37.

Zubieta, R., 2014. *How can Peruvian authorities protect archaeological sites from vandalism?* Peru This Week. Translated by R. Chase. 11 Mars.

Picture Credits

p. 4 Adapted from: *Gravure sur bois de Flammarion*. Wikimedia Commons, Camille Flammarion, 1888.

p. 6 *Shell fossil*. Pixabay, 2013

p. 8 *Niels Steensen*. Wikimedia Commons, J. P. Trap, 1686.

p. 9 *Title page of the* Prodromus. Wikimedia Commons, N. Steno, 1669.

p. 10 *Geologic history of Tuscany*. *Nicolaus Steno: Biography and Original Papers of a 17th Century Scientist*, N. Steno, 1669.

p. 11 *Some of the major radioisotopes used in radiometric dating*. T. Goodwill, 2014.

p. 12 *George Cuvier*. Wikimedia Commons, W. Pickersgill, 1831.

p. 13 *American Mastodon*. Wikimedia Commons, C. Knight, 1897.

p. 15 *Impact event*. Wikimedia Commons, National Aeronautics and Space Administration (NASA), 2004.

p. 16 *Thomas Huxley*. Wikimedia Commons, Lock & Whitfield, 1880.

p. 17 *Archaeopteryx lithographica*. Wikimedia Commons, LadyofHats, 2006.

p. 19 *Richard Prum*. Wikimedia Commons, MacArthur Foundation, 2009.

p. 21 *Ornithomimus edmontonicus*. Wikimedia Commons, S. Bergmann, 2004.

p. 22 *Anchiornis feathers*. Wikimedia Commons, Kumiko, 2011.

p. 23 *Xiaotingia fossil*. Wikimedia Commons, B. McAdam, 2011.

p. 24 *Illustration of Steno's Laws*. *Earth Science*, CK-12 Foundation, 2009.

p. 25 *Popcorn with frostwork*. National Park Services, P. Horsted, 2009.

p. 26 *Elk pictograph 1*. Grand Galleries of the Ancients, J. Q. Jacobs, 1997.

p. 27 *Native American petroglyphs vandalized*. Lake Mead NRA Public Affairs, Andrew Muñoz, 2010.

p. 28 *NASA Apollo 8 Earth rise*. NASA/Bill Anders, 1968.

p. 30 Adapted from: *Ancient theory of the Universe*. Wikimedia Commons, *Popular Science Monthly*, 1909.

p. 31a Adapted from: *Ptolemaic elements*. Wikimedia Commons, Fastfission, 2005.

p. 31b *Image of heliocentric model*. Wikimedia Commons, N. Copernicus, 1543.

p. 32 *Tychonian system*. Wikimedia Commons, Fastfission, 2009.

p. 33a *Diagram illustrating Kepler's laws*. Wikimedia Commons, Hankwang, 2007.

p. 33b *Ignition of Kepler's Delta II 7925-10L*. Wikimedia Commons, NASA, 2009.

p. 34 *Galileo's sketches of the Moon*. Wikimedia Commons, Galileo Galilei, 1610.

p. 35 *The far side of the Moon* .Wikimedia Commons, NASA, 1972.

p. 36 *Buzz Aldrin on the Moon*. Wikimedia Commons, NASA, 1969.

p. 37 *The South Pole-Aiken basin*. Wikimedia Commons, NASA, 1994.

p. 38 *Full Earth*. NASA, Apollo 17 Crew, 1972.

p. 39 *Joshua Lederberg lab*. Wikimedia Commons, 1958.

p. 40 *Carbon compounds from Mars found inside meteorites*. NASA, NASA/Johnson Space Center (JSC)/Stanford University, 1958.

p. 41 *Artist's concept of Europa water vapor plume*. NASA, NASA/ESA/K. Retherford/SWRI, 2013.

p. 42 Adapted from: *Figure 2.2 The geosphere, biosphere and noosphere. The biosphere and noosphere reader: global environment, society and change*, P. Samson and D. Pitt, 1999.

p. 44 *Hellisheiði geothermal plant*. Wikimedia Commons, H. Baldursson, 2008.

p. 45 *America facing its most tragic moment*. Wikimedia Commons, 1912.

p. 46 *Portrait of John Tyndall*. Wikimedia Commons, 2011.

p. 47. *Richardson's forecast factory*. National Oceanic and Atmospheric Administration (NOAA), 2007.

p. 48. *Earth radiation thermal balance energy budget atmosphere*. NASA Earth Observatory, 2014.

p. 49. *Schematic for global atmosphere model*. NOAA, 2012.

p. 50 *Galileo moon phases*. Wikimedia Commons, Galileo Galilei, 1616.

p. 51 *Hutton James portrait Raeburn*. Wikimedia Commons, H. Raeburn, c. 1798.

p. 52 *Ch Darwin-Emile Littré by André Gill*. Wikimedia Commons, A. Gill, 1878.

p. 54 *Mapping tools and telescope laying on a map*. Wikimedia Commons, 2009.

p. 56 Adapted from: *Clay tablet containing plan of Nippur*. Wikimedia Commons, H. V. Hilprecht, 1903.

p. 57 Adapted from: *Hecataeus world map*. Wikimedia Commons, B. Saint-Pol, 2006.

p. 58 Adapted from: *Song Dynasty map*. Wikimedia Commons, PericlesofAthens, 2007

p. 59 Adapted from: *Brain atlas*. Wikimedia Commons, Lentz065, 2011.

p. 60 *Johann Ruysch world map (1507-1508)*. Wikimedia Commons, Johannes Ruysch, 1507

p. 61 Adapted from: *Waldseemüller map*. Wikimedia Commons, Martin Waldseemüller, 1507

p. 62 *Mercator 1569*.Wikimedia Commons, Gerardus Mercator, 1569.

p. 63 *SRTM30PLUS color-encoded shaded relief image of North America (approximately 1km)*. USGS, NASA, 2008.

p. 64 *A Mayan temple*. Flickr, K. Simourd, 2007.

p. 65 *The earliest known design for a Han Dynasty (206 BC–220 AD) South-pointer*. Wikimedia Commons, 2006.

p. 66a *Statue of Flavio Gioia in Naples, Italy*. Wikimedia Commons, P. Lorente, 2005.

p. 66b *Pivoting compass needle in a 14th-century copy of Epistola de magnete of Peter Peregrinus*. *Epistola de magnete of Peter Peregrinus*, 1269.

p. 67 *GPS satellite constellation*. NOAA, 2008.

p. 69 *Painting of* HMS Challenger *(1858)*. Wikimedia Commons, W. F. Mitchell, 1881.

p. 70 *Map of the mid-ocean ridge system (yellow-green) in the Earth's oceans*. Wikimedia Commons, NOAA, 1996.

p. 71 *View of the bow of the* RMS Titanic *photographed in June 2004 by the* ROV Hercules *during an expedition returning to the shipwreck of the* Titanic. NOAA/Institute for Exploration/University of Rhode Island (NOAA/IFE/URI), 2004.

p. 72 *Eratosthenes method for determining the size of the Earth*. Wikimedia Commons, Gregors, 2011.

p. 73 *Abu Reyhan Biruni – Earth circumference*. Wikimedia Commons, N. Dilmen, 2010.

p. 74 *Earth gravitational model 1996*. Wikimedia Commons, F. G. Lemoine, *et al*., 1996.

p. 75 *Full Moon Luc Viatour*. Wikimedia Commons, Luc Viatour, 2006.

p. 76 *Edmond Halley*. Wikimedia Commons, c. 1710.

p. 77 *Halley's original diagram of hollow Earth*. Philosophical Transactions of the Royal Society of London, E. Halley, 1692.

p. 79 *A tomographic image of seismic velocities for North America using surface waves*. Serc Media, S. van der Lee, 2013.

p. 84 *Pele namakaokahai*. Wikimedia Commons, Hawaiian Volcano Observatory, 2008.

p. 85 *James Dwight Dana in 1843*. Wikimedia Commons, 1843.

p. 86 *Adapted from: Hawaii hotspot cross-sectional diagram*. Wikimedia Commons, J. E. Robinson, 2006.

p. 87 *ASTER Andes*. NASA, 2000.

p. 88 *Benoit Mendelbrot talking at TED (Technology, Entertainment, Design) conference*. Wikimedia Commons, Jurvetson, S., 2010.

p. 89b *Català: Mètode de Júlia. Zn+1 = Exp(Zn^3) Cx = -0.621 Cy =0.00 Zoom X9*. Wikimedia Commons, Ferrer, J.M., 2012.

p. 89c *Mandelbrot set*. Wikimedia Commons, Beyer, 2013.

p. 90a *Box fractal*. Wikimedia Commons, AnonMoos, 2013.

p. 90b *Menger 5*. Wikimedia Commons, Saperaud, 2005.

p. 91a *Britain fractal coastline combined*. Wikimedia Commons, Avsa, 2005.

p. 91b *Koch flake*. Wikimedia Commons, Wxs, 2007.

p. 92 Adapted from: *Chlorite mineral*. S. Singh, 2014.

p. 94. *Plinius Maior (Pliny the Elder)*. Wikimedia Commons, Natural Institute of Health and Human Services, 2012.

p. 95. *James Dwight Dana*. Wikimedia Commons, *Popular Science Monthly* 1, 1872.

p. 96. *Sphalerite, Galena, from the F. John Barlow Collection*. Wikimedia Commons, R. Lavinsky, 2010.

p. 97 *Ernst Ruska electron microscope*. Wikimedia Commons, J. Werther, 2006.

p. 98 *Cinabro*. Wikimedia Commons, Aangelo, 2007.

p. 99 *Basic alchemy*. alchemyofthegoddess.com, 2014.

p. 100 Adapted from: *Robert Boyle*. Wikimedia Commons, J. Keresboom, 1689.

p. 101a Adapted from: *Ferulic acid*. Wikimedia Commons, Shaddack, 2006.

p. 101b Adapted from: *Vanillin*. Wikimedia Commons, R. Mattern, 2007.

p. 102 Adapted from: *Nile River and Delta from orbit*. Wikimedia Commons, J. Descloitres, 2003.

p. 103 Adapted from: *Papyrus Ebers*. Wikimedia Commons, Aoineko, 2004.

p. 104 *Relief of Hatshepsut's expedition to the land of Punt*. Wikimedia Commons, Stavros (Σταύρος), 2008.

p. 105 *Mt. Cleveland ISS013-E-24184*. Wikimedia Commons, JSC, 2006.

p. 106 Adapted from: *Yugong nine provinces map*. Wikimedia Commons, H. Renzhi, 2014.

p. 109 *Vasily Dokuchaev (1895)*. Wikimedia Commons, 1895.

p. 110 *McKittrick tar seep north of Highway 58*. Wikimedia Commons, Lldenke, 2000.

p. 111 *Young James chemist*. Wikimedia Commons, J. Ferguson, 1906.

p. 112 Adapted from: *Spring pole for obtaining reciprocating motion.* Food and Agriculture Organizations of the United Nations.

p. 113 *Bus running on soybean biodiesel.* Wikimedia Commons, Adrignola, 2007.

p. 114 *Gold bearing vein Toi Kinzan*. Wikimedia Commons, PHGCOM, 2007.

p. 114 *Giza Plateau - Great Sphinx with Pyramid of Khafre in background*. Wikimedia Commons, D. Mayer, 2008.

p. 115a *Tutmask*. Wikimedia Commons, J. Bodsworth, 2007.

p. 115b *TurinPapyrus1*. Wikimedia Commons, Zyzzy, 2005.

p. 115c *Soft copper chisel.* UCL Digital Egypt, UCL, 2003.

p. 116a *Александрийский маяк*. Wikimedia Commons, 2010.

p. 116b *Octadrachm Ptolemy III BM CMBMC103*. Wikimedia Commons, Jastrow, 2007.

p. 116c *Placermine*. Wikimedia Commons, Bulwesator, 2003.

p. 119 *Birth of agriculture: the Fertile Crescent*. Wikimedia Commons, Roe, 2013.

p. 120 *Pietro Crescenzi's agricultural calendar*. P. Crescenzi, 1306.

p. 121 *GMO cultivation from 1996-2009*. Wikimedia Commons, Fafner, 2010.

p. 122 *Mayan temple of the Sun*. Wikimedia Commons, ricraider, 2007.

p. 123 *Xkipche Chultun*. Wikimedia Commons, HJPD, 2004.

p. 124 *Canon del Usamacinta*. Alfonsobouchot, 2012.

p. 125 *Grand Coulee Dam*, G. M. Erickson, 2009.

p. 126 *Artist concept of an early Earth*. NASA, 2014.

p. 128 *Creation of Humanity by Prometheus as Athena Looks On.* Wikimedia Commons, Jastrow, 2006.

p. 129 Adapted from: *Experiment Pasteur English*. Wikimedia Commons, Carmel830, 2010.

p. 130 Adapted from: *Miller-Urey-Experiment*. Wikimedia Commons, Xerxes2k, 2005.

p. 131 *DNA simple2*. Wikimedia Commons, Forluvoft, n.d.

p. 132, *View of Yellowstone*. L. Carfrae, 2006.

p. 133a *Hot spring*. L. Carfrae, 2006.

p. 133b *Bacterial mat*. L. Carfrae, 2006.

p. 134 *Black smoker in Atlantic Ocean,* Wikimedia Commons, 2006.

p. 136 *Charles Lyell Portrait*. Wikimedia Commons, 2015.

p. 137 *Eduard Suess Portrait*. Wikimedia Commons, 2015.

p. 138 *A circular Wilson Cycle*. James Madison University Geology, 2015.

p. 139 *Supercontinent cycle hypotheses*. R. N. Mitchell, 2012.

p. 140 *Alfred Wegener*. Wikimedia Commons, 1910.

p. 141 *This dynamic Earth: the structure of plate tectonics*. Wikimedia Commons, J. Kious, et al., 1996.

p. 142 *The genome diversity and karyotype evolution of mammals. Molecular Cytogenetics* 4 (22), A. S. Graphodatsky, V. A. Trifonov, and R. Stanyon, 2011.

p. 143 *Carbon cycle*. Wikimedia Commons, NASA, c.2006.