History of the Earth

Vol VII

ISCI 2A18 2016/17

History of the Earth VII

ISCI 2A18 2016/17

History of the Earth

Volume Seven

Authors

MONISH **AHLUWALIA**
LEENA **ALSHENAIBER**
LIZ **BALINT**
BRONWYN **BARKER**
PASCALE **BIDER**
SOMMER **CHOU**
VICTORIA **COLES**
JAROD **COPPENS**
MEGHAN **CRAUGHWELL**
TANYA **DANIEL**
AARON **DE JONG**
ARIANA **FRASCHETTI**
JACQUELINE **GARNETT**
MILA **GILLIS-ADELMAN**
KATIE **GRAHAM**
LEEOR **GREENBLAT**
GEORGE **HANNA**
NOAH **HOUPT**
GRAHAM **JOHNSTONE**
NOEL **KIM**
ASHLYN **LEUNG**
AILEEN **LIU**
ELSIE **LOUKIANTCHENKO**
ADRIEN **LUSTERIO**
SABRINA **MACKLAI**
CONNOR **MACLEAN**
SONYA **MARTIN**
BRYCE **NORMAN**
ISOBEL **SHARPE**
URSZULA **SITARZ**
JENEVA **SMITH**
MEGAN **SWING**
MONICA **TAKAHASHI**
SOPHIA **TAO**
ADAM **TWEEDLE**
ELIAS **VITALI**
GABRIELLA **WYNN**
JOSHUA **YACHOUH**
JONAS **YEUNG**
BRIAN **YU**
NICOLE **ZHANG**

Editors

CAROLYN **EYLES**
SABRINA **MACKLAI**
CONNOR **MACLEAN**
BRYCE **NORMAN**
SARAH **SYMONS**

Foreword

PRATEEK **GUPTA**

Contents

Foreword

At its foundation, science is about two things: discovery and communication. The authors of this book intimately understand this foundation. For science to excel it must shift away from siloed thought to recognize the various angles, perspectives and flavors to each problem. Each passage is a testament to this innovative style of problem solving, an innovative style that crops up again and again through history and around the world to address a diverse set of problems. As I read each chapter, the authors skillfully maneuver research in areas as vast as philosophy, history, policy and economics and weave it seamlessly with technical science, be it astrophysics, biochemistry, geochronology or anything in between, to execute a comprehensive story that effortlessly dances off of each page. These authors understand science: discovering whatever is needed to explain a story, and effectively communicating it.

It's no surprise. The authors are students of McMaster's Integrated Science ("iSci") Program. These students are trained in the same vein as the amazing groundbreaking scientists described in each chapter: as individuals observing their bodies, their societies, their world and their universe through a lens without boundaries. This penchant for discovery reminds me that scientists were and always will be the truest entrepreneurs: those who relentlessly pursue their curiosity and passions for the sake of humanity. Instead of disrupting markets, they disrupt human knowledge. Instead of raising financial capital and contributing to building companies, they raise intellectual capital and contribute to building schools of thought. Not one scientist described in this book felt content with staying within their externally-defined boundaries. This book is a celebration of the rebellious attitude of the game-changers that have shaped human history with their discoveries, consistently refusing to be defined by labels in their pursuits. I hope this book forces you to question restraints and to explore with freedom and boundless imagination.

This is exactly how the iSci Program taught me to view the world. Like the taste of a fine wine, this perspective has become more prominent with time. I love redefining labels. As a lawyer, I always get frustrated when people ask me "why the jump" when they learn of my background in science. Why is there a perceived "jump"? I seek to discover and understand my client's interests. From there, I research, I question, and

I explore. I use creativity, I use imagination, and I evaluate every scenario. As I redraft a document or tweak my arguments, I envision myself in a lab, mixing different compounds until I get it just right. I can then emerge from my lab to proudly communicate the final written contract or oral submissions with conviction. Each day is discovery and communication. I can never abandon those foundations of science.

The journeys travelled in this book inspire me to continue viewing my problems, my career, and my potential as boundless; as seamless; as timeless. As each chapter highlights, it is fascinating how age-old discoveries from decades, centuries, and millennia ago are still influencing and ushering modern thought today. It underscores how much the past affects the future. As an Integrated Scientist, I will always endeavor to feel new angles, to see new perspectives and to taste new flavors with everything that comes across me. Innovation can only happen that way. I implore you to read this book with that mindset as well. Maybe that unearthed problem can be solved with a new lens.

Prateek Gupta
Associate, Stikeman Elliott LLP

Honours B.Sc. McMaster University, 2013 (Integrated Science)
M.Sc. Western University, 2016 (Geology)
J.D. Western University, 2016

Welcome to a History of the Earth

-Integrated Science Class of 2019

Introduction

What species of life exists at the furthest depths of our ocean? How do we know that dinosaurs once roamed the Earth? Can we find life in the never-ending expanse of our galaxy? Is climate change the result of human activity? All great scientific research has stemmed from someone, somewhere, posing a good question. Science is shaped by curious humans asking these good questions - and seeking even better answers. Humankind's innate curiosity to understand the world around us is a trait that has prevailed since the beginning of our species, and has driven us towards the society in which we live in today. There is not a place in this universe that is untouched from our curiosity. Perhaps it is this curiosity, this undeniable drive to study more, learn more, and share more, that connects us beyond superficial factors like wealth and status. In the past, you didn't need formal education to be considered a scientist. All you needed was curiosity, and the drive to satisfy it.

There is no definite start to humankind's venture into the science of the natural world. While some were beginning to understand the chemical composition of soils, others halfway across the globe had spent their lives studying the stars that graced their night skies. There was no true distinction between biologist, chemist, astronomer, or physicist. There were only scientists. The history of the Earth that we can now access at the tips our fingertips is due to the insurmountable work made by some of the world's first *integrated* scientists. These individuals often risked their lives turning from the status quo and were dedicated to uncovering the truth. We owe a great deal to these scientists for without whom, we wouldn't have our computers, our compasses, our medical advancements, our industries - essentially without whom, we would not have our modern society.

Like all famous stories, this is a tale of great adventure featuring even greater people. This is a story of passion, of hard labour, of the unwavering commitment to the scientific pursuit. This is a story where a poor young female paleontologist can be placed at the same pedestal as the greatly renowned Aristotle. This is a story where a Muslim scholar can agree with the scientific theories of Christian scientists, despite any conflicts of personal matters. This is a story that transcends sex, race, and religion. A story that has been written long before our ancestors roamed this Earth and will continue long after we are gone. This is the history of the Earth.

"...we have to be prepared always for the possibility that each new discovery, no matter what science furnishes it, may modify the conclusions we draw."

—Alfred Wegener

Chapter 1: Rocks, Minerals, and Soils

Scientific understanding of the natural world has steadily and consistently progressed through time. Fortunately, most of the development of that understanding is tangible; it has been documented throughout history. One of the first subjects to peak human interest is our natural environment. From the classic to modern age, the composition of the Earth and the processes operating upon it have been comprehensively studied, recorded, and revealed.

There is nothing more striking than the world beneath our feet and in front of our eyes. From vast expanses of ocean as far as one can see to mountains so high that they touch the clouds, the natural world has inspired mankind for millennia.

This chapter will discuss the findings of several significant individuals in order to understand how their curiosity and influence shaped the course of man's comprehension of their surroundings. It will address the successes and hardships of their lives to highlight how their personal environments affected their specific viewpoints and opinions of Earth and the universe. This will serve to provide a glimpse back through time and will illustrate how the scientific method adapted and developed in response to cultural drivers. Furthermore, it will address the impact of notable scientific advancements through the ages, and will allow a comprehensive view of how humankind's understanding has shifted and developed through time.

The presumed uniformitarian nature of the Earth's processes are integral to its study; researchers that inspect our planet today are viewing identical process to those which had been observed during the Middle Ages, the Islamic Golden Age, the Enlightenment, and the Scientific Revolution. This is crucial in that the phenomena being investigated are timeless. Studies of these phenomena are also transferrable regardless of cultural differences, and can be confirmed centuries apart from initial conjectures. Earlier academics built the foundations for a modern understanding of geology and environmental science. As our understanding of the Earth constantly develops, our motivation to study it changes over time. The establishment of fundamental principles allows contemporary scientists to expand on these concepts in order to develop innovative technologies of immeasurable significance and application. Furthermore, it allows us to utilize our planet more efficiently and in a more sustainable matter. It may help to develop strategies to protect cities from natural disasters, or to study and control climate change. Most notably, an understanding of the Earth and its natural components now has a powerful role to play in issues outside of the subject of geology, such as urban planning and infrastructure, and even medical science.

Soil Perspectives in Antiquity

The science of soil, or pedology, is not often cited as an exciting and dynamic area of the earth sciences. Whereas volcanology and seismology

Figure 1.1: *The Mesopotamian region is bounded by the Tigris and Euphrates rivers. The first agricultural exploitation of soil occurred here some 10,000 years ago.*

focus on both enormous and devastating phenomena, pedology is, on its surface, far more suburban than its downtown counterparts. However, upon the realization that soils are a pillar of modern civilization given their role in agriculture, one becomes aware of just how important an understanding soils can be. As will be made evident, pedology, like other areas of science, was not well understood until the past several hundred years. This lack of understanding did not stop historic civilizations from using soil with certain practices, nor did it stop them from speculating why these practices produced the results they did. Just as a student may choose to apply a mathematical formula to specific examples before learning its proof, most of humanity's interaction with soil was one of exploitation rather than interpretation. This is not to say that the civilizations of antiquity were not interested in the soils as a science, but the absence of the modern scientific method limited what could be discovered and verified in this arena of knowledge. For this reason, pedology is an excellent case study of the progression of a human pursuit from a mere collection of practices to a science in its own right. This progression is apparent by studying how the Romans and Greeks interacted with soils versus the interactions of post-renaissance scientists.

The origins of practical soil usage can be dated back to ancient civilizations demonstrated by its application in various agricultural practices. However, soil as a distinct scientific discipline only emerged much later in human history with the development of the scientific method, compared to ancient times where soil characterization was based merely on physical observations and reasoning. Despite this, the historical perspectives of ancient civilizations on soil do provide merit for the basis of the modern and accepted science of soils, rendering the importance of understanding how knowledge and hypotheses of soil characteristics have evolved over time.

The earliest human attempts at strategically using soil date back to 10,000 BC in southern Iraq, evident through ancient agricultural establishments in these regions (Brevik, 2009). This general area, between the Euphrates rivers and Tigris of modern Iraq, was occupied by several ancient civilizations, including the Babylonians and Sumerians (Figure 1.1) (Brevik, 2009). The use of region-specific harvesting sites at this time is representative of recognition of different soil types, where agricultural establishments were set up on soils that were seemingly fertile. These physical observations, based on the merit of trial and error in finding adequate soils for growth, provides insight to the early progression of pedology, where initial understandings were very scarce.

The Greeks

A deeper understanding of soils was demonstrated by ancient Greek philosophers, who differentiated between soils as early as 2000 BC. Aristotle (384-322 BC) (Figure 1.2) was a Greek philosopher who believed facts obtained through observations structured the focal point of true understanding of the subject matter (Randall, 1960). The root of his understanding of soils, along with several other Greek philosophers, credited ancient Greeks as the first civilization with recorded writings demonstrating advanced understanding of soil properties.

Greek understanding of soils revolved around the connection between soil and life. Aristotle and Plato, another Greek philosopher, personified the connection between soils ability to give life and a mother's child-bearing capability (Brevik, 2009). Through observations of plant growth, Aristotle developed the humus theory of soils, stating that plants grow better in soils subject to manure or plant residues (Warkentin, 2006). Though at the time it was unclear what gave manure its soil-enhancing properties, the usage of darker humus soils was the basis for soil management in this era and for thousands of years to come. Greek philosopher Xenophon (434-355 BC), whose work imminently portrays the idea that life begins and ends in the soil, also supported the idea of manure as a way to improve agricultural growth in soil (Warkentin, 2006).

Aristotle, along with Greek physician Hippocrates (460-377 BC), suggested the contents of soils contained healing powers, and recorded eating soils in a process known as geophagy (Abrahams, 2010). Hippocrates was well regarded as a cornerstone in ancient medicinal practices, suggesting that geophagy was common during these times. It was believed that ingestion of various soils and earthly materials provided treatment for liver and stomach sickness (Abrahams, 2010). Continuing with the Greek connection of soils to life, Hippocrates pictured soils as the nutrient-bearing stomach of plants, providing evidence of the Greeks recognition of soils ability to supply water to the roots of plants (Blume, 2010). This was the baseline concept of the Greeks soil profile - the nutrient supplying ability of soils. Societal productivity, as stated by Plato, was heavily reliant on soil quality as it often meant devoting less men and resources to farming (Warkentin, 2006).

One of the first agronomic writings and soil classifications was created by Greek botanist Theophrastus. Theophrastus differentiated between soils and other earthly materials like clay and sand by their colour, texture, and relation to plant cover, otherwise known as the area covered by a plant species over a region of earthly materials (Arnold et al., 2012). His works refer to maternal-like characteristics of soil, recognizing soils over other earthly materials as having distinct life-giving properties. The Greeks also related working on the soil to religious beliefs, as poet Hesiod described in his didactic poem *Works and Days*. Hesiod, upon describing techniques for tilling and plowing to maintain different soils, suggested that the divine will of the Greek god Zeus is achieved through care of the soil, portraying farming knowledge as a divine and sacred dimension (Hesiod, 2006).

In spite of the Greeks demonstration of vast knowledge on soil and its applications early in human history, their collective work did not yet distinguish soil as a distinct scientific discipline. The Greeks obtained proficient soil knowledge by merely observing their surroundings, but never went as far as to construct theories by experimental means, a feat required to truly achieve the domain of science (Brevik, 2009).

The Romans

Roman civilization (500 BC - 5th century AD) expanded on the Greek's knowledge of soil due to the Greek's pre-existing influence on agricultural practices in regions that eventually came under Roman reign (Brevik, 2009). The Romans applied a more practical approach to their understanding of soil through agriculture, compared to the Greeks who undertook a more philosophical approach, yet still recognized soil for its motherly-like capability to sustain life (Warkentin, 2006). This approach resulted in far more detailed accounts of soil, albeit still built on the premise of Greek understanding.

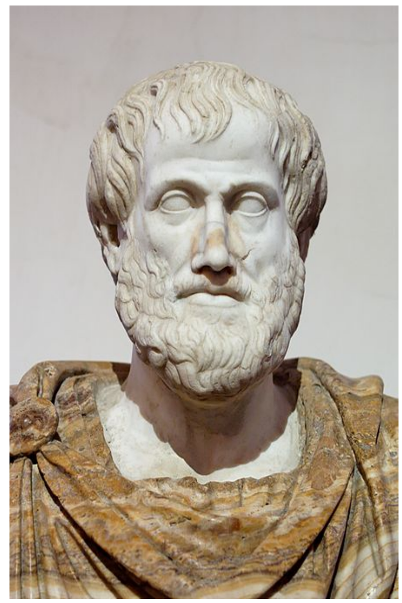


Figure 1.2: *A sculpture depicting the Greek philosopher Aristotle.*

Roman discussion of soil began with accounts from Roman senator Marcus Porcius Cato, often referred to as Cato the Elder, in around 250 BC (Warkentin, 2006). Cato, like the Greeks, recognized that the use of manure improved soil fertility. Cato's works on soil classification were displayed in his writing of *De Agri Cultura* on practical and profitable farming, which preserved the relationship of the Roman empire to its rural roots (Warkentin, 2006). The writings detailed soil classification based on their usage in farming, dividing soil into nine classes and 21 subclasses such as loose, dense, wet, and dry soil (Norman, 1968). These classifications differentiated physical aspects of soil that the Greeks narrowly touched upon, based on their production capabilities of certain plants (McCall, 1931). Cato described optimal techniques of soil ploughing, suggesting that only wet and humidified soil should be ploughed, otherwise causing soil to lose its fertility (Warkentin, 2006). From this, Cato developed a systematic overview of which soils were fertile for certain crops. This characterization developed a ranking system outlining profitable grounds for farmers to inhabit, based on specific plant growth Cato observed in soils of certain qualities (Norman, 1968). Cato also stated that maintenance of soils, by means of ploughing, was fundamental to managing the fertility of soils (McCall, 1931). His works corresponded to a shift in the agricultural revolution within the Roman empire, as advanced irrigation techniques and crop rotations were implemented between farming seasons to maximize soil fertility and increase crop production (Brevik, 2009). Cato's remarks initiated, from a historical perspective, the notion of soils as their own unique discipline by distinctively analyzing specific physical characteristics of soils that inherently determined Roman agricultural practices. However, this distinction was not made in his literature, as the progression of soil as a science was incorporated into his efforts to advance agricultural efficiency. Instead of distinguishing soil as a true science, Cato flourished in analyzing the practical aspects of soil in agriculture (Warkentin, 2006).

A more distinctive separation of soil into its own field was made in the 1st century BC by Roman scholar Marcus Varro. Much like Cato, Varro's work portrayed a dynamic understanding of soil, with consideration of the fact that soils were living and active entities that interacted with the natural environment in ways analogous to humans. This was a central feature of Roman soil understanding. Varro reiterated much of Greek philosopher Theophrastus' ideas of soil as a medium of plant growth (Brevik, 2009). Varro outlined that before farming, the life-bearing medium should be classified as rich, medium, or poor (Norman, 1968). Rich soils were those with known abilities to yield good harvests, compared to poor and medium soils. The classification of soils in these categories was determined by prior observations of plant growth in past farming seasons, similar to Cato's method of analyzing different soil mediums, and distinction of soils by colour, grain size, and physical appearance (Norman, 1968). Upon this, the designation of farming as a science was stated by Varro, involving soils as one of the major components (Warkentin, 2006). This was the beginning of the distinction of soil as its own unique field within agronomy.

After this point in Roman history, from the 1st to 4th century AD, there was a decline in advancement of soil understanding (Brevik, 2009). In fact, the decline of the Roman empire coincided with a standstill in contributions to soil science that remained all the way until the 19th century (Ahrens, Eswaran and Rice, 2002). There were conflicting views on whether previously used soils, that were evidently depleted of their life-bearing capabilities after a farming season, could be replenished or not (Brevik, 2009). This conflict halted the Romans analyses of soil fertility. However, it was believed amongst the Romans that soil quality in regards to immediate fertility of plants decreased as a function time and usage (Warkentin, 2006). The Romans, on the shoulders of Greek input, excelled soil utilization in the practical respect of agricultural techniques. In the midst of their attempts at observing and classifying soils, it was the Romans in hindsight who first provided the realms and practicality of soil science as its own unique discipline. However, like the Greeks, their knowledge on soils originated from observation rather than experimentation. The absence of experimentation obstructed the construction of soil as a scientific field.

The Middle Ages

Moving into the Middle Ages, advancements in the field of agronomy and soil declined compared to the previous rates of discovery and knowledge shown by the Greeks and Romans. Though soils knowledge did not cease to exist, inquiries into the natural world were dominated by religion which provoked more thought into rule of faith as opposed to logic and reason (Brevik, 2009). Considered as the dark ages of science, reasoning and justification for various phenomena leaned towards a faith-based answer, rather than through induction and rationalization. Some works of authors during this time period may also be lost in translation, thus rather unnoticed as opposed to non-existent (Warkentin, 2006). Byzantine culture, originating from the Romans in Turkey around 330 AD, built upon several of the ideas brought forth by the Romans (Brevik, 2009). The Byzantines discussed soils of their territory and like the Romans, assessed soil quality depending on crop output. Similar understandings were shown in the rest of Europe after agricultural struggles emerged immediately after the fall of the Romans (Brevik, 2009). Most of the improvements emerged in the 11th century, and focused of soil fertilization, including plows that turned over the top layer of soil for tilling. These tools were not very effective, however, and the field of agronomy and pedology remained stagnant until the scientific revolution.

Soil in the Scientific Revolution

The way our species has viewed soil since the aforementioned periods has changed in at least two respects. The first concerns how we personify the soil. Ancient civilizations compared soil to a motherly figure for its life giving and life sustaining properties (Warkentin, 2006). More recent civilizations, however, seem to compare it to a child, due to its fragility and dependence on external factors such as the regional flora and fauna and the bedrock on which it is situated (Jenny, 1941). The other respect concerns how our treatment of the soils has gone from an art to a science. Whereas the ancient civilizations used a variety of methods to maintain soil fertility, such as crop rotation and irrigation systems, modern post-renaissance scientists pursued an understanding of how these practices elevated the fertility of the soil. The engine propelling these two intellectual transformations was the scientific method.

As mentioned in the historical topic, ancient societies made valid points regarding the makeup of soil, observing that soils quality declined in proportion to their use, but they also believed patently false things about soils. For example, the Mayans believed that rocks and soil are isolated entities due to the fact that one seems much more suitable for life than the other, but we now know that a soil's properties are heavily influenced by the rocks from which they are formed (Brevik, 2009). The circulation of false information in ancient societies was reduced in the early 1600s with the widespread adaptation of the scientific method (Mead, 1923). The principles of rational thought, such as cause and effect, were preserved under this new method of discovery. However, unlike previous intellectual arenas, the validity of a prediction was based primarily on the degree to which it adhered to the results of experiments. This idea allowed for the filtration of false interpretations of reality (Mead, 1923).

Among the many results of the scientific revolution include the changing personification of the soil from a maternal to juvenile figure. This transformation came about due to realizations in the late 1800s that suggested the properties of soil are heavily dependent upon regional properties, including the life that appears to thrive on it. This new way of viewing the soil was not in agreement with the ancient maternal personification the soil once enjoyed.

The Birth of Soil Science

One scientist who helped pioneer this change in interpretation was Vasily Dokuchaev (Figure 1.3) (1846-1903), who is appropriately regarded as the Father of Soil Science (Bardgett, 2016). This title was awarded to him for several discoveries, any one of which could be considered the achievement of a lifetime. Among the most important, however, was the realization that the properties of soil, including its fertility, are functions of five variables: the bedrock on which it is situated, its topological relief, the life it supports, the climate to which it is subjected, and its age. The type of bedrock predicts a soil's prominent minerals (Bardgett, 2016). The bedrock is also a predictor of the porosity of the soil, and by extension, its capacity to support life. Soils formed from coarse-grained rocks such as sandstone quickly drain water after precipitation events, making for drier soil. However, soils underlain by limestone tend to have a greater proportion of clay, and therefore retain water to a much greater extent (Bardgett, 2016). The relief of the soil influences its properties, with porosity increasing with elevation. This trend is observed because descending rivers tend to move finer grained materials with more ease than large grained materials. As a result, sand tends to remain at the top of the valley while the clay and silt are moved downward (Bardgett, 2016). Vegetation influences the soil in innumerable ways, but one of which is through the type of organic material it supplies to the ground after death. The climate affects the fertility of the soil, as most chemical reactions, including those that occur in soil, increase with respect to temperature (Bardgett, 2016). Finally, age determines, among other characteristics, the depth of soil, which increases with age (Bardgett, 2016). Dokuchaev's work regarding the factors affecting soil formation was rigidly formalized using mathematics by the subsequent pedologist Hans Jenny. Like many important figures in math, Hans Jenny was born in Basel, Switzerland in 1899 (Bardgett, 2016). Jenny constructed a function that describes the soil properties as a function of the five variables asserted by Dokuchaev (Jenny, 1941).

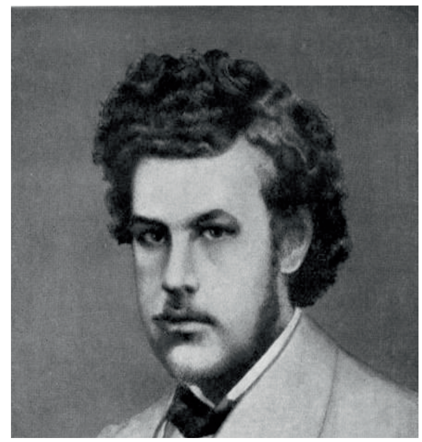


***Figure 1.3**: A portrait of Vasily Dokuchaev.*

The Evolving Personification of Soil

A more applied example of the evolving personification of soil can be found in the erosion of soil in the American Corn Belt in the 1940s. Extensive use of artificial fertilizers had replaced manure-based fertilization and as result, a drastic decline in the amount of organic material in the soil occurred. The natural protection organic materials provide against soil erosion was therefore in rapid decline, leading to widespread wind-based erosion of the soil

(Bardgett, 2016). Events such as these helped bring humans to the realization that often times soil is more dependent on organic material than plants are on soil. While soil is still considered an important element of Mother Nature, it is increasingly being viewed with a juvenile lens due its fragility and dependence on other factors.

A large part of the personification of the soil as motherly is predicated upon the assumption that life begins and ends in the soil (Brevik, 2009). The notion that soil is the starting point of many ecosystems was challenged, however, with the development of several scientific techniques. One of the key scientific tool that was responsible for this change in view is the chronosequence, which is based upon the assumption that different areas of a given ecosystem are of different age (Huggett, 1998). Because one cannot travel to different time periods, scientists can look at different areas of an ecosystem to determine the way in which ecological region's properties change as a function of time. This principle shares similarities with the principle of stratigraphic succession, which also makes assumptions regarding equivalences between temporal and spatial units (Van Wagoner, et al., 2012). This technique found that soil was not necessarily present in the youngest periods of an ecosystem, and that soil typically comes about after the introduction of lichens and certain grasses that facilitate the balkanization of rock into soils more conducive to other forms of life (Bardgett, 2016). This discovery lent significant opposition to Xenophon's belief that life begins in the soil, as it suggests that soil is the child, not the mother, of many forms of life.

Pedology's Reach

As progress in pedology accumulated, soil scientist began applying their knowledge to help solve pressing issues in society. Quite recently, pedologists have made promising achievements in solving criminal cases and in the restoration of compacted soils.

Figure 1.4: *Soil compression as a result of an external load.*

Soil Forensics

In the overview, it was mentioned that soils are central to the prosperity of human civilization due to their prominent role in agriculture. Pedology, however, permeates several other branches of society, albeit in far more subtle ways. For example, in the justice system, soil scientists have become relied upon for either corroborating with, or challenging the ever prevailing belief about a suspect's innocence.

While soil profiles have been used sporadically by prosecutors and defenders alike since the 1800s, it was only recently that soils have become a widely accepted and relied upon tool when constructing legal arguments. This increase in reliance comes in parallel with the increased sophistication of the methods available to soil forensics experts. Arguably the mother of this application of pedology is Lorna Dawson, who is responsible for the development of many of these methods. Dawson's effective marriage of pedology and forensics arose in response to the double murder of two 17-year-old girls in 1977. Impacted by this brutal tragedy, Dawson began looking for ways of applying geology to the pursuit of justice (Wald, 2015).

Soil presents a potent means of verifying criminality due to the many variables that describe soil. The abundance of variables makes it extremely unlikely that soils in adjacent regions will be identical to one another. The resulting uniqueness of a region's soil therefore makes it effective at giving the location of a suspect at a given time (so long as the same soil can be found on a suspect) (Wald, 2015).

Since Dawson's developments in the field, over 70 legal cases have been supplemented using the methods she has developed. One of the most famous cases solved was the very one which instilled Dawson's devotion for justice in the first place, the murders of the two 17-year-old girls. By matching several variables including plant residue between the suspect's boots and the field in which one of the victims were found, the prosecutor was able to show that Angus Sinclair was responsible for the murders.

Restoring Soils through Pedology

Another trend in pedology is the increased emphasis on the detection and treatment of compacted soil (Figure 1.4) (Soane and van Ouwerkerk, 1994). This new area of pedology arose in response to several factors. The first of which is the increased mechanization of agriculture in the 20th century. The use of heavy farm equipment in the latter half of the 20th century has increased the average density of soils by a significant degree. The increased consumption of meat in recent years has also led to the growth in livestock population. This increased roaming of livestock is therefore another cause of the recent increase in soil compaction.

The elevated focus by pedologists on soil compression is motivated by the devastating effects this trend has in several areas. Inversely proportional to soil density is crop productivity. It is therefore in a farmer's best interests to ensure his or her soil is not overly compacted. Furthermore, compacted soil is at a greater risk of undergoing erosion than soils with greater porosity. This is due to the accumulation of water on top of soil rather than the percolation of the water into the soil.

In 1994, the United Nations implored its international members to ensure the proper health of their soil. Implicit in this goal is to find solutions to the dangers of soil compaction (United Nations, 1994). However, before doing so, pedologists devised methods of detecting such compaction. In 2013, pedologists devised a method of detecting soil compaction using seismic surface waves, where artificially generated waves are passed through some medium. By measuring the velocity of the resulting wave, geologists can determine the extent to which the soil has been compacted, considering seismic waves move considerably faster in denser media (Donnihue, Forristal, and Donnihue, 2012).

One year later, a team of geologists and engineers further refined the methods available to determine the degree of soil compaction. In their study, they laid out the correlation between the electrical resistivity of soil as a function of its density, or compaction (Kowalczyk, Maslakowski, and Tucholka, 2014). Soil scientists have responded to the threats of soil compaction by mitigating compression from machinery. In 2013, Taghavifar and Mardani showed that we can minimize soil compaction by increasing the velocity with which equipment moves over soil. Furthermore, by limiting the number of passes made by machinery, we can further mitigate the resulting soil compaction. While this strategy focuses on the prevention of soil compaction, methods of soil regeneration have also been developed. For example, through the addition of alkaline substance into the soil, we can generate a more hospitable environment for earth worms. The effect of these organisms will help to restore the fertility of compacted soil (Russell, 1910).

Soils and Climate Change

Modern understanding of soils has also evolved a greater knowledge of the chemical composition of soils. This understanding of the chemical makeup of soils allows soil scientists to investigate the involvement of soils in climate change. Scientists are pursuing methods that focus on preserving carbon stored within the soil, as opposed to being released into the atmosphere as a potential method to reduce fossil fuel emissions. This process, known as carbon sequestration, also has potential benefits involving increased crop yield, making it a valuable enterprise for farmers. Carbon sequestration refers to any process in which carbon dioxide is removed from the atmosphere or from a carbon emission source, and stored in terrestrial environments or the ocean (Lal, 2004). Soil contains approximately twice the amount of carbon dioxide than is found in the rest of the atmosphere (Smith, 2012). With human contribution to fossil fuels on the rise, there is an increased need for economically feasible ways to reduce atmospheric carbon levels. Methods used to increase carbon sequestration include woodland regeneration, soil restoration, cover crops, no-till farming, and establishing new forests (Lal, 2004). Although these methods specifically aim to improve carbon sequestration processes, the majority of terrestrial carbon uptake is due to natural regrowth of forest land. Also, despite being economically friendly processes, carbon sequestration friendly processes are subject to several limitations. These include susceptibility to fire and disease, non-permeance, time limitations, and ineffectiveness (Smith, 2012). This leaves scientists with an evolving focus on how soil carbon sequestration can be improved without further negative trade-offs. An example of such a decision includes whether it is feasible to convert farmlands to forests to improve sequestration, at the expense of decreased crop production.

History of Mineralogy

Everything around us is made up of minerals. But what are minerals? A glimpse of the word tells us that MINErals are what we mine from the ground. The word "mine" comes from the Old Celtic meaning to dig in the earth, with the word originating around 1300 AD. The more contemporary definition of minerals are naturally occurring inorganic solid substances with definite chemical structures (Wenk and Bulach, 2016). The Celts were miners of salt, which made preservation of food possible and improved human lifespans (Boenke, 2005). However, the oldest mine in the world, located in The Lion Cavern, Swaziland, was operated to obtain a hair cosmetic called "Specularite Hematite" (Beaumont, 1973). The oldest mining town in the world, located in Maadi, Egypt, was neither used to obtain preservatives nor cosmetics, but centered around the procurement of copper ores for use in weaponry and tools (Shaw, 2003). Minerals served a variety of roles in ancient human civilizations, and even moreso today.

Introduction to Mineralogy

Evidence of cultures studying, classifying, and extracting minerals dates back centuries to ancient civilizations like the Egyptians, Greeks, and Chinese. Breakthroughs in mineralogy occurred with the advent of the microscope, and again in the modern era with the invention of crystallography. The study of mineralogy has many unqiue applications in fields including biology, ecology, geology, and anthropology. Its history is studded with scientific contributions from all around the world that have led to the modern-day practice of materials science.

Figure 1.5: *Theophrastus (370-287)*

Mineralogy is a subset of geology that deals with the chemical and physical structures of minerals, their formation, and their classifications. Minerals are immensely important to an industrial society such as our own, where they comprise the building blocks of our infrastructure. For instance, minerals are found in processed materials, plastics, fertilizers, steel, clay, coal, limestone, and bricks.

The study of mineralogy is strongly motivated by both economic incentives as well as scientific (specifically geologic) inquiry.

Theophrastus

The study of mineralogy dates back to the Ancient Greeks, where a primitive categorization of minerals was proposed by Greek philosophers Aristotle and Theophrastus. Theophrastus, a student of Aristotle, was born in 372 BC in Lesbos, Greece (Richards and Caley, 1956). Theophrastus, pictured below in Figure 1.5, attended the Peripatetic school under the pedagogical influence of Aristotle where he studied various philosophical and scientific phenomena. He then presided over the school, during which time he produced momentous scientific works relating to botany, mineralogy, and metaphysics.

His pivotal writing on mineralogy, *On Stones*, was a treatise of great importance; it continued to be referenced as a scientific authority late into the Renaissance period (Richards and Caley, 1956). The treatise included classifications of rocks and gems by characteristics such as melting point, as well as other similarities such as magnetic activity (Richards and Caley, 1956). In addition, Theophrastus produced a gradient scale of mineral hardness, a predecessor to the modern Moh scale (Richards and Caley, 1956).

Furthermore, Theophrastus made exemplary inroads into new areas of science. For example, he discovered that a mineral called "tourmaline" becomes electrically charged after heating, therefore marking the first observation on pyroelectricity in history (Dutrow and Henry, 2011). Today, this phenomenon can be found in semiconductors and transistors.

Part of the reason Theophrastus wrote on minerals and mining was economically driven. He wrote extensively on gold assaying, copper and silver mining, and his delineation of ore separation was practically useful. His writings were also heavily inspired by philosophy and metaphysics; Theophrastus and the Peripatetic school placed great value in deriving happiness from the external world. He considered the description of nature and motion to be pivotal to stave off the meaninglessness of life. As such, his works were not limited to mineralogy alone, but spanned a diverse array of disciplines, including botany, literature, drama, meteorology, philosophy, and music.

Pliny

Pliny the elder was an Italian naturalist who documented the origins and sources of ores and minerals in the fifth century BC (Healy, 1999). He described in great detail the physical and chemical nature of minerals. His magnum opus, *Naturalis Historia*, or Natural History, was one of the earliest encyclopedias in human history. In fact, five volumes of this work were dedicated entirely to the classification of "earths, metals, stones, and gems."

Pliny made multiple breakthroughs in mineralogy, including being the first to correctly identify that amber was a fossilized tree resin, through the observation of insects and through primitive crystallography. Like Theophrastus, his work was primarily driven by gold mining prospects in northern Spain. His writings on mineralogy proved exceptionally useful for gold prospectors.

Ancient studies of mineralogy were not unique to the Greek civilization alone. Abū al-Rayhān Muhammad ibn Ahmad al-Bīrūnī (973–1048), was a Muslim Persian scientist who developed a system of classifying the specific gravity of minerals (Sparavigna, 2013).

Albert Magnus – Alchemy and Early Metal Experimentation

While the aforementioned contributors to mineralogy made impacts in the identification, categorization, and sourcing of naturally occurring minerals and materials, Albert Magnus was an important figure in early materials chemistry, known in Medieval times as alchemy. Albert Magnus was estimated to have been born circa 1200 and lived until 1280, writing many volumes of work during his time (Grund, 2009). His work in the sciences came as a result of being a theologian and philosopher, where religious work had him travelling across Western Europe as a preacher of a crusade (Sighart and Dixon, 1876). Through his journeys, he stumbled upon many mines such as Goslar and Freiberg, and he spent much of his time inquiring on the transmutation of the observed metals through alchemy (Wyckoff, 1958).

Magnus had collected information from miners which after his lifetime had not been discussed in a scientific publication until the 1500s (Wyckoff, 1958). This information he collected, and his own experimentation, led him to publish *On Minerals* where he describes the methods through which ores could be deposited. Three descriptions for gold ore which he provides are: ores formed in stone as a vein, ores formed in stone as a separate stone (pyrite), and alluvial placers (Wyckoff, 1958). The pyrites were seen as having very little value, while alluvial placers served as the more profitable and thus more desirable ores (Wyckoff, 1958).

It was believed that all metals were merely forms of incomplete gold, where gold existed as the sole metallic species, and that elixir was the key to forming gold from these metals (Partington, 1937) . This elixir was said to be able to turn all metals into the true metals, gold or silver (Partington, 1937). Elixir was also called the philosopher's stone, and these were also equated to providing eternal life, as shown in Figure 1.6. Much of Magnus' learning drew on the knowledge of Aristotle and Persian writer, Avicenna, as seen in his critiques of mineral refinement where he discounts Avicenna's claims that gold is formed through yellowing copper with yellow tinctures (Partington, 1937).

***Figure 1.6:** An alchemist in search of the philosopher's stone – a legendary stone that could turn all metals into gold or silver. It was also referred to as an "elixir" which was a source of eternal life*

In defence of all metals, one of Magnus' claims was that methods of transmuting metals into gold or silver with dyes produced fake gold and fake silver, which he tested experimentally. As Magnus demonstrated, ignition of the fake golds and silvers turned them back into a metal of lesser value after a handful of trials (Partington, 1937). Magnus was modest, recognizing that his experimentation on gold likely could be replicated by any goldsmith and was used to easily recognizing the true value of a gold-like metal when trading goods (Partington, 1937).

While today's understandings of chemistry dive as deep as the subatomic level, in the 1200s, forms of alchemy were merely understood through observation with the naked eye. Magnus did not intend to begin understanding chemistry at such a detailed level but rather spent the better half of his research finding fallacies in methods of transmuting metals. His work details primitive recipes of preparing materials such as vermillion, vitriol, nitric acid, and oxidations of iron and mercury (Partington, 1937). Not much of his work was original, as his goal for writing was to compile an encyclopedia of all the known knowledge in his time. It is also noteworthy that Magnus was in a position of great influence; his great attention to alchemy caused many religious leaders to set out on alchemical discoveries despite being condemned by the superiors of the church (Wyckoff, 1958) . Not only was the condemnation related to tampering with God's natural materials, but those who practiced alchemy, specifically producing alchemical gold, were cause for cases of fraud due to the high value of fake gold to the general public when in reality, it was worthless (Wyckoff, 1958). In this time, it is clear to see that science was still very well-embedded in belief systems in contrast to Georgius Agricola's work in the 14th century.

Figure 1.7: *Georgius Agricola. Father of Modern Mineralogy (1494-1555)*

Georgius Agricola

Born in Saxony, Germany, Georgius Agricola (Figure 1.7) is often renown as the Father of Mineralogy for his extensive work as a successor to the likes of Theophrastus, Dioscorides, and Magnus in the field of mineralogy (Weber, 2002). The work he conducted was by no stretch free of error as atomic theory was yet to be discovered, but his ability to add 20 metals to the list of 60 known metals, and to be the first to describe bismuth and antimony as true primary metals, in addition to the already known metals: gold, iron, silver, mercury, tin, copper, and lead, is what set Agricola apart from those before him (Weber, 2002). He was also the first individual to be able to distinguish between igneous and sedimentary rocks (Weber, 2002). Volumes of work exist to describe the extent of the impact Agricola had in advancing the study of mineralogy.

After reflecting on his 1546 publication on mineralogy, the scientific community paid a great deal of credit to Agricola for refuting the theory of the four elements: wind, earth, air, and fire, so long before atomic theory, crystallography, and stoichiometry became fields of study (Weber, 2002). His classification of the naturally occurring materials revolved around hardness, melting point, smell, taste, solubility, and other observable features, and was found to be more practical when it came to scientific accuracy (Weber, 2002).

Agricola's primary work: *De Re Metallica,* published in 1553, is his most famous piece of work and had taken 20 years to write (Weber, 2002). It combined concepts of mining from a geological, physical, and medical perspective through discussing: prospecting, surveying, mining tools, metallurgy, smelting, and health problems related to mining. *De Re Metallica* stood out as the handbook for miners for 200 years after its publication (Weber, 2002).

Georgius Agricola's Challenges

It may be difficult to appreciate the impacts of Agricola's work without a proper understanding of the historical setting, and the views of the people in these times. As will be discussed, Agricola faced the prevailing barrier of the belief in magic and religion; people would hold religious ideologies in high esteem without thinking critically about the physical processes happening around them.

Take divining rods as an example, pictured in Figure 1.8. These were twigs that were enchanted with the power of the divines to tell prospectors the locations of ore veins. The origins of divining rods are not well understood by historians, and even Agricola aimed to discover the roots of the rod (Weber 2002). It is said in Book II of *De Re Mineralis* that though the belief that incantations and crafts were the routes to successful prospecting of the divining rods, Agricola refused to credit this method of prospecting as proper (Agricola, 1556). His argument against divining rods made him one of the very few individuals to challenge the idea until the 19th century (Weber 2002). The consistent ability for Agricola to produce successful claims is truly a quality setting his work apart from the masses. Even individuals to succeed Agricola such as Robert Boyle, who founded the National Royal Society, was convinced that the divining rod was a genuine prospecting method (Weber 2002).

In his defense, Agricola explains the more accurate, reliable, and scientifically sound method of prospecting involved being familiar with the methods that a vein could be deposited. Agricola cited skill as being necessary for determining the location of ores and utilized concepts in modern day sedimentology to support his argument (Agricola, 1556). Rather than use divining rods, he claimed that observing the sediment deposits in water bodies to locate ores was more practical, noting that rounded ore-containing sediments travelled long distances while less rounded ore-containing sediments must have been closer to the source vein (Agricola, 1556). This concept of erosion was not accepted until the late 1700s to early 1800s (Barton, 2015). Agricola was an advocate for using skills and observations to make accurate conclusions rather than relying on magic as a means of explanation. Although there were many who were superstitious and grounded their science in beliefs, the work Georgius Agricola put forward advanced the trend of conducting science at an observational level, and ultimately being more beneficial to advancements in society (Barton, 2016).

The Multiple Facets of George Agricola's Work

Along with others in the early days of science, Agricola was concerned with more than a single

Figure 1.8: *A sketch depicting what a typical prospector's divining rod looked like labelled as A. These were generally twigs that had a forked shape to them but and the type of wood would vary based on what prospectors were searching for.*

disipline as his books clearly dictate through detailed sections including medical and safety precautions, as well as the importance of sustainability in the environment as it relates to mining (Agricola, 1556). He even went as far as to provide advice for investors interested in gaining riches from mines (Agricola, 1556). George Agricola among other scientists throughout history paint a different, perhaps more meaningful definition of being an integrated scientist.

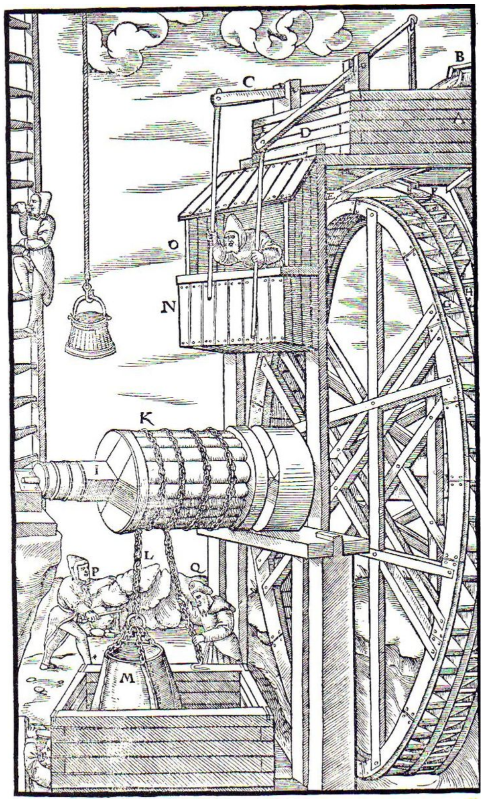


Figure 1.9: *An example of the water-powered mine hoisting system that Georgius Agricola had depicted in De Re Mineralis. The workers can be seen with pointed hats, smocks, and long clothing.*

On the health of miners, Agricola describes that there is no singular benefit from mining that is outweighs the health and well-being of a miner, going on to describe safety equipment that would be suitable for preventing afflictions like asthma, and suggesting waterproof boots to fight off gout. He is even credited with identifying radon as a health concern to miners though he suggested no method of preventing harm from radioactive materials (Agricola, 1556). Weber (2002) notes that the recommended safety equiptment Agricola describes in *De Re Mineralis* depicts an image of a gnome. This is due to gnomes being modelled after mining labourers in Medieval times. The most recognizable equiptment was the pointed safety helmet, seen in Figure 1.9 (Agricola, 1556).

Georgius Agricola talked of gases that smothered a candle's flame and caused breathing problems in those working within the mines (carbon dioxide), as well as a gas that had a wretched stench (hydrogen sulfide) (Weber, 2002). Mercury poisoning, arsenic poisoning, and other serious health concerns were also written as health concerns in his writings (Agricola, 1556).

Agricola recognized the anthropogenic impacts that rose as a result of mining, such as heavy metal pollution. In Book I of *De Re Mineralis*, he discusses the importance of crops and wild life as sources of food and how wastewater from washing ores contributes to habitat and ecosystem destruction, a concern that industries are still battling today (Agricola, 1556).

Agricola was describing acidic drainage, and the percolation of heavy metals or other chemicals used in mine waste water being a danger to water quality.

His advice on the economic front was evident in his methods of prospecting, for example providing a stronger foundation for mine formen to strike gold meant those interested in riches would become invested in Agricola's work. He also described four unique terrain that deposits could be found in and mined at, and the difficulties associated with each (Agricola, 1555). This not only gave insight into the scientific methods behind prospecting and mining, but again laid out the optimal working conditions for those seeking profits.

After his death in 1555, which according to legend occurred through a stroke during a heated religious debate (Weber, 2002), Georgius Agricola's work went on to inspire the likes of Nicolas Steno and other future geologists who further advanced the field of mineralogy and earth sciences (Barton, 2015).

X-ray Crystallography

Breakthroughs in scientific disciplines often come in lockstep with advances in technology. Mineralogy exploded with the introduction of X-ray crystallography. X-rays were discovered in 1895 by German scientist Wilhelm Rontgen (Glasser, 2013). Rontgen was performing various experiments with cathode rays, which emitted electrons from a vacuum-pumped tube made of glass. He noticed a fluorescent effect on a screen coated with barium platinocyanide, to conclude that the fluorescence was due to a novel form of radiation. Subsequently, X-rays were shot through mineral crystals in order to produce diffraction patterns.

In 1912, Max Von Laue, at the Arnold Sommerfield's Institute of Theoretical Physics in Munich, Germany, used crystals as optical gratings, and produced a diffraction pattern. He correctly assumed that small wavelengths of X-rays would diffract through an atomic crystal structure (Eckert, 2012). Unfortunately for Laue, Friedrich and Knipping published the findings of this experiment in the *Proceedings of the Royal Bavarian Academy of Science* before he did (Braggs, 1965). These findings led William

Braggs to construct an X-ray spectrometer in 1913 at Leeds University. Laue and Braggs correctly deduced the structure of sodium chloride (NaCl) using diffraction photographs, publishing the research in 1913 in the *Proceedings of the Royal Society of London* (Helliwell, 2013).

Ever since these discoveries, X-ray crystallography, through electromagnetic diffraction, has been the foundation for mineralogical research. In the 1920s, the structure of silicates and aluminum compounds was delineated, making significant contributions to metallurgy. More recently, the Mars Curiosity Rover, operated by NASA, used X-ray crystallography to detect the chemical and crystal composition of martian soil. An example of an image produced by X-ray crystallography is shown above in Figure 1.10.

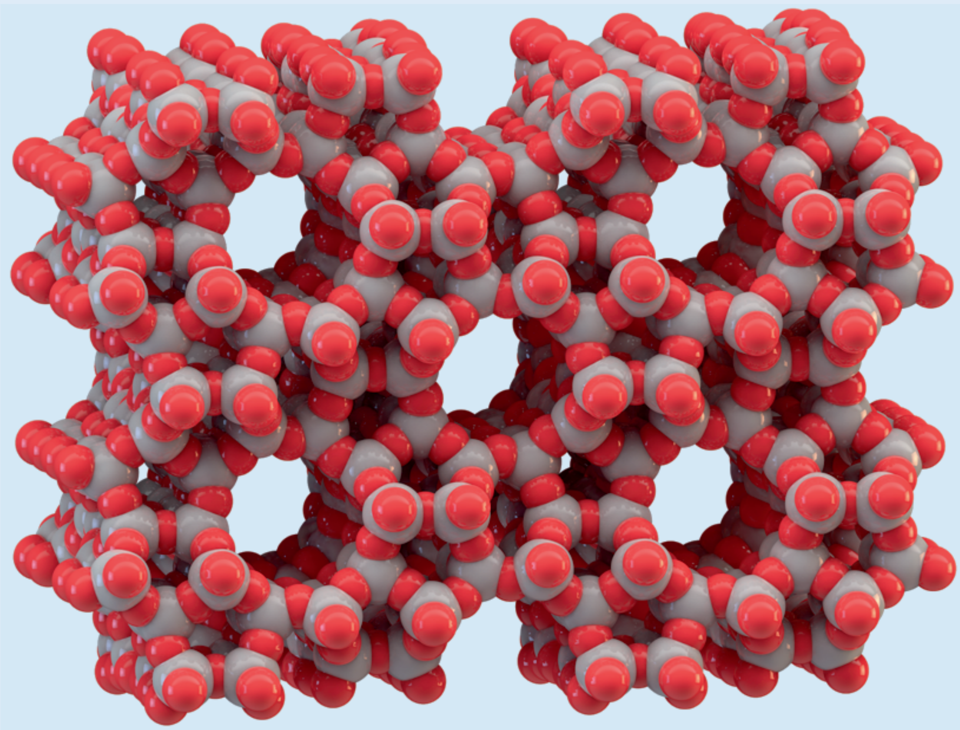


Figure 1.10: *Atomic structure of zeolite, provided by X-ray crystallography.*

X-ray crystallography has also allowed for the emergence of a new field, materials science. Materials science and engineering allows for the synthetic design and discovery of new materials, generally underlying consumer products, as well as satisfying private and public consumption demands. As such, this field is strongly driven by industry, given its highly lucrative nature.

Perhaps the most conspicuous evidence of mineralogical advancement is in the practice of modern mining. The 20th century was historically popular for mining gold, silver, coal, as well as other base metals to be integrated in industry (Miller, 2013). Modern metallurgy has allowed industry to purify and smelt useful ores, create structurally superior alloys, increase efficiency and reduce environmental damage. Crystallography has allowed unprecedented insight into the structure of modern materials and has revolutionized the mining industry.

The study of mineralogy is characterized by multiple defining moments; the initial classifications of rocks and minerals by Theophrastus, the arrival of the microscope, and the invention of many modern day innovations shaped mineralogical thought for the foreseeable future. Pioneers of this field began from a philosophical motivation, eventually being driven by technological advancements. With the introduction of more powerful tools, we can expect increasing subsets and offshoots of mineralogy to emerge, fulfilling important consumer demands in multiple areas of life, from cosmetics and health, to infrastructure and construction. What was once a mere careful observation of nature's exquisite gemstones has matured into the synthetic production of materials in an industrialized world; initially driven by philosophers desperate to seek meaning, now driven by a complex market seeking profit and scientific discovery.

Ibn Sina’s Contributions to Earth Science

The Middle Ages, from approximately 500 AD to 1500 AD, are often regarded as a difficult time in western Europe mainly due to the “Black Death” or Bubonic Plague. This time was known as the Dark Ages in Western culture, however incredible discoveries were made in other cultures during this time. Significant progress was made in the name of science, mathematics, and medicine during what was known as the Islamic Golden Age in the Middle East. Notably, a famous contributer to this blossoming era was the Persian polymath, Ibn Sina. Within the Italian Renaissance records, he would also be recognized as Avicenna for his philosophical work (Iran Society and Courtois, 1956).

Early Life

Ibn Sina (Figure 1.11) was born on August 7th, 980 AD in the village of Afshana, presently known as the Bukhara Region in Uzbekistan (Afnan, 1958; McGinnis, 2010; al-Naqib, 2000). Despite the political unrest in the Middle East at this time, Ibn Sina’s father who was also a scholar, was in full support for raising his child in a highly stimulating intellectual environment. It also helped that young Ibn Sina was naturally curious and driven. This curiosity would eventually lead to several earth sciences observations founded in Middle Eastern culture.

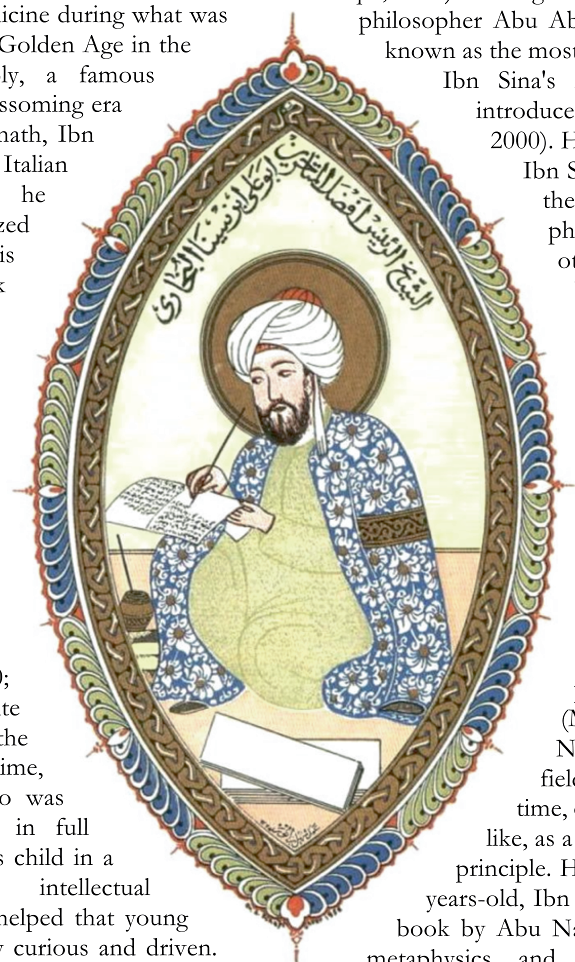


Figure 1.11: *Portrait of Ibn Sina, also known as Avicenna.*

Ibn Sina's first language was Persian, but this was considered a commoner's tongue (Afnan, 1958; al-Naqib, 2000). Encouraged by his father, Ibn Sina studied Arabic under Abu Bakr Ahmad so that he would be able to commmunicate among other scholars (al-Naqib, 2000). Once Ibn Sina mastered Arabic, he began learning from two more teachers. Although the names are unknown, one of his teachers taught the *Qur'an* while the other taught literary pieces (al-Naqib, 2000). By 10-years-old, Ibn Sina had essentially memorized the *Qur'an* and a substantial amount of literature (al-Naqib, 2000). His father decided to continue Ibn Sina's education by sending him to the school of Mahmud al-Massah in order to learn arithmetic, algebra, geometry, and “the movement of heavens” (al-Naqib, 2000). At the same time, he studied *fiqh*, or Muslim law, and the religious Sufism movement with Isma'il al-Zahid al-Bukhari (Iran Society and Courtois, 1956; al-Naqib, 2000). Throughout his education, it was philosopher Abu Abdallah al-Natli who is known as the most important educator in Ibn Sina's life. They were first introduced in 990 AD (al-Naqib, 2000). His influence persuaded Ibn Sina to pursue studying theoretical sciences and philosophy above all other interests (al-Naqib, 2000). As a result of Ibn Sina’s enriched youth, he was able to fully develop his natural inquisitive nature.

It's also important to consider that Ibn Sina struggled to understand the field of metaphysics, specifically the work *Metaphysica* by Greek philosopher Aristotle (McGinnis, 2010; al-Naqib, 2000). This is the field studying changes in time, objects, nature, and the like, as a result of some internal principle. However, at around 17-years-old, Ibn Sina reluctantly read a book by Abu Nasr al-Farabi regarding metaphysics and was then able to understand Aristotle's work (McGinnis, 2010; al-Naqib, 2000). This first documented struggle in Ibn Sina's life was a fundamental event in order for him to gain confidence in his conceptual learning and pursuit for knowledge. It also provided Ibn Sina the drive into writing so that others may understand his thinking. His many teachers, and consequently perspectives, likely allowed Ibn Sina to write in a more philosophical manner, rather than through scientific jargon ensuring clarity as well as dignified writing. As a result, his work was based on his own observations built upon previous scientists' work.

Political Atmosphere

During Ibn Sina's time, there was major conflict for the ruling dynasty. Power within the Abbasid dynasty was declining and thus began the rise of localized regional dynasties (Afnan, 1958). For Ibn Sina, he was governed by Samanid rulers and three other local dynasties in and on the eastern borders of Persia (Afnan, 1958). There was the Tabaristan dynasty, the Ziyarids dynasty, and the Buyids dynasty, which were all fighting for expansion and power to overthrow the currently most powerful Saminid dynasty (Afnan, 1958; Goodman, 1992). Under the Samanid dynasty, creative culture was approved, especially philosophy and poetry, except that it needed to follow Ala el-Dowleh theology (Afnan, 1958; Goodman, 1992). Eventually, an independent party within the Samanid dynasty would expand into a separate entity known as the Ghaznavid dynasty (Figure 1.12), which would overthrow them and take over the neighbouring three dynasties (Afnan, 1958). The leader, Sultan Mahmud, liked to gather famous poets and scholars and listen to their speeches (Afnan, 1958). Although Persian politics were not stable, the atmosphere towards thinkers and philosophers was relatively friendly.

His Journey

The first major event in Ibn Sina's life occurred in 997 AD when the current reigning prince, Nuh ibn Mansur, fell ill and physicians required Ibn Sina's assistance (Afnan, 1958). Thus, Ibn Sina was granted special access to a library accessible only to Samanid rulers, the Library of Bukhara (Afnan, 1958). It should be noted that this library was later burnt down and many accusations were directed at Ibn Sina, claiming that he selfishly destroyed the works so that he would be only one to have its knowledge. Nothing was proven and Ibn Sina continued his pursuit of knowledge.

At 21-years-old, Ibn Sina wrote his first book, *Majmu (Compendium)* (Afnan, 1958). He continued by writing commentary in his book, *al-Hasil wa al-Mahsul*, translated as the *Import and the Substance* within about 20 volumes. He then wrote a book on ethics called *al-Birr wa al-Ithm*, translated as *Good Work and Evil.*

When his father passed away, around 1002 AD, Ibn Sina's life changed drastically (al-Naqib, 2000). Though it is not known if his father's death was the reason for the sudden decision to travel, it may have played a factor on Ibn Sina's choice to move from his hometown. He moved to Gurganj and accepted employment under Sultan Mahmud, the Samanid ruler. He eventually needed to move again due to Ibn Sina's religious beliefs with the Sufi doctrines conflicting with the Sultan's personal Ala el-Dowleh theology (Afnan, 1958; Iran Society and Courtois, 1956). In Gurganj, Ibn Sina wrote *al-Muktasar al-Awsat*, translated as *The Middle Summary*. This is also the first mention of his pupil, Juzjani, who was the person that transcribed Ibn Sina's thoughts for this book (Afnan, 1958). Immediately after, Ibn Sina also wrote *Al-Mabda wa al-Ma'ad*, translated as *The Beginning and the Return*, as well as *al-Arsad al-Kulliya*, translated as *The General Observations* (Afnan, 1958). Ibn Sina continued to move city to city, for reasons not always known or stated in his journal, while writing many more books.

Finally, at around 1014 AD, Ibn Sina arrived at Hamadhan, arguably the most important city for his pursuit for knowledge (Afnan, 1958). This is where Ibn Sina began writing the physical chapters of the *Kitab al-Shifa*, translated as *The Book of Healing*, where his thoughts on earth science would

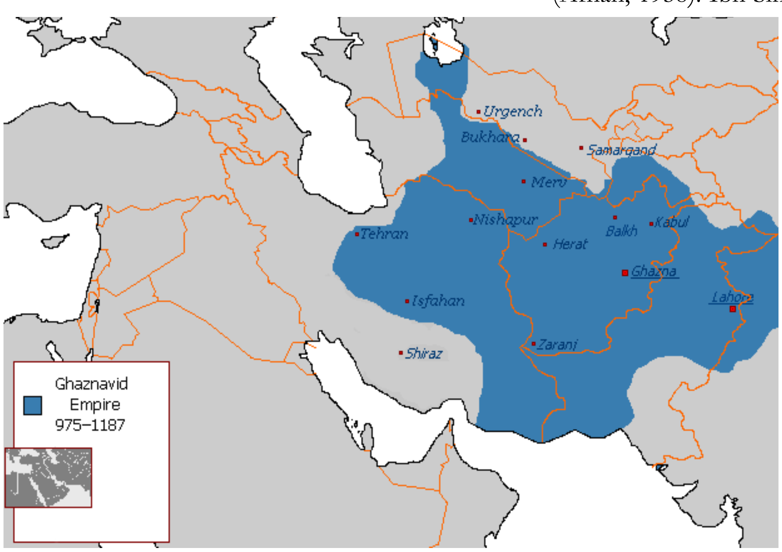


Figure 1.12: *Map of Middle East occupied by the Ghaznavid Empire from 975 to 1187 AD.*

eventually be recorded (Afnan, 1958).

In a sudden change in loyalty, Ibn Sina switched his allegiance from the sons of Shams el-Dowleh to the ruler of Isfahan, Ala el-Dowleh (Afnan, 1958). For his protection, he went into hiding with the help of friends within the city. As a result of his numerous hours of spare time, Juzjani suggested that Ibn Sina continue to expand *The Book of Healing* (Afnan, 1958). It is thought that Ibn Sina wrote a rough draft that highlighted 20 main topics, each about eight sheets long of subtopics and jot notes (Afnan, 1958; McGinnis, 2010). Furthermore, it is theorized that Ibn Sina wrote for two days straight by basically going through his "brainstorm" list and fully expanding his own comments (Afnan, 1958). Ibn Sina wrote approximately 50 sheets which completed the whole section on natural sciences and metaphysics with the exception of his books on animals and plants (Afnan, 1958; McGinnis, 2010). One source says that Ibn Sina was imprisoned soon after (Afnan, 1958), while another claims that friends were able to sneak out Ibn Sina, Juzjani, and two slaves into Ishafan immediately (McGinnis, 2010). Regardless, Ibn Sina would go on to travel to the city of Sabur Khwast, where he would complete *The Book of Healing*. The completion date is not unanimously agreed upon, but it is within the range of 1027 AD to 1030 AD (McGinnis, 2010).

Ultimately, it was a balancing combination of isolation and support from friends and family that led to Ibn Sina's work surrounding philosophy, medicine, and science – including earth science. Ibn Sina wrote over 200 books/sections about many topics, with *The Book of Healing* being a major literary and scientific piece. His thinking and observations were relatively accurate and it can be argued that his work was made prior to important geological figures from Europe such as James Hutton and Nicolas Steno. He shared his Islamic influences to better mold the thinking in the sciences and philosophy. Ibn Sina deserves recognition for his intelligent inquiry and observational skills. Furthermore, it is important to understand that Ibn Sina raised awareness for select earth science topics in a completely innovative perspective that places him in the ranks with other notable earth scientists.

More specifically, in *The Book of Healing*, Ibn Sina outlined major concepts of geology, three of which were granted their own chapters: On the Formation of Mountains, On Earthquakes, and On the Formation of Minerals.

Chapter 1: Formation of Mountains

In the first chapter: On the Formation of Mountains, Ibn Sina discussed how mountains such as the Valley of the Ten Peaks (Figure 1.13) form as well as highlight basic concepts of geology. Ibn Sina started the chapter by stating that in order to understand how mountains form we must understand the formation of rocks. He outlined the different ways rocks can form either through the hardening of clay or the congelation of waters that flows drop by drop or as a whole

Figure 1.13: *Valley of the Ten Peaks and Moraine Lake in Banff National Park, Canada.*

during its flow. The rocks that are congealed by water can form through chemical precipitation or a strong mineral force that solidifies it. Presently, this type of rock would be known as chemical or biochemical sedimentary rock.

Furthermore, Ibn Sina outlined that the presence of fossils in stones is the result of the petrification of plants and animals. He thought that particular fragments separated from rocky areas or mountains, typically as a result of earthquakes. These mountains would have unique characteristics that allow for this petrification. He also believed that fossilization occurred once there is contact with the earth. Additionally, he noted that plants and animals are more likely to fossilize in rock than fossilize in water. Ibn Sina did not mention the different fossilization methods, for instance traces, carbonization, and permineralization.

Ibn Sina also outlined, though later credited to Nicolas Steno, "The Law of Superposition". He stated that whenever land was exposed by the ebbing of the sea, a layer of land was left. This is observed by the piling of mountains layer by layer. Ibn Sina additionally noted that clay which formed the mountains was also arranged in layers. He went on to explain how one layer forms at a certain period of time, then another layer will pile on the first at a different period of time, and so on. Between two layers, there is a substance of different material which forms a division between them. However, petrification must occur at one point to cause this partition to disintegrate. This is the modern thought of rock strata, or rock units. These different strata, formed at particular depositional environments, are now fundamental in conducting stratigraphy and correlation analysis across continents.

Chapter 4: On Earthquakes

In chapter 4: On Earthquakes, Ibn Sina defined earthquakes and the factors that cause them. He began the chapter by stating that earthquakes are movements on the Earth's surface caused by movement under the Earth. This movement of the Earth is now known to be caused by plate tectonics, a theory proposed by Alfred Wegener in 1912 (Jacoby, 1981) and supported by Harry Hess in 1962 (Hess, 1962). Moreover, the body that moves underneath the Earth is: steam or smoke as strong in force as wind, a water body, a wind body, or fire that produces heat through combustion. This is now understood to be the result of convection currents in the Earth's mantle. Hot magma rises and cools as it approaches the crust which then sinks towards the core, where it is heated once again to restart the cycle of magma movement. This fluid movement allows for land bodies to move.

In this chapter, Ibn Sina addressed beliefs of Greek philosophers on earthquakes. For one, he addressed Archimedes' belief that earthquakes can be caused by something on top of the Earth's surface such as the violent falling of a mountain or large blocks of stone. In addition, Ibn Sina addressed Anaxagoras' belief that the cause of earthquakes is wind. He went on to disprove both claims using his own observations on geology, meteorology, and earthquakes.

Ibn Sina noted that earthquakes differ in the strength of their start and finish (i.e. their cause and effect). He differentiated between types of earthquakes by the direction of their movement: vertical, diagonal, and horizontal. This is a crucial observation since it is now known that earthquakes are a result of Earth movement. This shift in land originates at a fault and the sliding of land masses against one another. There are three types of faults: normal, reverse, and strike-slip (Figure 1.14). He also defined three types of earthquakes in terms of their movement: earthquakes that move in direction of the poles, shaky convulsing movement, and earthquakes that move upward and horizontally. Currently, earthquakes are not characterised by their movement but rather quantified by their magnitude in the Richter scale, invented by Charles F. Richter in 1935 (Richter, 1935). He also noted that shaking movement is a principle characteristic of earthquakes.

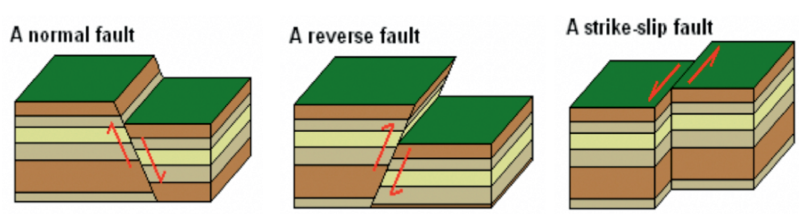


Figure 1.14: *The three types of faults that can cause earthquakes.*

Chapter 5: On the Formation of Minerals

In chapter 5: On the Formation of Minerals, Ibn Sina classified minerals and described properties of each category with examples. Ibn Sina classified minerals into four categories: rocks, sulphurs, fusible bodies, and salts. He noted that minerals can either be weak or strong in makeup, and some are malleable while others are not. Moreover, Ibn Sina discussed the solubility of the four classes of minerals.

In this chapter, Ibn Sina presented his experimental approach to show how dyes and other mineral compounds are prepared (Nasr, 1993). Ibn Sina's approach classifies him less with alchemical tradition and more with Medieval predecessors of modern chemists (Nasr, 1993).

Ibn Sina accepted the Jabrian theory for the formation of metals (Nasr, 1993). More specifically, Ibn Sina concured with the sulphur-mercury theory of metallic composition by stating that mercury, or something resembling, is the essential constituent element of all fusible bodies (Davis, 1928). The sulphur-mercury doctrine states that (Newman, 2014):

i. Metals are composed from mercury and sulphur within the Earth, but differ in colour and purity depending on the amount of mercury and sulphur
ii. Metals are composed of an earthy and watery component

Ibn Sina postulated that mercury and sulphur were not only metals, but rather they were compounded from primitive ingredients (Newman, 2014). Ibn Sina's description of metals, again, shows that he had genuine knowledge in the chemistry of metals that was employed by Medieval Latins (Davis, 1928).

Ibn Sina ended his chapter on minerals by addressing some common beliefs amongst alchemists; stating that chemists know that no change can be made in the different species of substances, though they can produce an appearance of such change (as in the case of fake gold). Although Ibn Sina had fame as an alchemist and magician in Medieval Europe, he was strong in his criticism of alchemists (Davis, 1928; Nasr, 1993). He presented his disapproval by saying that although the appearance of metals can be changed, their nature and essence does not change (Davis, 1928; Nasr, 1993). This shows that Ibn Sina was a firm believer in the impossibility of transmutation of one metal to another by human activity, also known as chrysopoeia (Nasr, 1993; Newman, 2014). The reason for Ibn Sina's disapproval of transmutation is due to a lack of evidence (Nasr, 1993). This is a true testament to Ibn Sina's intelligence and character for supporting observational science based on logic and substantiating evidence.

Modern Techniques for Earthquake Prediction

Building upon Ibn Sina's discussion on earthquake characteristics and causes, major research in earthquake prediction has been conducted. Earthquake prediction is defined as "a deterministic statement that a future earthquake will or will not occur in a particular geographic region, time window, and magnitude range" (Jordan et al., 2011). To this day, there is a lack of fundamental understanding in earthquake predictions, however, recent developments have allowed for earlier warnings than previously possible. Most prediction methods depend on diagnostic precursors, which are signals that can be observed before an earthquake. These precursors are monitored and measured using tools such as strainmeters, tiltmeters, and seismographs. Combinations of precursors can indicate the probability of an earthquake event and its magnitude, which ultimately depend on the location and timing. Typical precursors include changes in the stress, strain, and tilt of surrounding rocks as well as foreshocks.

Stress, Strain, and Tilt

The underlying cause of an earthquake is the sudden failure of a fault after the slow increase of tectonic stresses and frictional 'stick-slip' instabilities (Fagereng and Toy, 2011; Jordan et al., 2011). The rupture is dynamic and spreads quickly from a small fault patch across the fault surface, known as the nucleation zone (Jordan et al., 2011). This displaces the land on a side of the fault and radiates energy as seismic waves. Moreover, the frictional instabilities are a result of the release of elastic strain by shear failure on a pre-existing fault (Fagereng and Toy, 2011). The subsequent response to shear stress varies depending on the faulted rocks' characteristics and conditions (Fagereng and Toy, 2011).

Elastic rebound theory discusses the impact of stress on earthquakes and is based on "two crustal blocks moving steadily with respect to each other while slowly increasing shear stress on the fault that forms their tectonic boundary, until the fault reaches its yield stress and suddenly ruptures" (Jordan et al., 2011). This theory implies that following an earthquake, the probability of another earthquake on the same fault is relatively low, but this probability can increase as the process of stress renewal persists (Jordan et al., 2011).

It was previously believed that stress accumulates before an earthquake persists until that stress is released by faulting during the earthquake (Wu et al., 2013). As a result of new data, it is suggested that the stress begins to relax either minutes or months before an earthquake's occurrence (Wu et al., 2013). The relaxation duration is directly correlated to the magnitude of the approaching earthquake (Wu et al., 2013). With appropriate measurements, stress can act as a potential short-term diagnostic precursor to earthquakes.

A tiltmeter and strainmeter are used to monitor change in tilt and strain in rocks (Rikitake, 1983). A tiltmeter monitors reversal in tilting direction prior to an earthquake (Rikitake, 1983). A strainmeter detects changes in strain measurements leading up to an earthquake (Rikitake, 1983). Both observations can be used as short-term diagnostic predictors of an earthquake occurrence.

The uniformitarian belief in the topic of Earth deformation is that the process is slow and constant through geologic timescales (Fagereng and Toy, 2011). New theories suggest that the process of seismic slip is in fact common but does not always create destructive earthquakes (Fagereng and Toy, 2011). Furthermore, fault slips can be differentiated as seismic (earthquake related) and aseismic (non-earthquake related) based on speed (Fagereng and Toy, 2011). Seismic slips have fast speeds while aseismic slips have slow creeping speeds (Fagereng and Toy, 2011). Therefore, future studies are needed to determine the mechanism of seismic and aseismic slips, the characteristics of an earthquake nucleation site, and the factors governing the partitioning between seismic and aseismic deformation (Fagereng and Toy, 2011).

Foreshocks

Analysis of foreshock tremors can also be used to predict earthquakes. Since earthquakes typically occur in sequences, differentiation of the shocks is relative. The biggest earthquake and typically most damaging in a sequence is identified as the mainshock; smaller magnitude earthquakes prior to this main event are called foreshocks while smaller magnitude earthquakes following the mainshock are called aftershocks (Jordan et al., 2011; Lippiello et al., 2012). As a result, a foreshock is essentially a minor earthquake that precedes the largest earthquake. When monitoring earthquake activity, seismologists assume that each foreshock precedes a major earthquake event. For every foreshock recorded, the probability of a detrimental earthquake increases by 1% (Jordan et al., 2011). However, this assumption is flawed since foreshocks are retrospective and a highly variable predictor. Foreshock intensity and density depends on proximity to a fault line and type of faulting (Jordan et al., 2011). Worldwide, an average of 15% of main event earthquakes are preceded by one or more foreshocks that are within 1 unit of the mainshock's magnitude, within a 75 km radius, and occurred within 10 days (Jordan et al., 2011). Furthermore, while examining case studies, Rikitake (1983) noticed that foreshock occurrence would increase suddenly then decrease drastically on the day of the main earthquake. Further understanding of foreshock patterns and differentiating between foreshocks and the mainshock is crucial to future earthquake prediction.

Earthquakes in Canada

According to Natural Resources Canada (2016), seismologists record over 1000 earthquakes in western Canada annually. The high earthquake activity is due to this region being subjected to three types of plate movements: divergence, convergence, and transformations (Natural Resources Canada, 2016). Consequently, the seismic activity poses a great threat to western-bound Canadians and damage to the infrastructure and surrounding area, calling for the necessity of early preventive earthquake prediction methods. For example, on October 27, 2012, a 7.8 magnitude earthquake occurred in Moresby Island, British Columbia (Figure 1.15) (Bird and Lamontagne, 2015). Although there were no causalities and city damage was minimal, there were many critical consequences such as landslides and a tsunami. Improved earthquake prediction is valuable for evacuation purposes, possibly saving many human lives, as well as minimizing community damage.

Figure 1.15: *A map of the Haida Gwaii archipelago in British Columbia, Canada.*

"Man must rise above the Earth—to the top of the atmosphere and beyond—for only thus will he fully understand the world in which he lives."

-Socrates

Chapter 2: Astronomy and Geophysics

Astronomy is one of the oldest scientific disciplines – one which really showcases the dynamic nature of science, and has repeatedly changed how we view the universe and our place in it. For centuries mankind has been observing the heavens, searching for some hidden purpose or simply gazing in wonder. Over time, some curious individuals began to look closer. The Greeks and Babylonians were among the earliest civilizations to properly study the stars and planets, recording extensive observations, and developing many theories regarding our planet and other celestial objects. From them we find some of the earliest records of a spherical Earth, theories of gravity, and one of the first practical benefits of astronomy, the introduction of the calendar.

Much of these early astronomers' work was limited by the technology of their time, with access only to crude instruments and simple mathematics. However, as Sir Isaac Newton famously declared, "If I have seen further, it is by standing on the shoulders of giants." Scientists in the past and scientists today have always relied and built upon the work of their predecessors. Newton's own theory of gravity, one of the most fundamental laws of nature, would not have been possible were it not for the efforts of those before him. This new law, which connects the same force keeping our feet on the ground to that governing the motion of celestial bodies, brought about an entirely new view of the universe and helped to dispel many long-held theories. One of the best examples of this is the long held belief that the universe revolved around the Earth itself, a belief subject to heated debate and stubborn persistence, but which eventually yielded to the mounting evidence against it. With the adoption of the new heliocentric model, astronomers began to take on the challenge of explaining how the very solar system itself came to be. The hope is that understanding how our solar system originated will help to explain how other systems formed – systems which may also include planets that could harbor life. However, while some have already begun searching the stars for more planets, there is still much we do not know about our own home. It was only in the 1600s that we first recognized the Earth's magnetic field, a discovery that connected the work of scientists from across the globe. Even today, there is still much debate regarding how this field is generated.

The universe is incomprehensibly large and ever-expanding, a fact that some find utterly terrifying while others see as a source of wonder and inspiration. We are still far from understanding how everything in the cosmos fits together, but what we can be sure of is that each day we only move forward. The following chapter explores centuries of rigorous debate, overturned theories, and unwavering determination in our effort to understand the universe and our place in it.

Ancient Babylonian and Greek Astronomy

Astronomy is arguably one of the most fundamental of the sciences, as it is the oldest (Menon, 1932). From the beginning of time, people have been enthralled by the night sky and the secrets that it holds. Some of the earliest astronomical records come from Mesopotamia, also known as "the land between the rivers" (Leick, 2003). In the south of Mesopotamia there lived a group of people, known as the Babylonians, who are remembered as the most emblematic representation of Mesopotamian civilization (Leick, 2003). The history of the Babylonians spans some 1800 years, and it is believed that astronomy sprung from Babylon (Leick, 2003; Dreyer, 1906). Babylonian astronomy was both observational and theoretical, and they were known as careful, methodical night-watchers throughout the ancient world (Steele, 2006; Jones 2015). In fact, it is well established that the Babylonian astral sciences influenced the practice of astronomy in neighbouring cultures (Steele, 2006). One ancient civilization that the Babylonian astral sciences influenced were the Greeks, who shared a similar attraction towards the Earth and the "heavenly bodies", which refers to the stars and the planets. The Greeks approached astronomy with an analytical mindset and performed a number of calculations that were extremely accurate for the time period. Greek astronomy started as early as 8th century BCE and continued right up until the Hellenistic period (Goldstein and Bowen, 1983). The Hellenistic period brought about an increase in the knowledge shared between the Babylonian and Greek societies, leading to an era of exceptional astronomical discoveries.

Although there are numerous civilizations that made many astral discoveries, the Babylonians and Greeks had a significant impact on ancient astronomy and there is also evidence that they exchanged information (Steele, 2006). These two civilizations approached astronomy in very different manners, however, their works and interactions had a large influence on the development of astral sciences.

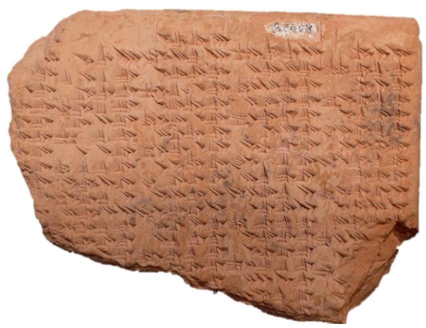


Figure 2.1: *An example of a Babylonian observational diary, dated between 193-192 BCE. This specific tablet is giving daily positions of the moon for a year.*

Early Babylonian Astronomy (2000 - 331 BCE)

Babylonian astronomy in the first millennium BCE was in great demand throughout the ancient world (Jones, 2015). The astral sciences that the Babylonian scribes pioneered had three major components (Steele, 2014). Their astronomy encompassed careful and systematic observations of astronomical phenomena; utilization of known planetary and lunar cycles to predict future phenomena; and the development of a mathematical, theoretical astronomy that was used to calculate astronomical phenomena (Steele, 2014). Rather than having specialists who focused on one specific type of astronomy, the Babylonian scribes practiced all three types of astronomy: observatory, predictive, and mathematical (Jones, 2015; Rochberg, 2000). This emphasis on utilizing observations to make predictions, and then using this information to create mathematical depictions of these predictions can be seen as a very primitive version of the scientific method.

Babylonian scribes took regular and systematic observations of the night sky (Steele, 2014). Astronomical diaries and similar texts demonstrate that these observations were made on a nightly basis that lasted from mid-eighth century BCE to sometime in first century BCE (Figure 2.1) (Sachs, 1974). For the most part, records show that the Babylonian astronomers focused mainly on observing cyclic phenomena that they could predict in advance (Steele, 2014). They seemed to pay special interest to the passage of the Moon or planets past 28 specific reference stars that they called "normal stars" (Jones, 2004; Steele, 2014). When the Moon or a planet passed these normal stars, the Babylonian astronomers would record the distance from the star using different units depending on whether they were recording the passage of the Moon or a planet. If the Moon passed a normal star, its distance above, below, and in front of or behind was measured. These units corresponded roughly to differences in celestial longitude and latitude (Jones, 2004; Steele 2007). However, if a planet passed one of the reference stars, only its distance above or below was recorded using units known as "cubits" and "fingers", where 24 fingers made up one cubit (Steele, 2003).

Although extensive records of the Babylonian observations have been preserved, there is very little information regarding the manner in which the Babylonian astronomers made their observations. Some textual references state that water clocks were used to measure the time of eclipses and the lunar six intervals (Steele, 2014). Historical records indicate that the Babylonians most likely used very simple instruments to make their observations (Steele, 2014). For example, it is likely that the scribes used nothing more than a graduated stick held at arm's length to measure the distance of the Moon and planets to the normal stars (Steele, 2014).

The Babylonians compiled their observational diaries to create "goal-year texts", which contained observations about planetary and lunar data (Sachs and Hunger, 2006; Steele, 2014). These were used to predict astronomical phenomena in an upcoming "goal" year by using the characteristic cycles (Sachs and Hunger, 2006). To predict planetary phenomena, the Babylonians recorded the period of one cycle for each planet (Steele, 2014). They assumed that the same phenomena would occur in the same location in the sky after one period (Steele, 2014). To make a prediction for the upcoming year, they would rely on observations made during the last cycle of the planet. The periods were not perfect, and so they typically made two small corrections in order to make their predictions more accurate. First, they would alter the period by a few days and occasionally make a 1-month correction to allow for intercalation in the calendar (Gray and Steele, 2008; Gray and Steele 2009).

The predictions that were made using the goal-year texts were subsequently recorded in two different texts that were called almanacs and normal star almanacs (Gray and Steele 2008). The almanacs and the normal star almanacs contained data that was arranged in a month-by-month basis. These were used to make observations in the future, and if an observation could not be made because of inclement weather, the information in the almanacs was recorded into the observational diary (Steele, 2014). Thus, the extensive and thorough astronomical texts that the Babylonians made formed a closed circuit of astronomy.

Early Greek Astronomy (800-331 BCE)

Ancient Greece is well known for its contributions to the sciences, especially astronomy. Astronomy was practiced by many ancient Greek philosophers, starting as early as 8th century BCE (Goldstein and Bowen, 1983). The Greeks made a number of contributions to astronomy including calculations on the shape of the Earth and improvements to the calendar. It is thought that ancient Greek astronomy was influenced by knowledge from Babylonia (Jones, 2015). In comparison to Babylonian astronomy, the Greeks focused more on theory and calculations rather than observations and predictions. The earliest records of a spherical Earth came from ancient Greece and led to further questions in astronomy, such as the circumference of the Earth and details on Earth's orbit (Berry, 1898). These questions would later be addressed in the Hellenistic period.

The shape of the Earth is a topic that has had much debate throughout history, and even to this day. The most widely believed theory until 6th century BCE was that the world was flat. This was the easiest theory to believe as the world had not yet been circumnavigated and there was no apparent curve to the horizon from the ground. The earliest known record of a spherical Earth theory came from Pythagoras (Berry, 1898). Pythagoras was a Greek philosopher and mathematician who lived in 6th century BCE (Kahn, 2001). He taught his students that the Earth and the heavenly bodies were spherical in shape (Berry, 1898). It is not known what proof, if any, Pythagoras had for this claim, but it is suggested that he may have determined that the Moon was a sphere and used it as an analogue for the Earth (Berry, 1898). The idea of a spherical Earth was passed down by the Greeks and adopted by the philosopher Plato. He stated, "...this earth of which we are speaking, if it could be seen from above, is to look upon like those balls covered with twelve patches of leather, many-coloured…" (Gallop, 1975). Again, there is no proof or explanation for why Plato believed the Earth was spherical but he too passed the idea down to his students.

One of Plato's students, Aristotle, is the person credited to have first provided proof for the sphericity of Earth (Berry, 1898). Aristotle outlined multiple reasons for why the Earth must be spherical. His first piece of evidence was the shape of the Earth's shadow on the Moon during a lunar eclipse (Stocks, 1922). The shadow across the Moon was always curved, thus if it was created by the Earth then the Earth itself must be spherical (Stocks, 1922). His second argument was that the stars seen overhead change, and some can no longer be seen when traveling north or south. He also remarked that the Earth must not be of a great size because these changes are noticeable over relatively small distances (Stocks, 1922). Aristotle's final point came from his theory that the Earth is the center of the universe and all "heavy" objects fall towards the center of the Earth (Stocks, 1922). This was Aristotle's explanation of gravity and in order for matter to fall downward at all points on Earth, it must be spherical in shape (Stocks, 1922). These simple observations and the ideas they inspired were an impressive feat at the time.

Aristotle had a theory to help explain the phenomenon of gravity, which he also used to support his idea of a spherical Earth. His theory was based upon the idea of light objects and heavy objects. Aristotle reasoned that all heavy objects, including earth and water, fall towards the center of the universe (Stocks, 1922). This is what causes objects to fall down and allows for the Earth to be in the shape of a sphere. Light objects include air and fire and they move away from the center of the universe (Stocks, 1922). Aristotle explained why the heavenly bodies did not collide into Earth by using the concept of centripetal motion. In his book, *De caelo*, Aristotle wrote, "...the motion of the heavens, moving about at a higher speed, prevents the movement of the earth, as the water in a cup, when the cup is given a circular motion…" (Stocks, 1922). This explained how the planets can be made of earth, yet still orbit around the Earth in a circular motion.

Ancient Greece used a variety of different calendars, depending on the village or city that one lived in (Hannah, 2015). One of the biggest difficulties for creating calendars is the fact that one year does not contain a whole number of days. This results in days being added or removed every so often in order to maintain the alignment of the seasons. One major contribution to the Greek calendar came from Meton of Athens. Meton discovered that 19 years is only two hours off of 235 lunar months (Berry, 1898). If a calendar could be created based upon this knowledge, then a day would only need to be dropped after 228 years. It is uncertain whether this was introduced as the civil calendar for Greece, but this fact would have been used as a standard to adjust other calendars regularly to keep them aligned with the seasons (Berry, 1898).

The Hellenistic Period (331 BCE-2 AD)

There is some evidence suggesting that the Greeks had some interaction, albeit limited, with the Babylonian astronomical scribes (Jones, 2015). For example, the lunisolar calendar that Meton of Athens suggested in the summer solstice of 432 BCE is analogous to, and possibly inspired by, the lunisolar calendar that the Babylonians had developed by at least 500 BCE (Jones, 2015). However, it was not until Alexander the Great conquered Babylon in 331 BCE that information really began to flow between these two civilizations (Dalley et al., 1998). This marked the beginning of the Hellenistic period. Knowledge from the astral sciences that the Babylonians had pioneered was transmitted to the Greco-Roman world and it would shape the development of future Greek astronomy.

The observational diaries that the Babylonians had created earned them a reputation among the Greeks as being great observers of the heavens. However, most of the Greek authors who alluded to the Babylonian excellence had limited and vague knowledge of what the observations actually consisted of and they often greatly exaggerated the timeline of the observations (Jones, 2015). Although there is evidence suggesting that the Babylonian predictive and mathematical astronomy was transmitted to the Greeks, there is little documental evidence depicting this transmission due to the ephemeral nature of the papyrus on which their theories were recorded (Jones, 2015).

Before the Hellenistic period, the only record of Earth's circumference was 400,000 stadia, which is referenced in Aristotle's *De Caelo*, and stated to be calculated by "the mathematicians" (Stocks, 1922). One stadia is estimated to be 185 metres, which makes the previous estimate of circumference approximately 74,000 km (Gulbekian, 1987). The actual circumference of the Earth varies due to its slightly elliptical shape, but around the equator is 40,075 km (Balasubramaniam, 2009).

In the Hellenistic period, Aristarchus of Samos was the first to try and estimate the size of the Earth through the use of astronomy (Weinburg, 2015). He calculated Earth's size relative to the Sun and the Moon, rather than producing an actual measurement in units (Weinburg, 2015). During an eclipse, the Earth will cast a shadow upon the Moon. Using observations of the size of these shadows (Figure 2.2), he determined

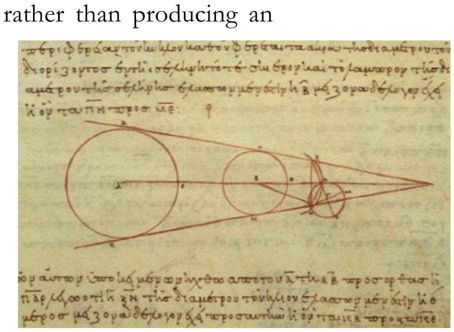


Figure 2.2: *A Greek copy of Aristarchus of Samos' notes on the sizes and distances of the Sun and Moon. Aristarchus used the shadows cast during eclipses to determine the sizes of the Earth, Sun and Moon relative to one another.*

that the ratio of the diameter of the Sun to the Earth was between 19:3 and 43:6 (Heath, 1913). This makes the volume of the Sun approximately 300 times that of Earth, which is a vast underestimate of the Sun's size (Heath, 1913). This error was due to the use of incorrect angles in his calculations (Weinburg, 2015).

Three more philosophers in the Hellenistic period attempted to calculate the size of the Earth, the first producing a number much larger than previous mathematicians, and the second producing the most accurate measurement yet. Archimedes was the first philosopher, and he stated that the circumference of the Earth was 3,000,000 stadia, and not any bigger, although it is unclear exactly how he came to this conclusion (Heath, 1897). In his treatise *The Sand-Reckoner*, he acknowledged that the circumference could be 300,000 stadia, but he stated 3,000,000 stadia was the upper limit (Heath, 1897). Not long after Archimedes, the Greek mathematician Eratosthenes calculated the size of the Earth by using shadows cast by sticks on the summer solstice (Brown and Kumar, 2011). Eratosthenes made one measurement at Syene (modern day Aswan) and another at Alexandria (Brown and Kumar, 2011). Using these measurements, as well as the distance from Syene to Alexandria, Eratosthenes made an incredibly accurate estimate of the size of Earth (Brown and Kumar, 2011). At Syene, the Sun was approximated to be directly overhead, meaning that it would cast no shadow upon the ground (Brown and Kumar, 2011). At Alexandria, which was assumed to be along the same longitudinal line as Syene, the angle created between the stick and its shadow was measured. This angle was measured to be 1/50 of a circle, and the distance between Alexandria and Syene was measured to be 5000 stadia (Brown and Kumar, 2011). Using these measurements, he calculated that the circumference of the Earth was 250,000 stadia, or 50 times the distance between the two cities (Brown and Kumar, 2011). This is a remarkably accurate calculation which translates to 46,250 km, making it close to the actual circumference of 40,075 km. It was also a convenient way of calculating the size of the Earth because although the precise length of one stadia is unknown, the distance between Alexandria and Syene is known so it can be confirmed that the measurement was accurate.

Posidonius was the final Greek philosopher in the Hellenistic era who attempted to calculate the size of the Earth (Fischer, 1975). Although his calculation was more accurate than Eratosthenes', it was a consequence of two errors in his math (Fischer, 1975). Posidonius used a similar approach to calculating the circumference as Eratosthenes did, but he used Rhodes instead of Syene (Fischer, 1975). He used the latitude difference between Rhodes and Alexandria to be 7.5° when the actual value was 5.25° and the distance between the cities to be 5,000 stadia, which is off by more than a quarter of the actual value (Fischer, 1975). The error in these two measurements counteracted one another, leading to a circumference of 240,000 stadia, which is approximately 44,000 km (Fischer, 1975). Eratosthenes' calculation can be thought of as the beginning of scientific geodesy (Fischer, 1975). It was the first calculation for the circumference of the Earth that gave an exact measurement in units and was determined using a mathematical approach. Although Posidonius had a more accurate estimation of the size of the Earth, Eratosthenes used the correct scientific approach and achieved an outstanding estimate for his time.

The obliquity of the elliptic refers to the angle of inclination between Earth's equator and its orbit around the Sun. The calculation of this angle was another of Eratosthenes' great feats, and he once again was able to obtain a very accurate value (Jones, 2002). Eratosthenes measured the angle to be 22/83 of a right angle, or 23°51'26", which is only off by about 7' (Jones, 2002; Berry, 1898). It is not known exactly how Eratosthenes calculated this value, but Jones (2002) believes that it was found using the latitude of Alexandria and the distance to Syene. Eratosthenes believed that Syene was located on the equator, so by finding the latitude of Syene, the obliquity of the elliptic can be determined. If the latitude of Alexandria is 31°, the distance to Syene is 5,000 stadia, and moving one degree of latitude corresponds to a distance of 700 stadia, then (Jones, 2002):

$$31° - \frac{5000}{700} \approx 23°51'26"$$

This gives the same angle that Eratosthenes obtained which suggests that this may have been the method he used.

Hipparchus was an astronomer working in the middle of second century BCE (Berry, 1898). He is regarded by many as not only one of the best astronomers of his time, but rather as one of the greatest astronomers of all time (Berry, 1898; O'Neil, 1986). Unfortunately, most of the work he produced has been lost, and what is known of him comes from citations in others' work (O'Neil, 1986). Hipparchus created, or at least widely developed, trigonometry which enabled him to apply numerical calculations to geometric figures (Berry, 1898). He made numerous and extensive observations of the night sky with as much accuracy as his primitive instruments permitted. He also referred to old observations made by the Babylonians, and compared them to more recent ones in order to see astronomical changes that would otherwise be too small to detect within a single lifetime (Berry, 1898). Finally, he used geometry, and the trigonometry that he had fathered, to represent the motion of the Sun and the Moon (Berry, 1898).

By using his own meticulous observations, and comparing them with that of others, Hipparchus ascertained that there were 94½ days between the vernal equinox and the summer solstice, and that there were 92½ days between the summer solstice and the autumn equinox (Narrien, 1833). In that time, it was believed that the Sun orbited the Earth, and so the difference in lengths of the seasons indicated that the Sun travelled across the celestial sphere more slowly during the summer than in the spring (Hughes, 1989). In order to calculate the eccentricity of the Sun's orbit, Hipparchus first assumed that the Sun moved in a circular path. Another assumption that he made, albeit incorrect, was that the Sun travelled at constant velocity throughout its orbit. Finally, he approximated the length of one year to be 365.25 days (Narrien, 1833). Using some basic geometry and the trigonometry that he had developed, he found the eccentricity of the Sun to be 1/24, or about 0.04167 (Hughes, 1989). Although the Sun does not orbit the Earth, this value is close to the eccentricity of Earth's orbit which is known to be 0.01672 (Hughes, 1989). The errors in his calculations are due to the erroneous assumptions that he made, mainly that the Sun had uniform speed (Hughes, 1989).

While the astral sciences that the Babylonians fathered included strong observations and accurate predictions, they also included attributing omens to celestial phenomena and personally oriented astrology (Jones, 2015). These aspects of the Babylonian astral sciences were transmitted to the Greeks during the Hellenistic period. At the end of the Hellenistic period, which was around second century CE, the practice of observations completely ceased (Berry, 1898). Similarly, mathematical astronomy steadily declined, as did most other sciences (O'Neil, 1986). Instead, the focus shifted to astrology. In this time, the Greeks systematized the art of astrology (Beck, 2015). Most citizens in this time believed that studying the movement of celestial bodies through astrology had the power to predict the future (Beck, 2015). Also around this time, Christianity was beginning to advent throughout the Greco-Roman world (Beck, 2015). After it was adapted as the official religion, pagans were not permitted to teach or share their views on secular matters that conflicted with those in the Scriptures (O'Neil, 1986). This marked the end of a golden age of astronomy, and it would be centuries before future astronomical breakthroughs occurred (O'Neil, 1986).

The Search for a New Earth

Advances in the field of mathematics and the development of new technologies has allowed humanity to make monumental astronomical discoveries. The Babylonians and Greeks were hindered by the crude instruments that they used, and the limitations of the simple mathematics that existed in that time. While ancient astronomy placed a focus on understanding the celestial objects within our own solar system, modern astronomy has advanced deeper into the universe in the search for habitable exoplanets. To do this, one of the main aims of modern astronomy is to detect temperate, Earth-like planets that might be habitable (Gillon et al., 2017).

This search for exoplanets, planets outside of our solar system, is relatively recent. It was not until 1995 that the first exoplanet orbiting around a Sun-like star was discovered (Mayor and Queloz, 1995). This discovery sparked an interest and, as technology advanced, the number of exoplanets that were discovered each year grew from tens to hundreds. This was largely due to NASA's Kepler mission, which in 2014, announced that it had discovered 715 exoplanets orbiting around 305 stars (NASA, 2014). This suggests that multi-planet systems, much like our own, exists elsewhere (NASA, 2014). The discovery of large numbers of exoplanets has led to a new question: could any of these planets support life?

Earth is currently the only planet known to harbour life (Snellen et al., 2013). As such, when searching for other planets that could support or have supported life, the most promising planets are those that are similar to the Earth. These Earth analogue planets are terrestrial, similar in size to Earth, and orbit within the habitable zone

(HZ) of their parent star. The HZ is the area around a star that could retain liquid water on its surface (Kane and Gelino, 2012). Liquid water is necessary for all life as we know it, and so it is the main requirement for a HZ (Ojha et al., 2015). The location of the HZ around a star depends on different properties, such as stellar flux and luminosity (Kane and Gelino, 2012). Stellar flux is the radiant energy passing through a unit of area per unit of time, and depends on the size and age of the star (Kane and Gelino, 2012). A larger star will have a greater stellar flux, which means that its HZ will be located farther away from the star. The size of a planet, its albedo, and its atmospheric composition can also have a big impact on habitability. The atmosphere helps to retain heat close to the planet whereas a high albedo, or reflectivity, will lower the temperature (Kane and Gelino, 2012).

Although a planet orbiting within its HZ is promising, there are more requirements that must be met if a planet is to support life. As previously mentioned, ideal exoplanets are those that have similar conditions to Earth. The major building blocks for life as we know it are carbon, oxygen, hydrogen, nitrogen, phosphorus and sulfur (Mertz, 1981). We can gain insight into the conditions of exoplanets by examining their atmospheres. This is done by observing the wavelengths of light coming from a star both before and during a transit of the planet (Seager and Sasselov, 2000). During a transit, the planet passes in front of the star and light must travel through its atmosphere. By analyzing the wavelengths of light absorbed as it passes through the atmosphere, the composition of the atmosphere can be determined (Seager and Sasselov, 2000).

The most common method used to discover exoplanets, which is the method used by Kepler, is the transit method (Jenkins, Doyle, and Cullers, 1996). When a planet passes between a star and a telescope, it blocks out some of the light. The amount of light that is blocked gives insight into the size of the planet, and the period of the planets' orbit can be determined from the frequency of the transit (Jenkins, Doyle, and Cullers, 1996). Currently, NASA's Kepler mission has discovered 2331 confirmed exoplanets and 4694 candidate exoplanets (NASA, 2017). About 59.5% of the confirmed exoplanets have a radius that is equal to or greater than 2 times the radius of the Earth (NASA Exoplanet Archive, n.d.). Many of the remaining 40.5% of planets are not located within the HZ of their parent stars. As of May of 2016, NASA announced that only 21 of the exoplanets Kepler discovered that are less than twice the size of the Earth are within their star's HZ (NASA, 2016). Similarly, many of these planets are so far away that studying their atmospheric composition becomes very difficult (Jenkins, Doyle and Cullers, 1996). As such, it becomes nearly impossible to determine if they do contain liquid water on their surface.

In February of 2017, NASA announced they discovered seven Earth-like planets orbiting around the ultracool dwarf star TRAPPIST-1, three of which are within the star's HZ (Gillon et al., 2017). This star system is analogous to the inner regions of our own Solar System (Figure 2.3) (Gillon et al., 2017). The TRAPPIST-1 star has a mass that is only 8% that of the Sun, and it is approximately the size of Jupiter. The small size of the star, combined with the transiting configuration of the exoplanets, will make it possible to study their atmospheric properties in depth (Gillon et al., 2016; de Wit et al., 2016; Barstow and Irwin, 2016). The six inner planets form a near-resonant chain, meaning that the planets' orbital periods are all near-integer ratios of each other and their orbits are aligned (Gillon et al., 2017; Mills et al., 2016; MacDonald et al., 2016). This means that the gravity of each planet has a significant effect on one another, suggesting that they formed in the outer parts of the system and then simply migrated inwards (Gillon et al., 2017). As such, the composition of the planets is likely different to that of Earth; namely, they are likely volatile-rich and less dense (Gillon et al., 2017; Raymond, Barnes, and Mandell, 2008; Alibert and Benz, 2017). It is expected that the three planets in the habitable zone could harbour oceans of water on their surfaces, which provides a possibility for life (Gillon et al., 2017). The other 4 exoplanets also have the potential to harbour water, but with less certainty (Gillon et al., 2017). The TRAPPIST-1 system provides renewed hope in the search for extraterrestrial life.

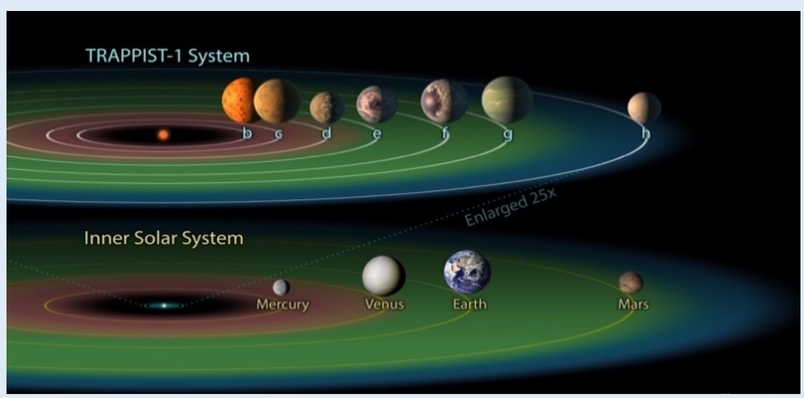


Figure 2.3: *The TRAPPIST-1 system and its size relative to the Solar System. The green area depicts the habitable zone around the star and demonstrates that 3 out of the 7 known planets are located within this region.*

Formation and Evolution of the Solar System

Ideas and theories surrounding the origin of the Earth and its development have existed since ancient periods. Only in the last 300 years have scientists begun to unravel the mystery of how the solar system came to be. This is because before this time, there was no notion of Earth being part of a planetary system; most people believed that Earth was at the center of the universe, with the Sun, stars, and all the other planets revolving around us (Woolfson, 2000).
The first step towards unveiling how the solar system spawned was the widespread adoption of astronomer Nicolaus Copernicus's heliocentric model, where the Sun became the system's center in which the planets orbited (Copernicus, 1976). Later in the 17th century, French philosopher and mathematician René Descartes theorized the first model of the solar system's origin that had actual scientific basis. In his book *Le Monde*, published after his death in 1644, Descartes outlined his model based on observations of fluid motion. He proposed that space was filled with some type of cosmic fluid that formed vortices around stars, implying that the Sun and planets had condensed from a large vortex that had somehow contracted (Descartes, 1979). This early model was largely qualitative and vague, and lacking physical basis as Descartes had no knowledge of the mechanics which govern planetary motion. Thus, Isaac Newton's *Principia* was the next major step forward. Its publication in 1687 provided the foundation of scientific principles upon which a proper model of the solar system's origin could be built (Newton, 2010).
Astronomical observations made by countless scientists over many years have spread great knowledge on the different characteristics of our solar system and beyond. Of these, four fundamental features constitute the basic requirements for any theory of the solar system's formation:

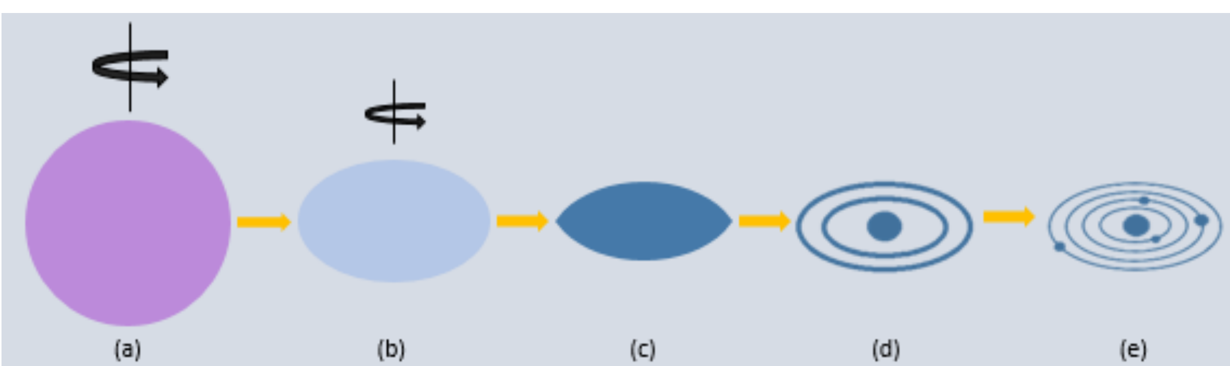
i. Such a theory must be able to explain the distribution of angular momentum, specifically why the Sun has such a slow spin;
ii. It must have a planet-forming mechanism that explains the planets' coplanar orbits together with the division of terrestrial and giant planets;
iii. Satellites and moons of planets must be explained;
iv. The theory must give a reason for the 7° tilt in the Sun's spin axis (Woolfson, 2000).

Many more characteristics of the solar system have been discovered over the years but these conditions are the most basic and the most relevant for a successful theory.

Over a century following Descartes's theory, came an idea from German philosopher Immanuel Kant (1724 - 1804). Kant described a process where a cloud of dust could take the form of a disk, and he speculated that observed nebulae may be regions of star and planet formation (Kant, 1755). Moreover, the advancement of telescopes in the 18th century led to much more accurate observations and consequently, better and more accurate theories. British astronomer William Herschel (1738 - 1822) published multiple catalogues of nebulae including some found around single stars, which he suggested may be linked to planetary formation (Herschel, 1789).

In 1796, French scientist Pierre Simon Laplace (1749 - 1827), having been influenced by the works of Descartes, Kant, and Herschel, developed what is credited as the first scientifically-based theory of the solar system's formation, illustrated in Figure 2.4 (Laplace, 1796). Laplace began his model with a spinning cloud of gas and dust in space. Over time, the cloud cools and begins to collapse, spinning faster as it does in order to conserve angular

Figure 2.4: *An illustration of Laplace's nebula theory. (a) A slowly rotating and cooling sphere. (b) The sphere begins to flatten as it spins faster. (c) The critical lenticular form. (d) Equatorial rings left behind. (e) One planet condenses in each ring.*



momentum (the same way an ice skater pulls their arms in to spin faster). The more the cloud shrinks the faster it spins, flattening out so it takes a lenticular form. Eventually the cloud spins so fast that material at its edge gets left behind, forming sets of equatorial rings; the central bulk collapses into the Sun while the material in the rings clumps together to form the planets. Similar, smaller-scale processes take place around these planets, forming natural satellites (Laplace, 1796).

Laplace's model was seen as monistic because it involved single systems forming the Sun and planets. It received wide support when it first came out as it was extremely straightforward, based on observed evidence, and had answers to most of the requirements of a solar system model. However, there was one major flaw that lead to its eventual downfall. Laplace's model failed to show how the Sun, which accounts for 99.86% of the mass in the solar system, has only 0.5% of its angular momentum evidenced by its slow spin (Woolfson, 2000).

The Chamberlain-Moulton model

The 1900's arrived with new observations of spiral nebulae which led to a new theory developed by geologist Thomas Chamberlain (1843 - 1928) and his associate Forest Moulton (1872 - 1952), a mathematician and astronomer. While we now know these spiral nebulae are actually entire galaxies like the Milky Way, Chamberlain and Moulton assumed they were part of our own galaxy and were convinced they provided a scenario for planetary formation (Chamberlin and Moulton, 1900).

Chamberlain and Moulton (1900) proposed the idea that when the Sun was young and more active another large star passed nearby and pulled material away in a tidal effect. Similar to the tidal effect of the moon, material from both sides of the Sun would be pulled away creating a symmetrical spiral formation. It was assumed the Sun would lose this material not as a stream but in irregular bursts, forming regions of different densities that would eventually cool to form planetesimals (Chamberlin and Moulton, 1900). Unlike Laplace's model, Chamberlain and Moulton's involves separate processes for planet and star formation making it a dualistic theory.

The Chamberlain-Moulton theory satisfied most of the basic solar system theory conditions but not without several flaws. These types of stellar interactions are far too rare to explain the huge number of observed spiral nebulae and there is no way the passing star could produce the 7° tilt of the Sun's spin axis (Woolfson, 2007). The theory was completely dismissed by 1915 when these spiral nebulae were discovered to be whole galaxies themselves (Woolfson, 2000).

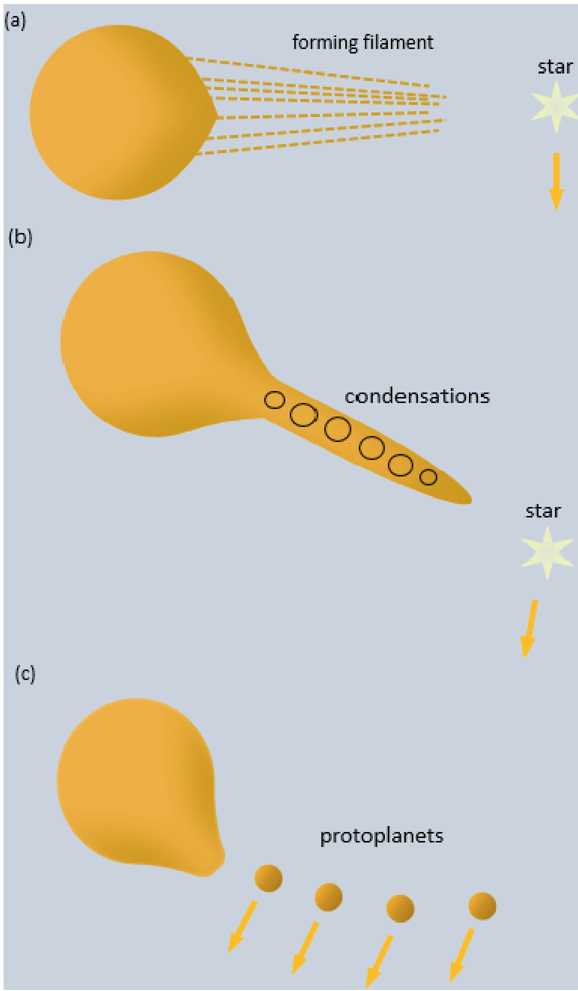


Figure 2.5: *An illustration of Jeans's Tidal theory. (a) Material is pulled from the tidally distorted Sun by the passing star. (b) Proto-planetary condensations form in the filament. (c) Proto-planets attracted by the retreating star.*

Jeans' Tidal Theory

Inspired by the work of Chamberlain and Moulton, British astrophysicist James Jeans (1877 - 1946) expanded the idea of stellar tidal interactions to further develop the dualistic tidal model (Figure 2.5). His model, put forward in 1916, began like the Chamberlain-Moulton theory with a massive star passing close to the Sun, raising huge tides. Streams of solar material left in the form of filaments; these condensed and broke up into multiple masses and protoplanets that collapsed to form the planets (Jeans, 1917). Additionally, as these masses passed close to the Sun a similar smaller scale tidal interaction occurred between the two pulling a filament from the planets to create satellites (Jeans, 1917). Jeans was a good theorist and thus provided mathematical-based analysis for his theory's different aspects. He was able to show how a tidally affected star distorts and derived what is known as *Jeans critical mass* - the condition for the minimum mass a sphere of gas in space can have for gravity to overcome thermal energy and allow for collapse (Jeans, 1917).

The theory was initially met with wide acceptance due to its strong theoretical basis; however, other scientists eventually began to find flaws in Jeans' model. In 1929, Harold Jeffreys determined (through a property of fluid dynamics called circulation) that since Jupiter and the Sun have similar densities, they should spin at about the same rate; in reality they differ by a factor of 70 (Jeffreys, 1929; Woolfson, 2000). In 1935, Henry Russel found that material pulled from the Sun by Jeans' method would not even reach as far as Mercury's orbit (Russell, 1935). Finally, Lyman Spitzer proved, using Jeans' own critical mass formula, that solar material with Jupiter's mass would have a temperature of 1 million Kelvin and would explode in space rather than collapsing (Spitzer, 1939). While his model could not be upheld, Jeans' Tidal Theory introduced a new set of theoretical analysis that could be used to review future theories.

The Accretion Theory

The next form of dualistic theory began with Otto Schmidt (1981 - 1956), a Russian planetary scientist. Observations at the time had begun to show regions in space where no stars could be seen since these regions featured dense clouds of dust and gas which absorb light (Woolfson, 2000). In 1944, Schmidt proposed the idea that occasionally a star will pass through one of these clouds and capture some of the material. This material would settle as a disk from which planets could form (Schmidt, 1944). He hypothesized that another nearby star would be needed to facilitate this capture; however, British astronomer Raymond Lyttleton (1911 – 1995) took Schmidt's idea and showed that another star was not necessary.

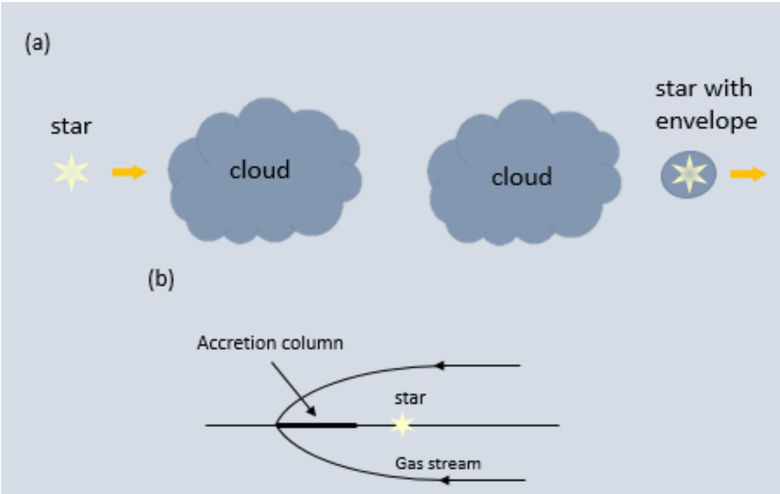


Figure 2.6: *An illustration of the Accretion theory. (a) A star picking up a gaseous envelope after passing through an interstellar dust cloud. (b) A diagram of how an accretion column forms behind a star in a gas cloud.*

Based on a mechanism first suggested by Bondi and Hoyle (1944), Lyttleton showed that as a star passed through the cloud material, it would be pulled inward and behind it forming an accretion column trailing behind, as illustrated in Figure 2.6 (Lyttleton, 1960). Some tangential motion left in the material would allow the column to surround the star and eventually form orbiting planets (Lyttleton, 1960). Though, this model assumed the Sun would enter the column at 0.2 km/s which is far too slow as gravitational attraction alone would have it going much faster (Woolfson, 2000). The very vague nature of this theory meant it didn't receive much support. Yet, this idea of capture would resurface again in the future.

The Vortex model

In the same year Schmidt first proposed his Accretion Theory, German astrophysicist Carl von Weizsäcker (1912 – 2007) suggested that the solar system could have formed by means of a pattern of vortices, similar to the ideas proposed by Descartes. Von Weizsäcker was able to show that a combination of multiple clockwise rotating vortices and a counterclockwise rotation of the whole system could cause particles to move in an elliptical orbit around a central mass (von Weizsäcker, 1944). Where these vortices met, material would collide at high speed, combine, and form condensations that could group together to form planets (von Weizsäcker, 1944).

Although this model has some valid conclusions, von Weizsäcker's theory was met with considerable criticism and failed to obtain much support. British mathematician Harold Jeffreys showed that this system was a high energy one and therefore could not form as the result of turbulence (Jeffreys, 1952). Furthermore, the theory does not deal with the formation of satellites or the slowly spinning Sun, both requirements of any valid theory.

The Protoplanet Theory

Observations have shown that many stars in galaxies form in clusters. In 1960, English astronomer and mathematician William McCrea (1904 – 1999) devised an entirely new theory based on these observations (McCrea, 1960). The model begins with a cloud of gas and dust that would go on to form galactic clusters. Within this cluster, streams of gas collide due to turbulence, compressing into higher density regions called floccules. These floccules move throughout the cloud colliding and combining and, once large enough, they begin to attract more floccules growing even faster. In each region, one dominant floccule becomes a protostar and smaller floccules, which would become protoplanets, are captured in orbit by the protostar. These floccules would join the star from different directions, resulting in a small angular momentum (McCrea, 1960).

After examining the model, Michael Woolfson pointed out that the floccules were too unstable and would break apart long before gathering sufficient mass (Woolfson, 2007). Following, McCrea modified the theory to have larger condensations, but this meant the angular momentum would not cancel out as well and the Sun would not have such a slow spin (McCrea, 1988; Woolfson, 2007).

Jeans' Theory Reassessed: Capture Theory

As previously mentioned, the demise of Jeans' theory was met by two main issues:

i. Material that came from the Sun was simply too hot to form a relatively cool planet.
ii. There is no explanation for how material from the Sun could be pulled far enough to form planetary orbits (Woolfson, 2000).

In 1964, an alternative model with ideas similar to Jeans' was proposed by Michael Woolfson (born 1927). This model was based on tidal forces between a young Sun and a passing protostar. Jeans proposed the idea that a protostar would produce tidal filaments in the Sun which would go on to break up into smaller gas clouds and eventually form protoplanets. Woolfson's model however, theorized that the filaments from these protostars interacted tidally with the Sun by essentially being captured as the protostar passed by it. This gave rise to the name of this theory - Capture Theory (Figure 2.7). Around this time, computers were becoming more common for mathematical models, and thus Woolfson proceeded to construct a model which would test Capture Theory and determine its mathematical and physical viability. Simulations were able to show that some of the material captured by the central star started moving around it in slightly elliptical orbits in a very similar way to the planets surrounding the solar system today (Woolfson, 1964). Some of the benefits of this model included that it overcame the limitations of Jeans' original ideas. While still a possibility, some of the initial conditions necessary for Capture Theory to be viable were slightly unrealistic; the protostars would need to be much more massive in size than what is observed today, and using the current solar system parameters does not yield a robust model of planetary system formation.

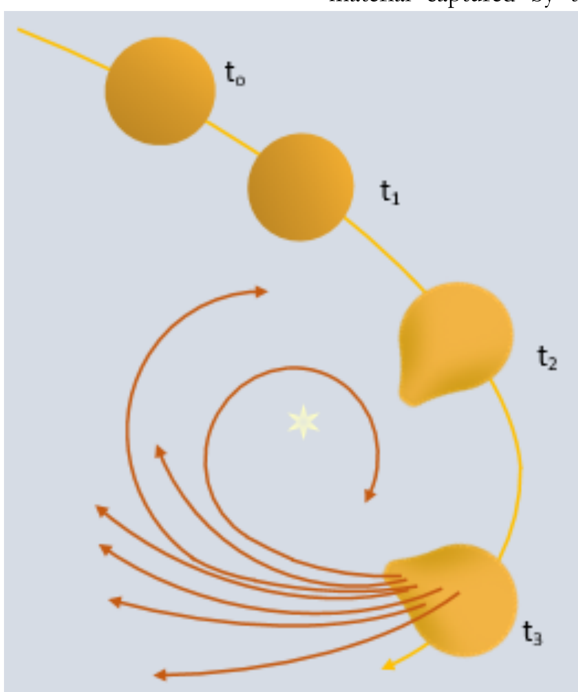


Figure 2.7: *An illustration of the disruption of a passing protostar with ejected material captured by the Sun.*

The Solar Nebula Theory

Up until the 1960s, most theorists exploring the solar system's origin focused on the macroscopic features. They generally did not attempt to look at some of the finer details such as asteroids and comets (Woolfson, 2000). The Solar Nebula Theory (SNT) describes the formation of the solar system through a nebula cloud made of collections of dust and gas scattered in space (Hoyle, 1960). Just like Laplace's theory, this idea builds on the assumption that a nebula existed in space where the solar system would be today. Collapsing under gravity, denser regions of gas and dust began to accumulate mass. Denser regions would become more massive and thus form protoplanets, protostars, and satellites over the course of time. As gravity condensed the gas, its rotation velocity increased which spread the gas into a rotating disc; evidence for this phenomenon can be seen today due to very low variation in the orbital plane of the solar system's planets (Hoyle, 1960). Due to conventional physics, the center of the rotating disc experienced the least amount of centripetal force, thus allowing most of the mass to accrete in the center forming what is known today as the Sun. Gravity again would compact the Sun and pressurize this ball of gas - causing it to heat up and become extremely dense. So dense in fact, that the gas particles began to fuse (Hoyle, 1960). In 1978, the aforementioned Laplacian nebular model was revived by Australian mathematician and astronomer Andrew Prentice. His theory was righteously dubbed as the Modern Laplacian Theory (MLT), and made an attempt at addressing the angular momentum problem in the original Laplacian Theory. Prentice's suggestions to resolve this issue involved the fact that dust particles in the original disc caused a drag force thus slowing rotation in the centre of the disc (Woolfson, 2000). Another phenomenon which may have accounted for the loss in angular momentum was also suggested by Prentice; by this mechanicsm, momentum was transferred from the Sun to planetesimals through its filament ejections (Prentice, 1978). This however, was also challenged due to mechanical failures in the model and computer simulations which failed to show conclusive results (Woolfson, 2000). Thermodynamically, this is a viable explanation for how stars work; however, evidence for this is nearly impossible to see since this process occurs over a period of millions of years.

21st Century Research on Planetary System Formation

Scientific research today is advancing at an incredibly rapid rate. Astronomy is now a field of study for millions of scientists globally rather than a few prominent figures such as Descartes or Laplace. Some stable nations of the world have allocated funds to organizations dedicated exclusively to astronomical research; among the most famous are the National Aeronautics and Space Administration (NASA), SpaceX, and the Canadian Space Agency (CSA). These organizations aim to answer some of history's biggest questions regarding our origins, future, and the search for extraterrestrial life. Scientific research supporting these questions is done through decade-long studies and missions in which groups of scientists come together to formulate hypotheses (National Aeronautics and Space Administration, 2013). Perhaps the most famous of these missions include the Mars rovers, and the Kepler mission, named after famous mathematician and astronomer Johannes Kepler. Since 1996, several unmanned missions to Mars were attempted; some of these include landers which drove on the Martian surface collecting scientific data (National Aeronautics and Space Administration, 2013, 2017; Sheehan, 1996). This data has provided scientists with a toolbox of hints regarding Mars's geological and hydrological history, which is critical in our understanding of the formation of Earth due to several similarities between the two planets (Sheehan, 1996). Moreover, the Kepler mission is a NASA-supported "Discovery mission" launched with the objective of finding exoplanets by taking long-exposure shots that measure the variable brightness caused by planets orbiting stars, as seen in Figure 2.8 (National Aeronautics and Space Administration, 2013). This has produced a database upwards of 2000 planets with the potential for extraterrestrial life, some of which are close enough that they may be used as analogues for Earth by observing their conditions as young planets (Foreman-Mackey, Hogg and Morton, 2014).

The Integration of Modern Theories of Planetary Formation

Many of the previously mentioned theories for the formation of solar systems stem from decades of scientific research. Arguably the most famous single scientist ever known was

Albert Einstein. Einstein was able to put together scientific ideas that were only proven to be correct 100 years after his original theories were formed (Gamow, 1988). Some of these led to momentous advancements in several fields of science, including the previously mentioned exoplanet discovery (Basri, Borucki, and Koch, 2005). A recently-discovered method of analysis which uses Einstein's principles of relativity was used to survey stars for massive, Jupiter-like exoplanets (Faigler et al., 2013). This reinforces the fact that exoplanet research is critical in not only theorizing how planets may form, but also to speculate on the conditions which dictate their size, distance from their star, and composition. These properties are important indicators of how Earth may have formed, since that theory is still debated today.

Another important modern theory is the ongoing development of a grand unified theory (GUT), famously dubbed as a "Theory of Everything"; this theory is a unification of all of the forces which govern how the universe forms and works (Buras, Ellis, Gaillard, and Nanopoulos, 1978). Thus, the development of this theory is a step toward providing an explanation of planet formation and the origins of the universe. Scientific evidence for a theory which combines all of the universe's forces is difficult to collect, and thus new theories rely on mathematical principles developed by historical scientists. In modern contexts, the research conducted ranges from the microscopic scales of subatomic particles to the macroscopic world of astronomy. This idea of a GUT requires the integration of theories in quantum physics with that of research in astronomy, geology, and planetary composition, and must fulfill those principles of a viable origins theory.

The knowledge of our current solar system is much greater than it was mere decades ago, but it does not indicate anything about the solar system's early life. What are debatably some of the most informative results from studies of the solar system are chemical and geological in nature; the similarities and differences in chemical composition between satellites and their planets may provide insight as to their origins, but may also say something about events that occurred following their formation (Woolfson, 2007).

The issues surrounding space exploration and paleontological analyses are very difficult to overcome. Luckily, some recent discoveries have shed light on this issue; these include finding of exoplanetary systems, which ruled out the uniqueness of our solar system. Unfortunately, no single theory can yet explain how planetary systems form, but insight into what a theory may look like can actually help develop an explanation. Any model for planetary system formation that explains how our own solar system formed must also be able to explain exoplanetary system formation just as well. Due to unknown forming conditions, this theory should also not depend on accurate tuning of various parameters of formation such as temperature, gas density, and composites, and thus does not fulfill all the criteria for a viable planetary formation theory (Woolfson, 2007).

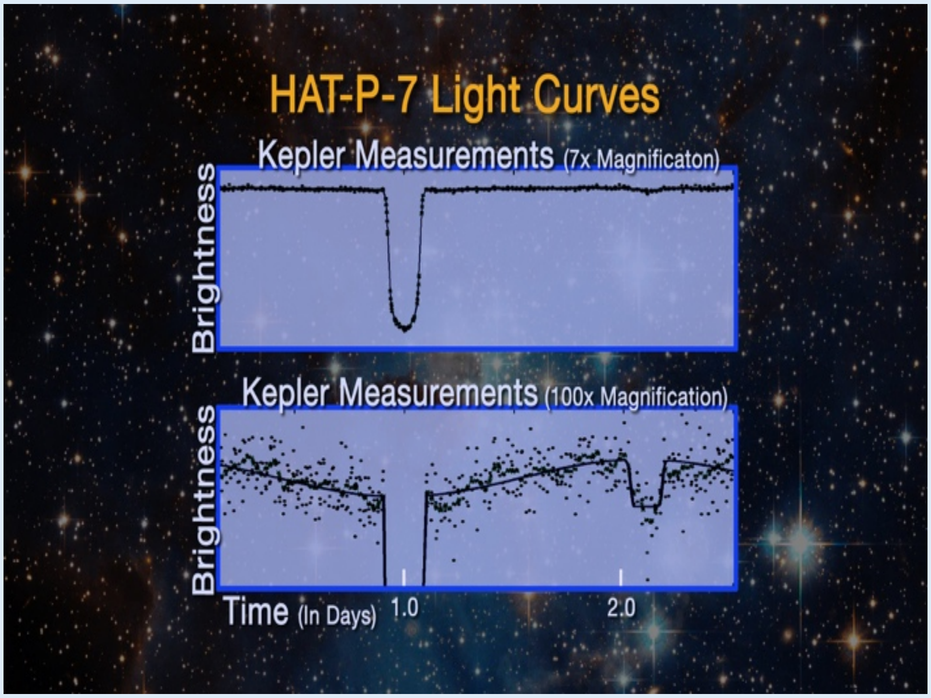


Figure 2.8: *Scientific observations from the Kepler mission which resulted in the finding of exoplanets; the dip in brightness of a star indicated a planet was orbiting around it and obstructing the camera's view.*

The History of the Theory of Gravity

Is there any phenomenon more evident than gravity? It is gravity that makes a projectile follow a curved path, or jumping off a building a bad idea. Gravity is responsible for keeping planets in orbit, binding stars to galaxies, and even the formation of the universe. The force of gravity is an intuitive and widely accepted phenomenon. Its existence has been embedded in our environment and observed throughout the history of humankind; however, it took thousands of years to coin the term "gravity" let alone formulate a descriptive mathematical law. Humans perceive gravity as a practical experience rather than a fundamental force. Since the Earth is so large and we only experience gravitational effects "downwards", it would be difficult to attribute this "attractiveness" as a general property of any mass. It wasn't until the late 17th century when Sir Isaac Newton first made this connection, as he recognized that the same "attractiveness" ruling the Earth is also responsible for the motion of celestial bodies bound in the heavens. Newton's discovery of the Law of Universal Gravitation resulted in a paradigm shift in our understanding of gravity. However, the story of gravity leading up to Newton, and eventually Einstein, contained many other paradigm shifts that involved astronomy, in particular, evolving ideas about the solar system. The ancient Greeks had a significant influence on Western science and speculated on an Earth-centered (geocentric) model that dominated Western Europe for thousands of years. The Greek model easily aligned itself with Christianity's Earth-centered theology that was passionately defended by both the Church and Aristotelians. It took many great contributions of modern science from figures such as Copernicus, Kepler, Galileo, and Newton to challenge this rigid paradigm and to gradually develop the idea of gravity (Moffat, 2008).

Figure 2.9: *A marble bust of Aristotle.*

The Ancient Greeks

In the 4th century BCE emerged one of the most influential philosophers and scientists to Western thought, namely Aristotle of Stagira (384-322 BCE) (Figure 2.9). He is famous for tutoring Alexander the Great and, for twenty years, was Plato's most outstanding student. Aristotle's cosmology was heavily influenced by the Platonic view that Nature's most perfect geometric shape in two dimensions is the circle, and in three dimensions is the sphere. The ancient Greeks believed that the Earth was spherical, but also fixed and immovable. This seemed intuitive since we do not sense the motion of the Earth. Greek astronomers also argued if the Earth were to move, then they would observe stellar parallax as stars changed position; however, it could not be confirmed by observations at the time.

In Aristotle's cosmology, the Earth was surrounded by concentric "crystalline spheres" that rotated with embedded celestial bodies. Aristotle proposed that the spheres were crystalline since an observer on Earth could see the "fixed" stars and other bodies through these spheres. Aristotle proposed spheres because the movement of celestial bodies required physical contact, while God is the agent that moves the spheres themselves (Moffat, 2008). The geocentric model gained popularity in 2nd century CE as Claudius Ptolemy (83-161 CE) made modifications to Aristotle's cosmology with epicycles, smaller miniature orbits to account for the apparent change in distance of planets, and deferent, the larger orbit of bodies. However, this complication could have been easily evaded by the heliocentric model proposed by Aristarchus of Samos (310-230 BCE). Aristarchus figured that the Sun was much bigger than the Earth so, it made sense for a smaller body to revolve around a bigger one. The heliocentric model correctly had the moon orbiting the Earth and the planets, including Earth, orbiting the Sun. He also concluded that the stars were too far away to observe parallax. Even so, his model was met with vicious opposition, and it is known that Stoic Cleanthes (331-232 BCE) led a campaign of popular resentment against Aristarchus and accused him of sacrilege for "displacing the hearth of the world" (Pedersen, 1996). The ancient Greeks still had no concept of gravity, yet Aristotle explained mechanics with the theorized elements that composed matter: fire, water, earth, and air. Earth and water possessed a quality called "heaviness", while air and fire possessed an opposite quality called "lightness". Since the universe has a centre, according to geocentrism, bodies that possess more "heaviness" will go towards the centre or downwards, whereas "lightness" will tend to move away from the centre or upwards. He also asserted that given two objects released at the same height, the object with more "heaviness" would reach the ground sooner than the less heavy object. Furthermore, it was assumed that the heavenly bodies contained a fifth element - the ether - to explain their immutable nature of neither being attracted towards or repelled away from the Earth (Aristotle, 300 BCE). Despite the lack of experimental evidence to verify these claims, Aristotle laid the foundation of natural science through reasoning and observations, which encouraged future generations to pursue science. With the geocentric model of the universe still prevalent, no one, according to any historical records, has suggested a notion of gravity that fully explains the mechanisms that uphold the planets and stars, while governing the behaviour of objects on Earth. It wasn't until much later that Copernicus revived Aristarchus' heliocentric model of the universe, resulting in the first of the upcoming paradigm shifts.

Into the Renaissance

The geocentric model is one of the longest running erroneous theories in the history of science. Ptolemy's model was widely accepted, aside from a few critical Islamic scholars in the 11th and 12th century. The geocentric view of the universe wasn't seriously challenged until the early 16th century by Nicholas Copernicus (1473-1543), a Polish astronomer who held a canonry at the Frauenburg Cathedral (Moffat, 2008). Copernicus found many anomalies with Ptolemy's system and was searching for a better model to explain observable phenomena. In *Commentariolus*, he argues that planets did not move uniformly, neither on the epicycle nor deferent, thus failing to agree with common sense and fundamental principles. Copernicus objected that Ptolemy's model did not adhere to the principles of uniform circular motion if it was to agree with the astronomical data. He also proposed the heliocentric model of the universe. As a canon, he knew the consequences of these heretical views. Thus his work *Commentariolus* was only circulated in manuscript copies among his friends and colleagues (Hall, 1970). In 1536, he was asked by Cardinal Nicolaus von Schonberg to publish his ideas in a complete work; however, Copernicus was hesitant. Finally, in 1543, Copernicus published *De revolutionibus orbium coelestium libri sex* before his death (Pedersen, 1996). Now that the Earth was no longer considered to be at the centre of the universe, the Aristotelian doctrine of "heaviness and lightness" became impossible. It is an observable fact that "heavy" bodies tend to move towards the centre of the Earth, but for what reason if the Earth is not at the centre of the universe? Copernicus postulates that not only the Earth, but other celestial bodies act as centres of "heaviness" as an "urge" for smaller bodies to attain unity, inching closer to the modern idea of gravity. Copernicus' *De revolutionibus* is credited for the reformation in astronomy that paved the way for other astronomers (Pedersen, 1996).

Even after the publication of *De revolutionibus*, the Copernican system was rejected by the most famous astronomer of his day, Polish astronomer Tycho Brahe (1546-1601). Brahe had a rare passion and skill for astronomy. He made bizarre tweaks to the geocentric model, with the Sun and Moon orbiting the Earth, while the five other known planets orbited the Sun. (Moffat, 2008). In 1576, he had constructed an observatory on an island off the coast of Denmark to host large astronomical instruments, some even the size of houses. For nearly 20 years, Brahe used enormous protractors to compile a comprehensive catalogue of the angular position of the five planets and hundreds of stars. This was all accomplished without the use of lenses and mirrors for magnification (Logsdon, 1998). Brahe had no concept of gravity and was attached to the idea of objects falling towards the centre of the universe in a geocentric model. However, he unwittingly contributed to the Law of Universal Gravitation, as his accurate measurements were used by both Kepler and Newton to arrive at a heliocentric model of the universe. In 1596, Brahe was intrigued by young Austrian mathematician Johannes Kepler's (1571-1630) *mysterium cosmographicum*. He was impressed by Kepler's mathematical predictions of the Copernican model that accounted for the distances of planets with a mere five percent error (Levenson, 1997). Brahe responded by inviting Kepler to his new observatory in Prague to act as an assistant. Kepler arrived in Prague with his family in the early 1600s to begin a brief but legendary collaboration with the esteemed astronomer. He had hopes of verifying his planetary theory with Brahe's amazingly detailed measurements, but was disappointed when he found that most of the work was raw data and required mathematical analysis. Furthermore, Brahe was possessive of this data and refused to share any more of it than needed (Freely, 2010). It wasn't until Brahe's deathbed a year later that he decided to release this vast trove of information to Kepler. Given the complete accuracy of Brahe's data, he found that none of it actually corresponded with his Copernican model. However, Kepler adjusted his model so that the planets moved in ellipses, with two foci, which matched Brahe's observations with high precision. As a devout Lutheran who had the same Platonic obsession with perfect circles and spheres as his predecessors, this discovery nearly drove Kepler mad. Nonetheless, he was convinced of this finding and, by the early 17th century, introduced his famous three laws of planetary motion. The notion of elliptical orbits brought astronomy to another paradigm shift (Moffat, 2008). Kepler also took another step towards gravity. Since a planet would move in an ellipse at different speeds, he removed the idea of "crystalline spheres" and asserted that the heliocentric Sun exerted some "force" on the planet. Kepler was quite close to the modern idea of gravity, but he attributed this "force" to some form of magnetism (Moffat, 2008). Meanwhile in Italy, Galileo was making his own astronomical observations of the solar system and progress towards the idea of gravity.

Falling towards Gravity

Galileo Galilei (1564-1642) was an Italian astronomer and contemporary of Kepler. It is almost certain that Galileo knew of Kepler's *Astronomia nova,* published in 1602, disclosing a heliocentric model with elliptical orbits, but he never made use of it (Langford, 1998). Galileo in a sense was a traditionalist who believed in perfectly circular orbits and supported the Copernican model. In addition, Galileo is perhaps most famous for his dispute with the Holy Inquisition for his support of a heliocentric model in 1633, an incident reminiscent to the persecution of Aristarchus. His pursuit of scientific truth granted him a sentence of house arrest, which he served for the rest of his life whilst remaining a devout Catholic. It is a common misconception that Galileo invented the telescope; it was actually first invented by a Dutch spectacle maker. As a gifted craftsman, Galileo is credited for its innovation and was the first to use it for astronomical observations. The telescope became a revolutionary instrument in the discipline of astronomy - for the first time in human history, the heavens could be observed beyond the naked eye (Van Helden, 1999). Galileo was able to make an observational prediction that confirmed the heliocentric model made by Copernicus half a century earlier. He did this by using a test devised by Copernicus to distinguish between a heliocentric and Ptolemaic system, namely by observing the phases of Venus. Moreover, Galileo saw that not every celestial body orbited the Earth, or even the Sun, when he discovered four moons orbiting Jupiter. Furthermore, Galileo also shattered the long accepted Greek idea that the Sun and Moon were perfect spheres. He had found dark irregularities on the Sun, known as sunspots, and discovered that the Moon was also jagged like the Earth (Langford, 1998). Although Galileo was famously known as being an astronomer, he is also considered to be the Father of Experimental Science. His contributions were critical to the development of the scientific method. In a sense, he was history's first physicist since he tested theories with experiments that brought mathematics and physics together (Moffat, 2008). He also challenged Aristotle's widely accepted doctrine of mechanics that claimed a heavier body would fall to the earth more rapidly than a lighter one. To test his theory, he attempted to investigate the effect of "heaviness" on motion; however, falling balls moved too fast for him to measure. Thus, the famed tale of Galileo and the Leaning Tower of Pisa is likely apocryphal, but he was able to arrive at an astonishing conclusion with a simple ramp experiment as it gave him a slowed down version of balls falling due to "heaviness". Through these experiments, Galileo developed the idea of acceleration and successfully measured the acceleration due to gravity to be 9.8 metres per second, per second. With this, he discovered the equivalence principle that proved that bodies fall at the same rate independent of their composition, thereby refuting Aristotelian doctrine once again (Gribbin, 2005). Galileo even anticipated Einstein by showing that motion is relative to the observer. These quantitative statements brought physics and mathematics together, thus turning physics into a science and paving the way for Newton's upcoming monumental discoveries (Moffat, 2008).

Did the Apple Fall Far from the Tree?

Isaac Newton (1642-1727) began his career in science as a student in Trinity College and proceeded to spend the rest of his life devoting his time to physics, theology, and alchemy (Brewster, 1831). He followed in the footsteps of his predecessor, Galileo, by providing mathematical descriptions of phenomena in the solar system. With Newton's unequivocal knowledge, investigations in celestial mechanics, and the invention of calculus, Galileo's idea of "heaviness" became the Law of Universal Gravitation.

The story goes like this: Isaac Newton sat beneath an apple tree pondering the universe when an apple fell and hit him on the head, causing him to "discover" gravity. The actual story is slightly different. In Woolshorpe Orchard, Newton questioned why an apple always descends perpendicularly to the ground, but the Moon never hurtled down towards the Earth's center (Stukeley, 1752). Newton answered this question in his famous book *Philosophiæ Naturalis Principia Mathematica* (or, the Principia) (1726). His theory was: if a cannonball was thrown with enough speed, it will overcome the pull of the Earth and go into orbit - like the Moon (Figure 2.10). He also concluded that the attractive force between objects must act between all bodies in space. This brought a paradigm shift that contradicted the Aristotelian belief that the laws governing the motion of heavenly bodies were different than the laws experienced on Earth (Newton, 1726).

Within the next few years, scientists began analyzing Kepler's third law. Robert Hooke, Edmond Halley, and Christopher Wren all claimed to have had an idea of an inverse square law for gravity, based on the fact that planets move in ellipses. Both Hooke and Halley reached out to Newton, in 1680 and 1684, respectively, urging him to work out the mathematics for planetary ellipses. Newton had unknowingly already calculated gravity's contribution to a planet's orbit about 20 years' prior (Moffat, 2008). Over the next few years, Newton perfected the mathematical proof. He later published and edited three editions of the *Principia,* which outlined his famous three laws in addition to the inverse square law for the gravitational force between bodies. He showed that gravity was the glue that holds the solar system together; it explained elliptical planetary orbits, how the planets were kept in orbit by the Sun's gravity, and how the gravitational pull of the Sun and Moon create the Earth's tides (Newton, 1728).

As fulfilling as the theory of gravity seemed at the time, it was not perfect. The motions of all the planets in their orbits due to the gravitational tugs from other planets were accurately described by Newtonian gravitation - except for Mercury. The amount of precession did not match what was predicted by Newtonian gravitation. To explain this discrepancy, Urbain Le Verrier in 1859 proposed the existence of a ninth planet called Vulcan. He suggested that Vulcan's gravity was influencing Mercury's orbit; however, no astronomical observations could observe the existence of such a planet. The question remained: was there a ninth planet or was something wrong with Newtonian gravitation (Moffat, 2008)?

A Relatively New Theory of Gravity

In 1861, James Clerk Maxwell published his first paper showing the equations of light as an electromagnetic phenomenon (Maxwell, 1861). Soon after, in 1900, Henri Poincaré proposed the assumption that electromagnetic radiation had to travel at the same speed in all directions and that the speed of light is the universal speed limit (Poincaré, 1900). Then, in 1905, Albert Einstein (1879-1955) was able to confirm mathematically that nothing could travel faster than the speed of light through the use of Maxwell's equations. This led to his famous special theory of relativity, first proposed in his paper *Zur Elektrodynamik bewegter Korper* (1905), which outlined the invariance of the laws of physics in all inertial systems and the universal speed limit of light. It also implied the unification of space and time into one system: spacetime (Einstein, 1905). In 1907, Einstein thought about incorporating gravity into relativity theory after realizing the inadequacies of Newtonian gravitation, the universal theory of gravity was based on at-a-distance action, wherein the force between bodies acted instantaneously. However, this violated the principle of special relativity asserting that nothing could travel faster than the speed of light (Moffat, 2008). Consequently, Einstein postulated the general theory of relativity.

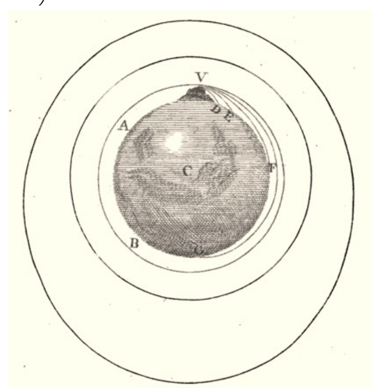


Figure 2.10: *A depiction of a cannonball launched into orbit imagined by Newton in the Principia, republished as A Treatise of the System of the World.*

Albert Einstein's general theory of relativity is fundamentally one of the most impactful achievements of 20th century physics, as it completely reformed the way in which science views gravity. In a thought experiment, Einstein imagined that a man falling freely would not feel his own weight. Thus, Einstein incorporated the principle of equivalence to explain that acceleration (inertial mass) and gravitation (gravitational mass) were indistinguishable, whereas Newton considered them as separate entities. The idea that acceleration and gravity were the same not only explained why a man falling would not feel his weight, but it also became the key stepping stone for Einstein's future endeavors. The above theory became known as the principle of equivalence (Einstein, 1916).

Using Riemann geometry and Gaussian co-ordinates, which were published earlier in the 19th century, Einstein related the geometry of spacetime to the amount of energy it contained (Einstein, 1916). In 1916, Einstein published a series of partial differential equations, now known as the Einstein field equations, which replaced Newton's Law of Universal Gravitation. Einstein painted an entirely new picture of what gravity is and how it works. General relativity provided a uniform description of gravity as a geometric property of spacetime, in the way that the curvature of spacetime is directly related to the energy of whatever matter is present. In other words, what can be felt as gravity is simply the warping of the fabric of spacetime caused by massive objects, such as the Sun, stretching the fabric (Einstein, 1916). Using general relativity, several predictions were made, and many were confirmed in subsequent years. First of all, general relativity accurately explained the deviations in Mercury's orbit and predicted that a massive object should distort that path of light (Einstein, 1916). In addition, general relativity predicted the existence of black holes and gravitational waves. In fact, Einstein never faced any actual critical acclaim until, in 1919, Sir Arthur Eddington measured the light deflection of the solar eclipse, and confirmed that the data matched Einstein's theoretical predictions (Moffat, 2008).

Furthermore, Einstein's gravitational equations completely redefined that way in which scientists understood gravity. Einstein's theory of general relativity not only directly predicted many phenomena, but it also allowed new technology to transpire in all areas of science and technology.

Modern Applications of Gravity

Gravitational Positioning System

One example of an application of general relativity is the Global Positioning System (GPS), a Global Navigation Satellite System. It is a network of satellites orbiting the Earth. These satellites send details of their position to GPS receivers on Earth that can then use these signals to calculate the exact position and speed of a person on Earth (Division on Engineering and Physical Sciences, 1995). However, this can only be done accurately through the assumption of general relativity.

Einstein's general relativity predicted gravitational time dilation. This refers to the elapsed time between events measured at objects at varying distances from a massive object (Einstein, 1916). In other words, the time recorded by a satellite in orbit would be different than the time recorded on Earth, thus, directly connecting GPS systems to general relativity. Clocks on the GPS must be synchronized with each other and Earth, based on position, for the navigation system to yield an accurate location of a person on Earth (Ashby, 2002).

GPS systems were first theorized by Dr. Ivan Getting. He proposed using a system of satellites to obtain precise data for rapidly moving objects and advocated strongly for satellite-based navigation systems that later became GPS (Paulikas, 2008). These satellite systems would contain atomic clocks that would be synchronized to atomic clocks on Earth to accurately measure the location and speed of an object on Earth (Ashby, 2002). In 1973, the GPS project was launched by the United States Department of Defense (DOD). It integrated concepts of several satellite navigation systems developed and proposed to the DOD since the 1960s (Division on Engineering and Physical Sciences, 1995). However, in 1983 the Reagan Administration stated that when GPS technology was fully operational, it would be available to the public (Office of the Press Secretary, 1983). Furthermore, former President Bill Clinton ordered the military to make data from the GPS network available to civilians (Office of the Press Secretary, 2000).

Originally, the GPS was developed to ensure stable military and navy navigation. The idea was for a network of 24 satellites to be configured in space. Dr. Bradford directed a group of engineers to design the Navigation System with Timing and Ranging (NAVSTAR) systems (Parkinson, B., 2003). In 1978, the first experimental NAVSTAR satellite was launched. By 1993, the 24th and final satellite was launched into orbit, completing the modern GPS system of satellites (Division on Engineering and Physical Sciences, 1995). While GPS is still used for military uses, it has numerous civilian navigation applications. GPS can accurately model the physical world and accurately model anything from mountains to oceans to buildings, as well as measuring crustal deformation to estimate seismic strain. Furthermore, GPS has improved mining operations, navigations, surveying, and agriculture (Hoque, 2016)

Gravitational Waves and LIGO

In 1916, Einstein predicted the existence of gravitational waves as a consequence of general relativity. These waves were expected to propagate at the speed of light due to perturbations in spacetime from an accelerating mass (Einstein, 1916). This assertion would be in stark contrast with Newtonian gravity, which assumes changes in gravity to be instantaneous rather than to propogate at a finite speed (Stroik and Putnam, 2013). Moreover, the existence of gravitational waves was quite controversial, and Einstein himself was skeptical of their detection due to their extreme weakness (Steinicke, 2005). Although Einstein's theory of general relativity has been thoroughly tested and widely accepted in the scientific community, the detection of gravitational waves would be an extreme illustration of general relativity. In the 1960s, Joseph Weber at the University of Maryland pioneered the search for gravitational waves by building large aluminum cylinders that vibrate in response to passing waves (Thorne and Weiss, 2016). Weber claimed to have detected gravitational waves; however, he was later discredited since no one could replicate his results. Despite this, Weber's determination managed to inspire the search for gravitational waves, an effort that continues today with the development of the Laser Interferometer Gravitational Wave Observatory (LIGO). The concept of LIGO is quite simple: it uses an interferometer that splits a laser into two arms of the same length (Figure 2.11). The laser is reflected back from the mirrors and reconvenes at the photodetector. A gravitational wave that passes by would warp spacetime so that the arms would stretch or contract, resulting in a different interference pattern as the two light beam travel different distances with respect to each other (Barish and Weiss, 1999). The history of LIGO involved the determination and imagination of a large number of scientists. In 1962, the idea of LIGO was conceived by Russian scientists Michael Gertsenshtein and Vladislav Pustovoit, and independently several years later by Rainer Weiss and Weber. By the 1970s, prototypes were built by Weiss at MIT, while Kip Thorne's research group at Caltech was investigating the theory of gravitational waves. To achieve enough funding, the research groups at MIT and Caltech were pressured by the National Science Foundation (NSF) to collaborate on the LIGO project in the early 1980s. For the next decade, the LIGO project struggled with funding and progress until Barry Barish was appointed to be the new laboratory director. Barish was able to convince the NSF to provide more funding and underwent efforts to organize LIGO's construction phase and the commissioning of LIGO's initial interferometers. In 1997, the facilities were nearly finished, and Barish started recruiting scientists beyond Caltech and MIT. Throughout the next two decades, the LIGO interferometers were undergoing improvements so that it could be sensitive enough to detect gravitational waves. Finally, on September 14, 2015, nearly 100 years after Einstein's prediction of gravity waves, LIGO's two interferometers achieved their first detection of gravitational waves from two black holes spiraling together and merging (Thorne and Weiss, 2016). This discovery was a huge milestone for the LIGO Scientific Collaboration (LSC) as scientists for the first time could observe the universe with a new lens. The LIGO Observatories plan to continue upgrades in the future and hopes to detect a variety of objects such as black holes, supernovas, and neutron stars on regular occasions (Chu, 2016). About this time, the LSC has grown to include approximately 1000 scientists from 75 institutions in 15 nations (Thorne and Weiss, 2016). All in all, the observation of gravity waves is a milestone accomplishment for humankind that demonstrates the progression of the theory of gravity due to the collaborative effort of many scientists throughout history.

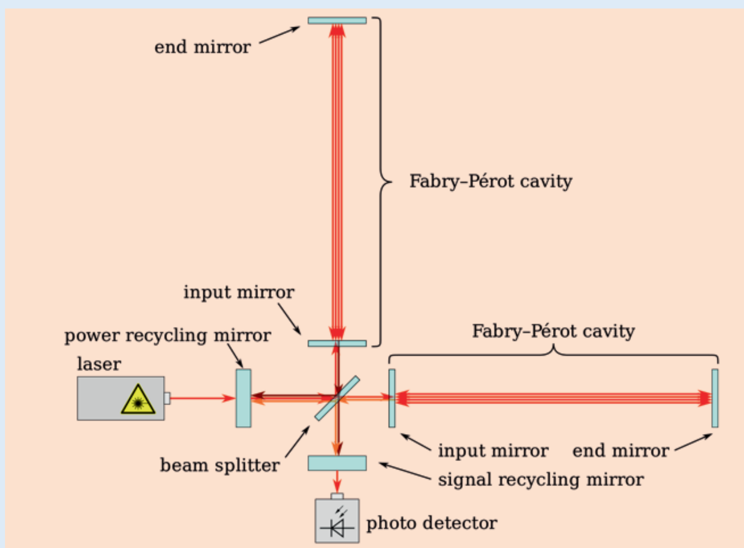


Figure 2.11: *The LIGO interferometer that detects gravitational wave. A gravitational wave passing by would stretch or contract the two "Fabry-Pérot cavity" arms.*

From Mysticism to Magnets: Discovering the Earth’s Magnetic Field

The first magnetic rocks were found millennia before science turned from the mystical to the physical; magnetic rocks in ancient times were often seen as spiritual, either gifts from God or signs of demonic work. Lodestones are the first documented and identified magnet in ancient texts, first appearing in a document from the seventh century BCE in ancient China (Du Tremolet de Lacheisserie et al., 2005). Without the modern understanding of magnetic field lines, dipolarity of magnets, magnetic inclination and declination, and the idea that Earth has a magnetic field, there were many theories that surrounded lodestones. Since then, many different scientists have contributed to the creation of compasses and our understanding of magnets. It was only with the accumulation of numerous published works, letters, sketches, and experiments that, in the year 1600 CE, William Gilbert was able to come to the culminating conclusion that the cause of many of the properties and behaviours of lodestones and compasses is due to the Earth itself being a magnet (Smith, 1968). This enabled the discovery confirming that the Earth’s molten core is what gives the planet its magnetic field.

Figure 2.12: *A directional spoon: This type of lodestone spoon is one of the first rudimentary south-pointing compasses used in ancient China.*

Early Magnets and Compasses

Before Gilbert could undergo his seminal experiments, many advancements in the understanding of magnets had to be completed, such as the discovery of lodestones as more than ordinary rocks. Lodestone (also referred to as loadstone), is a Middle-English word for ‘leading stone,’ and is a naturally magnetised magnetite. Although the use of magnetic materials in architecture predates the seventh century BCE text from ancient China that first mentions the stone, it is difficult to ascertain whether their magnetic properties were known. Rudimentary compasses were designed and implemented by the ancient Chinese for navigation by the first century BCE in the form of directional spoons (Du Tremolet de Lacheisserie et al., 2005).

The ancient Greeks developed their own understanding of magnetism during the same time period, and found much of their magnetite from the district of Magnesia in modern-day Turkey, the assumed origin of the word ‘magnet’ (Srinivasan, 1996). Thales is the first European to mention lodestone and its magnetic properties, and did so in 600 BCE (Smith, 1970). Thales is one of the first to break away from mythology and attempt to explain physical phenomena, although religion was still highly incorporated into his work (Magill, 2003). Thales assumed that since lodestone was able to influence matter around it, it therefore must have a soul (Tankha, 2006).

Rudimentary compasses are thought to have been first designed and implemented for navigational purposes in the first century BCE in ancient China, and comprised of a lodestone spoon free to rotate and pivot on a smooth board, as shown in Figure 2.12, and were thought as pointing south (Smith, 1968). However, it was only until the twelfth century CE that the use of compasses became prevalent in European society. Alexander Neckam, an English abbot and theologian, was the first to describe the use of compasses in 1187 (Smith, 1968). Neckam describes the compasses being used by sailors as a bobbing cork and a needle that would point north when spun (Neckam, 1190). There is some debate in whether or not the concept of compasses was introduced to the Europeans by the Chinese, or if they invented compasses independently. The European and Chinese compasses differed in their conformation and in which direction they identified as pointing in, north or south respectively (Smith, 1968).

Understanding the Magnet

Over the next few centuries, the lodestone was, for the most part, not further studied, even though myths about its attractive properties arose. In the early fifth century, Saint Augustine of Hippo, a Christian philosopher and theologian, wrote on the unusual behaviour of the mineral, believing it to be religious in nature, and that it is an example of "God's … power" (Augustine of Hippo, n.d.).

By the thirteenth century, the explanations of lodestone had shifted from religious or supernatural to physical concepts, more akin to how modern science is today (Smith, 1968). The understanding of magnetic rocks, including lodestone, and their possession of both north and south poles emerged by 1300 CE. Petrus Peregrinus de Maricourt was a French scholar, renowned for his experiments and publications on lodestone and its properties, most famously his letter later published as *Epistola de Magnete*. In his letter, written in 1269 CE, Peregrinus discusses ways of determining which direction each side of the rock points, the fact that the stone will always have two poles, even when the rock is split at the equator, and that like poles repel. He also described the ability of magnets to be forcibly repolarised. Aside from realising the dipolarity, Peregrinus also discovered that magnetic force is vertical and strongest at the poles (Smith, 1970). Additionally, he hypothesised how lodestone is attractive, describing one pole as passive and the other as active (Peregrinus, 1269).

There were several different theories on why lodestone and other magnets would result in a compass that always points in the northward direction. Many believed that they pointed to the North Star, as mentioned by the Cardinal Jacques de Vitry in his published work *Historia Orientalis* of 1220. He wrote: "An iron needle, after having been in contact with the lodestone, turns towards the North Star, so that it is very necessary for those who navigate the seas" (de Vitry, 1220) Others, like Peregrinus, thought that the needles would point towards the heavens. At this time, the Earth was undisputedly regarded as the centre of the universe, and God in heaven rotated around the Earth in a tenth sphere (the other nine being Saturn, Jupiter, Mars, the Sun, Venus, Mercury, and the Moon), and the axis on which this tenth sphere and our sphere coincide is the cosmological north pole. The North Star happened to concur with this axis (Smith, 1968).

Other European theories at the time hypothesized that the stones' direction would point in their rock of origin; most of the lodestones in Europe were from northern Europe. Guinicelli, of the thirteenth century, was one supporter of such claims. However, this was heavily refuted by Peregrinus, who correctly stated that lodestone deposits are found in many places other than northern Europe, so there wouldn't be such uniformity in the direction they point (Smith, 1968).

Major progress in the scientific understanding of magnetism and the Earth came in 1568, when Flemish mathematician and geographer Gerhard Mercator printed the first map, shown below in Figure 2.13, with longitude and latitude lines at right angles to each other, a creation for which he is most notable for (Smith, 1968). He had speculated in 1546 as to the reason why the latitudes geographically differ from the magnetic meridian lines. Mercator later defined this difference as magnetic declination. However, he assumed it was uniform across the Earth and therefore wrongly estimated the magnetic north pole. The realisation of magnetic declination led Mercator to conclude that the influence on compass needles must be due to a point on or in the Earth, not heavenly or towards the North

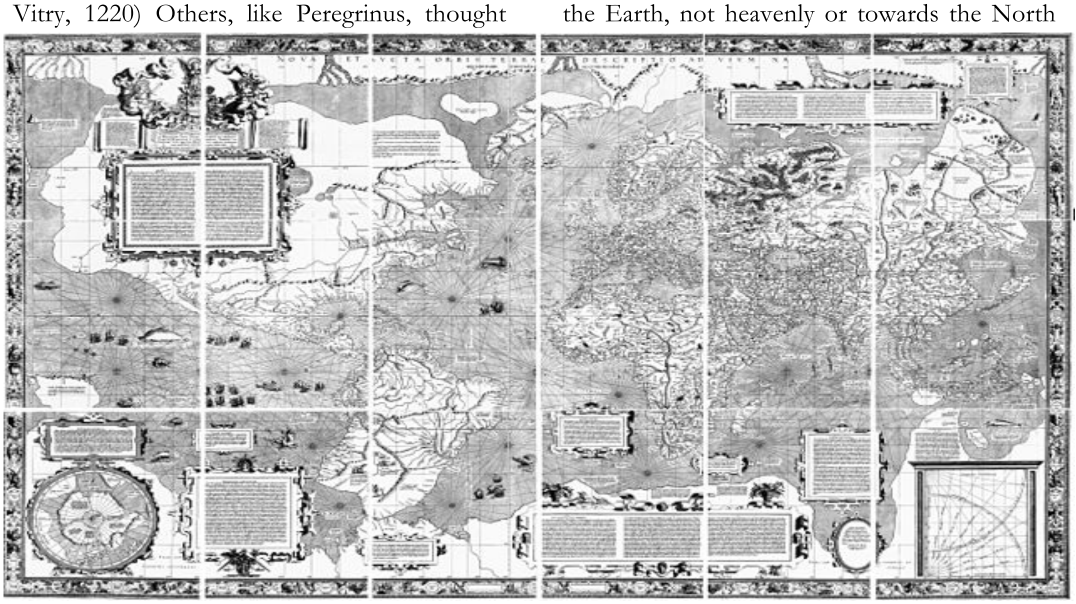


Figure 2.13: *Mercator's World Map: Mercator created the first map with mediator and latitude lines at right angles to each other in 1568.*

Star. Unfortunately, Mercator died six years before Gilbert published his work on the magnetic properties of the Earth, so he never realized that he was correct in thinking that the influence was within the Earth (Smith, 1968).

Another important discovery that had yet to be made about the properties of magnets, that would help Gilbert arrive at his infamous conclusion, was magnetic inclination. Robert Norman was a compass maker in London, England who worked in the same century as Mercator. His most famous book, *The Newe Attractive*, published in 1581, explains his independent discovery of magnetic inclination (Norman, 1581). Magnetic inclination is the term used to describe the angle between the horizon and the Earth's magnetic field lines, which varies across the planet and affects compass readings. Norman was the first to make a dip circle, which is used to find the angle between the Earth's magnetic field and the horizon. In his works, Norman describes how even on his best compasses, the needle point would dip down after swinging north. He was then determined to find a method of building compasses that would not have this dipping problem, and spent many years searching for the reason this phenomenon occurs. In the process, he also proved that the needle does not gain mass when attracted to a point, as many attributed the dip to an increase in mass of the needle (Norman, 1581). He eventually came to the conclusion that lodestones must have field lines, writing: "And surely, I am of the opinion, that if this virtue [magnetism] could be by any means be made visible to the eye of man, it would be found in spherical form extending around the stone in a great compass, and the dead body of the stone in the middle thereof, whose centre is the centre of his aforesaid virtue" (Norman, 1581).

Astonishingly, Norman discovered magnetic inclination even though he was unaware of Earth's magnetic field lines. This seminal discovery is believed to have been the piece missing that held Mercator back from the discovery of Earth's magnetic properties. Furthermore, it is also believed to be the key that helped Gilbert piece together his ground-breaking theory (Smith, 1968).

William Gilbert and the Introduction of Geomagnetism

William Gilbert was a sixteenth century English physicist and physician who is credited for first proposing the Earth as a giant magnet (Merrill, McElhinny, and McFadden, 1998). Published in 1600, *De Magnete* (On the Magnet) details Gilbert's experiments in disproving many of the myths surrounding magnets, such as garlic affecting the strength of magnetism, and how he arrived at his weighty conclusion (Gilbert, 1600). He was also the first to distinguish between magnetism and static electricity (Hager, 2014).

Gilbert was extremely critical of the more popular theories surrounding magnets at the time. It was a common held belief that magnets were magical in some way, either possessed by evil spirits or sent to help thieves. Some thought that when iron was hung from lodestone that the lodestone would absorb the mass and that the iron and lodestone would not weigh more than the lodestone itself. Others worried that ships needed to be constructed out of wooden pegs instead of iron nails, in case the nails would be pulled out by a large lodestone deposit (Gilbert, 1600). In the sixteenth and seventeenth centuries, even after Gilbert's publication, it was so feared that garlic or onions could cause a compass needle to lose its magnetic properties that many ships refused to serve garlic or onions in case a sailor then breathed on the compass (Bromehead, 1948).

One of Gilbert's first notable discoveries recorded in *De Magnete* is his experiments exploring the variation in magnetic inclination over the Earth. Using a spherical lodestone, called a terrella, Gilbert investigated the variation in inclination, using a variation of Norman's dip circle (Merrill, McElhinny, and McFadden, 1998). The terrella was also used to draw parallels between magnets and the Earth, in the positioning of the equator, meridian lines, the axis of rotation, and the poles (Gilbert, 1600). It was the study of this spherical magnet and the understanding of magnetic inclination from Norman's works, that Gilbert was able to make the leap to the Earth itself being a magnet. This revelation was only the second generalised scientific statement made about the Earth, the first being its near spherical shape (Merrill, McElhinny, and McFadden, 1998).

Response to Gilbert's Theory

A major setback to the acceptance of modern theories of the Earth's magnetic field was biblical authority, commonly accepted in the seventeenth century in which Gilbert published (Baldwin, 1985). Gilbert's writings especially sparked the debate of the validity of Copernican theory - the idea that the planets revolved around the Sun rather than the Sun and other planets revolving around the Earth, as shown in Figure 2.14. Copernican theory was a heavily debated and controversial topic in the seventeenth century (Baldwin, 1985). Gilbert's *De Magnete* revolutionized the debate by introducing magnetism into astronomy while making his hypothesis that the Earth, a celestial body, was itself a magnet. Based off of Gilbert's works, several scientists debated the validity of Copernican theory using magnetism. Although Gilbert did not explicitly write about heliocentrism, he did endorse the daily rotation of the Earth in agreement with Copernican theory (Baldwin, 1985).

One of the major contributors to the debate, who refuted both Copernican theory and Gilbert's hypothesis, was Anthanasius Kircher. Kircher was a well-known naturalist living in the seventeenth century and belonging to the Society of Jesus (Baldwin, 1985). As a Jesuit, Kircher was taught science and philosophy from a biblical perspective. He was the first person to use magnetic theories to debate geocentrism. He did agree that the Earth had some magnetic-like properties but could not accept that this meant the Earth could be a magnet itself. It is not shocking that Kircher disagreed with these theories, since he was a devout Jesuit and the church had called these new ideas heretical (Baldwin, 1985).

Other scientists, beyond the religious field, caused Gilbert's theories to not be easily accepted. A major opponent to Gilbert's theories was Martin Lister, a naturalist born into a wealthy family in 1638 (Unwin, 1995). In the late seventeenth century, Lister published a book that included a strong disagreement to the theories of Gilbert. In his book *A Journey to Paris*, Lister (1699) explained that due to the unknown of the effluvium, the quality of magnets that results in their attractive properties, hypotheses on the phenomena surrounding lodestone cannot be made. Furthermore, he stated that even the properties of lodestone are not well known enough to come to any feasible conclusion (Lister, 1699). He goes on to explain that if the effluvium was produced by the Earth, the Earth must be made of iron. Although he notes that iron mines are quite abundant on the Earth, he states that this iron quantity does not amount to much compared to the other rocks found on Earth, such as, chalk, limestone, and coal. Therefore, he concludes that since the majority of the Earth is not made of iron, it is impossible to believe that Earth is, itself, a magnet (Lister, 1699).

Advancements beyond Gilbert

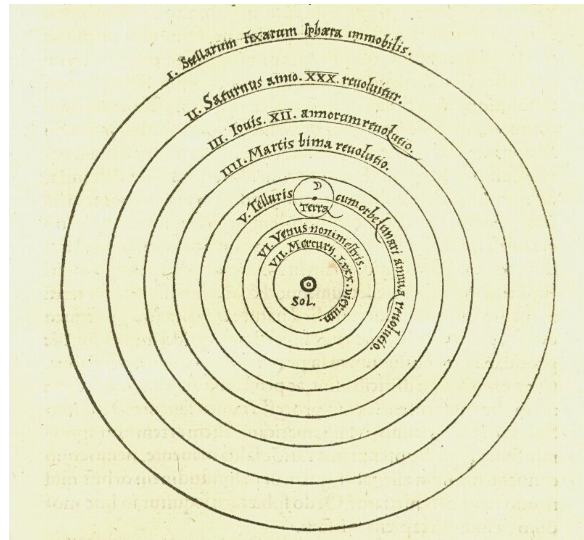


Figure 2.14: *Copernican heliocentric diagram that shows the planets rotating around the sun rather than the common held belief that the Earth was stationary and at the center of the universe.*

Several further advancements in understanding geomagnetism were put forth after the revolutionary ideas of William Gilbert. Some of these have been refuted while some are still accepted today.

A major contributor to magnetism after William Gilbert was Edmond Halley, a scientist born in 1656 to a rich Commonwealth family (Cook, 1998). In an article he published in the journal *The Philosophical Transactions of the Royal Society of London*, he explained that the Earth has four poles that continually change position over time. However, he understood that no magnet had been found to have anything other than two poles (Hutton, Shaw and Pearson, 1809). To explain this phenomena, Halley puts forth the idea that the Earth is actually a hollow spherical shell and has other spheres within it. Each of these spheres he believed to be magnetized and moves inside of the Earth. He believed that the movement of the spheres together could produce Earth's magnetic field (Hutton, Shaw, and Pearson, 1809).

Halley did admit to some of the flaws in his hypothesis, such that the inner sphere may bump up against the outer shell and break through it. As well, he mentioned that water on the Earth's surface could leak through the shell and into the hollow center, thereby draining the oceans (Hutton, Shaw, and Pearson, 1809). As someone living during a period where religion was still intermingled with scientific findings (Cook, 1998) he acceptably justified that "the Creator" could have constructed the Earth to keep water from entering the hollow sphere (Hutton, Shaw, and Pearson, 1809). The major flaw with Halley's work that causes it to no longer be accepted today is that he based his calculations off of the lunar mass found by Newton, which was later concluded to be incorrect (Kollerstrom, 1992).

A key player in the development of modern day understanding of Earth's magnetic field was Henry Gellibrand. In 1635, Gellibrand published a book using the findings made by Gilbert and adding the theory of magnetic variation (Gellibrand, 1635). Gellibrand defined variation as the deflection between the magnetic meridian and terrestrial meridian. He used recordings that mariners made of the direction the compass pointed towards at specific times in the day (Gellibrand, 1635). However, he used this information to put forth the idea of magnetic variation dependant on the position on Earth as well as the time of day. Most importantly, Gellibrand also compared current data with data taken 54 years prior to his publication and observed a 7-degree variation in where the compass was pointing. Despite this observation, he only speculated on reasons for the variation and failed to publish any hypotheses (Gellibrand, 1635).

Modern Theories on Earth's Magnetic Field

Today, it is no longer accepted that the Earth itself is a magnet. This has been refuted since it has been found that materials are not magnetic above a certain temperature, called the Curie point (Strangeway, 1970). When temperatures are above a few hundred degrees Celsius, it is understood that common materials lose their magnetic properties. It is also commonly understood that the Earth is well above these temperatures 20 km below the crust. Therefore, it has been concluded that the entire Earth does not act as one large magnet. Instead, it is now believed that the Earth's magnetic field is generated from rotations of Earth's outer molten core. Currently, the most accepted idea on how the magnetic field is produced is through magnetohydrodynamics, also known as dynamo theory (Strangeway, 1970). However, the generation of Earth's magnetic field is still not completely understood and remains a heavily debated topic today.

Dynamo Theory

Dynamo theory relies on the idea that the spinning of the Earth's outer molten core produces self-excitation and causes perpetual motion of the core (Strangeway, 1970). By definition, a dynamo is anything that converts mechanical energy into electrical energy. Since the Earth's outer core is believed to be a good electrical conductor, its motion changes the surrounding magnetic field. This is because it has been found that in these conducting fluids, a magnetic force is produced in the same direction as the fluid motion. Therefore, if there is a specific fluid motion in the Earth's outer core, it could result in the generation of Earth's magnetic field (Strangeway, 1970).

However, for the magnetic field to be produced,

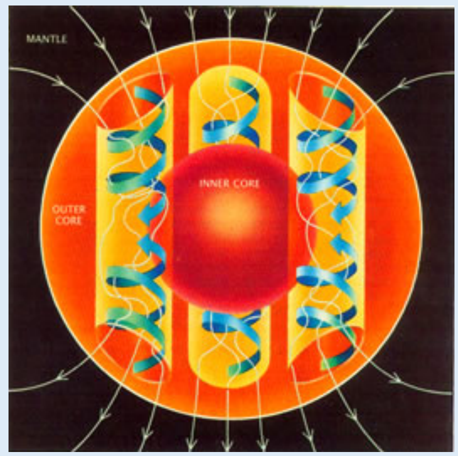


Figure 2.15: *Outer core convection diagram that is hypothesized to cause enough motion in the core to produce a self-sustaining dynamo.*

the motion of the fluid cannot be just from Earth's rotation around its axis. A second type of motion is required to produce Earth's magnetic field. There are various theories as to how this second motion could arise (Strangeway, 1970). One of the main hypotheses is that the core is radioactive, which would cause heating, and therefore a motion of convection currents would be produced as illustrated in Figure 2.15. Another theory is that chunks of the Earth's mantle may break off and enter the core which would also cause potential fluid motion. Several different motions could be added together to produce a magnetic dipole as has been observed on Earth's surface (Strangeway, 1970).

Complications of Dynamo Theory

A major difficulty with dynamo theory is that the equations which arise from this theory cannot be solved analytically. Only recently, researchers have been able to use computational simulations to model various versions of dynamo theory (Glatzmaier, 2002). This is done by integrating the dynamo equations with various conservation laws. Computational integration of these equations creates the values needed for a stable magnetic field that resembles the Earth's magnetic field at the surface to be generated

(Glatzmaier, 2002). A major drawback to current simulations is that they have been simplified for a spherical Earth, which is not accurate (Glatzmaier, 2002).

The first successful three-dimensional modelling of the Earth's magnetic field over time was published in 1995 by Glatzmaier and Roberts. This was notably a crude simulation but it did have some useful outcomes, such as the generation of magnetic field reversals (Glatzmaier and Roberts, 1995). Examination of the geological record indicates that the Earth's magnetic field has reversed hundreds of times. We know this because as certain rocks cool they record the direction of the magnetic field at that time. By dating these rocks, the direction of the magnetic field throughout Earth's history can be determined (Merrill, McElhinny, and McFadden, 2012). Therefore, for a simulation to be accurate, there should be field reversals. The simulation by Glatzmaier and Roberts found some sudden magnetic field reversals interspersed between longer periods of a stable field (Glatzmaier and Roberts, 1995).

Addition to Dynamo Theory

Although dynamo theory is the most commonly accepted theory for the production of Earth's magnetic field, there is still much debate. A controversial paper published in 2009 by Gregory Ryskin questioned the validity of dynamo theory. The paper proposes that secular variation in the magnetic field may be caused by the flow of ocean waters. Secular variation refers to the change in Earth's magnetic field within any timescale (from seconds to millions of years). Since Edmond Halley in 1692, it has been believed that secular variation is caused by the rotation of the Earth's core (Ryskin, 2009). Instead, Ryskin (2009) introduced the idea that since water is a good conductor, the movement of ocean currents may be strong enough to cause some variation in Earth's magnetic field. Using a mathematical model, his paper concluded that it is indeed possible that changing ocean currents could be the cause of secular variation. Although Ryskin was not suggesting that Earth's magnetic field is generated by ocean currents, his paper did bring into question the validity of dynamo theory.

There has been continued debate on the necessity of radioactive materials to produce the heat necessary for sufficient convection in Earth's core in order to generate a dynamo (Buffett, 2002). For there to be sufficient convection, there must be a specific heat flow in the mantle of the Earth. A paper published in 2002 by Bruce Buffett found that the current heat flow is adequate for the generation of the dynamo. However, he also found that in the past, the amount of heat flow required (before three billion years ago), cannot be produced by current estimates of the mantle temperature. Therefore, the paper suggests that heat could have been added through radioactive isotopes (Buffett, 2002).

Further studies specifically suggest that there is potassium in the Earth's core to allow for enough entropy for the dynamo to occur (Nimmo, Price, Brodholt and Gubbins, 2004). This was found by modelling a convection scheme and the cooling of the core. Nimmo et al. (2004) found that if the core is cooling quickly, there is enough entropy for the dynamo to operate but the size of the inner core in this model would be too large. Furthermore, if the core is cooling at a lower rate, the inner core would be a realistic size, but there would not be enough entropy for the dynamo (Nimmo, Price, Brodholt and Gubbins, 2004). Therefore, they calculated that the core would need a concentration of 400 ppm of potassium to slow down the process of core cooling and still have enough entropy for the dynamo. The paper also admits that there are other possibilities such that the core may not need to have potassium. For example, they suggest it is possible that the accepted thermal conductivity value of the core is not correct (Nimmo, Price, Brodholt and Gubbins, 2004).

Many questions still remain on the nature and cause of the Earth's magnetic field, including the exact specifications of dynamo theory and the composition of the Earth's core. Just as Gilbert relied on the findings of scientists before him, scientists today rely on previous findings to build on and come closer to fully understanding Earth's magnetic field.

"To live is the rarest
thing in the world.
Most people exist,
that is all."

-Oscar Wilde

Chapter 3: Life on Earth

The ubiquitous presence of diverse forms of life on Earth is one of the most beautiful phenomena on our planet. It begs the question, by what means did this diversity come to be? Such questions of origin are among the most integral queries to mankind. This chapter will offer a glimpse into the origins and evolution of life from both a historical and contemporary perspective. This expedition will include topics on the beginnings of life on earth, human evolution, and the mechanisms by which life is sustained.

Biological systems are made up of complex chemical and physical interactions within the natural world. The question of how they function cannot be answered without the employment of multiple scientific perspectives. It is the integration of a multitude of disciplines that equips scientists with the tools necessary to elucidate some of the greatest mysteries ever known. For example, an important discovery in the field of chemistry may be the missing link required to have a complete understanding of a biochemical cycle. An organism's evolutionary history may not be ascertained without a thorough understanding of geological and archaeological principles.

Progress is made not only through exploring what we do not yet understand, but also by questioning our beliefs. That said, contradiction of what is publicly accepted at the time often leads to immediate and harsh backlash. This chapter will examine the personal and political hurdles that scientists had to overcome for the sake of scientific progress. The tenacious and unapologetic voices of those who advocated for truth echo throughout history, and their perseverance has left a mark on society.

Milestones such as those explored throughout this chapter were not reached through one great epiphany, but were rather pieced together through the accumulation of a plethora of previously found knowledge. These ground-breaking accomplishments came through the connection of separate ideas that were amalgamated to produce whole theories and conjectures. Ultimately, no singular individual may lay claim to the development of our current understanding of the origins and evolution of life on this planet. Generation by generation, scientists stood on each other's shoulders in order to propel humankind forward to new insights. It is this slow but ever-present progress through cooperation and a yearning to understand our surroundings that makes the scientific process so wonderful. The relentless application of the scientific method continues today, and will persist into in the future as researchers further investigate new topics of interest.

The History of Scientific Thought Surrounding Human Evolution

In the 19th and 20th centuries, religion played a prominent role in the scientific thinking of European society. Based on the Christian religion, the prevalent belief was that humans were created by God and originated from Adam and Eve (Bowler, 1989). However, new theories surrounding the origin of the human species emerged in the 19th century, which threatened the traditional view of the Church's divine creation (Bowler, 1989).

In 1735, Carolus Linnaeus published *Systema Naturae*, which classified animals into kingdoms, classes, genera, and species. With his work, Linnaeus strived to reveal the order of God's design of the animal kingdom (Oldroyd, 1988). In 1809, naturalist Jean-Baptiste Lamarck published *Zoological Philosophy*, which was the first theory of evolution (Bowler, 1989). Lamarck believed that organisms acquired useful traits during their lives and then passed these on to their offspring. Conversely, traits that were not useful were not passed on (Bowler, 1989). While similarities between apes and humans had been previously commented on, Lamarck advanced the idea that humans may have came from apes. This theory was received with hostility, as Christians believed that humans had souls, while animals did not (Bowler, 1989). Therefore, if humans were once animals then this belief would be destroyed and so, many scientists attempted to discredit Lamarck's theory (Bowler, 1989). The next advancement in evolutionary theory occurred in 1844 when Robert Chambers anonymously published *Vestiges of the Natural History of Creation*, highlighting the philosophical issues with the theory that humans came from apes (Bowler, 1989). He wrote about evolution as the unfolding of a divine plan and that the human race was the product of progression through the animal kingdom (Bowler, 1989).

The study of geology and paleontology greatly contributed to the development of the theory of evolution (Oldroyd, 1988). In the early 19th century, Georges Cuvier theorized that one could determine successive periods in Earth's history by identifying fossils in each stratum of rock. He founded the theory of catastrophism, which stated that an abrupt change in animal and plant populations between one formation and the next occurred because of a catastrophic extinction (Oldroyd, 1988). However, Cuvier vehemently opposed the idea of evolution and asserted that there were no human fossils because the human race had appeared after the most recent geological deposits were laid down. This was the prevailing belief in the first half of the 19th century (Bowler, 1989). During the second half of the 19th century, theories on the origin of humans developed, which greatly affected the way human evolution was viewed. Many scientists contributed to these theories but specifically the work of Charles Lyell, Thomas Huxley, and Charles Darwin significantly advanced the understanding of the origin of human life (Bowler, 1989).

The Origin of Species

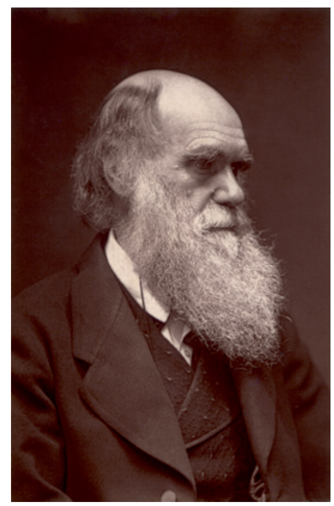


Figure 3.1: *A portrait of Charles Darwin, who wrote the* Origin of Species.

Charles Robert Darwin belonged to one of England's greatest intellectual families in the 19th century (Figure 3.1). Darwin was an archetypal liberal Victorian gentleman, who was interested in science from a young age (Oldroyd, 1988). Following an arts degree, Darwin began collecting marine molluscs and attended meetings of several natural history societies, which piqued his interest in this area (Oldroyd, 1988).

Although Darwin intended to enter the Church after his degree, he ended up as a naturalist aboard the *H.M.S. Beagle* on a five-year journey around the globe (Oldroyd, 1988). Just before leaving, he bought the first volume of Lyell's *Principles of Geology,* which profoundly influenced him and the observations he made on the voyage. Some of the phenomena observed on this trip played a large role in his evolutionary theory (Oldroyd, 1988). Throughout the trip, Darwin collected and preserved numerous species, including extinct giant mammals, whose fossils were very similar to extant forms. He crossed the Andes and noticed that the flora and fauna varied greatly on either side, despite nearly identical climates (Oldroyd, 1988). When they sailed to the Galapagos Islands, Darwin noted that the organisms were similar to those in South America but that they had unique communities

Jacqueline Garnett & Jeneva Smith

and forms that varied on each island. Specifically, he found finches to have unusual adaptations in feeding habits and varied beak sizes, as pictured in Figure 3.2 (Oldroyd, 1988).

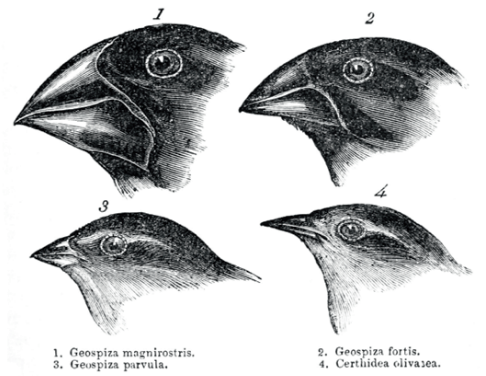


Figure 3.2: *Darwin's drawings of the different forms of finches he observed on the Galapagos Islands.*

All of these observations greatly influenced Darwin's thinking on evolution as he questioned what caused these seemingly strange occurrences in nature (Oldroyd, 1988). When he returned from this trip, Darwin had not committed to the question of the origin of species due to his religious beliefs, yet he certainly had developed thoughts on this topic. In 1837, Darwin published the results of his voyage in a book titled *Journal and Remarks,* but avoided writing his thoughts surrounding the origin of species (Oldroyd, 1988).

Shortly after, Darwin was elected as a Fellow of the Royal Society, which gave him a greater standing in the scientific community (Oldroyd, 1988). Near this time, Darwin began to suffer symptoms of what is thought to have been a psychosomatic disease, which allowed him to escape public scorn and become more reclusive as he lost interest in all things outside of scientific endeavour (Oldroyd, 1988).

Darwin first drafted *The Origin of Species* in 1844 but then studied barnacles for a few years, for which he received the Royal Society Medal for Biology (Bowler, 1989). After this study, he gathered more information on evolution and discussed his ideas with Lyell. Darwin was delaying publishing his theories due to the backlash from the public that he was certain to receive, but then in 1858, A. R. Wallace sent him a manuscript with virtually the same ideas (Oldroyd, 1988). Although Darwin was originally working on a longer piece titled *Natural Selection*, he quickly published *The Origin of Species* in 1859, as a shorter and more popular version of his theory. Around this time, Darwin became agnostic as he lost his religious faith (Oldroyd, 1988).

In this book, Darwin stated that individuals within a species vary, for example by hair colour or size, and that these variations are inherited by their offspring (Darwin, 1859). He argues that species' populations are limited by their environment, as there is insufficient shelter, food, and other resources within a habitat. This results in the struggle for survival between individuals within a species (Darwin, 1859). Darwin theorized that natural selection occurs when individuals that are better adapted to their habitat due to unique variations survive, while those without such variations do not. (Darwin, 1859). Thus, these advantageous variations will be passed on and eventually result in a divergence from their species. Darwin called this 'descent with modification' and described natural selection as the mechanism creating new species (Darwin, 1859). Following this explanation, Darwin dedicated the rest of his book to defending this theory and providing examples of such evolution (Darwin, 1859).

The Antiquity of Man

Charles Lyell was a well-respected Scottish geologist, most famously known for his publication on *The Principles of Geology* (Bowler, 1989). In this publication, Lyell challenged the common scientific rhetoric regarding the theories of deep time and popularizing James Hutton's theory of uniformitarianism, whilst also introducing geologic principles that are widely accepted today (Oldroyd, 1988). Although *The Principles of Geology* was by far his most influential work, Lyell's contributions to the world of science far exceeded his research on stratigraphy and geology alone. He also made vital contributions to the study and understanding of the age of the human race (Bowler, 1989).

Considering historical contexts at the time, and how religion and scientific thought were so interwoven, it was fundamentally necessary for the antiquity of man to be fully recognized before theories of evolution regarding the human race could be accepted (Bowler, 1989). Though not the first to introduce the concepts on the antiquity of man, Lyell's authority in the field of geology and his interdisciplinary approach served to validate his ideas and propel the notion forward (Bowler, 1989).

This was accomplished in February of 1863, when Lyell published his book *Geological Evidences of the Antiquity of Man.* This work synthesized an abundance of evidence collected over recent years by Lyell and several of his contemporaries. It served as a comprehensive compilation of empirical evidence that firmly established the antiquity of man as a fact (Lyell, 1863). At the time, the human fossil record was minimal, but also restricted in that few fossils were known at the time. Those that were known, such as partial skull caps of *Homo neanderthalensis*, were highly controversial and their relation to man was poorly understood (Lyell, 1863). Hence, scientists were only equipped with limited fossil evidence in the form of scattered or fragmented bones or stone tools. Although placing these artifacts relative to modern humans in time was beyond the scope of what Lyell could achieve, these archaeological finds were proof of past human activity (Lyell, 1863). Using his knowledge of stratigraphic succession and the order of deposition, Lyell was able to argue that since these fossils were found within the same strata as known extinct species, characteristic deposits, or other index fossils, man must have existed on Earth at the same time (Lyell, 1863). Thus, the antiquity of the human race was far beyond the current belief.

Lyell slowly worked backwards to extend the history of man. Through knowledge of Danish peat mounds and Swiss lake settlements, man had been shown to be extensive tool users and hunters during the Stone Age (Lyell, 1863). Lyell termed these periods the geologically Recent period (Lyell, 1863). Furthermore, in modern-day Belgium it was found that humans had been contemporaries of extinct mammalian species of the Pleistocene (Lyell, 1863). Flint implements had also been found in the basins of the Thames, Somme, and Seine rivers, along with other fossils of extinct mammals (Lyell, 1863). Some of these fossils had been artificially cut, which further points to human activity during this era (Lyell, 1863).

Lyell gathered geologic evidence from a number of other disciplines, including archaeology, anthropology, and paleontology in order to validate his position and theories on the antiquity of the human race (Lyell, 1863). This was particularly difficult in a time dominated with biases from theological ideologies. Indeed, Lyell initially struggled in his acceptance of such theories, and initially staunchly refuted theories proposed by naturalists, such as Lamarck and Darwin (Klaver, 1997). Over time, however, Lyell cautiously grew to endorse the idea of the transmutation of species (Klaver, 1997). This endorsement, together with *The Antiquity of Man* and its undeniable myriad of empirical evidence, allowed Lyell to transform the common scientific understanding at the time. Ultimately, this enabled scientists after him to further seek man's place within the animal kingdom, answering questions of relations, evolution, and origin. He received criticism from his good friend Charles Darwin, for this overly cautious endorsement of the transmutation of species in his tenth edition of *Geologic Principles* (Klaver, 1997). Nonetheless, his acceptance for the mechanism of evolution and the mere acknowledgement of the evolution of species marked a crucial change in the scientific mindset at the time.

Man's Place in Nature

In the very same year of Lyell's *Antiquity of Man (1863)*, Thomas Huxley also published his famous book, *Man's Place in Nature*. Like Lyell, many of the evidences had been previously proposed, but in this case it was through Huxley's own series of essays written on the topic. *Man's Place in Nature* marked the first significant publication in which the notion of evolution had been explicitly applied to humans. It consisted of three separate chapters, titled On the Natural History of Man-Like Apes, On the Relations of Man to the Lower Animals and On Some Fossil Remains of Man.

By studying the skeletal structure of man-like apes, such as gibbons, orangutans, chimpanzees, and gorillas, Huxley was able to argue their relatedness to Man as seen in Figure 3.3 (Huxley, 1863). The use of comparative morphology was essential since at that time, the only evidence that could be taken from fossils and skeletons derived from observation of their physical characteristics. He asserted that structural characteristics of the aforementioned apes were common to that of humans, including cranial capacity, dentition, and limb proportion (Huxley, 1863). He observed that Catarrhines, which includes Old World monkeys, apes, and humans, exhibited the same number of teeth as Man, both in the adult and deciduous teeth

Figure 3.3: *Drawings of different primate skeletons included in* Man's Place in Nature *to illustrate their similarities to man.*

(Huxley, 1863). Though limb proportion slightly varied between known primate genera and humans, their striking similarities founded the basis for their relatedness to each other (Huxley, 1863). On top of primatology, comparative analogy, and primate ethology, Huxley also examined embryology to assess the relatedness of Man to apes (Huxley, 1863). He argued that the study of development clearly displays the closeness or affinity of apes to humans. It was the general understanding that species that were more closely related to each other, and had more similar adult forms, would also parallel each other to a greater degree as embryos (Huxley, 1863). The nearly identical developmental stages of apes and Man greatly supported his argument as to their close relations.

The publication of *Man's Place in Nature* sparked major debate. To relate Man to primate was to question the uniqueness of humankind, and how God created humans in his image. Richard Owen, a famed English biologist and comparative anatomist, took great issue with Huxley's assertions as to the similarities between primate and human brains (Gross, 1993). In the addendum to *Man's Place in Nature,* Huxley addresses the Great Hippocampus Question, wherein Owen ascertained that the presence of the hippocampus minor, posterior horn in the lateral ventricle, and posterior lobe within the human brain was unique to Man alone (Gross, 1993). This contradicted what Huxley had previously asserted by the similarities between the brains of apes and humans in his original publication, where these features were shared amongst both Man and primate (Gross, 1993). Careful investigation served to prove Huxley correct in his original assessment, and further support the assertion that ape and Man are very closely related to one another (Gross, 1993).

Similar to Lyell, Huxley once staunchly refuted the notions of evolution put forth by the likes of Lamarck or Chambers. However, his skepticism ultimately faded as he became a steadfast proponent of the theory of evolution through natural selection (Thomson, 2000). Whilst Lyell and Darwin stayed away from controversy when possible, Huxley reveled in debate. He was very outspoken in this matter, and was commonly referred to as "Darwin's bulldog" (Thomson, 2000).

Huxley is famously known for his debate with Archbishop Samuel Wilberforce at the British Association meeting at Oxford, in 1860 (Thomson, 2000). Unfortunately, there is no written record of the debate, though various testimonies affirm that Huxley stated, "If then the question is put to me whether I would rather have a miserable ape for a grandfather or a man highly endowed by nature and possessed of great means of influence and yet employs these faculties and that influence for the mere purpose of introducing ridicule into a grave scientific discussion, I unhesitatingly affirm my preference for the ape" (Thomson, 2000). Huxley implored the scientific community to see past their long-held religious beliefs and objectively evaluate scientific evidence separate from God. He even coined the term agnosticism in 1869 and was greatly judged and condemned for his spiritual beliefs. It is therefore of the utmost importance to him that he remained a persuasive vocal figure, to convince others that to reconcile their spiritual views with the changing scientific understanding of the natural world. Huxley was an infamous, vital figure in the pursuit to not only accept and understand human origins but to accept science (Figure 3.4).

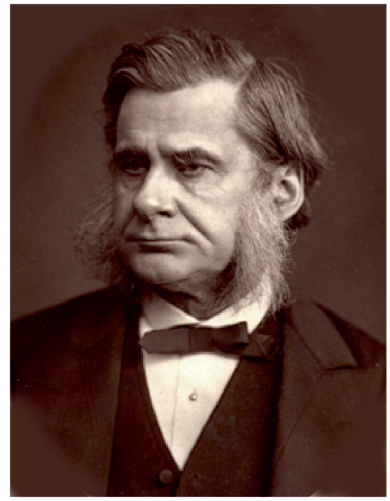


Figure 3.4: *A portrait of Thomas Huxley, who wrote* Man's Place in Nature *in 1863.*

The Descent of Man

Following *The Origin of Species,* Darwin published ten more books, with his second most important work being *The Descent of Man*, in 1871. Due to its controversial nature, he previously avoided the topic of origin of humans, but Lyell's publication on the topic encouraged him to pursue this theory (Oldroyd, 1988).

The first part of *The Descent of Man* is about the origins of Man and the second part focuses on sexual selection. He illuminates the fact that Man is under the same pressures as animals and thus, would be subject to the same evolutionary process, citing vestigial organs as evidence (Darwin, 1871). He compared animal and human mental powers, stating that some of the higher animals had means of communication and tool use. Darwin used the fossils found in Africa to suggest that Man originated there because Man's teeth are more similar to Old-World monkeys than those of North or South America (Darwin, 1871). As well, Darwin believed that differences in climate was the reason for the development of different races. His theory of sexual selection centered around the idea that sometimes the greatest competition among members of a species would be for sexual mates, using antlers and peacock feathers as evidence. This idea was criticized heavily at the time (Darwin, 1871).

The late 19th century saw a massive rejection of Darwinian principles. Scientists instead preferred theories that were more orderly and aligned with the Church's beliefs in which God designed the natural world (Oldroyd, 1988). *The Origin of Species* convinced the scientific community that evolution was real but Lamarck's theory of inheritance of acquired characteristics became increasingly popular, (Bowler, 1989). Natural selection suggested that the development of species is haphazard and random, which went against the fundamental belief that God designed the world. Thus, most scientists ignored the Darwinian theory of evolution into the 20th century to avoid challenging their religious beliefs (Oldroyd, 1988).

Together, the publications of Charles Lyell, Thomas Huxley, and Charles Darwin, along with their firm defenses established the antiquity of man into scientific orthodoxy. They propelled the ideas of evolution related to the human race into common scientific rhetoric.

Genetics and Human Evolution

At the time that Darwin, Lyell, and Huxley, were formulating their ideas on evolution and the age of man, they provided theories of the mechanisms by which such processes could occur. However, they had no concept of how these mechanisms were physically carried out (Bowler, 1989). They largely relied on the fossil record and morphological comparisons to confirm relatedness to other apes. Though the fossil record has greatly expanded since the time that Huxley was analyzing specimens, the field which has revolutionized our understanding of human origins is genetics (Bowler, 1989). Interestingly, around the same time that Darwin and his contemporaries were conducting their experiments, Gregor Mendel's research marked the first official understanding of genes. His experiments on pea plants displayed significant patterns for inheritance, and so began the study of classical genetics (Oldroyd, 1988).

Molecular Genetics

Within the next hundred years, the field of molecular genetics emerged and produced significant advancements in our understanding of inheritance. Arguably, one of the most important understandings came about through the Avery-MacLeod-McCarty experiment, whereby deoxyribonucleic acid (DNA) shown in Figure 3.5 was identified as the molecule responsible for the transfer of genetic material (Avery, MacLeod and McCarty, 1944). Finally, scientists could directly focus on the material responsible for inheritance and evolution, and start piecing together proof of human evolution. There are endless ways in which genetics served to further the study of human evolution, however, three indispensable tools have aided the study of human evolution. These include the concept of the molecular clock, mitochondrial DNA, and Y chromosome DNA.

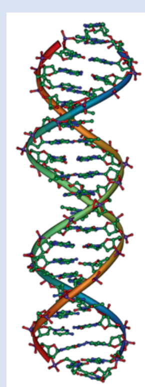


Figure 3.5: *A double-stranded DNA helix. DNA was discovered to be responsible for the transfer of genetic material.*

In 1962, Linus Pauling and Emile Zuckerkandl observed that the amino acid sequences of the hemoglobin proteins of different lineages (Zuckerkandle and Pauling, 1962). They were able to then extrapolate and generalize for any evolutionary distances between proteins, in that the rate of evolution remained approximately constant throughout time, which began the notion of the molecular clock hypothesis (Zuckerkandle and Pauling, 1962). This could then be used to estimate the time at which two species diverged from each other, by analyzing the number of changes in their genetic sequences (Zuckerkandle and Pauling, 1962). This was a key step towards understanding when humans diverged from primates to become a separate species.

Scientists needed to trace back human lineage; however, recombination within autosomal and X chromosomes would make it nearly impossible to accurately calculate common ancestors, since genealogies would become far too complicated. Scientists needed a simpler, and more reliant gene sequence, which came in the form of mitochondrial DNA and the non-recombining portion of Y chromosome DNA (Pakendorf and Stoneking, 2000). Mitochondrial DNA (mtDNA) is inherited exclusively through maternal lineage (Pakendorf and Stoneking, 2000). Conversely, Y chromosome DNA is paternally inherited (Pakendorf and Stoneking, 2000). This form of inheritance allows scientists to construct phylogenetic trees from a direct trace of lineage throughout time. In 1987, using the concepts outlined through an understanding of the molecular clock, Cann, Stoneking, and Wilson examined mitochondrial DNA in order to estimate the most recent common ancestor of every living human on Earth. The colloquially termed “Mitochondrial Eve” was said to have lived approximately 200,000 years ago (Cann, Stoneking and Wilson, 1987). These principles can be further extended to measure common ancestry between humans and other primate species. (Cann, Stoneking and Wilson, 1987).

Modern Human Evolution

Although the study of genetics was chiefly used to confirm that humans evolved from primates, it is also used to illustrate modern evolution occurring in humans. Recent evolutionary changes in humans has not been obvious but slight changes in our genetic makeup are occurring (Field et al., 2016). Scientists have studied population genetics in humans to identify changes in genes related to disease resistance, lighter pigmentation of northern populations, and adaptations to diet and altitude (Field et al., 2016).

One study conducted by Yair Field and his colleagues (2016) uses the Singleton Density Score (SDS), which identities recent allele frequency changes at single nucleotide polymorphisms by using the whole-genome sequence data. Singletons are single unique mutations near to the allele that arise from random sequencing errors during the production of the DNA (Knudsen and Miyamoto, 2009). These events are rare, so they only happen to one sequence. When selection for an allele is stronger, this allele spreads more rapidly and there is not enough time for many singletons to accumulate near it (Knudsen and Miyamoto, 2009). If an allele has been in the population for a long time then many people will have developed random singletons near this allele, whereas ones that spread rapidly do not have the chance to develop as many singletons. This technique can identify evolution in the human genome throughout the past 100 generations, which translates into approximately 2,000 years (Field et al., 2016).

Just over 3,000 people’s genomes were used in this study to determine evolution in the human race throughout this time. The largest values of SDS cluster were found at the lactase locus and second highest was the major histocompatability complex (MHC) region (Field et al., 2016). These alleles respectively code for the production of lactase, allowing the breakdown of milk, and proteins related to immune system function (Field et al., 2016). It was found that these traits spread quickly among the British, as well as alleles for blond hair and blue eyes. As well, there was strong selection at variants linked with lighter pigmentation of hair and eye colour (Field et al., 2016).

Another study used a similar method to identify selected traits. Single nucleotide polymorphisms were used to find patterns that veered from neutral variation in a predictable way that indicates selection events (Pickrell et al., 2009). This study analyzed people from 53 different populations to gain a better understanding of the geographic patterns of human evolution. This technique focused on detecting hard sweeps, in which a mutation spreads rapidly, reducing variation at linked sites (Pickrell et al., 2009). Soft sweeps include multiple mutations sweeping simultaneously at one locus, which is harder to detect, or an allele already segregating the population which becomes selectively favoured (Pickrell et al., 2009).

It was found that humans in colder climates were selected for larger and stockier body shapes to conserve body heat. Conversely, a ‘pygmy’ phenotype emerged in rainforest populations, which had adaptations to high humidity and food limitations (Pickrell et al., 2009). Those living in high altitude areas were found to have several adaptations to low oxygen concentration. Adaptations leading to disease resistance have also been discovered for malaria (Pickrell et al., 2009). Pigment alleles were found to have been the most strongly selected traits in human populations. Generally, it was found that selected traits were often shared with geographically close populations (Pickrell et al., 2009).

Modern molecular genetics has allowed scientists to accurately and comprehensively trace back the ancestry of humans in a way that Darwin and his contemporaries would never have imagined. While they were faced with the task of defending evolution itself, molecular genetics have allowed modern scientists to move far beyond that (Field et al., 2016). Now, as a well-founded and accepted theory in the scientific world, evolution is no longer a question but an answer; it is used and applied in various scientific sub-disciplines to solve a wide array of problems.

Oparin's *Origin of Life*

The enigma of the origin of life on our planet is one that has plagued scientists and philosophers for centuries. Despite the wealth of modern knowledge that has been elucidated in biology, chemistry, and physics, there is a gap in our knowledge concerning how all these disciplines came together to provide a viable solution. In other words, although biology is a highly evolved field, of which we, as a species, publish thousands of scientific papers, we do not yet have a firm understanding on how this field started. The evolution of chemistry of different compounds is still being understood to this day, as is the physics of membrane dynamics and the creation of macromolecules and cells.

This unfinished quest started many years ago, and involves a large cast of characters. One of the first people to address this question was, unsurprisingly, the Greek philosopher Aristotle. To the Greeks, life was eternal, and could appear spontaneously. Aristotle, drawing upon the works of other Greek philosophers Thales, Democritus, Epicurus, Lucretius, and Plato, articulated his theory of *Spontaneous generation* (Gotthelf, 2012).

Figure 3.6: *The French microbiologist, Louis Pasteur. Among numerous other achievements, Pasteur definitively disproved the theory of spontaneous generation of life.*

This theory that life can arise from dead matter was predominant, and held support until biologist Louis Pasteur disproved it with firm experimentation (Tyndall, 1905).

Due to the work by Pasteur, shown in Figure 3.6, a period marked by the theory of biogenesis began (Tyndall, 1905), in which the predominant theory was that life can only stem from other life (Oparin, 1953). Pasteur played a large role in providing a sound, scientific, and experimental approach to the question of the origin of life, but in doing so he made the question much more difficult to answer. If life can only come from life, how did life originally come to be? Dubbed the first scientist to publish a thorough, comprehensive explanation for the origin of life by means of chemical evolution, Alexander Oparin played a pivotal role in the evolution of thought regarding this topic (Hyman and Brangwynne, 2012). Having lived from 1894 to 1980 in the Russian Empire and later the Soviet Union, this remarkable scientist paved the road for countless researchers who came after him (Hyman and Brangwynne, 2012). The following will discuss his contributions to the field of the origin of life, analyze their credibility, and point to current studies in this field.

On Oparin and *The Origin of Life*

Alexander Oparin, shown in Figure 3.7, was a Soviet biochemist educated at Moscow State University who spent most of his scientific career studying the enzymes involved in metabolism and photosynthesis (Lazcano, 2010). One subject of particular interest to him was the origin of life on Earth; a subject that he claimed, "No religious or philosophical system, no outstanding thinker ever failed to give [...] serious consideration" (Oparin, 1953). To this effect, Oparin expanded his knowledge on the subject of early Earth, researching the geologic processes through which important chemicals could be liberated from inner Earth (Hyman and Brangwynne, 2012). Additionally, he analyzed the works of the great biologist Charles Darwin, educating himself on the theory of evolution by natural selection (Lazcano, 2010).

Oparin's wealth of research on the topic resulted in him publishing a short pamphlet named *The Origin of Life* in 1924, and a full book on the subject in 1936 of the same title (Hyman and Brangwynne, 2012). In the book, Oparin describes a well-substantiated hypothesis for the mechanism through which life originated on Earth (Oparin, 1953). In this piece of writing, Oparin described his ideas regarding the progression of simple molecular compounds, that were readily available on the primitive Earth's surface, through several key steps that eventually lead to the development of primary life forms (Oparin, 1953).

The Origin of Life, which was first translated to English in 1938 by S. Morgulis, makes apparent Oparin's dissatisfaction with many of the previous attempts on the topic. This is best exemplified in an excerpt in which Oparin denounced the claims of Stéphane Leduc, another researcher in the field, who believed that he had created an osmotic "cell" similar to a living cell:

> *The resemblance between Leduc's forms and living organisms is not greater than the external resemblance between a live person and his marble image, but no one seriously believes in Galatea's coming to life or in the visit of Pushkin's 'Stone Guest'* (Oparin, 1953, pp. 57)

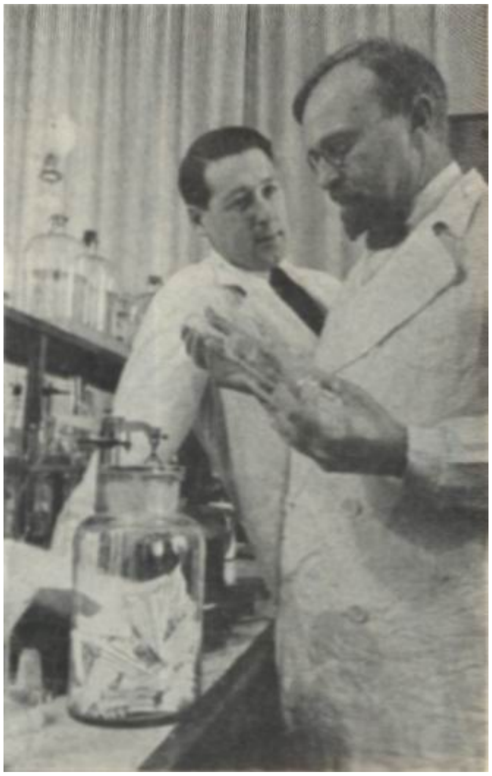


Figure 3.7: *Alexander Oparin (right) and his colleague, Andrei Kursanov (left) in an enzymology lab in 1938; two years after The Origin of Life was first published.*

Harsh criticisms of this nature exist throughout Oparin's book and illuminate the irrationality that preceded him in his field of research (Oparin, 1953).

Alexander Oparin's book was revolutionary in that it integrated multiple fields of science, including philosophy, astronomy, chemistry, geology, and biology into a novel hypothesis on the origin of life (Chela-Flores, 2001). In particular, his focus on the formation and development of the early Earth was significant, as it allowed him to firmly reject the hypothesis of Panspermia, which states that life originated elsewhere in the universe and then arrived at Earth at some point in the planet's history (Raven et al., 2016). In Oparin's time, this was one of the leading theories on the origin of life (Oparin, 1953). Additionally, his geochemical knowledge of the early Earth and solar system allowed him to determine which elements were present on the early planet, in what form they were stored, and in what reservoirs (Oparin, 1953). This led to the dismissal of the long-standing idea that the first living things were bacterial autotrophs; a logical postulate that will be explored later (Oparin, 1953).

Oparin was fascinated by the formation of Earth and the chemical dynamics throughout its history (Oparin, 1953). He believed that, in many ways, the evolution of chemical compounds was indistinguishable from the evolution of organisms (Oparin, 1953). As he explains in *The Origin of Life*, the evolution of Earth's geochemistry began when a large wave of hot gas from the Sun was ejected into space due to the nearby passage of another large star (Oparin, 1953). Oparin believed that this ejected material formed the planets of our solar system (Oparin, 1953). He then went on to trace the movement of two elements that are vital to the formation of life: carbon and nitrogen (Oparin, 1953). He postulated that the former was stored in the form of carbides in the Earth's core until volcanic eruptions brought it to the surface where it reacted with water to form hydrocarbons (Oparin, 1953). Similarly, he explained that nitrogen was stored in the early Earth's core in its ionic form until it reacted with water to form ammonia (Oparin, 1953). Additionally, Oparin's research into the early Earth led him to believe that the atmosphere that prevailed in the era of the origin of life was a reducing one, in contrast to modern Earth's oxidizing atmosphere (Oparin, 1953).

At the time of his book's original publishing, most researchers believed that the first organisms to live on Earth were bacterial autotrophs. (Fry, 2006). These autotrophs would be analogous to modern cyanobacteria, and are known to produce stromatolite fossils, as shown in Figure 3.8. It was largely believed that these early beings assimilated carbon dioxide into complex organic compounds through the use of solar energy, similar to the autotrophs present today (Oparin, 1953). Oparin disagreed with this for several reasons. Firstly, his experience studying enzymatic assembly lines led him to believe that photosynthetic metabolism was too complicated

Figure 3.8: *Stromatolites remains of cyanobacteria in Glacier National Park, MO, date to 1 Gya. According to Oparin's doctrine, cyanobacteria could not have been the first organism on to exist on Earth.*

to have originated primarily (Oparin, 1953). Heterotrophic strategies, wherein organic materials are broken down for sustenance, are much simpler in their requisite cellular organization (Oparin, 1953). Additionally, Oparin's study of the movement of chemicals in the early Earth led him to the conclusion that the compounds required for autotrophic metabolism would not have been available during life's genesis (Oparin, 1953). He reasoned that if no carbon dioxide was present on early Earth, then organisms that relied on it to live could not have survived (Oparin, 1953).

Oparin's deep understanding of the primordial conditions of early Earth led Oparin to the conclusion that the first organisms to exist on the planet were heterotrophic bacteria, which gleaned nourishment from organic compounds (Lazcano, 2010). While this theory was not popular within the scientific community at that time, Oparin did have an important ally who shared his views: John B. S. Haldane (Fry, 2006). Haldane, a well-known British biologist at the time, published a paper in 1929 that stated many of the same arguments as Oparin (Haldane, 1929). This paper was written independently of Oparin's 1924 pamphlet on the same topic, and led to the two biologists becoming the faces of the hypothesis of the origin of life by chemical evolution (Lazcano, 2010). This theory was appropriately dubbed the Oparin-Haldane Hypothesis (Fry, 2006).

After *The Origin of Life*

In 1959, a duo of scientists consisting of Stanley Miller and Harold Urey published a seminal paper in *Science* that tested the first step of Oparin's hypothesis (Miller and Urey, 1959b). That is, they aimed to demonstrate that simple organic molecules could form the chemical components of the early atmosphere and oceans of Earth with the help of only a condenser tube, heat, and electric sparks, which are analogous to lightning. (Miller and Urey, 1959b). After only one week, the researchers found that milligram quantities of amino acids were formed in their simulation of the primordial soup (Miller and Urey, 1959b). While it was later shown that the Miller-Urey experiment used starting materials that did not exactly match the early atmosphere conditions (Chyba, 2005), it still provided a large boost to the credibility of Oparin's ideas.

Oparin's fascination with the origin of life went far beyond his written works. He went on to organize the first international scientific conference on the origin of life in Moscow in 1957 (Chela-Flores, 2001). According to an article written by Russian biochemist and former associate of Oparin, M. S. Kritsky, published in *Applied Biochemistry and Microbiology* (2005), the conference "opened a new epoch of scientific life". Kritsky went on to write that over 100 participants, 7 of whom would go on to win a Nobel Prize, attended the event.

In addition, Alexander Oparin was one of the founding members of the International Society for the Study of the Origin of Life (ISSOL) and was the first president of the organization (Kritsky, 2005). The society, which supports further research into the origin of life, now has over 500 members spanning over 20 countries (ISSOL, 2014). Additionally, the president of the society was, at one time, Dr. Stanley Miller of the "Miller-Urey" team that tested Oparin's hypothesis of the evolution of organic molecules (ISSOL, 2017).

Of course, many of the specifics of Oparin's ground-breaking book have been proven false over many years of extensive research on the topic. Firstly, Oparin did not have a full understanding of molecular genetics, and thus his model is simplified to a certain degree. Also, he did not comprehend cellular membranes to the extent of what we know today, and instead focused on the structure of protein aggregates called coacervates as a means of protoplasm isolation from the environment (Hyman and Brangwynne, 2012). Lastly, modern paleo-environmental evidence suggests that the atmospheric conditions of early Earth were not as Oparin predicted (Orgel, 1998). It is now generally accepted that the atmosphere of the Earth at the time of life's origin was not as reducing as Oparin thought (Orgel, 1998).

Despite his inaccuracies, Oparin provided the first well-constructed mechanism through which life could have originated on the planet, laying the foundation for the field of prebiotic chemistry. He blurred the line between the evolution of life and the evolution of geochemical cycles on the planet, inspiring countless scientists to follow in his footsteps (Kritsky, 2005). Above all else, Oparin elevated the scientific standards of his time through his humility, his commitment to logic, and his aversion to presumption. In the concluding chapter of his great book, he wrote:

> *A weak attempt has been made in these pages to draw a picture of this evolution without losing contact with the ground of scientifically established facts* (Oparin, 1953, pp. 246-247)

Political Turmoil

An important factor to consider when looking at any scientist's work, including Oparin's, is the social and political climate in which they lived. These factors have the capacity to both subconsciously and consciously contribute to their work, either in a positive or a negative way.

Oparin's life, as important as it was for the progress of science, was lived out in an incredibly tumultuous time in the anthropogenic history of both the Earth and Oparin's native Soviet Union. Oparin graduated from Moscow State University in 1917. In that same year, Russia's October Revolution, commonly called the Bolshevik Revolution, took place (Samaan, 2013). This was preceded by an earlier revolution in which the Tsarist government was destroyed (Pipes, 1969). The second Bolshevik revolution involved the uprising of Russian workers and peasants, through which a socialist society was created, dubbed the Socialist Federative Soviet Republic (Fitzpatrick, 2001). Following the Russian Civil War in 1917, the Soviet Union was created in 1922. With this change in name came an entirely new political climate involving the nationalization of all services, companies, and banks.

More importantly, this change in governmental structure was accompanied by a strong shift in philosophical and social views. One of the most impactful philosophies brought about by the second Soviet Revolution was *Dialectical materialism*. This philosophy encompassed three main laws, brought forth by Engels' Science of Logic (Engels, 1973). These laws were as follows:

i. The Law of the unity and conflict of opposites
ii. The Law of the passage of quantitative changes into qualitative changes
iii. The Law of the negation of the negation

These sets of laws played an important role not only in the politics of the time, but were heavily applied to the scientific disciplines being taught and developed. This unsteady and new political and social climate reached its apex during Oparin's most formative years, and had a strong influence in his writings and ideations (Fry, 2006). Oparin's thinking was most definitely influenced by Marxist ideology, saying that the origin of life is "merely one step in the course of its historical development" (Hyman and Brangwynne, 2012).

Oparin's theories are steeped in the social and political climate of the Soviet Union during the 1920s and 1930s. This is particularly clear when one considers the emphasis that he placed on the concept that life is simply an extension of the evolution of chemical systems (Oparin, 1953). In *The Origin of Life*, Oparin repeatedly points out the similarities between biological systems and complex chemical systems, essentially suggesting that they are of the same kind (Oparin, 1953). This homogeneity of matter and life agreed strongly with the concept of *Dialectical Materialism*, mentioned previously (Fry, 2006). Oparin even referred specifically to German philosopher, and co-founder of Marxism, Friedrich Engels, in his book (Figure 3.9). He explained how Engels rejected both the theory of the spontaneous generation of life, and the theory of eternity of life; viewpoints which were adopted by Oparin (Oparin, 1953). This underlying message in his writing made him very well-liked within the Communist party in the Soviet Union (Fry, 2006). This association improved his stature within his own country, but would go on to be a detractor of his work later in his career (Fry, 2006).

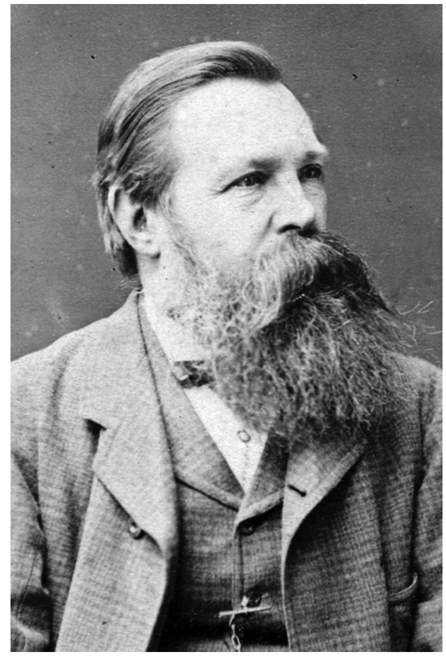


Figure 3.9: *Friedrich Engels was a German philosopher who founded Marxist theory with Karl Marx.*

Influences

Another important factor to consider when assessing Oparin's undoubtable contributions to the study of the origin of life are his scientific and social influences. From famous scientists to political figures, the people he looked up to and was surrounded by played an important role in shaping his academic career and his philosophies.

In his book *The Origin of Life*, Oparin mentioned several individuals from whom he drew scientific inspiration. One of Oparin's greatest influences was Louis Pasteur (Oparin, 1953). His novel experiments played a large role in refuting Aristotle's theory of Spontaneous Generation (Oparin, 1953). Oparin admired Pasteur's meticulousness, and attention to detail in his experimental efforts (Oparin, 1953). He adapted these qualities into his own work (Oparin, 1953).

Another association that played an important role in Oparin's career was his friendship with Trofim Lysenko, seen in Figure 3.10. A scientist

Figure 3.10: *Trofim Lysenko (left) with Joseph Stalin (right). His association with the Soviet Government was evidenced by his speaking at the Kremlin.*

himself, Lysenko was an agriculturalist and biologist (Gordin, 2012). Although he was interested in a wide range of topics, his doctrines have been coined with the term "pseudoscience". Endorsed by Stalin, and thus the Soviet government, this pseudo-scientific approach involved opposing much of Western science, including Darwinism and genetic inheritance (Gordin, 2012). The association between this pseudo-scientist and Oparin is evident in some of his writing, such as when he stated that "DNA is the end product of metabolism and the nucleus is the dustbin of the cell." (Hyman and Brangwynne, 2012). This sort of discourse suggests that Oparin was either responding to, or propagating, Soviet government propaganda. In fact, once Stalin died and the pseudo-scientist, Lysenko, was discredited, Oparin was forced to resign from his position as the Secretary of the Academy of Science due to his support of the man (Hyman and Brangwynne, 2012). Undoubtedly, Oparin was a talented intellectual man who contributed a lot to the field of his research, but his questionable associations provide an interesting backdrop to his scientific legacy.

Modern Theories on the Origin of Life

Oparin's influence in the field of biology cannot be contested. Although many of his postulates were disproved or dismissed, some of his work remains incredibly important today. He created a solid foundation on which other scientists could further their understanding. The famous Miller-Urey experiment is a testament to Oparin's influence as it tested a crucial part of our understanding of prebiotic chemistry (Miller and Urey, 1959a). The Miller-Urey experiment has paved the road for other important scientific discoveries relating to current understandings of the origins of life.

With an increasingly complex understanding of molecular biology, it seems that some of Oparin's quickly dismissed ideas have more merit than previously thought. His work on life arising from liquid-like macromolecular assemblies now has lots of scientific backing. Additionally, the compartmentalization and catalysis of RNA in liquid droplets is a direct support of Oparin's idea of the primordial "RNA world" (Hyman and Brangwynne, 2012). Thus, even some ideas that were originally dismissed in the scientific community have now been proven to have merit.

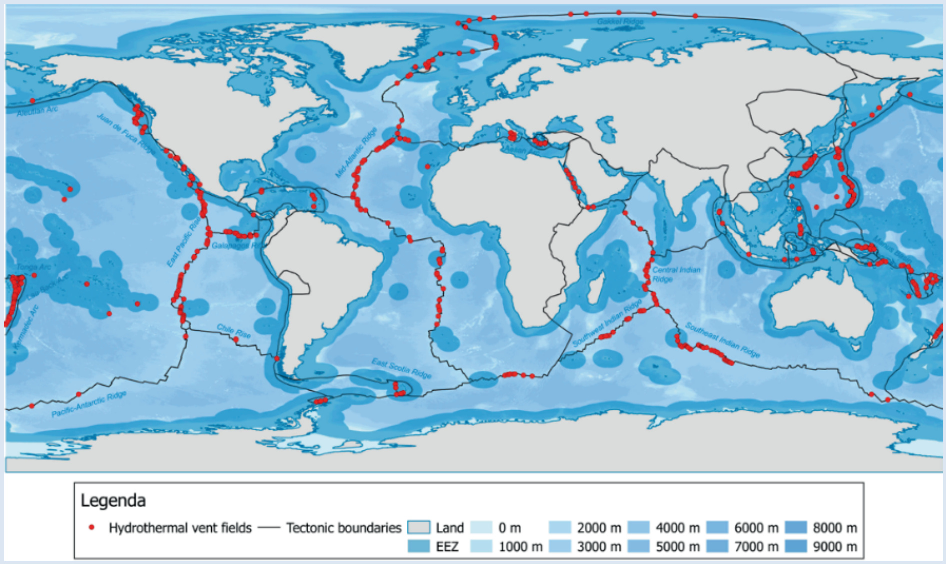


Figure 3.11: *Modern distribution of hydrothermal vents in the Earth's ocean. Martin and Russell's hypothesis on the origin of life on Earth states that organisms originated near hydrothermal vents.*

Building on of Oparin's work, there is currently vast amounts of research encompassing many different fields on how life originated on Earth, or if it even started on this planet.

One of the current leading hypotheses on the subject is the idea that life originated at or around hydrothermal vents on the ocean floor, whose global distributions are shown in Figure 3.11. Advocated mainly by William Martin and Michael J. Russell, this theory is an elaboration on Oparin's idea of abiotic evolution. Martin and Russell (2008) propose that chemoautotrophic bacteria were the first organisms to exist on the planet, and their root was in the geochemically active regions around deep sea hydrothermal vents (Martin et al., 2008). The team believes that compartmentalized chemical reactions within iron monosulphide precipitates were the precursors to free-floating prokaryotic life (Martin and Russell, 2002). While differing in complexity and many specifics, this theory still hinges on the basic concepts of chemical evolution, first described by Oparin. This demonstrates the lasting influence that Alexander Oparin has had in the field of prebiotic chemistry.

Some researchers suggest that life might have developed elsewhere in the universe and has been transported to our Earth. This theory is called the Panspermia Hypothesis (Raven et al., 2016). Although Oparin claimed to have disproven it, there is a lot of current research on this theory, in different areas of Earth. Oparin believed that there weren't any organisms that could survive the radiation present in the vacuum of space (Oparin, 1953). However, since then a lot of research has shown that there are organisms that can survive solar radiation, such as tardigrades (Jönsson et al., 2008). This has re-opened a lot of research on the validity of the Panspermia hypothesis.

Some research looks at the upper atmosphere and the possibilities of transporting extra-terrestrial life forms (Yang, Yokobori and Yamagishi, 2009). Other organizations are looking *within* the planet for meteorites that might contain extra-terrestrial life (ANSMET, The Antarctic Search for Meteorites | CWRU, 2017). Other ideas also include Oparin's original idea of a primordial soup from which all life originated. There are many different theories, none of which have definite proof.

One of the biggest remaining unanswered questions is how exactly DNA or RNA building blocks could have been organized into a genetic code. The physics of self-assembling RNA/DNA molecules has not yet been explained, and there is no evidence of their formation (Himbert et al., 2016). These questions have a profound underlying implication involving the need for divine intervention in creating life. Is divine intervention in fact necessary for creating the first RNA molecules, or could they have been created on their own in prehistoric conditions? These fundamental questions concerning the formation of life on our planet has sprouted entire institutes whose purpose is to explain the origin of life in the universe. The Origins Institute, located at McMaster University in Hamilton, falls under this category. This institute seeks to understand the physics behind the creation of macromolecules that could give rise to ordered self-replicating life on Earth. Within Origins, there is an entire new discipline called astrobiology, which explores not only how life has arisen here on Earth, but how it could arise on other planets.

The study of the origin of life is an interdisciplinary one. Its history is rich and involves a large group of individuals spanning thousands of years all trying to solve one of the most fundamental questions of humanity. The research that Oparin conducted earned him the title of "20th century Darwin", and his work remains an integral and important part of the field. Although the quest is not yet over, continued research will continue to bring us closer to answering the question of how life might have originated on Earth.

Shedding Light on the Discovery of Photosynthesis

Photosynthesis may now be called the most vital physio-biochemical process for the existence of life on this planet, however the mechanism for transforming light energy into chemical energy was unknown for centuries. As early civilizations began to cultivate crops, philosophers concluded that plants obtained all necessary nutrients from the soil, which was later defined as Humus theory (Devlin and Barker, 1971). This idea was accepted until the late 1700s when further experiments were conducted by multiple scientists, in order to develop new theories about this complex process.

Discovery of Oxygen

Joseph Priestley (1733-1804), seen in Figure 3.12, was an English chemist who was very interested in the mechanisms behind different processes that he observed around him, especially those involving biological material (Devlin and Barker, 1971). He conducted a number of experiments between 1771 and 1777 to analyse the reaction mechanisms for both combustion and respiration (Hall and Rao, 1999). After visiting a local brewery, he focused his early work on the gas released during fermentation, which is now known to be carbon dioxide. Priestley utilized fermentation vats provided by the local brewery to observe how combustion and animal respiration were affected by the gas released in this process, which he termed as "fixed air" (Devlin and Barker, 1971). He observed that when small animals such as mice or frogs were held above the vats, they appeared lifeless until removed from the "fixed air". Additionally, Priestley exposed a burning candle to the "fixed air", and observed the extinguishment of the flame (Devlin and Barker, 1971).

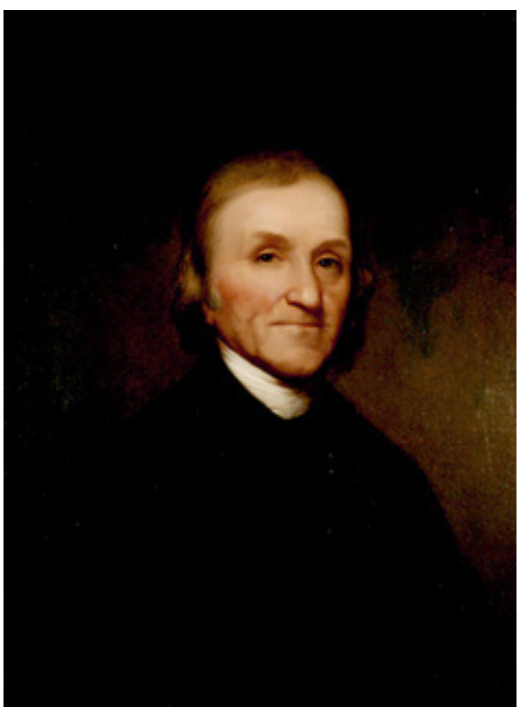


Figure 3.12: *Artist's portrait of the British scientist, Joseph Priestley, who is most recognized for his discovery of oxygen. Additionally, he is known for the invention of soda water and his research on electricity.*

Based on these observations, Joseph Priestley conducted a further experiment where he placed a burning candle within a closed container and observed that the flame was extinguished after a given period of time. The resulting air in this container was unable to support the life of a mouse, which led Priestley to conclude that this air was similar to the "fixed air" released from fermentation (Hall and Rao, 1999). Having previously noticed that candles burned well when in close proximity to plants, Priestley placed a sprig of mint in the closed container for several days to observe its effects on combustion and animal respiration (Priestley, 1772). The presence of the mint sprig in the container allowed for prolonged burning of the candle and supported the life of a mouse. Priestley found that the "fixed air" was "restored" by the presence of the plant, which he referred to as "dephlogisticated air" (Priestley, 1772). Although not aware of the chemical processes occurring within the plant and candle, Priestley had just discovered the relationship between oxygen and carbon dioxide in photosynthesis (Devlin and Barker, 1971). This observation was the first step in the discovery of photosynthesis and provided a basis for following scientists to conduct further experiments and draw new conclusions.

Significance of Light

Jan Ingen-Housz (1730-1799) was a Dutch physician who took great interest in Priestley's work after attending a ceremony where Priestley was awarded the Copley Medal of the Royal Society in 1773 (Devlin and Barker, 1971). While visiting England, the Dutch scientist decided to replicate and build upon Priestley's experiments. Previous researchers had noted the presence of bubbles on the leaves of plants when submerged in water and exposed to sunlight. They concluded that this was attributed to the heat provided by the sunlight (Magiels, 2010). Ingen-Housz hypothesized that the formation of bubbles was actually due to the light energy from the Sun as opposed to heat. In the summer of 1779, he conducted over 500 experiments and trialled many different experimental setups (Devlin and Barker, 1971; Magiels, 2010). In these experiments, he manipulated the light intensity and the part of the plant placed within the container (Magiels, 2010). Ingen-Housz concluded that the release of "[dephlogisticated air] begins only after the Sun has for some time made his appearance above the horizon" and that this process "is not performed by the whole plant, but only by the leaves and the green stalks" (Ingen-Housz, 1779). Ingen-Housz's results emphasized the importance of the green parts of the plant, now known as chlorophyll, and the presence of light for photosynthesis.

In 1782, Jean Sénébier (1742-1809), a Swiss botanist, extended the work of Ingen-Housz to identify the conditions necessary for photosynthesis to occur. Similar to the methodology of Ingen-Housz, Sénébier focused on the "dephlogisticated air" bubbles produced by submerged plants when exposed to sunlight. In addition, Sénébier altered the concentrations of "fixed air" within the water sample (Sénébier, 1782). He observed that the illuminated leaves submerged in water containing no "fixed air" did not produce any bubbles, however the presence of "fixed air" promoted the formation of bubbles. Based on these observations, Sénébier developed a model which explains the cycle of "fixed air" and "dephlogisticated air" through the biosphere (Sénébier, 1782). He believed that the plants absorbed the "fixed air" and released "dephlogisticated air", which then combined with another compound to regenerate the original "fixed air" (Sénébier, 1782). Sénébier continued his work on photosynthesis until the late eighteenth century, but his discovery of this cycle was considered his greatest achievement (Devlin and Barker, 1971).

After the work of Priestley, Ingen-Housz, and Sénébier, many of the factors involved in photosynthesis had been identified (Devlin and Barker, 1971). Scientists following this worked to bring these discoveries together into one coherent idea of the process.

Identification of Chemical Species

Until the late eighteenth century, the elemental composition of air was not known. Antoine Lavoisier (1743-1794) was a French scientist, who is considered one of the fathers of modern chemistry (Govindjee and Kroggman, 2004). He redefined the components previously known as "fixed air" and "dephlogisticated air" as the chemical compounds carbon dioxide and oxygen, respectively (Devlin and Barker, 1971). As a result, Ingen-Housz continued his studies and concluded that plants absorb carbon dioxide from the air.

In 1797, the Swiss scholar Nicolas-Théodore de Saussure (1767-1845) studied the quantitative relationship between carbon dioxide and oxygen in photosynthesis, now known as stoichiometric coefficients in the photosynthesis equation. In contrast to his predecessors, his experiment was one of the first times that analytical measurements of chemicals were taken (Rabinowitch, 1971). From the measurements, he discovered that the intake of carbon dioxide was equal to the amount of oxygen released by the plant (Hall and Rao, 1999). Additionally, de Saussure was the first to recognize the role of water absorption in this process. Furthermore, he believed that the oxygen released through photosynthesis originated from carbon dioxide rather than water (Saussure, 1804).

Conservation of Energy

Julius Robert Mayer (1814-1878) was a German physician and physicist who first identified the Law of Conservation of Energy in 1842 (Mayer, 1845). He then applied this law to photosynthesis and recognized that plants convert light energy into chemical energy, which is stored in organic matter. Subsequently, Mayer noted that this conversion of energy in photosynthesis is essential as it provides necessary organic materials for all animal life (Devlin and Barker, 1971). Based on his contributions, the process of photosynthesis could be described as the following relationship (Hall and Rao, 1999):

$$CO_2 + H_2O + \text{Light Energy} \rightarrow O_2 + \text{Organic Matter} + \text{Chemical Energy}$$

Following Mayer, the French plant physiologist and chemist Jean-Baptiste Boussingault (1801-1887) conducted multiple experiments which measured the volume of carbon dioxide absorbed in comparison to the volume of oxygen released during photosynthesis. He confirmed the work of de Saussure, as the stoichiometric ratio of carbon dioxide to oxygen was 1:1 (Hall and Rao, 1999).

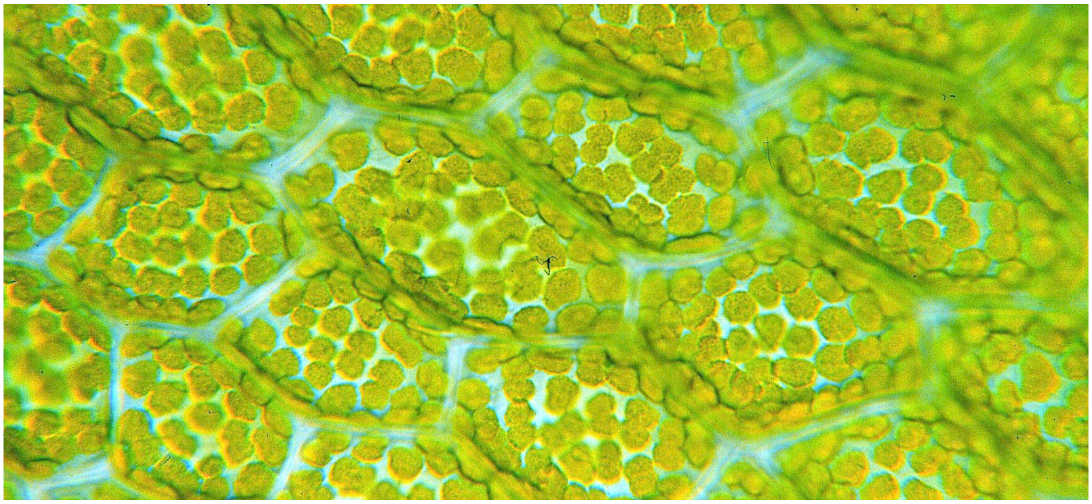


Figure 3.13: *Light microscope image of chloroplast structures in plant cells. Hugo von Mohl was the first to identify and sketch the structure of a chloroplast, however their function was determined 50 years later.*

Characterization of Chloroplast Function

In 1837, the German botanist Hugo von Mohl (1805-1872) created the first known description of chloroplasts in plant tissue, shown in Figure 3.13. He noted starch grains present within the chloroplasts, however von Mohl did not associate this with photosynthesis (Devlin and Barker, 1971). The significance of the starch grains was not fully understood until further experimentation was conducted in 1862 by a fellow German botanist, named Julius von Sachs (1837-1897) (Sachs, 1862). von Sachs exposed one half of starch-depleted leaves to sunlight, while the other half of the leaf remained shaded. After a given period of time, the leaves were treated with iodine vapour and their colouration was observed (Hall and Rao, 1999). In the half exposed to the sunlight, dark purple iodine-starch complexes were observed, whereas the shaded leaves showed no noticeable colour change (Sachs, 1862). The work of von Sachs demonstrated the production of starches in photosynthesis, which further explained the presence of starch grains in chloroplasts (Hall and Rao, 1999). This finding led to the alteration of the previously stated photosynthesis equation to the following:

$$(CO_2)_n + H_2O + \text{Light Energy} \rightarrow (O_2)_n + \text{Starch} + \text{Chemical Energy}$$

Although it was known chloroplasts were involved in photosynthesis, there was no evidence which indicated that this process occurred within the chloroplast. Theodore Wilhelm Engelmann (1843-1909) was a German botanist who utilized the green algae *Spirogyra* to study the relationship between chloroplasts and oxygen production in 1882 (Engelmann, 1882). Motile, aerobic bacteria were added to the green algae and it was observed that after some time, the bacteria were concentrated in areas with chloroplasts. Since the oxygen-requiring bacteria were attracted to these areas, Engelmann concluded that the chloroplasts were involved in oxygen production in photosynthesis (Hall and Rao, 1999). Additionally, after illuminating the algae with a broad spectrum of light, he recognized that the bacteria were concentrated in areas illuminated with blue and red wavelengths, while there was no bacteria accumulation near green wavelengths. This provided the necessary evidence to suggest that chloroplasts are the active site for photosynthesis (Engelmann, 1882).

Light and Dark Reactions

At the beginning of the twentieth century, many studies focused on the impact of changing light intensity, temperature, and carbon dioxide concentration on photosynthesis (Hall and Rao, 1999). At high light intensities, it was observed that the rate of photosynthesis reached a plateau. Furthermore, as temperature and carbon dioxide concentration increased, the rate of photosynthesis was unaffected at low light intensities, but increased at greater light intensities. The mechanism behind these observations was further understood due to several experiments conducted in the following decades (Hall and Rao, 1999).

In 1905, a British plant physiologist known as Frederick Blackman (1866-1947) proposed that photosynthesis is a two-step process which includes both light-dependent and light-independent reactions (Hall and Rao, 1999). He noted that in multiple light saturation curves, the saturation point was always observed at the same light intensity. To explain this observation, Blackman predicted that the second step of photosynthesis was enzymatic, and thus concluded that the rate of photosynthesis was not entirely dependent on light (Blackman, 1905). Additionally, the light-independent reaction had a large temperature coefficient, which is characteristic of enzymatic reactions. Blackman also acknowledged that the light-independent reactions can occur in both dark and light conditions (Blackman, 1905).

American scientists Robert Emerson (1903-1959) and William Arnold (1904-2001) studied the rate of oxygen production in relation to the illumination of plant cells for defined time intervals (Emerson and Arnold, 1932). Suspensions of *Chlorella* cells were exposed to a condenser flash which provided light energy for 10^{-5} seconds. Emerson and Arnold measured the rate of photosynthesis following illumination and discovered that the maximum efficiency occurs when 1 of every 2500 chlorophyll absorbed a photon. From this, they concluded that the overall rate of photosynthesis is determined by the enzymatic rate as opposed to the number of chlorophyll molecules (Emerson and Arnold, 1932).

Photosynthetic Equation

Prior to the 1930s, it was believed that the splitting of carbon dioxide was due to the light energy absorbed during photosynthesis. However, some bacterial species were identified that were able to conduct photosynthesis without the use of light energy or the production of oxygen. The Dutch microbiologist Cornelius Bernardus van Niel (1897-1985) redefined the photosynthetic process in 1931, and suggested that a suitable hydrogen donor substrate, such as water, was split by light energy instead of carbon dioxide (van Niel, 1932). This produces a reductant, which then reduces carbon dioxide, and an oxidant, which is re-released as the original hydrogen donor substrate. van Niel later recognized that water was the suitable hydrogen donor substrate used by green plants and algae, which led to the creation of the photosynthetic equation which is still used in present day (Hall and Rao, 1999):

$$CO_2 + 4H_2O + \text{Light Energy} \rightarrow O_2 + (CH_2O) + 3H_2O$$

As previously mentioned, de Saussure originally hypothesized in 1797 that the oxygen molecule produced originated from carbon dioxide. Approximately 135 years later, van Niel contradicted this belief when he stated that water was the source of the oxygen released, although there was no concrete evidence to support this (van Niel, 1932). It was not confirmed until 1941 when American chemists Samuel Ruben (1913-1943) and Martin Kamen (1913-2002) used oxygen-18 isotopes to show that oxygen originated from water instead of carbon dioxide. Ruben and Kamen exposed photosynthesizing cells to water enriched with ^{18}O and observed that the oxygen produced also had a mass of 18 (Ruben et al., 1941). In addition, Ruben and Kamen were the first to isolate the carbon-14 isotope, which was later used to identify pathways in photosynthesis (Hall and Rao, 1999).

The Hill Reaction

Robert Hill (1899-1991) was a British plant biochemist who studied the dynamics of photosynthesizing particles at Cambridge University. Hill isolated chloroplasts in plant cells and suspended them in solution. In his first experiments, Hill illuminated the chloroplasts in the absence of electron acceptors such as carbon dioxide which prevented the production of oxygen. During further experimentation, he added artificial electron acceptors such as potassium ferrioxalate or potassium ferricyanide, which resulted in the evolution of oxygen. Based on these observations, Hill concluded that the production of oxygen is independent of the presence of carbon dioxide, but instead is reliant on electron acceptors. Hill initially defined this relationship as the "Chloroplast reaction", however it later became known as the Hill Reaction (Govindjee and Kroggman, 2004). The Hill Reaction is significant as it gives evidence to the independence of the oxidation of water to oxygen and carbon fixation to starches. This finding led to further research regarding the enzymatic processes involved in carbon fixation.

Calvin Cycle

Although the mechanism for the light-dependent reaction was now established, the mechanisms of the light-independent reactions were not yet understood. In 1950, the American biochemist Melvin Ellis Calvin (1911-1997), seen in Figure 3.14, used radioactive ^{14}C and *Chlorella*, similar to Emerson and Arnold, to identify the chemical reactions involved in the light-independent reaction of photosynthesis. Calvin terminated the growth of the algae at different stages and identified different radioactive compounds which he had isolated by paper chromatography (Calvin, 1989). The identified compounds were used to classify the reactions involved in the light-independent step in which carbon dioxide is consumed to form carbohydrates, which was defined as the Calvin Cycle (Calvin, 1989). In 1961, Calvin's contributions awarded him the Nobel Prize for Chemistry (Hall and Rao, 1999).

From 1771 to present day, scientists from all backgrounds have developed an understanding of the mechanistic pathways involved in the complex process of photosynthesis. Each scientist involved in this discovery relied on knowledge from their predecessors, as well as their own findings, in order to redefine the current understanding of this vital process. Photosynthesis is now recognized as one of the most essential pathways for life to exist, and the origins of this process are still being studied in present day (Devlin and Barker, 1971).

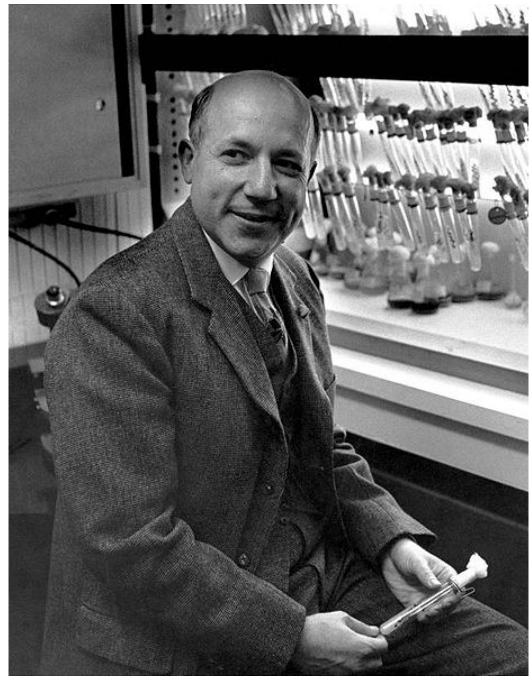


Figure 3.14: *Calvin working in the Lawrence Berkeley Laboratory in 1962 at the University of California, Berkeley. He was the head of the Chemical Biodynamics Laboratory, where conducted his work on photosynthesis.*

The Origin of Oxygenic Photosynthesis

During the Paleoproterozoic era, there was a large increase in the concentration of oxygen in the atmosphere, which is referred to as the Great Oxidation Event (GOE). Prior to the GOE, it was thought that the oceans were anoxic environments due to an overwhelming lack of phototrophic organisms (Satkoski et al., 2015). The increase in oxygen levels is believed to have been caused by the emergence of oxygenic photosynthesis in prokaryotes about 2.3 Ga. However, there is an ongoing debate about the specific time at which oxygenic photosynthesis evolved on Earth, as there is geological evidence that suggests this process evolved prior to the GOE (Buick, 2008).

The Isua Greenstone Belt is an Archean marine deposit located in West Greenland that consists of clastic metasediment, metabasalt, and banded iron formations (Rosing and Frei, 2004). Analyses of these sediments indicated that oxygenic photosynthesis was occurring approximately 3.7 Ga. The samples were separated through column chromatography and analysed with mass spectrometry in order to determine the concentrations of uranium (U) and thorium (Th) within lead (Pb) isotopes. When oxygen is present in the atmosphere, U is transported into the sediment as a uranyl complex, whereas in the absence of oxygen, U is transported with Th in mineral particles into the sediment. Thus, the concentrations of U and Th in the lead isotopes are used to identify the oxidation state of the atmosphere and biosphere in paleoenvironments. The samples obtained from the Isua Greenstone Belt had low concentrations of Th, which suggests that there were high levels of oxygen in both the atmosphere and biosphere (Rosing and Frei, 2004). Further, it is believed that phototrophic plankton existed in this environment due to high levels of carbon-13 and carbon dioxide present in the samples. The evidence presented in this 2004 study supports that oxygenic photosynthesis evolved over 3.7 Ga, long before the GOE (Rosing and Frei, 2004).

Samples obtained from the Manzimnyama Banded Iron Formations (BIFs) of the Fig Tree Group in South Africa give evidence for the evolution of oxygenic photosynthesis dating back to 3.2 Ga (Satkoski et al., 2015). Sediment samples deposited in both deep and shallow water facies were used to compare the oxygen levels in each depositional environment (Satkoski et al., 2015). Similar to the study conducted by Rosing and Frei (2004), the concentrations of U and Th in Pb isotopes were used to determine the oxidation state of the

Figure 3.15: Stromatolites deposited during the Cambrian period in the Hoyt Limestone in the area now known as New York. These structures are also commonly found in Australia and Brazil, and are dated at 1 to 3.7 Ga.

environment. Moreover, the concentrations of iron-56 (^{56}Fe) isotopes in the sediment were used to indicate the amount of oxidation occurring at the time, where high levels of ^{56}Fe were suggestive of very low concentrations of free oxygen (Satkoski et al., 2015). It was found that the levels of Th and ^{56}Fe were greater in the deep water than the shallow water facies, which provides evidence for the presence of oxygen-producing microorganisms in the shallow water environment. Higher levels of oxygen were discovered in sediments deposited in the upper water column 3.2 Ga, therefore demonstrating the evolution of oxygenic photosynthesis prior to the GOE (Satkoski et al., 2015).

Further evidence was provided through analyses of manganese (Mn) oxides which also suggest that oxygenic photosynthesis evolved before the GOE, approximately 2.95 Ga (Planavsky et al., 2014). The oxidation of Mn in the water column requires significant concentrations of free oxygen. Isotopes of molybdenum (Mo) were analysed in samples from the Sinqeni Formation of the Pongola Supergroup in South Africa. The nature of the Mo isotopes indicated that Mn oxides were present during the deposition of the sediment. Through paleoenvironmental analysis, it was determined that this sediment was deposited in a nearshore setting (Planavsky et al., 2014). Due to the presence of Mo isotope signatures found, it suggests that oxygenic photosynthesis was occurring in the shallow marine environment, allowing for the accumulation of oxygen about 2.4 million years prior to the buildup of free oxygen in the atmosphere (Planavsky et al., 2014).

Similar to radioisotopes, stromatolites, as seen in Figure 3.15, also give evidence for the time at which oxygenic photosynthesis evolved (Buick, 2008). Stromatolites are sedimentary structures containing the fossils of microorganisms, such as cyanobacteria, which date back to about 2.7 Ga (Buick, 1992). A study conducted by Buick in 1992 focused on stromatolites deposited in isolated lacustrine environments from the Tumbiana Formation in Northwestern Australia (Buick, 1992). Due to the lack of energy and nutrient sources in the lacustrine environment as well as low levels of iron and sulphur, Buick concluded that the biogenic nature of the stromatolites was due to oxygen-producing organisms. Thus, the presence of these microorganisms gives evidence to suggest that the GOE occurred several million years after the evolution of oxygenic photosynthesis (Buick, 1992).

As demonstrated by the studies above, there is controversy surrounding the time period during which oxygenic photosynthesis evolved. Although there is strong evidence to support the accumulation of oxygen prior to the GOE, current predictions range within a time period of about one billion years. Further, scientists face difficulty in analysing paleoenvironmental conditions and determining the timescale for evolution due to the lack of sediment preservation. Our ability to analyse the geologic record is constantly improving with emergent technologies and the introduction of new evidence, although the exact time period in which oxygenic photosynthesis evolved may never be known.

"Why has not anyone seen that
fossils alone gave birth to
a theory about the formation
of the earth, that without them,
no one would have ever
dreamed that there were successive
epochs in the formation of the globe."

–Georges Cuvier

Chapter 4: Paleontology

The field of paleontology is arguably one of the most heavily debated scientific topics, with a lengthy history of opposing socially acceptable ideas. A few thousand years ago, people began noticing strange items in the ground; through their observations and attention to the world around them, they inferred that these materials once belonged to living creatures. These theories, often infused in folklore, were passed down orally, but in some regions, were lost over time. When they reappeared, they did not receive the same acceptance as they did in the past, and scientists in this field faced opposition and disapproval at every turn. Despite their controversial situations, many scientists pushed the boundaries of scientific thought and worked relentlessly to uncover the mystery behind these strange objects.

This chapter begins by exploring the beliefs and folklore surrounding fossils held by ancient civilizations and demonstrates the significance of field observations and analysis of previous work to improve our current understanding of paleontology. This is contrasted with modern techniques, such as laser stimulated fluorescence and radioactive dating, which allow modern paleontologists to study fossils in ways that historical observational methods did not.

Next, influential paleontologists and their theories pertaining to fossil origins are presented as a journey through which key scientists laid the foundations for subsequent discoveries. This section of the chapter describes how these individuals contributed to their field and influenced current theories of evolution. Modern molecular analytical techniques and their use in ancient DNA studies of fossils are shown to be essential for furthering our understanding of the fossil record and extant life on Earth.

The final section of this chapter will focus on the significant contributions of women in geology, despite the difficulties that arise from being a female scientist in a man's world. Mary Anning's skill and dedication to her field are evident in her perseverance and determination to be recognized for her contributions. Her influential position as a woman geologist helped make it possible for other women like Jillian Banfield to receive better treatment and recognition for her work in geomicrobiology and environmental microbiology.

Despite a history riddled with controversy and opposition, the dedication of paleontologists throughout history has led to a continually growing understanding of previous lifeforms on Earth. These scientists laid the foundation for new discoveries and created an opportunity for all people to challenge their current understandings and biases in order to learn more about the world around them. Ultimately, the history of paleontology reveals a deep-rooted curiosity within humankind and a desire to learn about previous life on Earth.

Early Paleontology; From Mythological Belief to Modern Thought

Paleontology is a modern science that straddles evolutionary theory, vertebrate and invertebrate anatomy, geology, and several other fields; however, the historical perspective intertwined within paleontological knowledge cannot be forgotten. Paleontology has always been primarily a historical science – a means through which humankind attempts to reconstruct the past and the otherworldly through the study of fossils like shown in Figure 4.1. While paleontological knowledge continues to advance rapidly today, there are few elements of paleontology that can be claimed as completely new. Some theories concerning dinosaur biology claimed as new published in the 1970s had been widely discussed as early as the advent of the twentieth century (Mayor, 2001).

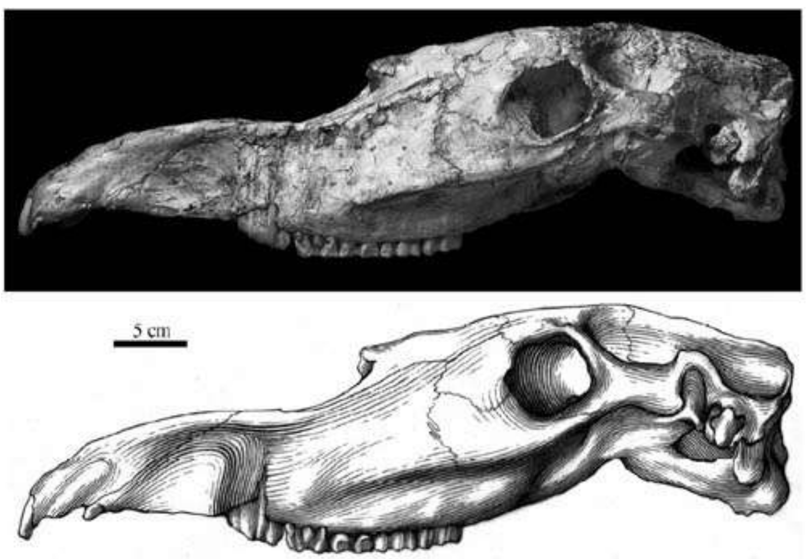


Figure 4.1: Hipparion *skull found from the early Pleistocene.*

The beginnings of paleontology are typically traced back to early European attempts to understand the historical, geological, and biological relevance of fossils. The earliest work cited as a modern attempt to interpret the meaning of fossils is a book, *On Fossil Objects (De Rerum Fossilium),* written by Conrad Gesner in 1565 (Rudwick, 1999); however, the "fossil objects" studied and described by Gesner were not all ancient paleontological remains. As the Latin word *fossilis* means "dug up", the objects he described included minerals and concretions, in addition to fossilized organic matter. If anything is made clear by his work, it is the fact that interpretation of these ancient artifacts was extremely difficult without modern geological understanding and biostratigraphic knowledge. The fossilized remains he observed were often mixed with the remains of extant organisms and found far from their place of original deposition. With little understanding of the natural world, tropical environments that contained the greatest amount of biodiversity, marine life beyond the shoreline, and the belief of a 4000-year-old Earth, fossil interpretation was greatly limited (Mayor, 2001). But while the early Europeans' understanding of the information contained within fossils was not great, if not less than Gesner's attempt, the ancient Greeks had begun measuring, describing, and displaying fossils nearly 2000 years before the European philosopher. Through written works, art, and oral tradition, the ancient Greeks had shared their paleontological observations and interpretations for centuries. Moreover, the ancient Greeks and Romans were not the only early civilizations that understood the historical, cultural, and scientific value of fossilized remains. Written records and folk stories have shown that the ancient Egyptians had possibly used fossilized hippopotamus bones as worship offerings and that early Chinese civilization understood track fossils were footprints left by ancient beings (Mayor, 2001; Xing et al, 2011).

As oral traditions implicating fossils continue to be retold, even today, approaching geomythological traditions from a historical science perspective yields merit. Paleontologists have successfully traced geomythological traditions back to fossils, and even communicated with local citizens to learn of conspicuous fossil sites. Furthermore, attempting to understand the crude beginnings of scientific thought in ancient paleontology have yielded significant results for modern paleontology (Xing et al., 2011). While the earliest collectors of fossils often came to different conclusions, early paleontology provides insight towards predominant schools of thought at the time and illustrates the emergence of the scientific process. Due to the longevity of past influential paleontological works, it is incredibly important that the history of paleontology, as well as the development of scientific thought within the field, be examined more closely.

Ancient Greece and Rome

As powerful civilizations distinguished by their complex culture and sophisticated thought, the Ancient Greeks and Romans have been credited for several great cultural inventions. Although the landscape of ancient Greece contained marble columns, religious temples, and elaborate statues, it also contained megafauna fossils from the Miocene, Pliocene, and Pleistocene eras as well. As the ancient Greeks and Romans collected, measured, and put the fossils on for display, they continued to record their findings in writing and oral folklore. The first Roman emperor, Augustus (63 BCE – CE 14), constructed the first paleontological museum on one of his villas on the Island of Capri. It has been theorized that several large elephant bones had been transported into Rome's ports from Africa or the Levant because of Emperor Augustus' fondness for large bones (Mayor, 2001); however, in antiquity, giant bones, tusks, and teeth of giant extinct mammals were often believed to be relics and remains of giant heroes and ancestors from mythological times. States were believed to have fought over these legendary artifacts – a fossil coup eventually resulted in the Peloponnesian war. Fossils that were collected and placed in temples by the ancient Greeks and Romans were treated as sacred treasures and acted as great sources of cultural pride and identity (Mayor, 2007).

While the ancient Greeks treated fossils as mythological relics, they had begun to make hypotheses about the world before them by using fossils. Finding small fossil shells in sixth century BCE, Xenophanes had inferred that the fossils were remnants of once-living animals (McMenamin, 2007). Moreover, ancient Greek philosophers believed that fossil shells discovered quite far from the shore acted as evidence for former oceans; however, the ancient Greeks also made some incorrect conclusions using the fossil record evidence. Although fossil bones of vertebrates on the island of Samos were correctly identified as such, they were believed to belong to Neades, strange awe-inspiring beasts, and Amazons who had died in battle (Solounias and Mayor, 2004). The Miocene sediment in which beige-coloured fossils were found was reddish (Figure 4.2). It was named Panaima, meaning "all bloody place" or "bloodbath", because it was believed that the soil in the area was dyed red by the blood of the slain Amazon warriors. As *Hipparion,* an extinct

Figure 4.2: *An extremely well preserved* Mammuthus Primigenius *skull and lower jaw. Although it is typically associated with northern Europe and Siberia, they roamed down to southern Europe during the last Ice Age.*

genus of horse, skulls are the most common fossils on Samos, they may have been related to the horses ridden by the mythical warriors in battle (Solounias and Mayor, 2004). Sometime after 331 BCE, the Greeks learned of elephants from Alexander the Great's conquests in India. It is suggested that the ancient Greeks correctly recognized the Miocene mastodon fossils of Samos as a species of elephant as early as 100 CE (Solounias and Mayor, 2004).

Figure 4.3: *A well preserved three-toed dinosaur footprint. Track fossils such as these may be the inspiration for the Chinese divine bird myths.*

Unfortunately, several internationally reputed historians of paleontology began to perpetuate the modern myth that fifth century BC Greek philosopher Empedocles studied fossilized elephant skulls in Sicilian caves. The belief that he related them to the Cyclops, the one-eyed giant encountered and killed in a cave by Odysseus in Homer's *Odyssey*, is also fictitious (Mayor, 2001). This urban legend has been traced back to Austrian paleontologist Othenio Abel in 1914 and 1939 (Abel, 1914). When he speculated that ancient Greek sailors might have mistook the nasal opening of elephant skulls as the eye socket of a one-eyed giant, he falsely attributed this theory back to an ancient philosopher, Empedocles; however, there is no surviving record that has proven that Empedocles had any knowledge of prehistoric faunal remains (Mayor, 2001). Willy Ley, a historian of paleontology in the 1940s, added the false claim that Boccaccio had cited Empedocles in fourteenth century AD after identifying fossilized elephant bones in Sicilian caves as "the bones of Polyphemus" (Ley, 1948; Swinton, 1966). As these influential historians of paleontology were continually cited, findings were often left unchecked and this resulted in the creation of the "institutional myth of modern paleontology" (Mayor, 2001).

Ancient China

While vertebrate fossils have been a backbone for paleontological attention, fossilized footprints left by extinct animals have garnered attention worldwide as well. In China, folklore beliefs regarding dinosaur footprints have been passed on through oral tradition in at least five regions with visible track sites. While folk stories were expressed in mythological terms, the basis of the folklore is qualitative and quantitative track fossil observations spanning generations (Xing et al., 2011). These iconological folk stories contain details that reveal information such as size, sedimentology, and morphology of the tracks. While there were several interpretations of these track fossils, the most popular interpretations could be classified into four categories: gods or heroes, plants, mythical birds, or mammals (Xing et al., 2011).

Track fossils in Chabu, Inner Mongolia have been identified and well known by the people in the region by at least the 1950s (Xing et al., 2011). The large three-toed prints were locally named "*Shen niao* (divine bird) tracks" due to their resemblance to footprints of an enormous bird, as shown in Figure 4.3. The herdsmen of the region believed that the prints were wishes for human happiness left there by the divine bird *Shen niao* (Xing et al., 2011). It is believed that the presence of smaller avian footprints interspersed between the larger theropod footprints may have led the herdsmen to assume that all the tracks had been made by birds of different sizes (Li et al., 2009).

Abundant dinosaur tracks were also discovered in the Yunnan, Guizhou, and Liaoning provinces. Local people often refer to the track fossils as the footprints of the *Jin Ji* (Golden Chicken) and festivals dedicated to worshipping the Golden Chicken exist (Xing et al., 2011). While observations were made and recorded through oral tradition, storytellers lacked an understanding of fossilization. It was believed that the Golden Chicken had made the tracks by directly making footprints in stone. These tracks were believed to represent "a pathway to heaven" (Zhang, 2002).

In 1862, the Qing Dynasty named a 750-year-old rock shelter near a rich collection of dinosaur tracks *Lianhua Baozhai*, which roughly translates to "the mountain stronghold protected by lotus" (Xing et al., 2011). The shelter and track site are located at an erosional break where mudstone has been eroded away from layers of sandstone. Mud cracks were interpreted as the veins of lotus flowers.

Hadrosaur tracks with digits II-IV and clover-shaped metatarsophalangeal pads in combination with the mud cracks were interpreted by the dynasty as the preserved petals of the lotus flower (Xing, Wang, Pang, and Chen, 2007). Fossilized ripples were correctly identified as a past subaqueous environment and were interpreted as evidence for an aqueous habitat containing lotus flowers (Xing et al., 2011).

Shanghaijing (The Classic of Mountains and Seas) is believed to be the oldest oral mythogeographical legend that was compiled in third century BCE (Birrell, 1999). In second century BCE, a Chinese folk story noted that a canal was named Dragon Head Waterway because there had been “dragon bones” found in the canal (Mayor, 2001). The phrase dragon bones were used as a catchall term and often referred to fossilized remains of extinct mammals and dinosaurs. These fossilized remains were also believed to have potent effects within traditional Chinese medicine (Zhen, 1961).

North America

As Europeans began to cross the Atlantic, settle in North America, and interact with the First Nations people, they began to notice how the Native people held a reverence for the ancient bones found throughout these mysterious lands. Many of the early settlers who had a fascination with fossils began to work with the First Nations to find these fossils, not only for science, but for monetary gain, as mastodon ivory was a highly regarded commodity due to its scarcity in Europe. One of the main fossils found in these regions were mastodon fossils, as the animals would become trapped in the various sulfur rich bogs and swamps, decaying their organic materials but preserving the valuable skeletal remains, shown in Figure 4.4. (Mayor, 2005).

Individuals such as the French officer Fabri, who accompanied Baron Longueuil down to Louisiana in 1748, noted that the First Nations people referred to the mastodons as “the grandfather of the buffalo” (Mayor, 2005). With its large tusks, which could be mistaken for horns and a large bulky body, the relation between the mastodon, a large elephantine creature, and the North American Bison, one of the largest North American herbivores in the region of the Southern United States, could easily be mistaken. This demonstrated the First Nations understanding that these fossils of ancient fauna they found had some relation to the current species that walked the Earth.

The European settlers were also using comparative physiology to link ancient species to current ones. Some First Nations groups located in Canada showed Lousi-Jean-Marie Daubenton, a French naturalist, the teeth of the Mastodon, which unlike elephant teeth, contain sharp-pointed teeth, indicative of a carnivore, and told tales of how boats overturned due to something in the water (Mayor, 2005). These features combined with reports from Africa in regards to the large hippopotamus, which was known to be aggressive, found in bodies of water, and had sharp teeth, lead Daubenton to believe that these teeth belong to an ancient hippopotamus species, demonstrating the idea of relating modern species to ancient fauna (Mayor 2005). Unfortunately for Daubenton, he had imagined the hippopotamus being extremely large – much larger than the Nile crocodile due to accounts from African explorers and the Bible, and the teeth of the mastodon were not the right size or structure for a hippopotamus (Mayor, 2005). Eventually, these fossils lead to conflicts as many of the European settlers desired to return them to their home countries to provide them with the reputation and monetary gain which came from discovering and collecting these fossils, with many being stolen and misplaced over the years.

Figure 4.4: *Fossil of* Mammut americanum *in Tokyo, Japan.*

Britain

In Britain, around 1769, one of the most influential geologists at the time, William Smith (Figure 4.5), was also making extreme headway in the study of palaeontology (Laseron, 1969). As he began excavating the English countryside to dig channels, he began to notice something. As he dug down through the various strata, he began to observe fossils present within the layers (Laseron, 1969). These fossils were unique to various strata, and Smith recorded them. As he continued his work, he began to notice that within different regions of the country there existed identical strata deposition layers, and moreover the surrounding vertical layers were also identical to that of the other region (Laseron, 1969). Using these observations, he saw that the various time periods that took place in Earth's history could be relatively dated by the use of these indicator fossils, which acted as distinct markers.

Figure 4.5: *William Smith, one of the most influential geologists of his time.*

Modern Paleontological Techniques

Palaeontology has come a long way from its historical roots of observation and comparison between the ancient fauna and flora and the current analogous species. Now, researchers are able to implore a variety of techniques that allow them to more accurately date fossils, relate ancient species to modern ones, and properly identify fossils.

One current technique implemented by palaeontologist is the use of laser-stimulated fluorescence to help highlight small fossils that are not visible due to their small size, as well identify the type of tissue the researchers are dealing with, whether it be bone, soft tissue, internal organs, or scale and feathers. This provides researchers the opportunity to revaluate previously collected fossils and better analyze their characteristics and help provide a more accurate depiction as to what the organism was truly like. Kayle et al (2015), analyzed a supposed micro raptor species originally found in Liaoning, China, but the small bone fragments made it extremely difficult to get a positive confirmation of this identification. When placed under the UV light of the laser, it was actually found that the fossil actually belonged to an ancient fish species, as indicated by the higher fluorescence of the teeth and bones of specimen (Kaye et al., 2015). This technique allowed for a misidentified species to be properly classified, and provide a better image of the organism's environment in which it died and became preserved in.

Another modern technique that is used is radioactive dating of fossils. By using radioactive isotopes within fossils, we can see how the compounds that are trapped within the fossil decay according to their half-life. By detecting the percentage of the parent material and the percentage of the decayed isotope, you can accurately determine the age of a fossil. One example of this is a fossil that was dated to the late Cretaceous period via indicator fossils found (Ke-Qin and Dong, 2006). When radioactive dating was applied, it was found that the isotopes found within placed the organism actually living during the middle of the Jurassic period (Ke-Qin and Dong, 2006). The technique provided evidence that anomalies can occur and that the geologic time record can be disturbed and distorted, requiring more accurate forms of dating to be used.

One of the most interesting advances in modern paleontology is the application of molecular analytical techniques to fossilized remains at the biomolecular scale. These analytical techniques can be used to detect the presence of preserved macromolecules such as proteins, DNA, lipids, and polysaccharides. Investigations at the molecular scale typically examine whether or not any original biological or chemical material persists and if they are still viable for other molecular biology applications. Analysis of the diagenetic products stemming for the original biomolecules can also be used to study molecular preservation and degradation patterns (Higby Schweitzer, 2004).

Moreover, molecular paleontology has allowed evolutionary biologists to examine the phylogenetic relationships in extinct organisms at a genetic level rather than by phenotypic morphology alone. With use of modern biological techniques such as DNA isolation and purification, DNA amplification through polymerase chain reactions (PCR), and genetic sequencing, the mitochondrial DNA from relatively modern fossils (around 100,000 years old) has been successfully used for many phylogenetic studies (Waggoner, 2001; Yang, Golenberg, and Shoshani, 1996). Moreso, in 1996, Yang and his colleagues successfully sequenced cytochrome *b* genes from both *Mammut americanum* (the American Mastodon) and *Mammuthus primigenius* (the woolly mammoth) fossils. Comparing these genetic sequences with those of living elephants, it was revealed that the extinct woolly mammoth is phylogenetically closer to the Indian elephant (Figure 4.6) rather than the African elephant (Yang, Golenberg, and Shoshani, 1996). These genetically based findings confirmed results obtained from both morphological and immunochemical studies that would not have been possible prior to the advent of modern molecular paleontological techniques.

Figure 4.6: *A bull Indian Elephant* Elephas maximus indicus*, one of the closest modern descendants of the mastodon.*

Modern analytical techniques have also been applied to fossilized plant specimens. Conventional use of the flowering plant macrofossil record is not sufficient to determine the botanical origin of amber, fossilized plant resin; however infrared spectroscopy and nuclear magnetic resonance spectroscopy can be used to compare the spectra of fossilized samples with modern day tree resins. These comparisons can then be used to determine the botanical source of fossilized resin samples (Lambert, Frye, and Poinar, 1990). Ancient amber artifacts can also be traced back to their original source and as such, can be used to approximate historical trade routes.

While molecular paleontology remains a relatively new field, its potential is only being slowly realized. As techniques are developed and improved, the amount of information that can be extracted from fossilized remains will only increase. Ongoing research into fossilization processes is important as this contributes to a stronger understanding of evolutionary processes and degradation of biomolecules. Additionally, elucidation of molecular diagenesis across geologic time scales and identification of biomarkers in preserved material aids in the search for evidence of extraterrestrial life (Higby Schweitzer, 2004). In order to detect extinct life on other planets, the range of diagenetic alterations to biomolecules, at least on Earth, must be better understood. Nevertheless, molecular paleontology still has much evidence to provide for the existence of life on other planets; however, modern paleontological research will continue to contribute to the greater understanding of evolution, extinction, and fossilization on this one.

Conception and Evolution of the Field of Paleontology

In modern day, the idea that fossils are the remains of organisms, which hold the key to unlocking information about the Earth's past, is believed as fact. This belief, however, has not always existed, and in the seventeenth century the idea that fossils represent extinct organisms was considered controversial hearsay, especially in Europe. Our modern understanding of fossils was built through the contribution of many thinkers throughout history, starting in ancient Greece and extending into the time of Darwin. It was these thinkers who made possible modern geologic and paleobiologic work.

Exploration of Fossils Throughout Antiquity and Early Renaissance

Humans have always harboured a curiosity towards fossils, and many attempts to understand their meanings and origins were made in antiquity and the Renaissance. Ancient thinkers like Xenophanes, Aristotle, and Leonardo da Vinci largely recognized fossils as the remains or impressions of once living organisms, but this concept was lost in time, only to be rediscovered and expanded upon in the centuries that followed (Figure 4.7).

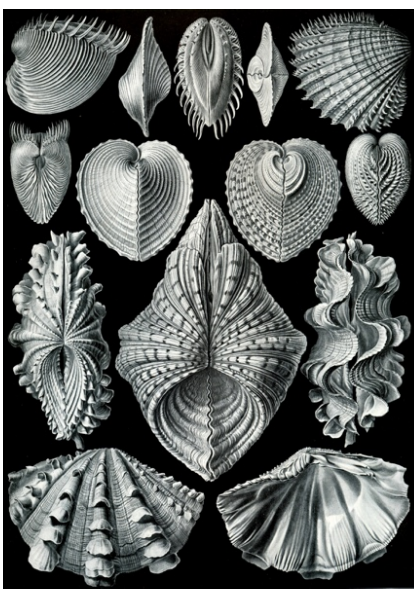


Figure 4.7: *An artist's rendition of fossils similar to those Xenophanes and Da Vinci likely analyzed, allowing them to come to early conclusions on the origin of fossils.*

Xenophanes (550-475 BCE), an ancient Greek philosopher, found solids which he recognized as the remains of shells. Often these shells were found far from sea, in unlikely places like mountains. This led Xenophanes to conclude that the animals to which these shells once belonged to had been carried inland by water. He hypothesized that the shells were then covered by mud, which subsequently dried, allowing the shells to be found within dry rock (Desmond, 1975). These sophisticated early ideas represent the beginnings of fossil research, though it should be noted that the shells in which Xenophanes wrote bore a strong resemblance to extant molluscs. This was common in early fossil research, and allowed philosophers and thinkers to more easily recognize them as organic.

Similar writings were done by Leonardo da Vinci (1452-1519) many years later. Though these writings were never published, they outlined his analysis of well-preserved shells and his conclusions not only about the organic nature of their origin, but also about possible characteristics of the deceased organisms (Rudwick, 1976). Though these shells again bore resemblance to extant molluscs, da Vinci noted that there were perplexing differences. He, like Xenophanes, understood that the fossils had been formed due to the layering of sediment, and rejected a popular idea that the biblical flood was involved in their formation (Rudwick, 1976). Had da Vinci announced and spread these ideas, they likely would have been considered hearsay, garnering little support from his contemporaries. In the eyes of da Vinci, however, these contemporaries were simply ignorant, lacking his ability to accept the idea of a changing world (Rudwick, 1976). In this way, da Vinci's ideas provide a glimpse into the culture of his time, and act as a basis upon which philosophers and naturalists of the sixteenth and seventeenth century began to build.

Sixteenth and Seventeenth Century Observations

Throughout the sixteenth and seventeenth centuries, the wealthy collected strange objects which had been dug up from the Earth. These objects consisted of what we now know to be minerals and fossils, but at the time were considered oddities, confined to the Curiosity Cabinets of the elite (Bowler, 1992). One such member of the elite was Pope Pius V (1504-1572), whose papal collections contained many items which would later be classified as fossils. These fossils and geologic oddities were collected by Michele Mercati (1541-1593), a papal physician and the director of the Vatican's Botanical Gardens. The collection consisted largely of *glossopetris*, or tongue stones (Davidson, 2000). Mercati later published a catalogue of his collection, and due to the emphasis he placed on the *glossopetris*, many historians believe he understood that they were scientifically important specimens, though he failed to recognize their exact importance (Davidson, 2000). It was not until the work of Nicolaus Steno (1638-1686) that the importance of these pointed rocks became known.

The business of collecting and dealing geologic oddities continued, as naturalists began to explore what these substances represented. Some naturalists preserved ideas of antiquity, believing that fossils were the physical representations of mystical forces occurring within the rocks (Bowler, 1992). Others, like seventeenth century polymath Robert Hooke (1635-1703), began to see fossils in a different light. Hooke conducted many experiments using microscopes and recorded his observations in his 1665 publication *Micrographia: or some physiological descriptions of minute bodies made by magnifying glasses with observations and inquiries thereupon*. The seventeenth of these observations, *Of petrify'd wood and other petrify'd bodies*, included his observations on fossils, or "curious figur'd bodies", as he called them (Hooke, 1665). In his writings, Hooke noted that these strange bodies could be found in solids of vastly different physical characteristics, such as colour and hardness. He not only correctly recognized some of these bodies as shells, but observed differences in the ways that they had been produced, with some bodies appearing as if they had been filled in while others like a mold had been made around them. Contrary to the ideas of philosophers of the time, Hooke believed these bodies had been produced by the movement of mud, clay, and other particles over the shells of living things. This went against the common view that they were created due to some mystical forces within the Earth (Bowler, 1992), laying the foundation for modern paleontology and providing an early scientific method with which to examine such specimens.

The Writings of Nicolaus Steno

The ideas of Mercati and Hooke were further elaborated on in the writings of Nicolaus Steno, seventeenth century geologist and anatomist. Steno's involvement with these curious solid bodies began in 1666, when he was asked to examine the head of a large shark which had been captured by fishermen (Duffin, Moody, and Gardner-Thorpe, 2013). Steno conducted a thorough analysis, publishing his findings in his paper *Canis Cachariae* (1667). The paper explores many anatomical details of the shark head, including the brain, eyes, ears, and most notably, the teeth (Figure 4.8). While dissecting and analyzing the specimen, Steno found an interesting parallel between the shark's teeth and *glossopetris*, the same rocks which had held a special place in the Papal collections of the 1500s. In the final pages of his paper, Steno listed eleven observations, which he followed by six of his own hypotheses, the last of which stated his belief that *glossopetris* stones were fossilized shark teeth (Duffin, Moody, and Gardner-Thorpe, 2013). This conjecture was of particular importance as the stones were much larger than the teeth of modern sharks, indicating that the ancient shark was likely much larger.

Figure 4.8: *Nicolaus Steno's sketch of a shark head, with special emphasis placed on the teeth of the shark. It was this image he used when making his assertion that tongue stones, or glossopetris were shark teeth that has been fossilized.*

Steno's revelations were further expanded upon in his *Prodromous to a Dissertation Concerning a Solid Body Enclosed by Process of Nature Within a Solid* (1669). In his investigation on the origin of these stones, Steno found it necessary to expand his query to other substances, which he referred to as bodies formed in aqueous environments. From this, Steno rationalized that in order to fully understand where a potential fossil was produced, one must first understand what it is and how it might have been formed (Steno, 1669). Nicolaus Steno understood that many philosophers would disagree with his ideas, likely on the principle that one could never be certain of the origin of these solid bodies. He hoped to use experimentation and logical arguments to convey his ideas such that no other naturalist could disagree with him. Steno made four bold claims, firstly asserting that solid bodies are composed of particles which can be affected by external forces. He then went on to distinguish between solids and liquids, stating that the particles of a liquid are in constant motion and move apart, while the particles in a solid rarely move away from one another, and that the production of a solid body involves the movement of particles. His last assertion, made in three parts, listed forces which could alter the motion of particles in bodies: fluids, other organisms, and the potentially divine force which allowed for the initial movement of particles. Steno followed this by stating that

> [I]n the case of...solids, whether of earth, or rock, which enclose on all sides and contain crystal, selenites,

> marcasites, plants and their parts, bones and the shells of animals, and other bodies of this kind which are possessed of a smooth surface, these same bodies had already become hard at the time when the matter of earth and rock contained them was still fluid. And not only did the earth and rock not produce the bodies contained in them, but they did not even exist as such when those bodies were produced in them (Steno, 1669, p. 218).

With this statement, Steno began the modern field of paleontology, and gave new insight into the fields of stratigraphy and geology. Steno's use of rigid experimentation complemented by well substantiated rationales deviated from the way many naturalists and philosophers of the time wrote, but nonetheless pushed for the beginning of public acceptance of his ideas. The belief that fossils contain the remains of organisms solidified in rock no longer appeared as inconceivable as it once did, and with the contributions of other thinkers from the seventeenth and eighteenth century, the concept slowly morphed into what it is today. The remainder of *Prodromous* is dedicated to important notions in stratigraphy and geologic dating, establishing Nicolaus Steno as the grandfather of geology and a key figure in the conception of the field of paleontology (Figure 4.9).

Figure 4.9: *Sketch of Nicolaus Steno, often credited as the grandfather of geology for his revolutionary notions in the fields of stratigraphy and paleontology.*

Eighteenth Century Ideas and Their Implications on Early Theories of Evolution

Scientific exploration of fossils continued into the eighteenth century, as thinkers of the time began to ask more complex questions about fossils and what clues they held to understanding the evolution of life. George Cuvier (1769-1832), eighteenth century French naturalist and anatomist, played an important role in developing the fields of paleontology and anatomy. His anatomical comparison of living and fossilized elephants established the idea that fossils may not only represent organisms of the past, but that these organisms might differ from those of the present. After becoming employed by the National Museum, Cuvier obtained the engravings of a fossilized animal which he was asked to study, and concluded that the organism was unlike any found on Earth. He quickly concluded that this organism, which he named Mastodon, represented a species that once existed but has since died out. He noted that the massive animal appeared to have characteristics of both an elephant and a hippopotamus. This notion led many of his contemporaries to insist that the fossil was not a new, extinct animal, but instead was made up of the bones of two separate, well-known ones (Rudwick, 1976). Cuvier's writings, however, held the key to revolutionizing the perception many naturalists of the time had about extinction. Cuvier realized that by analyzing the fossils of large mammals, which surely no man could claim still existed, he could in essence prove the theory of extinction. From the National Museum, Cuvier obtained fossil samples of an 'elephant', later identified as a mammoth. He compared these samples with the skeletons of modern elephants and, through his expertise in anatomy, was able to determine that the two were not the same species (Rudwick, 1976). This difference was particularly noticeable in the appearance of the lower jaw of both animals (see Figure 4.10). Cuvier was likely not the first man to put forth the idea that this fossil was separate from modern elephants, but he was the first to conclusively prove it (Rudwick, 1997). Since the fossil elephant was clearly a distinct species from modern elephants, and does not currently exist, it must have existed once and died out.

Cuvier's work shows a dynamic world, just like the early theories of evolution. It was Lamarck (1744-1829) who set forth a theory of evolution by use and disuse, believing that life had been generated spontaneously, and was altered and made to be more complex over time. The mechanism of this change was through an offspring's ability to inherit acquired traits of the parent (Bowler, 1992). He believed in a hierarchy of organisms, and he began to use these new ideas when analyzing fossil samples (Rudwick, 1976). Lamarck's belief that organisms evolved into one another, with no discrete beginnings and ends to species, directly contrasted Cuvier's belief, on the basis that if evolution proceeded seamlessly then the fossil record would also be seamless. Cuvier found that this was not the case, with drastic breaks in the record, which he believed indicated extinction and migration periods (Rudwick, 1976). These ideas paved the way for Darwinism and the modern theory of evolution.

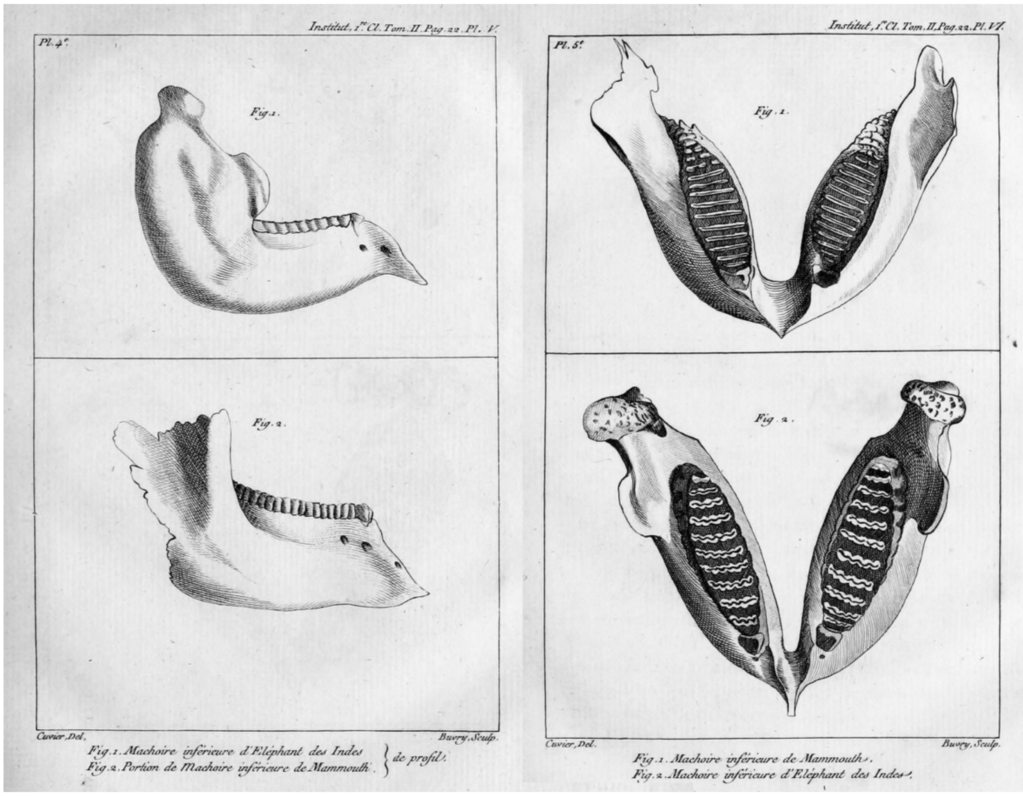


Figure 4.10: *Cuvier's illustrations of the teeth and jaw of a modern elephant (top left and bottom right) and a mammoth (bottom left and top right). This illustration was crucial in Cuvier's definitive statement that the two were separate species, paving the way for theories of evolution and extinction.*

Fossils and Darwinian Theory of Evolution through Natural Selection

In 1859, Charles Darwin (1809-1882) published his famous work, *The Origin of Species*, which became the foundation of modern evolutionary biology. Within his work, Darwin analyzes the geological succession of fossils and how these observations contribute to and support his theory of natural selection. Darwin argued that species of different genera and classes do not change at the same rate or degree. In old tertiary beds, shells of extant species were found amongst many extinct species. Similar observations of crocodiles and other reptiles in sub-Himalyan deposits were observed by Scottish geologist and paleontologist, Hugh Falconer. Similarly, geological distribution showed differing rates of change among genera, as land-shells and coleopterous insects from Madeira island differed greatly from closely related organisms in Europe, yet marine shells and birds had hardly changed. These observations led Charles Darwin to conclude that between two consecutive formations, the forms of life contained within are rarely observed to evolve at the same rate or even by the same degree. In accordance with his theory, he proposed that there is no fixed law that causes all organisms of the same region to change at the same time or in the same magnitude.

In his book, Darwin comments on the presence of the European Chalk formation across the world, in locations such as North America, South America, Tierra del Fuego, and the peninsula of India. He noted that each of these locations contained organic remains that closely resembled the European Chalk formation (Darwin, 1859). The book was published many years before the conception of supercontinents, thus it is unsurprising that Darwin supposed that these forms of life were changing simultaneously all around the world at the exact same time. He described the parallel succession of these organisms around the world as being explicable by his theory of natural selection. The theory he proposed suggested that new species are formed by new varieties of an organism with competitive advantage over the previous form. The advantage over older forms would allow them to dominate, and thus the parallel succession of these species aligned with his theory of new, dominant species spreading and varying. This concept of parallel succession would be further developed in future years after the proposal of continental drift by German geophysicst and polar resesarcher Alfred Wegener in 1912 (Rogers and Santosh, 2004).

As previously described, Cuvier proposed theories surrounding extinction and extinction events, which were largely agreed upon by Darwin. After discovering a tooth of a horse embedded amongst remains of Mastodon, Toxodon, and other extinct megafauna, English biologist and comparative anatomist Sir Richard Owen identified that the tooth belonged to an extinct species despite its resemblance of extant horse teeth (Darwin, 1859). Darwin used his observations to investigate extinction and its causes. The foundation of the theory of natural selection was the belief that a new species succeeds due to competitive advantage, and subsequently, those organisms that do not evolve become extinct. His observations of fossil records led him to conclude that there is no fixed law that determines how long a single genus or species will survive before becoming extinct. However, Darwin disagreed with Cuvier and other geologists such as Elie de Beaumont and Murchison, who sustained beliefs that many organisms on Earth became extinct due to periods of "catastrophes" (Darwin, 1859). Darwin believed that, through the study of the tertiary formations, extinction of a species occurs gradually, with the species becoming extirpated in many different locations until the species is completely eradicated from the world. Presently, it is generally understood that although many species undergo this gradual extinction described by Darwin, there have been five major extinction events in the Paleozoic and Mesozoic eras, which supports Cuvier's theory (Raup and Sepkoski, 1982). Despite this difference in theories, it is evident that the growing field of paleontology contributed to Darwin's proposal of natural selection, and has ultimately influenced the development of the field of evolutionary biology and modern molecular phylogenetics.

Ultimately, the origin of the field of paleontology is not simple, nor is it linear, but the journey towards a modern understanding of fossils facilitated deeper understandings in a variety of other fields. The identification of fossils and an understanding of how and when they occur led to important notions in stratigraphy. The realization that fossils represent extinct organisms allowed for development of theories of evolution. Today paleontology has become a very different field, involving many sophisticated techniques to gain a better understanding of how certain fossils might be connected. These modern techniques are quite different from Hooke's microscopy observations or Steno's logical reasoning, but the conception of the field of paleontology has had important impacts not just on our understanding of the history of the Earth, but also on the way science as a whole is conducted.

Ancient DNA Analysis and Molecular Phylogenetics

The field of paleontology has evolved immensely with the advance of scientific understanding and technology. Amongst our growing knowledge of molecular properties of cells came the desire to study fossils at the molecular level. One of the first ancient DNA studies analyzed DNA of *Equus quagga*, a South African squid that went extinct in 1883 (Higuchi et al., 1984). In 1984, Higuchi et al. used bacterial cloning to amplify small DNA sequences of the squid. Two of the clones containing pieces of mitochondrial DNA (mtDNA) were sequenced, and they found that these sequences differed by 12 base substitutions to the extant Equus zebra (Higuchi et al., 1984). From these sequences, they determined that there was little to no modification of the DNA sequences over time, and that both species examined had a common ancestor approximately 3-4 million years ago, as fossil evidence from the genus previously indicated (Higuchi et al., 1984). Next, in 1985, 23 Egyptian mummies were investigated for DNA content, with one mummy containing DNA that could be cloned in a plasmid (Pääbo, 1985). Pääbo (1985) found that not only can pieces of mummy DNA be cloned, but there was also little to no alteration of the DNA. This information was crucial in advancing research investigating ancient DNA, and led to further analysis of the DNA of extinct fossil species that still occurs to this day.

The development of Polymerase Chain Reaction (PCR) analysis in 1983 by Kary Mullis has been one of the most influential scientific developments in the 20th century. For example, PCR led way to the Human Genome Project and enabled the analysis of DNA sequences from many ancient species (Thomas et al., 1989). PCR is extremely useful for studying archaeological remains since the technique synthesizes a large number of copies of DNA molecules even when there are damaged molecules present, as is often the case in fossils due to post-mortem modifications (Pääbo, 1989; Thomas et al., 1989). For example, the invention of a universal PCR primer by White et al. (1990) has significantly advanced fungal phylogenetics and ecology, allowing for the study of ancient and extant fungi.

Soon, research began to focus on conditions and treatment of fossils required to restrict post-mortem damage as well as contamination. The influx of research in ancient DNA led to many claims that were later refuted due to contamination, such as when Woodward, Weyand, and Bunnell (1994) thought they had discovered DNA from a dinosaur, which was in fact contaminated with human mtDNA (Allard, Young and Huyen, 1995). In 2000, a widely used set of criteria were proposed by Cooper and Poinar, outlining standards to prevent contamination and degradation of the DNA, and to provide controls to verify data (Cooper and Poinar, 2000). For example, their guidelines outlined the necessity of using multiple extraction and PCR controls, as well as repeating the experiment using different DNA extracts from the specimen with different overlapping primers, to detect possible contamination. More recently, Pruvost et al. (2007) proposed that freshly excavated and unwashed fossils contain a significantly higher amount of DNA than those that have been washed and stored in museums, and they encourage scientists to revise their treatment of fossils to better preserve their DNA for phylogenetic studies. Ancient DNA continues to be studied in an effort to better understand the relationship between organisms and to build a more complex phylogenetic tree.

Innovative technological discoveries continue to shape the field of molecular paleontology. The invention of next generation sequencing technology has significantly contributed to ancient DNA research. Next generation sequencing allows millions of sequencing reactions to occur simultaneously. This reduces the amount of time required for sequencing and produces larger quantities of data (Shapiro, 2013). Due to the massive implications of more efficient technology, there are already many studies of ancient DNA using next generation sequencing. The first of these studies used emulsion PCR and a next generation sequencing technique, pyrosequencing, to sequence a Siberian wooly mammoth (Mammuthus primigenius) sample (Poinar et al., 2006) shown in Figure 4.11. The results demonstrated a 98.55% identity between the mammoth and African elephant (Loxodonta africana) and that 45.4% of the sequences aligned to the African elephant genome (Poinar et al., 2006). In 2008, Miller et al. used the pyrosequencing technique on ancient DNA from hair shafts, producing a total of 4.17 billion bases. They found that 80% of the sequence corresponded to mammoth DNA (Miller et al., 2008). Through whole-genome mammoth-elephant comparisons, Miller et al. (2008) estimated an identity of 99.4% and that the mammoth and elephant differ at approximately one residue per protein. Ultimately, the study has extended the knowledge gained by previous mammoth-elephant studies and demonstrates that differences between populations that are not observable in the fossil record can be explored in greater depth through genome sequencing.

Scientists continue to explore ancient DNA and develop new techniques that will help to further understand the differences between extinct and extant species at a molecular level.

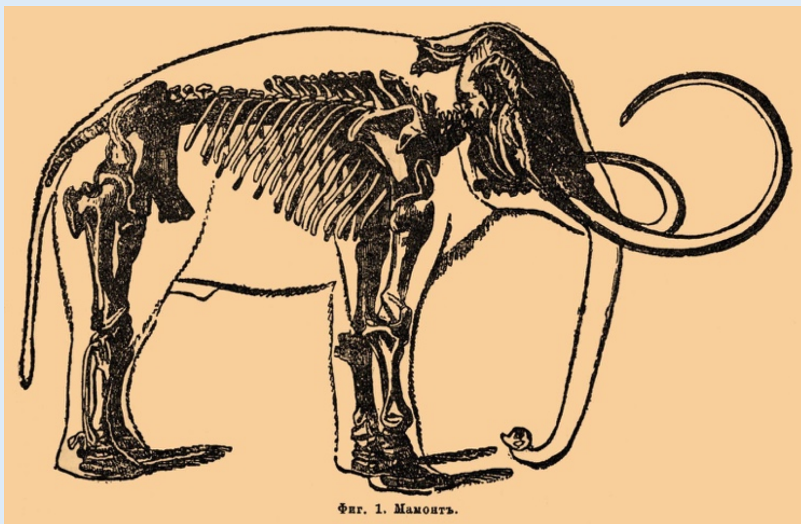


Figure 4.11: *Illustration of the wooly mammoth. The DNA of the wooly mammoth has been sequenced using modern molecular techniques.*

Mary Anning: Discoveries and Legacy

The study of the Earth and its geological processes has intrigued scientists throughout the ages. In the early 1800s, Great Britain was going through a period later known as the Industrial Revolution, which gave rise to great social, scientific, and economic changes (Torrens, 1995). This time allowed for the field of geology to develop further, as people began to question religion and the world around them. Furthermore, this curiosity led to many discoveries about the materials present on our planet, as well as give insight into how life came to be. During the Industrial Revolution, the increased amount of mining and the hunt for resources exposed the different strata throughout the country which revealed many geological relationships that had not yet been studied (Goodhue, 2004). As the field of geology became more recognised and thought of as a true science, the continued observation and documentation of fossils played a crucial role in the understanding of ancient life on Earth. Geologists discovered creatures that were present throughout history, and also learned about the environments in which these creatures thrived. Those who studied these fossils became known as paleontologists. Paleontology is the perfect combination of biology and geology, as it is the study of ancient life, and may provide insight into evolutionary paths (Goodhue, 2004). There have been many famous paleontologists throughout history, but none as insightful and determined as a woman by the name of Mary Anning. The jigsaw puzzles of knowledge that are fossils intrigued Mary from the time she was young girl. In Anning's time, the field of paleontology was mostly reserved for rich and educated men (Davis 2009). Her family and the life that she lived would influence her to learn all she could and to never give up. Despite her many hardships, her incredible perseverance allowed her to put forward numerous discoveries and create the legacy that she has left behind today.

Influence of Early Experiences

Mary Anning lived both an extraordinary and challenging life, unlike that of anyone else, especially during her early years. She was born in May of 1799 in a village called Lyme Regis, along the English Channel (Goodhue, 2004). Life at the time was not easy for many. The Anning family was poor and of the several children they had, only two survived, likely due to diseases such as smallpox and measles caused by overcrowding and extremely poor sanitation (Torrens, 1995). Mary and her older brother Joseph developed a very strong bond as siblings and spent much of their time together. The two went through a lot along together, including when Mary herself was struck by lightning as a

Figure 4.12: *Cliffs at Lyme Regis, Mary Anning's hometowm. These cliffs are a part of the Blue Lias group, and are abundant in fossils.*

baby (Torrens, 1995). Moreover, Lyme Regis served as a very interesting place to live, as the cliffs of Dorset were right next door. The cliffs were made up of the Blue Lias group, consisting of beds of shale and limestone littered with fossils (Figure 4.12). Every storm that passed uncovered more and more treasures (Vincent, 2014). Mary's father, Richard Anning, began collecting fossils when she was young, which immediately caught Mary's attention. She loved to learn and even though she received very little education, she gained lots of knowledge from her family. When she was only a couple years old, her father brought Mary with him to the cliffs when he was fossil hunting (Goodhue, 2004). This act was frowned upon because of her age and her gender, as well as the dangers the cliff posed not only to children but to anyone (Goodhue 2004). Anning had a close bond with her father, as well as the cliffside where she lived, and digging fossils with him was something she truly loved. Her father worked as a carpenter, and hunted fossils as a passion, both of which he taught Mary about. The close relationship she had with her family and the town in which she lived had a huge impact on her life and her later work. The fall season of 1810 was devastating for Mary as her father passed away at the age of 44 from a fall along the cliffs, leaving her family in a huge debt and void of any financial support (Davis, 2009; Elder, 1982). Despite the tragedy, Anning chose to continue doing what she loved, and follow in her father's footsteps along the cliffs of Lyme Regis. Shortly after Richard Anning's death, Mary, Joseph, and their mother Molly continued selling their fossil finds as a family, while being supported by the welfare offered at that time. Mary and Joseph spent most of their time looking for fossils in the following years, which further sparked the remarkable career Mary Anning had as a young adult.

Work and Discoveries

Mary Anning was recognised as the first female paleontologist, an astounding feat for her time (Vincent, 2014). The biggest turning point in her career was the first discovery she made with her brother Joseph. Fossil hunting had been a part of Mary's life since childhood, and at the age of 12, she and Joseph uncovered a fascinating specimen (Vincent, 2014). The extraordinary fossil was approximately four feet long, with a skull similar to that of a lizard, and gigantic eye sockets (Figure 4.13). Joseph hired men to excavate the fossil, thinking it may have been a large crocodile, while Anning began to look for the rest of the specimen. It took her about a year to discover the rest of the skeleton, as more of the cliff had to erode away for her to obtain access (Goodhue, 2004). The final specimen ended up being a 17-foot skeleton which had flippers, a long sharp snout, a fishlike structure, and the underside like that of a reptile. This discovery caught the attention of English geologist William Conybeare, who purchased the fossil from the Anning family (Creese and Creese, 2006). The discovery was intriguing due to the fact that no one knew exactly what the creature was. In 1818, the name *Ichthyosaurus* was given to the creature and credit for the discovery was given to Conybeare alone (Vincent, 2014).

At this time, Mary's career was just beginning. She began to study fossils and shells more closely, and learned a lot about the creatures she uncovered, even without a formal education. She also studied other publications, especially analyses of the various *Ichthyosaurus* specimens she had dug up (Goodhue, 2004). Throughout her time as a young fossil hunter, Anning studied findings other than shells, including fossilized feces, known as coprolites, and small invertebrate animals. Some of these specimens were beautifully preserved, and sold to different

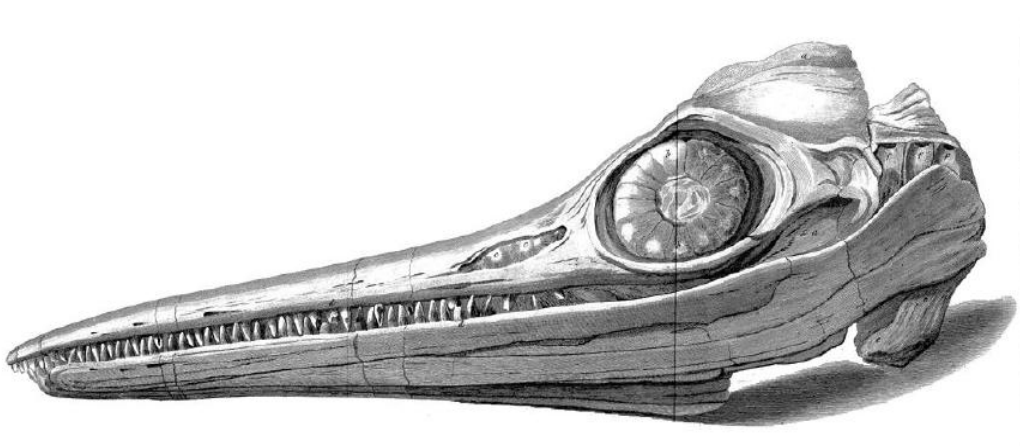


Figure 4.13: *Drawing of an* Ichthyosaurus *skull from a specimen found by Joseph and Mary Anning when Mary was only 12 years old.*

museums in the area. However, this was not an easy practice. Initially, the specimens sold to museums were not recognised as discoveries made by anyone in the Anning family. This discredit did not change how Mary felt about her work; it only pushed her to keep discovering more. Anning was one of the first of her time to make her fossil hunting a full time job, as she worked to take over her family business. She opened "Anning's Fossil Depot" in front of the home where she and her mother lived (Goodhue, 2004). While fossil hunting she often guided other scientists through the cliffs where she made her discoveries, forming friendships along the way (Goodhue, 2004). This connected her to many powerful people and opened up many opportunities that would never normally have been available to someone of her gender and social standing. Some of her friends included the famous Charles Lyell, William Buckland and his wife, and William Conybeare. She also had a chance to work with some of these scientists of a higher standing, which was beneficial for Anning because they had more resources than she did. Anning often worked alongside William Buckland. Research into fossilized feces was something Anning and Buckland conducted in their spare time. Mary was the first to determine their origin and the fact that specific knowledge could be learned about the creature's lifestyle. For example, the spiral shape of a coprolite can help paleontologists understand the shape of that animal's intestine (Goodhue, 2004).

By the age of 24, Anning had accomplished many things in her career. Mary finally received credit for one of her *Ichthyosaurus* specimens that she had sold, and received praise for the number of specimens she had unearthed and their contribution to geology (Goodhue, 2004). She also uncovered another interesting species, later to be called *Plesiosaurus* (Figure 4.14). It was approximately nine feet long, and had an incredibly tiny head in relation to its body. This specimen was also named and studied by William Conybeare, and the findings were published under his name. Again, this did not dissuade Anning from her work, and she was later given credit for the discovery. Along with her major discoveries, Mary found pieces of several fish specimens such as the ancient shark *Hybodus*, and other fossilized fish (Goodhue, 2004). In 1826, Anning almost gave up on her career in fossil hunting due to rough financial times (Goodhue, 2004). Instead, she decided to work even harder as a scientist and a reputable business woman. Her third major discovery

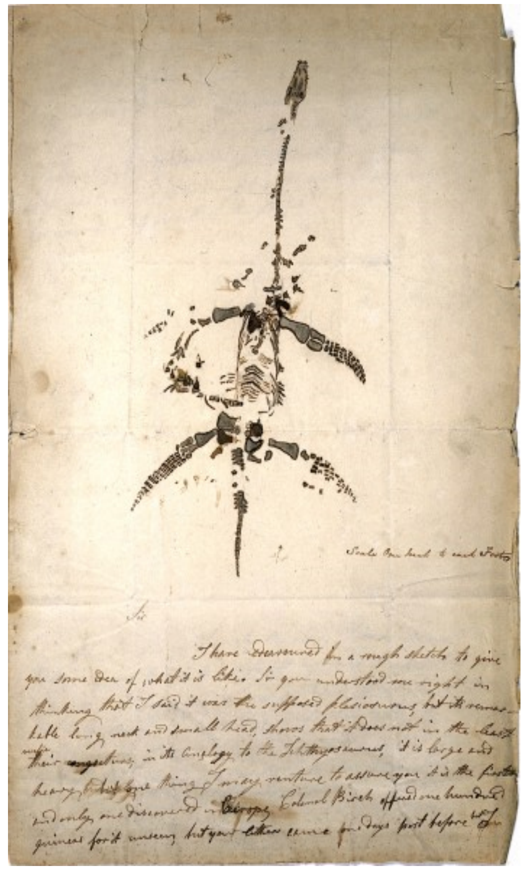


Figure 4.14: *Autograph letter concerning the discovery of Plesiosaurus, written by Mary Anning.*

stood out from previous work, as she uncovered a winged reptile, known as a Pterosaur, later named *Dimorphodon*. This discovery was followed by yet another odd invertebrate called *Squaloraja*. With each discovery, she became more trusted and highly regarded in the field of geology. Mary never stopped pushing herself to learn all she could from the stormy coast of Lyme Regis. Mary Anning never gave up, every discovery meant something to her, and could be used to inspire and intrigue people of all ages throughout the world. Her love for her family, her home, and the natural world allowed Mary to become one of the most important paleontologists of her time. Overall, she overcame many hardships throughout her life, and was able to leave a lasting impact not only within the field of geology but in society's impression of women.

Impact of Society on Anning's Career

The Industrial Revolution led to an increased need for quarrying and canal digging, which exposed the land's sedimentary stratigraphy and fossils. Subsequently, geology arose as a new discipline of science and was practiced almost exclusively among upper class men (Davis, 2009). At this time, fossil collecting was seen as fashionable, and collectors discussed their specimens at social events. Unfortunately for individuals such as Mary Anning, society as a whole discouraged the ambitions of female geologists until the late twentieth century (Burek and Higgs, 2007). In general, there was a perception that women lacked the intelligence and understanding to undertake serious science, especially one that involved field work. Women were not allowed to become members of scientific societies, including the Geological Society of London (Davis, 2009). Nonetheless, there were some working female geologists. Occasionally, wives of prominent geologists acted as assistants and would accompany their husbands on trips, helping them collect various fossil specimens. Rarely would women work independently; however, those who did were mostly of high social standing (Davis, 2009).

Mary Anning was not a typical woman in geology. She was not married, had little formal education, and came from a poor economic standing (Davis, 2009; Creese and Creese, 2006). When Anning was young, her father died and left the family £120 in debt (Davis, 2009; Elder, 1982). Therefore, she did not fit in with upper class members of society practicing geology at the time. Mary was rarely given credit for her work; she sold specimens to men who published the findings and often did not mention her name (Davis, 2009; Creese and Creese, 2006). The discovery of *Ichthyosaurus* and *Plesiosaurus* are often said to be William Conybeare's discoveries, the man who Anning first sold the fossils to (Creese and Creese, 2006). Even some more recent geological writings have failed to credit Mary for her accomplishments. Mary Anning left virtually no written record of her work, aside from several letters and one brief note (Figure 4.14) (Davis, 2009; Creese and Creese, 2006). This may have also contributed to the little recognition she receives for her work. Notably, Mary seemed to be somewhat of a feminist. In an unpublished notebook unrelated to her work, she wrote the following:

> And what is a woman? Was she not made of the same flesh and blood as lordly Man? Yes, and was destined doubtless, to become his friend, his helpmate on his pilgrimage but surely not his slave. (Davis, 2009).

This demonstrates that Anning was not afraid to be a lower class woman in geology, as she believed women and men were equals. It paints Mary Anning as a strong, opinionated, hard working woman who was not afraid to rise above the social and gender barriers of her time.

Controversy involving Mary's gender and social standing aside, she had fairly respectful relationships with her fellow geologists (Davis, 2009). As she gained more attention through her discoveries, she became well known to other geologists throughout Europe and Britain (Creese and Creese, 2006; Elder, 1982). For example, famous biologist and paleontologist Sir Richard Owen thought so highly of her work that he convinced the British Museum to provide her with a pension of £40 per year (Elder, 1982). In addition, Scottish mineralogist Thomas Allan claimed that Anning was an interesting person with an extremely strong knowledge about her specimens (Davis, 2009). This demonstrates that Anning knew what she was doing to a high degree, did very important and influential work, and played a key role in progressing her field. Despite the hardships Mary Anning faced during her career related to her gender and social class, she was still respected and recognized by other key geologists in her time.

Anning's Impact on Society

For the majority of her life, Mary Anning was known as a collector and seller of fossils in her hometown, Lyme Regis (Davis, 2009). Even though she sold most of her important specimens such as *Ichthyosaurus* and *Plesiosaurus*, Mary was well aware of their geological significance (Davis, 2009). For example, Anning wrote the following in a letter to a fellow geologist: "[...] the hooked tooth is by no means new; I believe M. De la Beche described it fifteen years since in the Geological Transactions, but I am not positive; but I know that I then discovered a specimen, with about a hundred palatal teeth, as I have done several times with different specimens" (Creese and Creese, 2006). Anning contributed a great deal to the collections and knowledge of paleontologists at the time, and heated battles and debates over her discoveries occasionally ensued (Elder, 1982). It was very clear that she uncovered important fossils which played an important role in the growth of paleontology. Mary's specimens also helped ameliorate religious beliefs that were prominent at the time (Davis, 2009), ones that resisted the ideas of evolution and extinction (Ferngren, 2002).

Despite the profound impacts Anning had on the geological community, she had quite a different impact in her hometown. Especially in the later years of her life, Mary was disrespected

Figure 4.15: *Stained glass window commemorating Mary Anning at St. Michael's Parish, a church in Lyme Regis.*

by residents of her village Lyme Regis (Davis, 2009; Elder, 1982). Residents viewed her work as nonsense and deemed her simply a tourist attraction (Elder, 1982). They did not believe her science was legitimate (Elder, 1982), and moreso claimed that her fossil collecting attracted large numbers of bothersome tourists (Davis, 2009). Additionally, she was accused by some residents of drug and alcohol abuse later in her life, however it was unbeknownst to them that she was suffering from cancer (Elder, 1982). Mary Anning died of cancer on March 9, 1847 at the age of 47 (Davis, 2009). She was buried in Lyme Regis, and in 1850, a stained glass window in the parish was unveiled in Mary's honour (Figure 4.15) (Torrens, 1995). She was eulogized by Henry De la Beche, an English geologist, paleontologist, and first director of the British Geological Survey (Davis, 2009; Torrens, 1995). More importantly, this eulogy was published in the Geological Society's journal, despite the fact that Anning was never allowed to join as a member. It was claimed to be the only case where a non-member was so honoured (Davis, 2009). This demonstrates that despite prejudices against her, Anning was an influential and successful geologist who made important discoveries that were well recognized in the geologic community.

Anning, called "the Princess of Paleontology", died as an honoured, renowned paleontologist responsible for some of the key geological discoveries in her time. She spent her time doing what she loved with the people who meant the most to her in a place she would forever call home. The legacy she created through the breathtaking and highly advanced discoveries of her time made her one of the most influential female scientists to this day. Terry Sullivan wrote the following tongue twister in 1908, inspired by Anning's legacy: "She sells sea-shells on the sea-shore, The shells she sells are sea-shells, I'm sure For if she sells sea-shells on the sea-shore Then I'm sure she sells sea-shore shells" (Davis, 2009).

Women in Geology Today: Jillian Banfield

Women as Role Models in Science

Dervilla Donnelly, an influential female physicist, claimed in a speech at the launch of a women in science initiative that "women are no longer discriminated against in science" (Burek and Higgs, 2007). Even today, statements like these remain controversial. Many believe that female scientists still face challenges that male scientists do not, such as the responsibilities of motherhood. Despite this controversy, it is clear that women in science, including geology, have come a long way in the past few centuries. To comprehend where women in geology are today, it is important to understand the work and roles of women in the past (Burek and Higgs, 2007).

Since the 18th century, women have contributed to the field of geology, and their contributions grow as time passes. An important female figure in geology is Mary Anning, who collected and sold fossils in the early nineteenth century (Burek and Higgs, 2007). Other famous female geologists include Janet Watson, the first female President of the Geological Society of London, and Marie Tharp, whose work contributed to the idea of seafloor spreading (Burek and Higgs, 2007). The persistence of these women paved the way for modern female geologists. A concrete example of a successful woman in geology today is seen in Jillian Banfield.

Jillian Banfield

Jillian Banfield is a leading researcher in geomicrobiology and environmental micro-biology at Berkeley (Anon, 2016). Hailing from Australia, Banfield completed her PhD in the

United States. Besides the United States, she has also taught in Tokyo, Japan. Banfield has many prestigious honours and awards to her name. Today, Banfield teaches in the Department of Earth and Planetary Science and Environmental Science, Policy, and Management at Berkeley (Anon, 2016). In her lab, she uses genomics to study how microbes shape and are shaped by their natural environments. She works to reconstruct the genomes of microbes to understand their impacts on their environments.

Genomics is very important to the field of geology. The mapping and sequencing of genomes of microbes and the analysis of their function plays a critical role in the understanding of both modern and ancient bio-geochemical cycles and other environmental processes (Banfield and Marshall, 2000). For example, analysis of microbes on early Earth can help geologists understand the demise of the oxygen-poor environments. Additionally, geological information is required in order to understand the environments that control metabolic and microbial community structure (Banfield and Marshall, 2000).

Some of Banfield's most prominent work involves the role of microbes in acid mine drainage. Acid mine drainage occurs when water becomes heavily polluted by minerals containing metal sulphide, forming net acidic solutions (Johnson and Hallberg, 2005). This often occurs in areas with abandoned or currently active coal mines (Figure 4.16). Metal sulphides, most often pyrite, that are exposed to air and water though mining activities become oxidized and generate sulphuric acid, which is released into the water (Edwards et al., 2000). Acid mine drainage greatly contributes to the pollution of surface water, posing risks to the surrounding environment. Microscopic organisms worsen this effect; they accelerate the rate of reaction of pyrite, causing even more sulphuric acid to be produced (Edwards et al., 2000). Due to the fact that microbes are involved in the production of sulphuric acid water pollutants, it is essential to sequence and understand their genome, which can be used to explore the nature of the microbial community. Banfield's research helps us understand what conditions the microbes require to survive and thrive in their environments, and how they contribute to the rate of sulphuric acid production (Tyson et al., 2004). For example, Banfield found that acidophilic bacteria, those that thrive under very acidic conditions, are not known to significantly contribute to acid mine drainage production (Edwards et al., 2000). However, they do significantly impact the global iron and sulphur cycles, therefore they are still important to study and understand.

Figure 4.16: *The results of acid mine drainage, which often occurs in areas with abandoned or currently active coal mines.*

Women in Science: The Future

The success of current women in science, including geology, depends on the success of those that came before them. Mary Anning was a renowned female paleontologist who kept pushing forward even in the most difficult of times. She succeeded in a time where women, as well as people of lower social and economic class, were looked down upon. Anning had a successful career, making it possible for women in the field today, such as Jillian Banfield, to have create their own remarkable legacies. Each and every female discovery in science pushes new boundaries and brings us closer to Dervilla Donnelly's vision; for no women in science to be discriminated against in any way.

"It is a curious situation that the sea, from which life first arose should now be threatened by the activities of one form of that life. But the sea, though changed in a sinister way, will continue to exist; the threat is rather to life itself.."

–Rachel Carson

Chapter 5: Oceanography

Similar to other fields of study, the emergence of oceanography can be accredited to the insatiable human urge to comprehend all natural processes and the secrets they hold. Upon reaching a certain level of understanding in geodesy and geography, it was time to explore what lay deeper in the Earth beneath our feet, or more specifically, below the ocean's surface.

Ancient explorers and cartographers would spend years navigating through rough waters in hopes of finding the answers they sought after. Whether it was to discover an uninhabited piece of land to claim as their own, or to identify the respective locations of land masses, each group needed the sea. The greatest bodies of water that render our planet an orb of blue were, and still are, needed for human survival. Perhaps one of the most well-known uses for these vast water networks was their role as ancient trade routes. As time passed and curiosity ensued, it became of greater interest to investigate what lay beneath the surface. Historically, it was widely accepted that aquatic biota only existed within a certain depth from the water's surface and venturing any deeper would only yield cold, dark water. Nevertheless, scientists dared to venture deeper into the unknown and their discoveries were nothing short of remarkable.

Excursions such as the *Challenger Expedition* were responsible for unveiling a variety of useful facts and information such as water temperature and depth, as well as living specimens. These were shown to be vital to the development of oceanography. In addition, technological advancements generated the opportunity to acquire a greater breadth of knowledge about our plant's oceans. Developments such as the Ocean Observatories Initiative gave rise to a method for monitoring oceanic processes that occur over time. Collecting the data made available through this initiative has been extremely beneficial in monitoring the variations of seawater over time and also played a role in providing information on climate change and global warming.

In addition to learning more about the sea itself, the scientific branch of oceanography has revealed a plethora of marine life that resides within the Earth's vast waters, but we still do not know everything about life in the oceans. The search for life has now extended beyond Earth, and yet little is still known about what lies within the depths of our seas. Scientists now understand that the ocean's contents cannot yet be quantified, but as long as human nature has its way, this will not be accepted. To this day, research continues and scientists strive to further uncover what lies within one of Earth's best kept secrets.

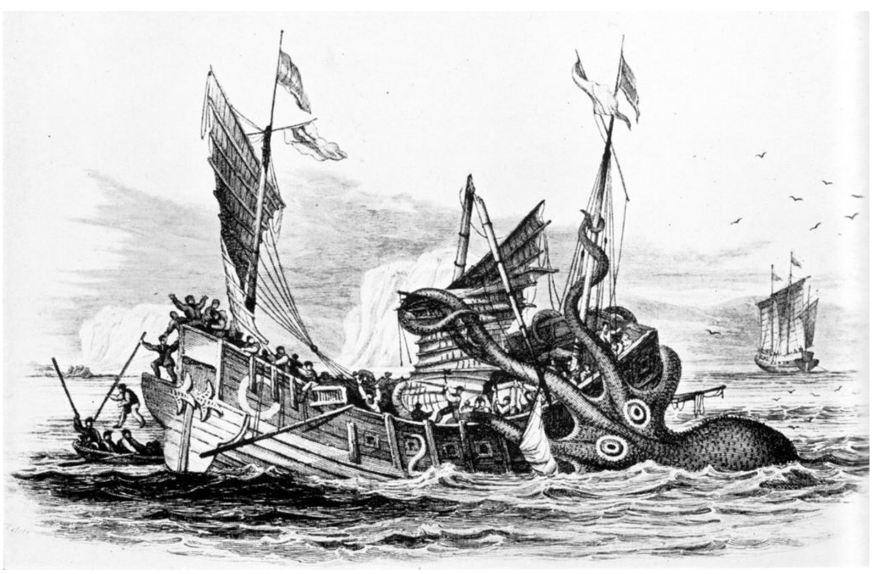
History of Ocean Exploration

In recent years, rovers have been sent to Mars and probes have imaged Pluto in stunning, high-resolution photos. Human civilization has started to explore beyond our solar system, yet much of Earth's oceans still remain a mystery. In fact, planetary geologists have mapped the surface of the Moon and the majority of Mars to a greater accuracy than our Earth's own ocean floor (Copley, 2014). The curiosity and wonder we have for space is very similar to how ancient cultures and civilizations have viewed the ocean: vast, unknown, and dangerous. Throughout the ages, as technology advanced and societies developed, perspectives on the ocean began to shift. They evolved from impenetrable boundaries to challenging obstacles to conquerable beasts filled with diversity and wonder. The following will be an exploration of the vast history of oceanography and will highlight the many explorers and scientists that have contributed to this ever-growing field.

Early Seafarers and Settlers

When did people first navigate over water? To answer this question, scientists and researchers turned towards archaeological evidence. Oars, paddles, boats, and other navigational instruments and equipment are all discoveries that point to seafaring behaviour (Bednarik, 1997). The earliest boats were discovered in the peats of Holland and took the form of ancient canoes. They were dated at over 8000 years old (Bednarik, 1997), suggesting that humans have been traversing water for at least that long, although older Mesolithic paddles have also been uncovered (McGrail, 1991). After the Pleistocene Era, people began to use more complex tools including serrated edges (Zvelebil, 2009), which may have allowed them to manufacture these paddles. In Europe, evidence for early navigation is difficult to find as many artifacts were unable to be preserved due to ocean regression during the Pleistocene Era (Bednarik, 1994). However, evidence for the European occupation of the Greek island Kelfallinia as early as the Paleolithic Age supports early ocean-crossing hypotheses, since this ocean distance of 6 km must have been traversed in that era (Warner & Bednarik, 1996).

Figure 5.1: Artist depiction of Kraken, an ancient mythological sea monster, attacking a merchant ship.



Ocean floor exploration began as early as 4500 BCE in ancient civilizations such as Greece and China (Stewart, 2011). Divers part of these coastline cultures practiced "breathhold diving", diving into the depths of the ocean without any special equipment. They would scour the seafloor for resources such as food, corals, and sponges (Stewart, 2011). Natural sponges were especially high in demand because of their versatility in bathing and cleaning, wound dressing, erasing ink, and as water canisters for drinking (Pronzato and Manconi, 2008). However, without any special technology, these sponge divers were only able to reach a depth of 30 meters, and a submersion time of up to five minutes. As a result, they stayed close to shore and were not able to explore the deep depths of the sea (Warn, 2000).

In the early exploration days, the ocean was subject of much mystery and mythology. Some cultures believed that the ocean was an infinite entity, stretching beyond the horizon indefinitely (Roberts, 2003). It would have been difficult for early civilizations, from their historical perspective, to conceive that the ocean would someday be traversed, mapped, and photographed in its entirety. Ancient cultures considered the ocean to be an object of great fear; they saw it as powerful and disturbing, and a home to a plethora of large and dangerous creatures (Roberts, 2003). For example, the Bible mentions the enormous sea creature Leviathan many times, describing it as "a beast rising out of the sea, with ten horns and seven heads" (Revelation 13:1). Another example includes the Kraken in Norse mythology as depicted in Figure 5.1, a terrifying beast that swallowed ships and petrified sailors (Lindow, 2002). The mythology surrounding the ocean in this period of early exploration reveals that from the first to thirteenth centuries, much less was explored and understood compared to the modern day.

As early as 3000 years ago, Polynesian explorers began to settle in the islands of Polynesia, a region located in the Pacific Ocean off the coast of Australia (Wilmshurst et al., 2010). These settlers originated from the western coast of the Pacific Ocean in the area located geographically south of modern-day China (Feinberg, 1988). Recent research with high-precision radiocarbon dating suggests that the colonization was rapid, with the earliest settlement being Samoa in 800 BCE (Wilmshurst et al., 2010). However, more distant islands, such as Hawaii, were settled as late as 1200 CE (Wilmshurst et al., 2010). The Polynesian seafarers were successful navigators since they were able to traverse parts of the Pacific Ocean. They accomplished this without more modern tools such as compasses to help with navigation; instead, they relied on generations of tenuous observation, taking notes on ocean currents and wave directions (Feinberg, 1988). The Polynesians lived in harmony with the ocean and hence were able to create the earliest versions of oceanographic maps from pieces of bamboo and wood. Locations of islands were marked with shells, and they were even able to mark the direction of ocean currents and waves (Feinberg, 1988).

Besides exploration and settlement, trade was also an important drive behind ocean exploration, as will be the case with the Phoenicians. As ancient economies grew, it became more efficient to transport goods via sea than by land. In particular, the civilizations surrounding the Mediterranean Sea began seeing water as an avenue for transport (Aubet, 2001). Phoenicia was an ancient civilization situated on the east coast of the Mediterranean, named after the Greek term for the primary product that they exported, a Tyrian purple dyed cloth (Moscati, 2001).

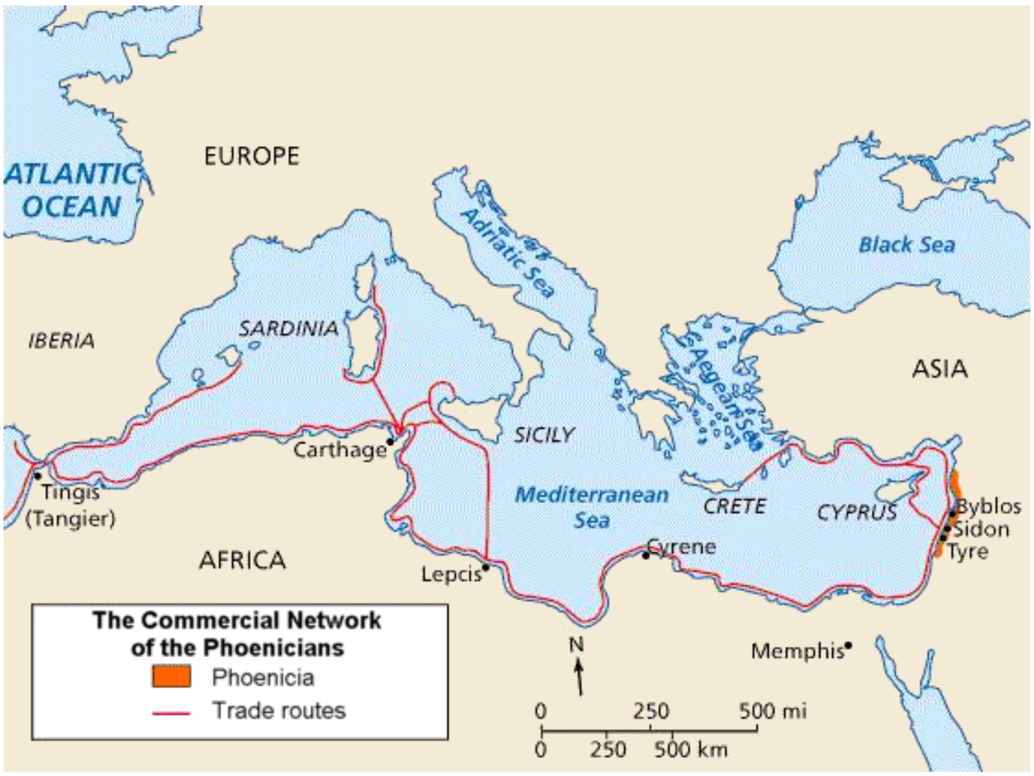


Figure 5.2: Map of Phoenician trade routes. Phoenicians traded along the coast of the Mediterranean Sea and out into the Atlantic Ocean.

The Phoenicians were powerful traders and established a sea route along the coast of the Mediterranean Sea as shown in Figure 5.2, exporting to countries such as Greece, Egypt, and even ancient Britain (Suggs, 1960). To maintain their monopoly on trade, they were very secretive of their routes, their cartography, and their knowledge of winds and currents (Aubet, 2001). They are also recognized as the first users of Polaris, the North Star, for navigational purposes (Aubet, 2001). Although most of their activity was in the Mediterranean Sea, the Phoenicians did explore parts of the oceans as well, trading up to where modern day Britain is situated and even managing to circumnavigate Africa (Moscati, 2001).

Birth of Navigation of Transoceanic Exploration

In the 1400s, trade was a major part of the European, Middle Eastern, African, and Asian economies (Hugill, 1995). Oversea trade became a faster and more efficient alternative to the overland Silk Road. However, a disadvantage to sea routes was that many countries situated along popular sea routes could control trade passages and canals and could heavily tax the goods and ships passing through. Thus, many goods that eventually made its way to Europe were very expensive. As the demand for Asian goods, such as spices and silk, rose it became essential for Europeans to search for faster and cheaper trading routes, such as an alternate pass to Asia that avoided the heavily-taxed route that passed by Egypt (Hugill, 1995).

Prince Henry of Portugal, since nicknamed Henry the Navigator, pioneered maritime science in accordance with this endeavor (Russell, 2001). He recognized that to find more efficient trade routes and to effectively navigate ships, one must have a deep understanding of the maritime environment. As a result, he founded an institute for marine science, the first recognized oceanographic institute (Davies, 1964; Russell, 2001). Promising seafarers would travel to Portugal in search of knowledge about ocean currents and the science of ocean cartography. Engineers in the institute developed novel navigational tools and instruments, and oceanographers compiled information on currents and landscape in order to make detailed oceanographic maps (Russell, 2001). These instruments and maps became a crucial foundation for future expeditions, one of which was Christopher Columbus's famous voyage in 1492.

Also prompted by the discovery of novel trade routes, Columbus was the first to sail a round trip between Europe and North America, earning him a pivotal place in history (Schesinger, 2007). This trip was not only significant in the history of ocean exploration, but also in human history and societal evolution since Columbus had a large impact on the Natives of the North, South, and Central Americas. He and his successors exploited the Natives through torture and slavery in order to profit from resources in the new land. Some historians estimate that 50% to 90% of natives died from a combination of exploitation and disease brought upon by the European settlers (Roberts, 1989). Many believe that it is this voyage that set the precedent for European attitude towards Natives for future colonization and interaction (Schesinger, 2007). This legacy of European settlement in North America would have additional reverberating impacts on the biosphere. Europeans brought over many invasive animals and vectors to the continent, changing the landscape of North America and the lifestyle of the Native Americans (Crosby, 2003). The reverse is also true, with North American organisms and diseases, such as tobacco and syphilis, reaching Europe (Crosby, 2003). In essence, the legacy of ocean exploration has had lasting impacts on human and ecological history.

Another remarkable journey was that of Ferdinand Magellan of Portugal. Still in search of a trade route to Asia, Magellan's crew managed to accidentally circumnavigate the globe between 1519 and 1522 (Chandler and Steinberg, 1987). This journey was one of notable scientific significance from a European perspective because it proved Earth's sphericity (Fritz, 1994). Furthermore, any animals observed by Magellan's crew had not previously been known to Europeans, including the Magellanic penguin, named after the explorer himself (Fritz, 1994). After the crew arrived back in Portugal, they found that their dates were off by one day, even though they had maintained the ship's log to their best abilities. Since they had been sailing westward, against the direction of Earth's rotation, they ended up being one day behind. This anomaly drew attention to the need for an eventual international date line (Chandler and Steinberg, 1987).

Discovery of the Gulf Stream and Ocean Currents

With modern scientific knowledge, it is well understood that ocean currents play an important role in regulating the Earth's climate. Less dense, warmer equatorial waters are carried towards the poles while denser, colder water is cycled back to the equator (Rahmstorf, 2003). In addition to regulating climate, ocean currents also cycle important nutrients and gases to stimulate the biosphere (Rahmstorf, 2003). However, before the 1700s, not much was known about the ocean currents. In fact, the ancient Greeks, thinking that only rivers could carry currents, considered ocean currents as giant rivers. The word “ocean” stems from the Greek word *ōkeanos*, meaning “giant river encircling the world” (Cresswell, 2004).

While the ancient Greeks noticed the ocean currents, it was Benjamin Franklin who first documented them through empirical observations. Benjamin Franklin is well-recognized for his role in American diplomacy, but less known for his contribution to science, particularly for discovering the Gulf Stream. In the mid-1700s, he observed the ocean currents off the coast of eastern United States, noting in particular its warmth and its high velocity, and the fact that it stretched up to the north and turned towards Europe (De Vorsey, 1976). The Gulf Stream had since been used to speed up transportation of exported goods and mail to Europe, exemplifying the importance of the study of oceanographic science in human societal evolution (De Vorsey, 1976).

Matthew Fontaine Maury, active in the 19th century, was credited for much of the work uncovering and studying the rest of the ocean currents (Maury, 2003). He earned his nickname “Pathfinder of the Seas” by detailed charting wind and ocean currents, as shown in Figure 5.3, and compiling them into a comprehensive publication titled *Wind and current charts* (Maury, 1850). He also published the first extensive oceanographic book published in 1855, *The Physical Geography of the Sea*, which is recognized today as the classic oceanographic textbook (Maury, 2003). Knowledge of currents enabled sailors to dramatically reduce the time needed for journeys. Maury also took interest in prominent marine animal life, pioneering scientific interest in marine biology. He used navigational logs to determine the migration route of whales and, using the patterns gathered, proposed the theory of the Northwest Passage (Williams, 1963). This was the idea that there was a channel up north that was void of ice and was therefore passable to sailing ships. The theory arose because Maury hypothesized that whales, as mammals, needed to surface and breathe along their migration routes that extended into the Arctic, and hence would require an ice-free passage (Williams, 1963).

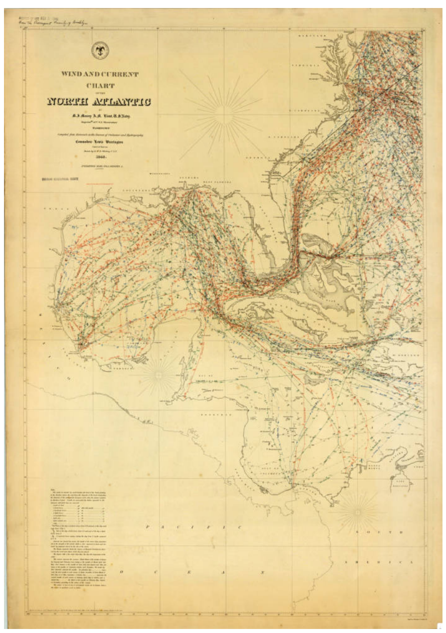


Figure 5.3: *Detailed current diagrams sketched by Matthew Fontaine Maury from his observations, as published in his 1850 compilation,* Wind and Current Charts.

Deep Sea Exploration and Beyond

By the mid-late 1800s, the goals of explorers and oceanographers had changed. The world’s oceans were almost completely mapped and the fear of turbulent waters started to wane (Guberlet, 1964). Thus, the pursuit of science took researchers below the surface.

In 1860, the transatlantic cable, a wire that ran across the bottom of the Atlantic Ocean for telegraphic communication, broke forcing it to be hauled to the surface for repairs. Surprisingly, they lifted not only the cable, but also many creatures that clung onto it. At the time, it was thought to be impossible for sea creatures to live at depths greater than 600m, and yet this cable lay almost two kilometers beneath the surface (Guberlet, 1964). This sparked a series of expeditions that sought to discover more about the diversity that lived within the ocean and answer deeply pressing questions about the limitations of life on Earth.

One of the first great men to explore the deep sea was Charles Wyville Thomson, a well-known Scottish naturalist who took great interest in the biota of the oceans. His interest, combined with competition with the Scandinavians led to the British funding the first great oceanographic expedition, known as the *Challenger*. The mission was to learn everything about the sea. It boasted a staff from a wide variety of scientific backgrounds and the mission itself is regarded as the beginning of oceanography as an organized science (Guberlet, 1964). The crew collected samples at various depths through a technique known as dredging which is the use of a net system to excavate materials from bodies of water and move it elsewhere (Bray, 2008). After a four-year expedition from 1872 to 1876 that covered all oceans excluding the Arctic, the collection Thomson had acquired was enormous. Information and diagrams of the collected materials filled fifty volumes of published work (Herdman, 1923). However, on top of its inherent success, it also inspired others to venture further and deeper.

In the late 1800s, Alexander Agassiz used his engineering expertise to improve oceanographic equipment. His efforts to increase dredging efficiency and improve sounding capabilities, allowing for better measurements of the depths of oceans, resulted in his ship *Blake* to complete what the *Challenger* could in an entire day, in under two hours. In 1893, Fridtjof Nansen of Norway began a series of expeditions to explore the North aboard the *Fram*. Murray and Hjort explored the biota of the deep Atlantic beginning in 1910 aboard the *Michael Sars*. All these and more were inspired by the *Challenger*, but it was not until the time of William Beebe and Otis Barton in the 1920s that humans physically descended deep into the sea (Guberlet, 1964).

In 1929, the precursor to the submarine was born and named the bathysphere, *bathy* being Greek for *deep* (Broad, 1997). It was a 5400-pound ball, 4’ 9” in diameter, with steel walls over an inch thick as shown in Figure 5.4. It contained three, 3” thick quartz windows, a searchlight, and a 400-pound steel door. It was pressure resistant to at least a quarter of a mile, enabling Beebe and Barton to enter the high-pressure environment of the ocean depths. It was secured to the *Ready*, a large barge that lowered the sphere into the water in the summer of 1930 for tests and, eventually, a manned mission. This machine was the first of its kind and the sights were fascinating to the scientists. After multiple descents, they were able to describe the life that existed at various depths. It was so successful that it was upgraded and modernized in 1934 to dive twice as deep, and Beebe and Barton continued to descend off the coast of Bermuda (Guberlet, 1964; Broad, 1997). The bathysphere was a great accomplishment, and paved the way for further developments including submarines, sonar technology, and the Mohole, because humans wanted to go even further.

Figure 5.4: *The Bathysphere as shown on display at the National Geographic Museum.*

In 1909, Professor Mohorovicic observed that the velocity of earthquake waves suddenly changed at a certain depth. This implied a change in medium, and the boundary between the mantle and crust was named the Mohorovicic Discontinuity, or Moho for short (McLeish, 1986). By 1957, a solid hypothesis had been built around the structure of the Earth and The Mohole Project was born. The project was set out to accomplish a feat never previously imagined: to drill a hole into the Moho. To work towards this goal, the *CUSS I* ship was used and it was pushed to surpass all previous ocean drilling records (Guberlet, 1964). The first phase of the Mohole Project was a success and demonstrated that the vessel had the capability to drill to the Moho. Unfortunately, in 1966, the US congress decided to cancel funding, and thus, the project folded (Rozwadowski et al., 2004). However, all was not lost. The project itself provided valuable information in the form of cores and fossils and also as samples of basalt, dolomite, and globigerina ooze, which is sediment composed of tiny fossils (Guberlet, 1964). These samples provided further insight into the formation and evolution of the oceanic crust (Rozwadowski et al., 2004). The expedition also provided support for the theory of plate tectonics, an idea that is widely accepted today (Teagle, 2011). Though it was discontinued, many important findings were still made during its operation.

Future Outlooks

Throughout the times, historical context has shaped societal attitudes towards the ocean and its study. The oceans are a vast mystery yet they are intrinsic to our societies and way of life. In ancient times, the sea served as an obstacle to transport or trade. However, this viewpoint eventually subsided in favour of a desire for adventure and scientific discovery. Scholars began sailing the world, mapping and studying its surface, and eventually, its depths. In fact, some even tried to go beyond the bottom of the ocean, attempting to reach the Mohorovicic Discontinuity. Today, knowledge of the oceans enriches a great diversity of scientific disciplines. Oceans serve as climate regulators, centers for biodiversity, and stores of valuable resources. With modern technology built upon millennia of historical insights and developments, we can study the ocean like never before, allowing us to both monitor and further exploit them. In fact, in doing so, we might discover answers to the age old question of how life originated on our planet. To conclude, the study of the ocean is an exemplary illustration of how historical contexts, perspectives, and developments help shape the modern body of knowledge we have available to us today.

The Oceanographic Observatories Initiative

As of today, we have accomplished many cartographic feats. We have been successful in mapping the entirety of our planet's surface since the time of Henry the Navigator, and we have been successful in mapping the landscapes of other planets in our solar system. Yet, much of the ocean still remains a mystery. Inherently, the ocean is a challenging environment to monitor. Radio waves are unable to penetrate the surface, machines are subject to corrosion and high pressures, and sensor activity is prone to biota interference (Brasseur et al., 2009). However, as the importance of the ocean grows, there is an increasing need to understand the roles the oceans play in the Earth's processes. This objective crosses many disciplines and expands upon the efforts of many explorers, scientists, and engineers who came before us. To satisfy our curiosity and research needs, we are looking for a system that not only allows us to monitor oceans but also provides real-time data and predictive capabilities. The solution to these needs is a system known as the Ocean Observatories Initiative (OOI).

The OOI was established by the United States National Science Foundation (NSF) to create an international system for ocean monitoring and data collection. It began with the formation of the International Ocean Network (ION) in 1993, which brought countries around the world together to discuss the possibility of a multinational observation system. The idea gained more momentum in the early 2000s as reports were released by the NSF that pushed for awareness and appropriate stewardship of the oceans. In response, the NSF established the OOI Project Office, and later the OOI Program Management Office, in 2004 and 2007 respectively. These offices worked with many universities and governmental agencies to design the entire system, and in 2009, they received permission to begin construction (Killeen, 2010). On June 6, 2016, the NSF announced that the system was officially in place and data was being transferred smoothly (Witze, 2016).

The OOI as a system consists of three major components. The first is a series of 925-kilometre-long fibre optic cables that lie off the coast of Seattle, connecting instrumentation situated along the Juan de Fuca tectonic plate (Witze, 2013). This is known as the Regional Scale Nodes Endurance Array, as shown in Figure 5.5. With this, the US will monitor seismic activity and investigate nearby formations including Axial Seamount, an active underwater volcano, and Hydrate Ridge, a hydrothermal methane vent (Cowles et al., 2010). The second component includes an array of instrumentation and roving gliders supported by moorings that collect data about the waters from floor to surface. This takes place along both coasts of the United States.

The third component builds on the second by adding additional roving gliders that monitor deep-water sites in the north and south. Overall, there is a total of approximately 760 sensors and an interdisciplinary system that can collect data on temperature, acidity, density, oxygen levels, and many other variables. This system is larger and broader in scope than other systems such as DONET and DONET2 in Japan and NEPTUNE in Canada, and provides more insightful and automated information than the dredging techniques that were used in the past (Witze, 2013).

Figure 5.5: *The Ocean Observatories Initiative station map. The regional scale nodes endurance array is shown off the coast of Seattle and consists of over 925km of fibre-optic cables to monitor the Juan de Fuca plate.*

This project had significant financial costs. After 10 years, $386 million USD in construction costs, and a projected $1.8 billion expenditure over the course of its projected 25-year lifespan, critics assert that such an investment is not worthwhile to monitor such a small percentage of the world's oceans. Despite the criticism received, the OOI's breadth and ability is unprecedented. For example, a cable observatory is necessary to properly understand the activity of Axial Seamount, especially since it is set to erupt within the next decade (Witze, 2013). Sending individual shipboard expeditions are a short-term and inefficient solution in comparison (Isern, 2006).

This system sets out to answer many questions about seismic activity, climate variability, ecosystem dynamics, fluid-rock interactions, and many others in various scientific disciplines (Isern, 2006). It serves as a baseline for modern oceanographic research, and as international collaboration expands and technology advances, we will develop a more comprehensive understanding about the deep and mysterious oceans of our planet.

The *Challenger* Expedition

Misconceptions about the Ocean

In the mid-1800s, precious little was known about the depths of the ocean, and there were many widespread misconceptions about the world beneath the waves. These included notions such as Forbes' Azoic Zone hypothesis, which stated that no life could exist at the bottom of the ocean (Anderson and Rice, 2006). This statement was readily accepted by the scientific community, as it seemed obvious that no living organism would be able to survive at such cold temperatures, under such pressure, or in such complete darkness (Anderson and Rice, 2006). According to Forbes, the number of plants and animals dwindled as the sea approached greater depths, and altogether disappeared at depths around 550m (Anderson and Rice, 2006). Other incorrect theories about the ocean included the popular notion that the specific gravity of water was so great that nothing could ever sink all the way to its bottom (Spry, 1877). Moreover, it was once thought that the ocean's temperature was uniformly around 4°C (Sears and Merriman, 1980). But perhaps the most erroneous belief of all was that there was not much to be discovered at the bottom of the ocean, and that it wasn't worth exploring (Sears and Merriman, 1980).

The Telegraph

By the 1860s, there was a growing interest in learning more about the ocean bed. The construction of the first trans-Atlantic telegraph had necessitated much studying and mapping of the Northern Atlantic (Phalen, 2014). With plans to build many more trans-oceanic wires, it was becoming increasingly important to find out more about ocean depth, temperature, ecosystems, currents, and bottom composition (Spry, 1877). Additionally, there was some measure of nationalistic pride at stake. Throughout the construction of the telegraph, Britain had pioneered deep-sea exploration (Phalen, 2014). However, Germany and Sweden were beginning to catch up in this field by sending expeditions to the Atlantic and Arctic, respectively (Deacon, 1997). In light of this political and economic climate, two naturalists, Charles Wyville Thomson and Wiliam B. Carpenter, lobbied the English Royal Society to increase its study of marine depths (Deacon, 1997). This influential organization of naturalists and physicians decided to launch the first entirely scientific ocean exploration expedition (Spry, 1877).

Lightning and *Porcupine*

In 1868, the Royal Society convinced the British Admiralty to lend them a ship for scientific purposes (Deacon, 1997). The old and shabby *H.M.S Lightning* was sent out on a six-week trip in the North Atlantic. During this trip, Wyville Thomson carried out dredging at a depth of nearly 1.2 kilometres, a record at the time (Spry, 1877). It was also discovered that the ocean depths were not uniformly at a temperature of 4°C, but in fact varied greatly from location to location. Furthermore, the expedition fished up a rich diversity of marine organisms from a depth of 990 metres, thus bringing into question the Azoic zone hypothesis (Deacon, 1997). In light of these intriguing findings, it seemed imperative for the Royal Society to pursue further investigations. In 1869, the Society sent out the *H.M.S Porcupine* to continue the work of the *Lightning*. The *Porcupine* again sailed around Great Britain, Ireland, the Faroe Islands, and then down the coast to Gibraltar (Spry, 1877). The studies conducted on this journey revealed more variation in deep sea temperatures, the existence of life at an even greater depth, as well as the existence of water circulation throughout the ocean. However, many questions remained to be answered. Exactly how deep underwater could organisms survive? Of what material was the ocean floor made? What was the exact shape of the great ocean basins? Was it possible to measure the speed and direction of the oceanic currents? In order to answer these questions and more, the Royal Society hatched a plan for a three-to-four-year systematic exploration of all the oceans around the world (Spry, 1877). Thus, the *Challenger* expedition was born.

The Team

The crew that was chosen to man the *Challenger* included both naval professionals and scientists. Among these were Captain G.S. Nares and second F.L.P. Maclear who both came from scientific backgrounds (Spry, 1877). Charles Wyville Thomson was chosen to lead the scientific department, as he had been involved with both the *Porcupine* and the *Lightning* expeditions (Deacon, 1997). He was assisted by several naturalists including the Canadian John

Murray, who later proved instrumental in finishing the *Challenger* mission (Deacon, 1997). Finally, J.Y Buchanan acted as the ship's chemist and physicist (Spry, 1877).

Materials and Methods

The *H.M.S Challenger* was a spar-decked corvette class ship (Spry, 1877). Although initially meant for army use, all but two of its guns were removed to make space for its new scientific purpose (Spry, 1877). It was fitted with cabins for the Captain and the Head of Scientific staff, as well as laboratories for the chemist, a studio for the photographer, and rooms for analysing data and specimens (Spry, 1877).

The scientific activities that would be run by the ship included taking ocean depth measurements, temperature readings, and water samples from many different depths (Spry, 1877). Sounding, or taking up samples from the ocean floor, was another important scientific activity, along with dredging, which consists of dragging a net along the bottom of the ocean to collect living specimens. In order to carry out these activities, very specific equipment had to be designed, as shown in Figure 5.6. First, Hydra model sounding apparatuses were improved upon so that they would be able scoop up more sediment (Deacon, 1997). For the expedition, J. Buchanan created a new type of slip water bottle shaped like a cylinder with a stopcock on either end connected by a rod (Deacon, 1997). This mechanism allowed water to pass through the cylinder on the way down, but any upward pull would activate the closing of the stopcocks, thus allowing water to be collected at any depth (Spry, 1877). Furthermore, this device conserved the dissolved gasses within the water (Deacon, 1997). The dredging mechanism was composed of a net inside an iron frame with hemp tassels along the edge in order to stir up and capture marine organisms (Spry, 1877). The most delicate instrument to be used on the expedition were the Miller-Casella thermometers. These mercury-filled thermometers were doubly-coated in glass to isolate them from the ocean pressure (Spry, 1877). Given the fabrication technology of the time, each thermometer had unique features and each required unique calculations to correct inaccuracies (Sears and Merriman, 1980). In order to take temperature measurements at different depths, dozens of thermometers had to be attached to a rope at regular intervals then plunged into the water (Spry, 1877). The Miller-Casella thermometers then recorded the maximum and minimum temperatures they encountered (Spry, 1877). While other thermometers were used throughout the journey, only data collected by the Miller-Casella instruments was used in the official challenger reports (Sears and Merriman, 1980). Thus equipped, the *Challenger* was ready to set off on her adventure.

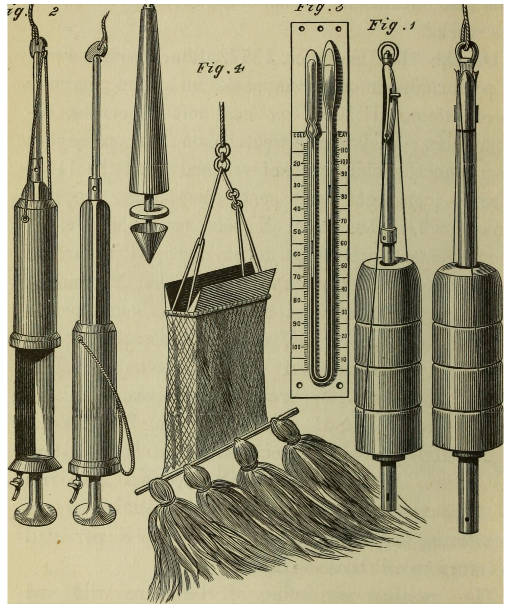


Figure 5.6: *Tools used by the Challenger crew. From left to right: two slip water bottles, a weight, a dredge, a thermometer, two sounding apparatuses.*

The Journey Begins

On December 21, 1872, the *Challenger* set sail from Portsmouth, England, with a team full of hope for the journey that lay ahead. Right from the start, however, the *Challenger* faced many difficulties. Nine days into their voyage, the first dredge was set over and capsized because of the rough water conditions encountered (Shephard and Stewart, 1972). A few days later, a second attempt at dredging once again failed because the dredge got caught on something at the bottom and carried away (Shephard and Stewart, 1972). It was clear that this journey would be challenging, and it was decided that the first segment of the voyage, from England to the Canary Islands, would serve as introductory work. The team took that time to get the machinery in working order, assign the staff members their various tasks, and establish a routine of labour (Thomson, 1877). The true work of the expedition would begin at Tenerife.

Trawl for the Haul

"The mud! Ye gods, imagine a cart full of whitish mud, filled with the minutest shells, poured all wet and sticky and slimey on to some clean planks," wrote Sub-Lieutenant Lord George C. Campbell aboard the *Challenger*

(Shephard and Stewart, 1972). "But this cruise is memorable in the annals of the *Challenger*, as during it we first tried the trawl instead of the dredge, which revolutionized eventually our dredging system." On January 15, the crew made their first attempt using trawl in place of a dredge. The experiment in dredging was a success; they were able to collect a greater abundance of specimens, including larger ones (in addition to the small invertebrates the dredge could only collect). Despite the fact that this trawl operation took a bit longer due to its lighter weight and larger surface area offering more resistance in the water, the trawl was rarely entangled and always fell in the right position (Thomson, 1877).

The Voyage after Tenerife

On February 14, 1873, with pleasant weather and a light evening breeze, the *Challenger* left Tenerife, the largest of the Canary Islands. The introductory preparation was done, and real work of the expedition had begun. The following days consisted of rigorously regular data collection. At each station, soundings were taken by the Hydra, temperatures at the bottom and surface of the ocean were recorded, and the specific gravity of the deep water was measured. Dredging was performed, ooze was sifted, and many specimens were analysed (Thomson, 1877). There was a surprising amount of life at the bottom of the ocean; new specimens were being found and classified. Thus far, the sediment they collected from the ocean floor was entirely composed of globigerina ooze, a grey-coloured paste of calcium carbonate (Figure 5.7). This calcareous sediment was vastly made up of the shells of various foraminifera, a class of marine protists that have been extant since the early Cambrian Period (Foraminifera, 2017). The foraminiferal shells in the globigerina ooze came primarily from the *Globigerina* and *Orbulina* genuses. In addition to the foraminiferal shells, the shells of pteropods, heteropods, and pelagic gasteropods were found in the mix (Thomson, 1877). The globigerina ooze was quite soft at the surface, but became firmer below the surface layer. The 2-inch-thick layer under the soft surface consisted of shell fragments cemented together by a calcareous paste, resulting in the firmer consistency. Below this layer, the globigerina ooze was made up of a consistent calcareous paste that was a grey colour due to the decomposition of organic matter (Thomson, 1877). The expedition continued quite smoothly and productively. On February 25, however, the crew sounded a depth of about 5 kilometers and lowered the dredge, only to bring it back up and to their shock, find it completely empty.

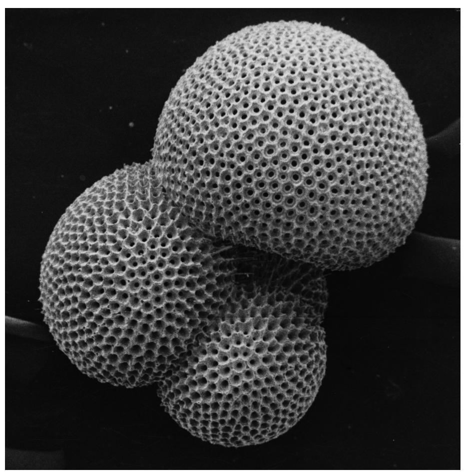


Figure 5.7: *Globigerina. A genus part of the class of protists,* Forminfera. *Globigerina shells make up globigerina ooze on the ocean floor.*

Red Clay

The next day, they repeated the operation with extreme precaution. The previous day's disappointment was caused by one of two reasons: the first being the possibility that the dredge had never reached the bottom due to a local current or the drift of the ship, or the second possibility that everything had been washed out of the dredge on its way to the surface. The haul brought in on February 26 was quite shocking to see. Up from a depth of about 5.8 kilometers, their deepest haul so far, the dredge contained sediment radically different from the grey calcareous globigerina ooze they had collected from the ocean floor. This sediment was a red clay, perfectly smooth, and without a trace of organic matter. This clay was so fine that it would remain suspended in the water for days, with a colour and consistency resembling that of chocolate. For deposition of such fine sediment to settle out of suspension, the water would have to have been absolutely still. When they analysed the red clay, they found that it was composed of silicate of alumina and sesqui-oxide of iron, with a small quantity of manganese (Thomson, 1877).

How did such a drastic change occur from the globigerina ooze, abounding in organic matter, to the virtually inorganic red clay? Perhaps there was a current that would sweep away any organisms falling from the surface, preventing them from settling to the bottom. However, this speculation was not plausible. If a current were strong enough to move small organisms, it would have enough energy to prevent the fine red clay from settling from suspension. It appeared that the only explanation for the lack of organic matter in the red clay was caused by chemical action resulting in an abyssal environment that was deleterious to organic material. The red clay was produced by the removal of carbonate lime that was so abundant in the globigerina ooze. Evidence for this was that the shells of pteropods and other surface molluscs were almost entirely absent. The few that were found amidst the red clay were brittle and yellow, indicating their rapid decay. Moreso, the foraminifera, instead of being white, were brown and broken up (Thomson, 1877).

Canadian naturalist John Murray dug deeper into the origins of the red clay. Upon careful observation, Murray established that a large portion of the red clay was produced by the decomposition of feldspathic materials (silica-rich minerals) in the same way most clays are produced. The red clay was also abundant in manganese peroxide-containing nodules, which Murray also thought resulted from decomposed volcanic material. Murray determined the source of the feldspar to be from pumice, a light and porous volcanic rock, formed from the rapid solidification of the gas-rich froth of glassy lava (Figure 5.8). Pumice was found in various stages of decay over a cast part of the ocean bed, especially in the red clay areas. Throughout the expedition, they eventually found pieces of pumice ranging from the size of a pea to the size of a football distributed throughout their entire route. Near volcanic centers such as Azores and the Philippines, the pumice was observed in even greater abundance (Thomson, 1877).

More specifically, Murray believed that the pumice at the bottom of the sea was formed by subaerial volcanic action - that the pieces fell onto land and were washed out into the water by rain and rivers, rather than having fallen directly onto the water. After a time, the pieces of porous pumice would become waterlogged and sink down to the abyss. Evidence for this was found on many occasions. During the *Challenger's* visit to Ascension Island in the South Atlantic Ocean, many pieces of volcanic material were found floating on the water's surface after a heavy rainfall. People made similar findings before and after the expedition which further suggested the volcanic origins of the red clay. Pieces of volcanic rock were picked up that had travelled to the shores of Bermuda. Charles Darwin noticed fragments of pumice on the shores of Patagonia, and anti-Darwinist Louis Agassiz observed them in the Brazilian reefs. After the voyage, there was a volcanic eruption in Iceland, and a ferry was blocked due to large amounts of pumice floating down the river on which the ferry was travelling (Thomson, 1877).

Figure 5.8: *Pumice. Light and porous volcanic rock, formed from the rapid solidification of the gas-rich froth of glassy lava.*

In short, evidence largely suggested that the red clay was derived from volcanic debris.

Across the Atlantic

By March 14, the *Challenger* was beginning to approach land. They took a sounding of a depth of around 2.6 kilometers, and the ocean floor again changed drastically in its characteristics. Instead of red clay, the sediment was once more composed mainly of calcareous foraminiferal shells of various species, mixed with broken spicules of siliceous sponges. They mapped out a cross section of the bottom of the Atlantic, roughly along a path that followed the Tropic of Cancer, the Northern tropic. The section was similar to the bottom character further north found in the latest atlases of the time: it had a plateau with relatively gentle undulations. Along the coasts of Europe and North Africa, there was a shallow belt past which the ocean floor dipped suddenly to a depth of 3.7 to 4.6 kilometers. Past the Canary Islands, the ocean deepened gradually to 5.8 kilometers, forming a wide valley. At a longitude of 43° W, they discovered that the sea floor began to rise again to a depth of only 3.5 kilometers, and once again deepen. In this they encountered the Mid-Atlantic Ridge. They established that the Atlantic Ocean was divided by ridges into three basins (Thomson, 1877).

For the first 130 kilometers of their journey, the ocean floor consisted of volcanic muds and sands that were produced from the volcanic rocks of the Canary Islands. The ocean floor for the next 480 kilometers was composed of the regular grey, calcareous globigerina ooze, yielding on the surface and firmer below. In this section, the depth of the ocean varied between 2.8 and 4.1 kilometers. From Tenerife onwards for 2400 kilometers, the ocean floor was made up of red clay consisting almost completely of the silicate of red oxide of iron and alumina. At many stations, there was also other inorganic matter mixed in the red clay; these included particles of peroxide manganese and, near volcanic areas, fragments of pumice. The ocean depth in this segment ranged from 5.8 to 4.7 kilometers (Thomson, 1877).

In general, from shallower to deeper regions, the calcareous globigerina ooze gradually passed into pure clay. This transition was extremely gradual, extending over several hundreds of meters. The shells in the globigerina ooze would lose their defined outline and appear more and more rotten with a brown colour. The shells would become increasingly mixed with the red clay until the lime carbonate was virtually completely removed. Usually, by a depth of 4.5 kilometers the red clay completely replaced the calcareous formation (Thomson, 1877).

The Pacific Abyss

On March 23, 1875, the *Challenger* team collected a sample from the bottom of the Pacific, near the Caroline Islands in the southern Pacific. The ocean floor here had a shocking depth of 8.3 kilometers. The abyssal sediment that they collected here was different from any they had seen on the expedition thus far. It was similar to the red clay, it was fine-grained, a reddish brown colour, and mostly void of lime carbonate. However, it was different from the red clay they were used to seeing. This sediment was grittier, and the lower layers were compacted to the point of lithifying. When observing the sediment under a microscope, they found that it contained a great amount of radiolarians. These protists were quite unfamiliar to the British naturalists, but were key in supplying the sediment for this formation. In light of this, they named this type of sediment radiolarian ooze (Thomson, 1877). This would later turn out to be a part of the Marianas trench (Kunzig, 2000).

Figure 5.9: *Watercolour rendition of H.M.S. Challenger. Painted by Benjamin Shephard aboard the Challenger.*

The Return Home

On May 6, 1876, the *Challenger* made her last deep-sea observation at the 345th station in the middle of the Atlantic. From this point, they made their way homeward as fast as they could. The expedition was coming to an end, but their troubles were far from over. An unplanned stop was made at Vigo Bay on the Central American coast, however. The scientific leader, Charles Wyville Thomson, writes: "these winds were dead in our teeth, and as our coal and fresh provisions began to get low, we in our weariness and impatience were driven to the verge of despair." (Thomson, 1877). Once the weather cleared up, the *Challenger* speedily made her way home. On May 24, 1876, after three and a half years, the *Challenger* anchored and the expedition was complete (Figure 5.9). The results of this expedition showed that life could exist even in the greatest depths of the ocean, revealed the composition and topography of the ocean floor, and a wealth of knowledge was amassed on the properties of ocean water and currents.

New Discoveries from Old Material

By the end of the expedition, the scientists of the *Challenger* had accumulated such an extensive collection of specimens that it took more than a decade to bring all the results of the expedition to publication (Deacon, 1997). The samples included animals, plants, rocks, and water. In 1921, following John Murray's death, his family donated many of his sediment samples to the prestigious Natural History Museum in London, England, which now conserves them as part of their Ocean Bottom Deposit Collection (Ocean bottom deposit collection, 2017). These specimens were packaged in glass jars and either dried or preserved in spirits (Ocean bottom deposit collection, 2017; Sears and Merriman, 1980). Additionally, the data collected on the expedition has been conserved in the many volumes of the series *Report on the Scientific Results of the Voyage of the H.M.S. Challenger during the Years 1873-1876* (Thomson, 1877). Even though they were collected well over a century ago, the *Challenger* samples and data remain a wealth of knowledge about our planet and its waters. To this day, the collected information from this landmark expedition is still used in scientific studies.

Understanding Ancient Processes

The samples collected on the *Challenger* expedition continue to give us information about some of the most inaccessible places on our planet (Dekov et al., 2010). Notably, they are often used to learn more about conditions around hydrothermal vents. Even today, samples from around these geologic features are scarce. Any data, no matter how old, is valuable. Studies as recent as 2012 have used *Challenger* data to study the formation processes of metalliferous sediments such as smectite around hydrothermal vents (Dekov et al., 2010; Cuadros, Dekov, Arroyo and Nieto, 2011). New technologies have been used in order to identify the elements and minerals present in these samples. While the naturalists on the *Challenger* were able to do this to a certain extent, X-ray diffraction, scanning electron microscopy, energy dispersive X-ray spectroscopy, transmission electron microscopy, as well as analytical electron microscopy allow us to discover much more about these samples and their formation processes (Cuadros, Dekov, Arroyo and Nieto, 2011). Because they were collected so long ago, the *Challenger* samples also give us some insight into what conditions would have been like in the oceans before the 20th century. Since *Challenger*, our planet has seen drastic changes such as the dawn of the industrial revolution, greater carbon emissions, increased chemical usage, and many more. These events have all had a heavy impact on our environment. *Challenger* data can be used to determine what isotopes and elements were present on the ocean floor in the late 1800s, and this data can then be compared to modern seafloor composition (Dekov et al., 2010). For example, a 2010 study used *Challenger* samples to characterize lead isotope ratios in the South-East Pacific before the popularization of leaded gasoline (Dekov et al., 2010).

Understanding Climate Change

Perhaps the most important environmental change that has occurred since the *Challenger* expedition has been an overall warming of the climate. As the atmosphere has warmed, so have the oceans. Therefore, studying variations in ocean temperature over time can give valuable insight into the processes of global warming (Roemmich, John Gould and Gilson, 2012).

When measuring current ocean temperature, modern day technology allows us to obtain data that is much more precise and detailed than in the past. Sounding and dredging operations have been replaced with more efficient techniques. For the past decade, temperature and salinity measurements have been recorded around the world by the Argo program. This international initiative was launched in 2000 and relies on the principle of independent and self-sufficient profiling floats recording data in every ocean on earth (Costoya, deCastro and Gómez-Gesteira, 2014). These floats are programmed to sink to a depth of around 1000m and remain underwater for nearly ten days. After, they return to the surface where they transmit their location and findings via satellite (Argo Canada, 2017). The satellites relay the information back to shore in real time, where the information is immediately available to researchers (Roemmich et al., 2009). Each float is designed to be able to take around 200 profiling measurements during its lifetime (Figure 5.10) (Argo Canada, 2017). Currently, the project has over 4000 floats free-floating globally (Argo Canada, 2017).

A 2012 study compared the *Challenger* temperature recordings from around the world to current data collected by the Argo project. By comparing *Challenger* data with the modern Argo data set, researchers were able to determine that mean oceanic temperature has risen by 0.59 °C±0.12 at the surface in the past hundred years. Just below the surface, the temperature rise has been less extreme, warming by only 0.39 °C±0.18 at 366 m, and 0.12 °C±0.07 at 914 m. Additionally, it was found that the Atlantic Ocean has been heating up more than the Pacific (Roemmich, John Gould and Gilson, 2012).

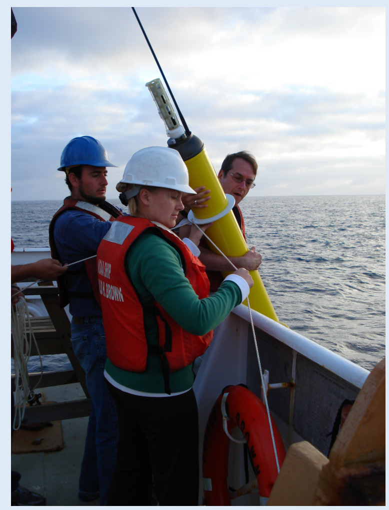


Figure 5.10: *Releasing an Argo float.*

Working with *Challenger* data is not without difficulty. Because of the quality of the instruments available at the time, the temperature data is riddled with systemic errors that are often difficult to correct (Sears and Merriman, 1980). Due to the construction of the Miller-Castella thermometers, all temperature recordings taken have a slight heat bias (Roemmich, John Gould and Gilson, 2012). Therefore, it can be concluded that the ocean temperatures were actually cooler at the time than those recorded by the *Challenger* expedition, and therefore the current calculations of ocean warming are conservative estimates.

Nevertheless, such discoveries give scientists valuable information as to how climate change is affecting our oceans. Today, the *Challenger* expedition continues to improve our understanding of the world around us.

*"Fire made us human,
fossil fuels made us modern,
but now we need a new fire
that makes us safe, secure,
healthy and durable"*

—Amory Lovins

Chapter 6: Geology and Industry

Planet Earth is an abundant source of countless natural resources that we have learned to use in a variety of ways. Energy, in particular, is fundamental to the growth of civilizations and is used in heating, fuels, and the advancements of new technologies. Prior to the nineteenth century and the development of the coal industry, almost all energy came from renewable sources such as wind, rivers, and in some cases, natural hot springs. Today, however, with the impacts of climate change becoming increasingly evident, we are beginning to return to more sustainable, alternative sources of energy.

Exploitation of geological resources requires a proper understanding of different environments and how they impact each other. The oil industry has played a huge role in the development of sedimentology, one of the key fields of science used to uncover hidden deposits of this valuable substance. Oil is a key component of modern society and its impact on economies, politics, and international relations is evident across the globe. The Alberta oil sands, for example, are a huge source of revenue and employment in Canada. With a history dating back to the early European explorers, the development of the oil sands highlights many advancements in science and engineering but is also the topic of much controversy and debate.

With more and more evidence of the detrimental effects of the oil industry and the persistence of climate change, extensive research has been devoted to investigating alternative means of energy production. With the majority of the Earth's inherent supply of thermal potential remaining untapped, many see geothermal energy as a promising source of renewable energy. However, while large scale geothermal power plants are a product of modern society, humans have been taking advantage of natural heat sources from the Earth for centuries. Geothermal gradients have had a huge impact on the cultures of early Europeans and Native Americans. These gradients were a source of spiritual connection while also having therapeutic applications and use in the development of new technologies.

Science is an incredibly dynamic process that defines how we understand the natural world. As we learn more, we can develop better technologies that improve our lives or tell us even more about the world around us, and so on. But we often fail to consider our impact on the environment and the future of our planet. It is important for us to acknowledge this impact we create, and work together towards a more sustainable future.

The Cultural Significance, Understanding, and Use of Geothermal Gradients throughout History

Geothermal gradients have been used throughout history to serve a variety of functions by many different societies, both ancient and modern. Geothermal gradients have been exploited as thermal hot springs, used for ancient heating systems, had their by-products harvested for an array of purposes, and have been studied throughout history to form the modern notion of geothermal power generation. Thermal hot springs, specifically, were revered for their healing powers and spiritual connections by many ancient societies, and their waters have also been used in residential heating systems. Geothermal by-products, such as iron oxides and perlites, were also used for a wide array of purposes. The geologic origins of geothermal gradients were theorized about by many influential ancient scientists such as Aristotle and Hippocrates (Allbutt, 2001). Geologic theories presented by ancient scientists, such as Aristotle, then contributed to the modern notion of geothermal power generation (Cataldi and Chiellini, 1995).

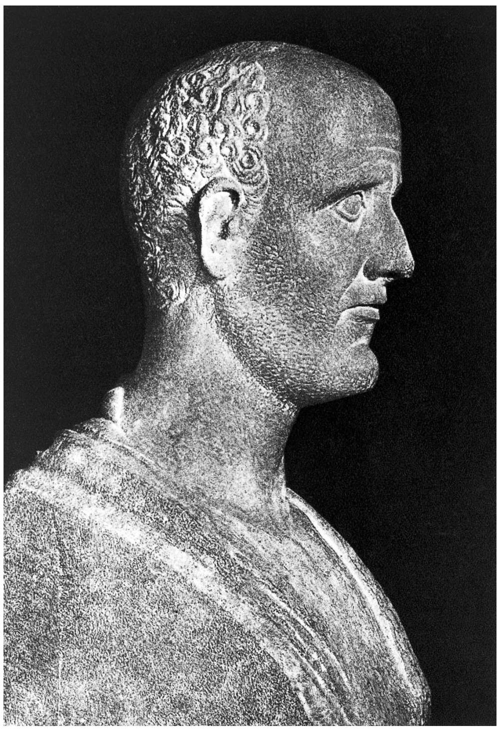


Figure 6.1: *A likeness of the Greek physician Asclepiades of Bithynia, who was the first individual to medically author and recommend thermal hot springs as a treatment for various maladies.*

Ancient Greek and Roman Medicinal Uses of Hot Springs

Ancient Greek and Roman culture was characterized by many significant developments, such as the establishment of medicine and medicinal practices. These advancements led to the establishment of several new and innovative therapeutic techniques, such as the use of hot springs for healing purposes.

The healing powers of hot springs were recognized by many influential people in this time; however, not by Hippocrates of Kos, the father of modern medicine. In his book "*On Airs, Waters, and Places*" from approximately 400 BCE, Hippocrates regarded waters from thermal hot springs as the second worst water for the maintenance of good health (Littré, et al., 1881). This helped to popularize the use of cold running springs for healing. Many physicians following Hippocrates, such as Antonius Musa, who famously cured the Emperor Augustus of an abscessed liver, further popularized the use of cold springs as a substitute for hot springs (Bell and Murphey, 1859). The popularity of cold springs was also described by the Roman lyric poet Horace in his book "*Satires and Epistles*", published around 22 BCE, which chronicles his distaste of Antonius Musa's recommendation of cold springs, while maintaining that he would much rather use hot springs (Horace, 2002). However, interest in the therapeutic uses of hot springs was renewed following the death of Augustus' nephew, Marcellus, whose demise was a direct result of his time spent in a cold spring (Allbutt, 2001). It was not until the influence of Asclepiades in the 2nd century BCE, whose likeness is shown in Figure 6.1, that the therapeutic use of hot springs was advocated for (Allbutt, 2001). In fact, Asclepiades was one of the first physicians to recommend hot spring baths to his patients for healing purposes (Allbutt, 2001).

Ancient Greek and Roman Understanding of Hot Springs

During this time, thermal hot springs were thought to arise from both geological and spiritual influences. Many distinguished philosophers of the time theorized that hot springs were caused by inherently geological phenomena. Hippocrates, for example, described their manifestation as being through the "violence of heat" (Littré, et al., 1881). On a similar note, Aristotle suggested that subterranean fires and pneuma (exhalations) were the cause of thermal hot springs in his book "*Meteorology*", authored around 300 BCE (Aristotle, 1952). In addition, there were others who described the origins of hot springs to be of a more spiritual nature. For example, it was a widely held belief that hot springs were the place of residence of Hades, Persephone, and other chthonic gods (Allbutt, 2001). As such, these places were regarded as holy, and individuals would frequently bring small offerings in the form of pins, rags, small coins, and shells to give to these gods in exchange for healing (Allbutt, 2001). Furthermore, other beliefs maintained that heat from the hot springs was due more to the water's blessing by the gods, than their residence within them (Allbutt, 2001).

Architecture of Ancient *Thermae*

To inspire healing from the gods, the ancient Greeks and Romans constructed large and opulent bathing structures, called *thermae*, around hot springs. One of the most notable *thermae*, the Thermal Springs of Kaiafas, was located in southwestern Greece. These pungent thermal springs have been described by several notable Greek and Roman travellers within their logs. These included Strabo (in his book "*Iliaka*" book 8, chapter 3) in the first century BCE, and Pausanias, depicted in Figure 6.2, (in his book "*Descriptions of Greece*" Book V ("*Elis*"), chapters 5 and 6) in the 2nd century BCE (Baba, Bundschuh, and Chandrasekharam, 2014). According to the logs, Kaiafas was connected to a grotto thought to be the sacred sanctuary of the Anigrides Nymphs (Baba, Bundschuh, and Chandrasekharam, 2014). These nymphs were regarded as minor female deities, who would heal those afflicted with leprosy and other dermal diseases that bathed within the waters of Kaiafas (Larson. 2001). However, healing was only granted to individuals who performed a specific ritual, as described by Pausânias (Frazer, 1898). Individuals who wished to be healed would first pray to the nymphs, then offer them small sacrifices before bathing in the muds surrounding the spring (Frazer, 1898). The muds were then washed in the thermally heated spring waters of the Kaiafas, and individuals were healed as they "wipe(d) off the sick parts of their body" (Frazer, 1898). The pungent odor of the springs was also attributed to the fact that mythical Centaurs used the waters to wash away venom from Hydra's bites or, according to Pausânias, from Hercules' poisonous arrows (Baba, Bundschuh, and Chandrasekharam, 2014; Pausânias, 1898).

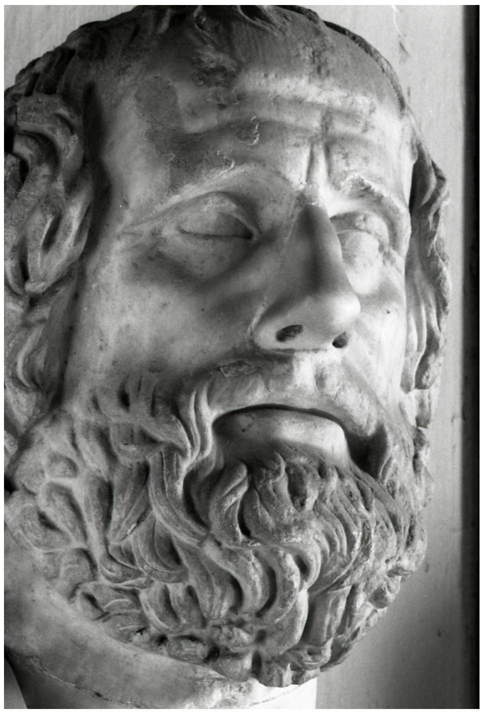


Figure 6.2: *A bust depicting the likeness of the Greek traveller and geographer, Pausânias, who was active during the 2nd century BCE.*

Native American Usage of Hot Springs

Hot springs were also a cornerstone in Native American culture, specifically within tribes of north-western North America where there is an abundance of thermal springs (Lund, 1999). In fact, almost every hot spring in North America displays evidence of use by early peoples (Lund, 1993). Various stone artifacts, such as bowls, have been found near many hot springs, indicating heavy usage by ancient Native Americans. Extensive usage of thermal hot springs also gave rise to a number of names assigned by the different tribes that used them. For example, the Shoshone tribe located in Wyoming referred to thermal hot springs as "*Bah-gue-wana*", meaning "smoking waters" (Lund, 1999). For Native Americans, hot springs were also a neutral area where warriors from opposing tribes were allowed safe passage, refuge from battle, and were permitted to use the water's healing powers to heal battle wounds (Lund, 1999).

Native American Understanding of Hot Springs

The miraculous healing powers of hot springs were revered, as it was believed that the "*Great Spirit"* resided within them (Lund, 1993). The *Great Spirit*, according to written logs of orally passed stories, is a powerful force who provides guidance, wisdom, and assists in survival (Jennings, 1978). The *Great Spirit* was believed to heat the waters through his breath, and bestow *Mother Earth*'s healing powers within them (Lund, 1993). Other tribes, such as the Sts'Ailes tribe in western British Columbia, had similar views on the origin of waters from thermal hot springs, which they referred to as "*Warum Chuck*" (Lund, 1993). The Sts'Ailes tribe believed the medicinal hot spring water was sent to the surface by a deity below who heated them (Lund, 1999). The tribe further believed that the waters would remain heated until there was no sickness left in the land (Lund, 1999). Thermal hot spring waters were also believed by the Sts'Ailes tribe to possess supernatural, in addition to medicinal, properties. They were convinced that heightened levels of endurance were granted to individuals who drank the hot spring water (Lund, 1999).

Native American Hot Spring Folklore

The use of hot springs by Native Americans goes well beyond the written record. For example, the Hot Springs in Arkansas, or "Valley of the Vapors" as it has also been called, were estimated to have been used for over 2,000 years (Lund, 1999). Historical tales that were orally passed down throughout generations, as well as archaeological evidence, document both the reverence of hot springs as well as their usage. Such evidence includes hundreds of approximately 2000-year-old petroglyphs that were spread around Legend Rock in Wyoming (Lund, 1999). These petroglyphs, illustrated in Figure 6.3, show aspects of ancient Native American life, including depictions of hot spring usage (Lund, 1999). Stories passed through word of mouth also play a large role in Native American hot spring reverence. One key anecdote concerns the Nez Perce tribe of the Pacific Northwest. This tale describes a near confrontation between members of the tribe and the U.S. General Otis Howard in 1870 (Lund, 1999). Out of fear of an impending battle, some Nez Perce left their children at a hot spring for protection while they prepared for battle (Lund, 1999). After the fear of confrontation had passed, the Nez Perce returned to the hot spring to find their children safe and sleeping (Lund, 1999). It was due to this fable that the hot spring was named "Sleeping Child Spring".

***Figure 6.3:** Ancient petroglyphs, estimated to be over 2,000 years old, at Legend Rock in Wyoming. These petroglyphs depict aspects of ancient Native American usage of thermal springs.*

European Documentation of Native American Hot Spring Use

The earliest written account of Native American hot spring use lies within the travel logs of the French Naval captain and explorer, Jean-Bernard Bossu. In his log, which dates back to 1771, he describes the ritual hot spring bathing by the Quapaw tribe (Bossu, 1963). Bossu also wrote that the hot spring waters were esteemed among Native American physicians (Bossu, 1963). The American explorers, Meriwether Lewis and William Clark, also documented Native American hot spring use twice in their encounters. Once in their 1805 expedition, and again in their subsequent return journey in 1806 which led them to the Lolo Hot Springs in Montana (Lewis, Clark and Ambrose, 1997). In Lewis' journal entry for June 29th, 1806, he described his time bathing in the Lolo Hot Springs with Native Americans (Lewis, Clark and Ambrose, 1997). He noted that the Native American tribe which he encountered alternated between using warm and cold spring water. They would remain within the hot spring for as long as they could bear, and then quickly ran to bathe in an ice cold stream nearby.

Ancient Speculations, Theories, and Perspectives of Geothermal Energy

In addition to ancient beliefs on the origins of hot springs, the causes of other geologic events such as earthquakes, volcanism, and other forms of thermal manifestations were often speculated upon and later attributed to geothermal energy. At the start of the 6th century BC, Anaximenes believed the deformation of the Earth's crust as it "dries" in periods of arid temperatures and "swells" in instances of precipitation was the cause of earthquakes (Cataldi and Chiellini, 1995). In the next century, the philosophers with the most notable scientific thoughts were Herodotus and Hippocrates. Herodotus generated descriptions of a plethora of Greek thermal manifestations and noted that some of these pneumae would form after instances of volcanism and reported them as "great clouds of fire" (Cataldi and Chiellini, 1995). At the same time, Hippocrates had reached the conclusion that water salinity was directly correlated to temperature (Cataldi and Chiellini, 1995).

Following the 5th century BC, prominent historical theories on geothermal energy could be found in Aristotle's book "*Meteorology*". In it, philosopher Democritus attributed earthquakes to fluctuations in subterranean water flow and pressure (Cataldi and Chiellini, 1995). In the same book, Aristotle proposed his own theory of earthquakes. He agreed with the notion that earthquakes were the product of pressure build-up; however, Aristotle theorized that rather than water pressure, it was gaseous pressure due to the thermal expansion from Earth's "internal fire" which caused earthquakes (Cataldi and Chiellini, 1995). This is similar to his theory on the origin of hot springs. The next period from the 3rd century BC to approximately 400 AD was a time of intense speculation regarding volcanism and explosions. It is during this time that detailed descriptions of phreatic explosions, the eruption of Mount Vesuvius, and even the warning signs of earthquakes were published.

Uses of Geothermal By-Products

Although historical uses of hot springs generated by geothermal gradients largely included their functions as medicinal baths, their applications did not stop there. A great array of geothermal by-products were relied on for buildings as well as used for arts and homemade items. For example, certain hydrothermal compounds and pyroclastic products (bentonite, perlite, etc.) could be found in homemade pottery, as well as in cement or other building materials (Cataldi and Burgassi, 1999a). Borates and iron oxides were also commonly desired as pottery glazes, as shown in Figure 6.4 (Cataldi and Burgassi, 1999a).

Thermal bathing itself as a cultural practice peaked in the early AD centuries when it was incorporated into everyday routines; however, following the fall of the Roman empire, it was no longer as widely used and a steep decline was observed (Cataldi and Burgassi, 1999a). Following the long recession, the same balneotherapeutic customs began to re-appear in the Late Middle Ages (Cataldi and Burgassi, 1999b). In addition to the customary re-instatement of hot spring baths, these regions gave rise to numerous hydrothermal minerals which were consistently used from the 11th to the 16th century. Yellow sulfur, green vitriol, blue vitriol, and boric acid in particular were extremely important due to the fact that they were used in the development of a variety of pharmaceutical compounds to treat conditions ranging from hemophilia to eye disease (Cataldi and Burgassi, 1999b).

The Chaudes-Aigues Geothermal Heating System

A small town known as Chaudes-Aigues in Europe is recognized as having a flourishing geothermal history. In the Late Middle Ages, starting from the 1300s, mentions of hot water distribution to local houses were discovered in property documentation in exchange for "*sous*", the monetary unit used at the time (Gibert and Jaudin, 1999). Within a century, water distribution in Chaudes-Aigues had developed to reach approximately 20 houses via pinewood pipes and was used not only for heat, but also for washing wool, treating textiles, and for general healthcare (Gibert and Jaudin, 1999). By the 1500s, the technological developments within the area allowed residents to wean off wooden pipes for distribution, instead, relying on channels (Gibert and Jaudin, 1999). Following the French Revolution in 1789, the hot water emanating from the spring was re-allocated to permit domestic heating within the town (Gibert and Jaudin, 1999). Eventually, the mayor of Chaudes-Aigues was required to intervene when the hot water pipes began to lack

Figure 6.4: *A porcelain vase made between 1722-1735 in Yongzheng, China. Its glaze is made from iron oxide, a geothermal by-product.*

in maintenance and started degrading. A plan was drawn which maximized the number of houses supplied with hot water to a grand total of 350 households (Gibert and Jaudin, 1999). The application of heat generation from geothermal methods was revolutionary and paved the way for further developments in geothermal research. Advancements in the field require a delicate balance and understanding of geology, geognosy, geography, ecology, and thermodynamics.

Geothermal Energy as a Modern Renewable Power Source

Progressive societal development in the modern world is driven by technological improvements. The US Census Bureau (2017) estimates the world population for 2017 to be around 7.4 billion people, with a projected population of almost 9.4 billion by the year 2050. The rapid increase in the number of Earth's inhabitants has inevitably sparked the urgency to find or produce more natural and capital resources. Therefore, the demand for material items as well as food and shelter will increase. This then raises the question of whether there are enough resources on this planet to provide for the number of people on it, specifically, if there will be space to build more housing units, and if a sufficient amount of electricity can be generated to supply these units. These concerns have led scientists to investigate alternative methods of energy generation, including geothermal energy.

Geothermal Power Plants

Earth's intrinsic thermal energy, which geothermal power plants exploit, is especially appealing as an alternative energy source because the natural heat of the core is not a tangible resource that can be suddenly depleted (Duffield and Sass, 2003). In order to harness the maximum amount of thermal energy, geothermal power plants must be built in areas of heightened tectonic activity, such as those along plate boundaries (Duffield and Sass, 2003). An extremely desirable region for further geothermal development is the rim surrounding the Pacific plate, referred to as the "*Pacific Ring of Fire*" (Duffield and Sass, 2003). For this reason, some of the largest geothermal installations of this time are located in New Zealand, Japan, and Mexico (Berman, 1975). In addition to these, other major plants can be found in areas such as Iceland, Italy, and California (Berman, 1975). As of 2016, it was estimated that approximately 93-94% of the Earth's geothermal potential still remained untapped (Matek, 2016). This indicates that there is ample room for improvement within the field of geothermal energy research which could give rise to major breakthroughs that will not only facilitate increased electricity supply to meet demands, but also contribute to a greener Earth through the application of renewable technologies.

Principles of Geothermal Power Generation

Although the concepts of geothermal energy are fairly simple, environmental conditions vary around the world. This brings forth the need for several different types of geothermal power generating stations specially designed for certain environmental conditions. Currently, there are three main types of geothermal plants: direct-steam, flash steam, and binary (Rafferty, 2000).

Direct-steam geothermal plants are used in vapor-dominated areas, which are extremely rare due to the fact that most geothermal areas contain liquid reservoirs, in lieu of vapor, below sea level (Allis, 2000). There are currently only four locations in the world - The Geysers (USA), Larderello (Italy), Kamojang (Indonesia), and Darajat (Indonesia) - that have been confirmed as vapor-dominated areas (Allis, 2000). These areas directly produce dry, superheated, and saturated steam which the direct-steam generators take advantage of (DiPippo, 1999). This steam is fed into a power generator to turn various impulse-reaction turbines (DiPippo, 1999). This fairly simple concept was used by some of the earliest geothermal power generating stations in both Italy and the USA around the turn of the twentieth century (Rafferty, 2000). Although relatively efficient, the reliance of direct-steam plants on the gas emanating from vapor-dominated areas makes them highly inefficient and costly if installed in any non- vapor dominated areas.

Flash-steam geothermal plants take advantage of the abundance of liquid-dominated geothermal resources using similar principles as those used by the direct-steam plants (Allis, 2000). They are also the most common type of geothermal power plant (DiPippo, 1999). Flash-steam plants use the high temperature water/water-vapor mixtures produced by many geothermal resources under high pressure, as shown in Figure 6.5 (DiPippo, 1999). High levels of pressure are able to decrease the boiling point of water, causing it to undergo flash evaporation when exposed to reduced amounts of pressure (Allis, 2000). This produces saturated steam, that is then used to turn turbines. However, only some of the high-temperature water is able to flash to steam. The high-temperature liquid water is then injected back into the geothermal resource to increase its longevity (Allis, 2000). Flash-steam geothermal plants, like direct-steam, are inefficient for use in areas with low-temperature geothermal resources.

Binary geothermal power plants, unlike direct-steam and flash-steam plants, are specially designed to utilize low-temperature geothermal resources (less than 150°C) (Rafferty, 2000). This is done through the usage of a "working" fluid with a low boiling point, such as isobutane and isopentane, or a mixture of water and ammonia (DiPippo, 1999). The working fluid is exposed to the heated waters of the geothermal resource, which have been pumped to the surface (DiPippo, 1999). This causes the fluid to vaporize, and then power a nearby turbine (DiPippo, 1999).

The ability to exploit the Earth's internal heat has allowed for the rapid development of geothermal power plants around the world. In fact, some countries are already taking advantage of their geographic location and the thermal activity associated with their positioning near or on tectonic plate boundaries. For example, the country of Iceland employs geothermal energy to power most of the country, with over 90% of the population's homes powered by the Earth's intrinsic heat (Lund and Boyd, 2016). Beyond this, approximately 70% of Iceland's primary energy supply is derived from geothermal energy sources (Lund and Boyd, 2016).

Future Directions of Geothermal Energy

In recent years, the importance of renewable energy sources, such as geothermal energy, has been heavily emphasized. Renewable energy sources are expected to provide 20-40% of global energy by the year 2050, and 30-80% of primary energy by 2100 (Fridleifsson, 2003). Geothermal energy will have a large influence on meeting future energy demands, as it possesses a technical potential of 5000 exajoules (EJ), which can more than satisfy the global yearly energy consumption of 400 EJ (Fridleifsson, 2003). Expanding the reach of geothermal energy and maximizing its technical energy potential will involve the use of innovative new generation stations as well as further exploitation of existing geothermal resources. Currently, new geothermal energy generators that exploit hot dry rock, geo-pressured and magmatic geothermal resources are in the developmental process (Barbier, 2002). Hopefully, with further research, these technologies can provide a more efficient, more sustainable future.

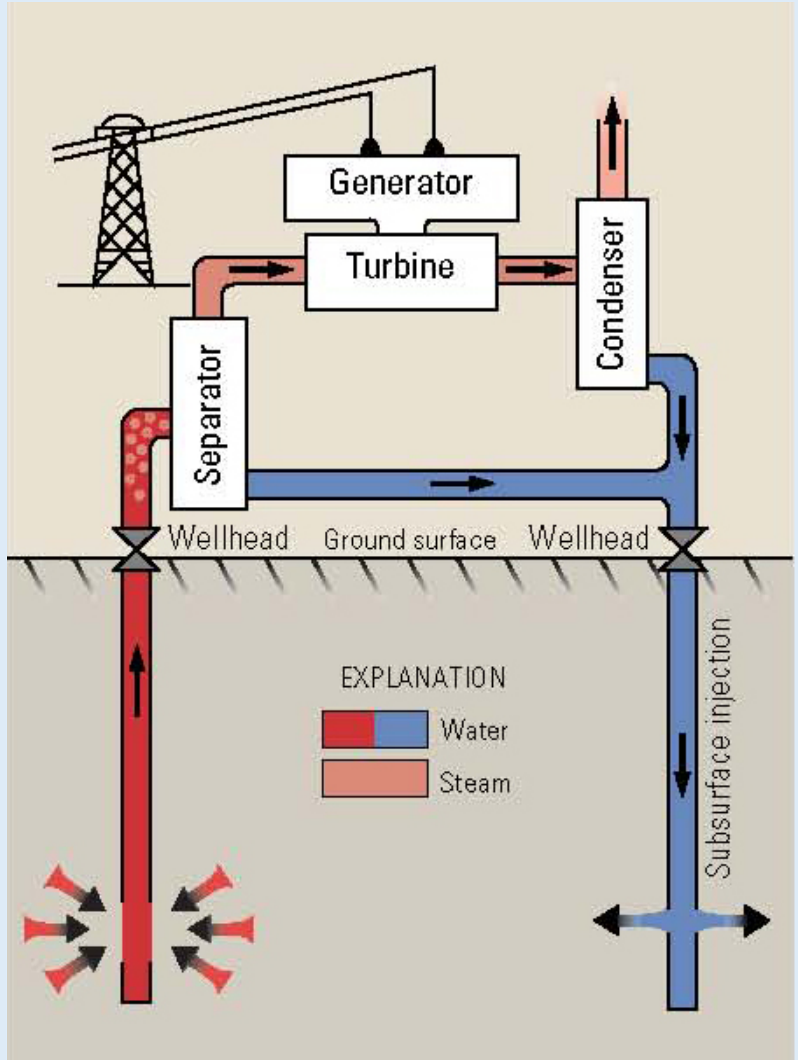


Figure 6.5: A diagram depicting the main components of a flash-vapor geothermal power plant.

The Development of Sedimentology

Science is a meticulous process of refining and redefining our understanding of the physical and natural world. In 1962, Thomas Kuhn published one of the most famous theories on scientific development in his book *The Structure of Scientific Revolutions*, and later refined this theory in a 1970 paper. In this literature, Kuhn postulates that scientific understanding does not steadily progress, but instead undergoes periods of revolution and refinement (Table 1). Kuhn's theory has notably been applied to turbidity current theory by Walker (1973), but can also be applied to the field of sedimentology as a whole. The oil industry is an integral part of this development in sedimentology and the mid-twentieth century spurred both crisis and revolution. Although the oil industry is arguably no longer the influence that it once was, its past involvement has lead to the modern development of sedimentology as an interdisciplinary study. The following will document this development of sedimentology from the perspective of Kuhn's postulates. Furthermore, all of these ideas are exemplified by the history of sedimentological studies at McMaster University, in Hamilton.

Table 1. Stages of Scientific Development (Kuhn, 1970)

1. *Early Random Observations.* No guidance from pre-existing theory; each worker develops his own hypotheses.
2. *Emergence of First Paradigm.* One of the hypotheses proves successful and is adopted by a group of scientists – it then guides their research activities.
3. *Crisis.* Facts or experimental results are found to be at variance with the paradigm. As more discrepancies are found, a state of professional crisis may develop.
4. *Revolution.* A new theory, capable of explaining the discrepancies, emerges. During a scientific revolution, the old paradigm is rejected and replaced by a new one.
5. *Mopping up.* The new paradigm is elaborated during a period of "normal science" (or "mopping-up operations").

Early Random Observations: From Ancient Greece to Early Facies Models

The establishment of the field of sedimentology is generally agreed by most American historians to have occurred in 1859 (Middleton, 2009). However, long before this time period, the ancient Greeks recorded the earliest hypotheses on how the Earth and its sediments formed (Oldroyd, 1996). Although many of these thoughts were based on thought experiments, they were surprisingly accurate and ahead of their time.

Many ancient Greek ideas about geological processes were documented by the Latin poet Ovid in the first century AD, who attributes the roots of these thoughts to Pythagoras. He was a mathematician and philosopher who lived in sixth century BC and he first reasoned that the Earth was round (Oldroyd, 1996). Pythagoras also influenced the thought of a later philosopher, Heraclitus, who believed that Earth was in an eternal flux in which earth changed to water, which then changed into air, which finally changed into fire, before this process was reversed (Oldroyd, 1996). These speculations fit well with the four element theory that was rising to prominence in Greek philosophy at this time. A later historian, Herodotus (484-425 BC), further developed thoughts about the shaping of the Earth. Herodotus developed the first recorded hypotheses about river deltas. Herodotus compared the Nile River Valley with the Red Sea and reasoned that if a large river were to flow in the Red Sea, it would gradually fill up with loads of sediment like the Nile and the Nile Delta (Oldroyd, 1996). After observing shells and black soil in the hills of the Nile Valley, Herodotus concluded that the Nile Valley had been deposited over thousands of years (Oldroyd, 1996). There are additional documented ideas from Herodotus on the submarine formation of flat land and earthquakes preceding river formation (Oldroyd, 1996). Later philosophers, most notably Plato and Aristotle, built further on Herodotus's work; however, Herodotus's thoughts can perhaps be categorized as the first random observations and hypotheses of sedimentology. Herodotus observed landforms and considered existing processes to think about how the Earth may have been shaped over many years.

Thought processes similar to those of the ancient Greeks about the Earth were not documented again for millennia. Geological principles were gradually developed after the eighteenth century until specialized fields emerged, including stratigraphy, the precursor to sedimentology. Nicolaus Steno (Figure 6.6), who also studied anatomy and paleontology, began this process by first recognising stratification in 1669 and describing his famous three principles for the deposition of strata (Steno and Winter, 1968). Steno's work was not able to progress much further, because as a bishop he was unable to think outside of the literalistic religious doctrine of the time (Okada and Kenyon-Smith, 2005). Later, other observations and hypotheses emerged, such as Neptunism and Plutonism. James Hutton, William Smith, Charles Lyell, and Amand Gressly can be credited with much of the further progress of stratigraphy into the mid-nineteenth century. This includes the establishment of facies, which was critical for sedimentology to begin. These developments are documented in detail by Okada and Kenyon-Smith (2005).

Figure 6.6: *A painting of Nicolaus Steno as a bishop.*

Sedimentology can be broadly defined as the study of sediments and sedimentary rocks to determine how these rocks reformed, with particular emphasis on the environment at their time of formation (Okada and Kenyon-Smith, 2005). With this definition in mind, the work done by Henry Clifton Sorby from 1859-1908 likely marks the beginning of observation and hypotheses in sedimentology as a separate field from stratigraphy (Okada and Kenyon-Smith, 2005). Sorby was a gifted microscopist, and used this skill to study sedimentary rocks under a microscope (Folk, 1965). While most geologists were only concerned with these rocks for their places in the strata, Sorby hypothesized that their characteristics could be used to reconstruct paleogeographic conditions (Okada and Kenyon-Smith, 2005). Sorby's position of influence within the Geological Society of London allowed him to communicate his ideas to a large, influential audience and essentially lay the foundations for sedimentology (Pettijohn, 1975). German geologist Johannes Walther continued to add new hypotheses in sedimentology with publication of his Law of Correlation of Facies in 1894 (Middleton, 1973). Walther grew up as a privileged child who was given every opportunity to succeed in academia (Reyment, 1991). His work focused on organic sediments before he travelled the world to study reefs and deserts (Middleton, 1973). From his observations, he concluded that consecutive layers of sediments were formed in once laterally adjacent environments (Middleton, 1973). While many of his contemporaries neglected James Hutton's Principle of Uniformitarianism, Walther applied it quite accurately in his law (Reyment, 1991). Unfortunately, Walther's work was not widely accepted during the time of his publication because it challenged conventional theories (Reyment, 1991). Walther's work was only referred to as comparative lithology, although it can be considered as some of the earliest observations and hypotheses within the field of sedimentology. Later work, which built on the foundations of Sorby and Walther, was completed throughout the early twentieth century. The term 'sedimentology' was not actually used in a publication until 1927, although early random observations and hypotheses had already begun (Middleton, 1978).

It is important to note that at this point, the oil industry had already started at this time and was hiring geologists; however, it was not yet particularly concerned with the science of sedimentology (Middleton, 2004).

Emergence of the First Paradigm

The broad questions originally asked regarding sedimentology had begun to be answered, which set the path for new, more narrowed questions. Now that facies and sedimentary rocks were better defined, the term 'sedimentology' was created. Moreover, the field itself was recognized and a collection of accepted theories and research emerged.

The first sedimentology textbook was written by Hatch and Rastall in 1913 on the petrology of sedimentary rocks, with another book on petrology following in 1916 by Cayeux (Middleton, 2009). It is quite interesting, yet unsurprising when considered, that the oil industry played a great role in the development of sedimentology (Middleton, 2004). In the 1950s, it is believed that the oil company Shell knew more about carbonate sediments than any university at that time (Middleton, 2004).

Sedimentary petrology was a large field in the early twentieth century, with many of these geologists studying heavy minerals, defined as a mineral with a specific gravity of greater than 2.85 (Okada and Kenyon-Smith, 2005). This was particularly common in Great Britain and continental Europe, with a great discovery made in 1916 by Illing (Okada and Kenyon-Smith 2005). He said that in a given basin, the sedimentary units that compose said basin tended to have a unique collection of detrital minerals (Okada and Kenyon-Smith, 2005). Illing's work can be considered part of a first paradigm in sedimentary petrology. This paradigm was further improved with the development of the "heavy mineral correlation," which is used in stratigraphy and had a great influence on the search for petroleum (Okada and Kenyon-Smith, 2005). The interest and dedication to sedimentary petrography was highlighted by Milner's 1922 *Principles of Sedimentary Petrography*, an outline to the study of detrital minerals of sands.

Three years prior to this revolutionary book, C.K. Wentworth published "A Field and Laboratory Study of Cobble Abrasion" in the *Journal of Geology*. This master's thesis marked another incredible advancement in the field - the transition from a subjective, qualitative approach to the implementation of quantitative measurements (Okada and Kenyon-Smith, 2005). While he was not the first to use quantitative measurements, Wentworth set a standard for this technical approach to the field (Okada and Kenyon-Smith, 2005). Wentworth even attempted to devise a procedure for grain sizes; however, Parker Trask was ultimately successful in this endeavour (Okada and Kenyon-Smith, 2005).

Sorby, the geologist and microscopist, is referred to as "the father of petrography", in part because of his theory which dictates that the ratio of solids to voids in argillaceous rocks varies with depth (Rubey, 1927). In due course, many more studies were performed based on this theory in order to determine its validity and to continue to learn about the effects that gravity can have on sedimentary structures (Rubey, 1927). This innovation also allowed for new insight into anticlines and unconformities, such as Hedberg's 1926 study (Rubey, 1927). In 1927, a discussion by W.W. Rubey was published, discussing Hedberg's work (Rubey, 1927). This led to a dialogue of papers between Rubey and Hedberg, whom replied to Rubey's discussion around two months later in August of 1927 (Hedberg, 1927).

In contrast to Sorby's excellence and title of the patriarch of petrography, it has been argued that rather Lyell truly confirmed sedimentology as a scientific discipline. Before Sorby's time, Lyell was willing to consider new ideas even if they contradicted accepted theories (Leeder, 1998). In Lyell's "Principles of Geology," published in 1830, he dictates many impressive concepts regarding sedimentology (Leeder, 1998). These concepts included the creation of geologic periods based on characteristics (Leeder, 1998).

Sedimentology had an overall strong start; however, as with nearly any field, contradictions arose and created arguably more challenges than the blank canvas of a new discipline.

Crisis: The Search for Oil

In Kuhn's crisis stage, mounting evidence discredits accepted theories leading to the eventual rejection of such theories. Crises are difficult to pinpoint in sedimentology as a whole because there are many processes within the field. As a result, the study of these individual processes exhibit their own respective crises and revolutions. Within this context, the economic motivation to find petroleum deposits from 1930 – 1950 fuelled studies of sedimentary rocks and strata. The search for oil lead to a crisis in not only the sedimentary theory of how petroleum was formed and trapped, but also how sediments were studied.

In 1930, the oil industry became very interested with stratigraphy and sedimentology when the East Texas oil field, a stratigraphic trap (Figure 6.7) and the largest oil field at the time, was discovered (Middleton, 2004). This discovery made petroleum geologists question the theoretical framework that they had previously used to find oil. Oil was in increasing demand as automobile production and sales skyrocketed (Dietsche and Kuhlgatz, 2015). The leading petroleum geologist of the day and Dean of the School of Mineral Sciences at Stanford University, Arville Irving Levorsen, suggested in 1934 that many oil fields were trapped in unconformities and later coined the term "sedimentary trap" (Berry, 1965). Levorsen later argued in 1941, with a large audience at a symposium to celebrate the fiftieth anniversary of the University of Chicago, that microscopy should be applied to study the strata and sediments within the context of petroleum geology (Middleton, 2009). With these words, he encouraged colleagues to expand their scope beyond stratigraphic layers. It was also at this symposium when William Krumbein presented his paper, “Principles of sedimentation and the search for stratigraphic traps” (Middleton, 2009). These events not only began to change the contemporary trends in sedimentology research, but also influenced the future of sedimentology by greatly encouraging many Departments of Geology in the United States to teach undergraduates microscopic petrography (Middleton, 2009). This crisis set the context for a revolution in sedimentology.

The growing influence of the oil industry in sedimentology was exemplified by McMaster University’s School of Geography and Earth Sciences in the 1950s. These times marked the hiring of two of the school’s most famous sedimentologists, Gerard V. Middleton and Roger Walker, whom had strong ties to the oil industry. Middleton was an active member of the American Association of Petroleum Geologists and worked in the summer for Shell Development company. Similarly, Walker was an esteemed member of the Canadian Society of Petroleum Geologists. (Middleton, 2004).

Revolution: A New Search Strategy

The natural progression of any scientific discipline after any crisis is a revolution: the substantiation and acceptance of a theory among a group of contradicting theories. As Kuhn (1970) suggested, the discrepancies are accounted for and a new, more accurate theory arises. This, in turn, allows for continued progression in the respective field.

As the oil industry grew to meet the demand of automotive vehicles, power, and manufacturing, sedimentology became an essential aspect of successful oil extraction (Friedman, 1985). The American Petroleum Institute began Project 51 as a study of modern depositional environments in a professional and methodical manner - as a true science (Friedman, 1985). Additionally, sedimentation in the northern coast of the Gulf of Mexico was studied in a manner that set a standard for subsequent studies (Holmes, 2011). Researchers were able to describe the facies relations and distributions of sediments with these procedures, an incredibly important success for sedimentology and for the oil industry at large (Holmes, 2011). Project 51 was an interdisciplinary project, and required concepts from sedimentology, biology, and chemistry (Shepard, 1955).

Some of the procedures used in Project 51 were Wentworth’s grade sizes to estimate the volume and quantity of sediments in sifts, which then enabled researchers to characterize environments (Shepard, 1955). Biostratigraphy, with the use of both macro- and micro-organisms, such as Ostrocods and Foraminifera, respectively, was used (Shepard, 1955). In particular, statistical analysis of the collections of such organisms was helpful in the relation of different terrestrial and hydric environments (Shepard, 1955). The Mississippi Delta was one of the regions studied in this project, which provided great insight into deltaic and river environments (Moody, 1955). The researchers

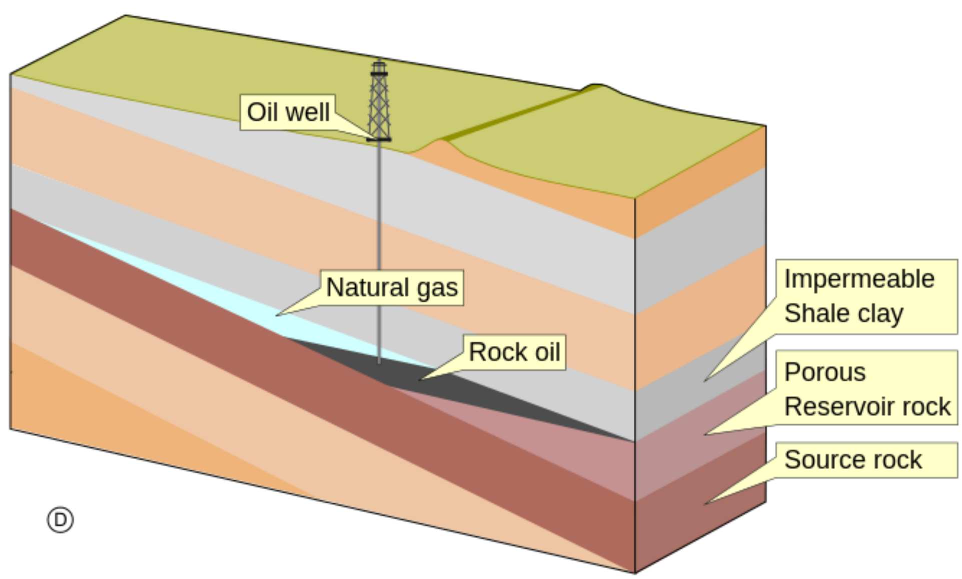


Figure 6.7: *A diagram for a stratigraphic trap is shown. There are numerous types of stratigraphic traps in which oil can be found.*

were able to determine many relationships from these environments, such as the distance of chemical compounds, like calcium carbonate, from rivers of origin. The abundance of clay minerals based on the distance from the continental shelf, viewed as the shore, and from river mouths was another relationship determined by the researchers (Shepard, 1955). Similarly, grain sphericity and smoothness was related to environments, and sorting and skewing were also related to environments (Shepard, 1955). The deposition of clays, silts, and sands was also found to be related to the environment and this allowed for computation of patterns in such depositional environments (Shepard, 1955). This new, deep understanding of the Gulf of Mexico enabled the discovery and extraction of oil from reservoirs of thick-deltaic and delta front origins, sandstones, and carbonates (Holmes, 2011).

Project 51 substantiated the relationship between sediment size and sphericity to depositional environment (Shepard, 1955); however, the discovery of coarse sediment in deep water contradicted the logical patterns determined by the project (Brenchley, 1985). Turbidity currents were introduced as an explanation to this contradiction by Kuenen and Migliorini in 1950 (Brenchley, 1985). Turbidity currents are a type of gravity current, which is a type of flow (Brenchley, 1985). These currents occur when sediment in a medium causes an excess of density and as a result, they were believed to be a likely mechanism of transport for coarser sediments to deep water (Brenchley, 1985). Research on turbidity currents was prominent and impressive, particularly at McMaster University because of Drs. Middleton and Walker. The experiments of Dr. Middleton, as a professor in the Department of Geology, made an incredible impact in research on turbidity currents, especially the coarse-grained turbidite model (Middleton 2004; Brenchley, 1985). This model describes a "sharp, scoured base, a negatively graded lower division, an intermediate massive, stratified, graded-stratified division and an upper division with dish and pipe structures" (Brenchley, 1985). The structure results due to long-distance transport by turbidity currents (Brenchley, 1985). This is in contrast to the medium and fine grained turbidite models (Brenchley, 1985).

Other revolutions from the mid-to-late twentieth century include more laboratory experiments to understand bedforms from waves and rivers, mathematical models of sedimentation flows, theory and quantitative approach to sediment transport, applications of geophysics to sedimentology, and recognition of deep-sea clastic sediments rather than the previously believed calm, deep ocean (Brenchley, 1985).

Geophysical Study of Bright Spot Strata

By 1980, the petroleum industry was gradually contracting research in facies models when it was found that new technological advances in geophysics enabled a relatively efficient way to find new oil wells (Middleton, 2004). Large-scale basin analysis was revolutionary and beyond this, sedimentology had also diversified in its 'mopping up'. By 1967, a great majority of its studies were outside the scope of the oil industry (Kölbl, 1967). However, this field continued to benefit from the technological advances made in connection to petroleum. There were advances of these geophysical techniques within the oil industry, as well as benefits from the oil industry in sedimentology to refine the theories produced during the revolution of the 1960s and 1970s.

The Oil Industry

The continued success of the oil industry is dependent on the use of geophysicists and the principles they study. The most important technique to the field is the seismic method. Geophysicists enable an effective approach to the investigation of oil fields due to the application of concepts, including the seismic method, to determine the layers of strata beneath the Earth's surface (Yilmaz, 2001). This allows the oil companies to know exactly where the oil reservoirs are, rather than the guessing game that used to be common practice (Friedman, 1985).

The seismic method has three major principles, each with distinct applications in the oil industry, academia, and economic geology as a whole (Yilmaz, 2001). The oil industry mandates exploration seismology, which entails the search for hydrocarbons and the discovery of oil fields up to a depth of 10 kilometres (Yilmaz, 2001).

In contrast, geological engineers participate in the delineation of near-surface geology, typically for coal and mineral searches up to 1 kilometre. This study is referred to as engineering seismology (Yilmaz, 2001). Earthquake seismology is used by seismologists to closely examine the crustal structure of the Earth up to 100 kilometres deep in order to detect and understand earthquakes and plate tectonics (Yilmaz, 2001).

Geophysicists were able to greatly increase the productivity of oil fields with two and three dimensional seismic imaging, as these images allow for the prediction of gas and oil reservoirs, thereby allowing oil companies to place wells appropriately (Anderson et al., 1996). Sound frequencies are transmitted and the record of overlapping acoustic reflections is used to map the varying stratigraphic layers and structures within the given area (Anderson et al., 1996). Oil is then extracted from these strata by sending sound frequencies into the strata that match the resonance frequencies of the specific stratigraphic layers, particularly the rock matrix and hopefully the oil (Ellingsen, 2002). The frequencies allow for a decrease in the strength of the cohesive and adhesive bonding of the gases and oils which, in turn, enables an easier extraction process (Ellingsen, 2002). Areas with high hydrocarbon content in the strata are known as "Bright Spots" – the landscape of which often fills with oil wells that use this technology (Anderson et al., 1996). The acoustic frequencies emitted in "Bright Spots" are also used in classic seismology to determine faults, which can often be sources of earthquakes (Wang, 2002). In 1999, an unusual earthquake that hit Taiwan activated the Chelungpu thrust fault and the seismic method outlined above was accurately used to map the fault structure (Wang, 2002).

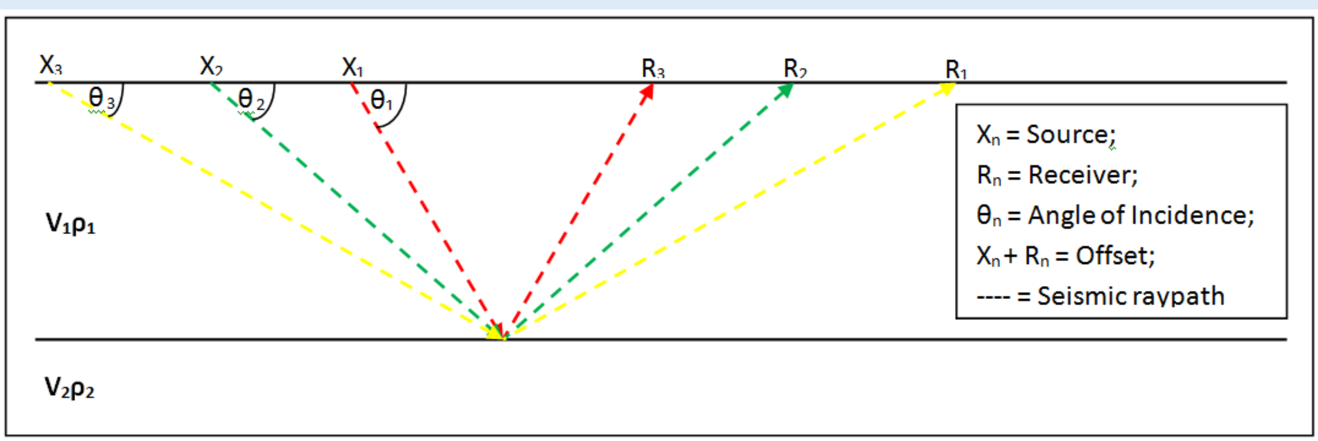
Academic Progress

The use of the seismic method in areas of high geothermal activity greatly increased due to the interest in geothermal energy sources (Foulger, 1982). Progress in seismic imaging is imminent and very relevant to the expansion of both academia and the oil industry. The ambition of seismic imaging (Figure 6.8) has shifted from merely a technique used to accurately find oil to one that can potentially create an accurate depiction of the Earth's interior (Etgen, Gray and Zhang, 2009). Strides have been made in this area, including the work of Dave Hale from the Colorado School of Mines (Hale, 2013). He used computational algorithms to improve the quality of three-dimensional fault images, depict fault surfaces, and fault throws (Hale, 2013). He combined the information he gathered to create a holistic model of fault structures using spatial warping (Hale, 2013). While there is still a great deal of manual labour required in these processes, progress has been made in the discipline; however, faults that intersect each other are still quite a challenge in seismic imaging (Hale, 2013).

The McMaster Connection

Geophysics is also used to study sediments at McMaster University. Within the McMaster Earth Surface Processes Research group, Joseph I. Boyce uses ground penetrating radar (GPR) to study the groundwater and characterize environmental sites and magnetic profiles to study sediments in urbanized environments (see Boyce, Pozza and Morris, 2001). The prominence of sedimentologic research at McMaster University owes a great debt to the work of Middleton and Walker, who were strongly connected to the oil industry.

Figure 6.8: *A visual depiction of vibrational wave pathways, which are used to find oil and the focus of earthquakes.*



The Discovery and Development of the Alberta Oil Sands

Canada has a diverse geological landscape. One of Canada's defining features is the Athabasca Oil Sands located in northeastern Alberta next to the Canadian Shield. This deposit of bituminous, tar-like sand was formed in the Devonian period from the deposition of organic sediment (Carrigy, 1973). Over millions of years, the organic matter turned into oil through heat and compression. The oil rose through the rock layers and was trapped in early Cretaceous quartzose sand (Carrigy, 1973). Through glacial erosion, these layers were exposed in the Athabasca region, mainly along various local river beds (Mackenzie, 1911; Franklin, 1828). The Alberta oil sands are currently a topic of controversy as there are many positive and negative implications of oil sand extraction. These oil sands have a long history of discovery, exploitation, and development that has established them as an important part of Canadian history.

First Explorers and First Encounters

Before the settlement of North America by the Europeans, Aboriginal people occupied the Athabasca region (Pentland, 1985). The Cree, Chipewyan, and Métis people lived off of the land and were the first to encounter and use the oil sands (Alberta Geological Survey, 2000). The Aboriginal people utilized the stickiness of the bituminous sand to repair damages and cracks in their canoes (Mackenzie, 1911). The course of history may have been vastly altered if not for a First Nations Cree Chief in the early 1700s, Captain Swan. He was a peacemaker between the Aboriginal people and the European settlers. In 1719, he sent a sample of the bituminous sand as a peace offering to Henry Kelsey, Governor of the York Factory, a settlement and Hudson Bay Company trading post. In the accounts book of the York Factory, Kelsey recorded this exchange as "a sample of that Gum or pitch that flows out of the banks" (Pentland, 1985).

The North American fur trade is an important aspect in the history of the Athabasca Oil Sands. Two rival companies, North West Company and Hudson Bay Company, both wanted to establish profitable fur trade routes with the Aboriginal people in the Athabasca region. As the two companies competed for business in the western part of North America, it pushed them to send more explorers to the region (Government of Canada, 2016). This led to further documentation of the land and sparked the interest of the Geological Survey of Canada (Government of Canada, 2016).

The first European to explore and make observations on the Athabasca region was Peter Pond in 1776 (Government of Canada, 2016). A fur trader and cartographer, Pond was determined to map the unknown regions of Alberta while also establishing a direct trade route between the local Aboriginal people and the North West Company (Government of Canada, 2016). These initial expeditions to the Athabasca region were followed by many more avid explorers. Sir Alexander Mackenzie was an important historical figure as he was the first person to travel across North America from Montreal to Alberta (Mackenzie, 1911). He worked with Pond on expeditions for the North West Company, increasing his familiarity and intrigue in the region. In his published accounts of his journey, Mackenzie noted bitumen on the banks of the Slave, Clearwater, Athabasca, and Mackenzie rivers (Mackenzie, 1911; Alberta Geological Survey, 2000). Mackenzie also documented outcrops of lignite that were constantly on fire that would be again noted by John Franklin more than 20 years later (Franklin, 1828). In working with the Aboriginal people to explore the region, Mackenzie was shown how to repair his canoe with the bituminous sand from the region. This is one of the first documented uses of the Alberta oil sands.

In 1825, John Franklin started his second expedition that spanned the course of 3 years. In his time, he explored the northern shores of Canada and made his away along the Mackenzie river down to Lake Athabasca and the Athabasca river (Franklin, 1828). He made many observations about the various types of muds, bituminous clays, lignite, and overlying sandstone of the region, and noted how the lignite and bituminous shale deposits were similar to those on the Arctic coast (Franklin, 1828). Without these first observations and expeditions from the various explorers in the late 1700s and early 1800s, there may not have be as much of an interest in the oil sands as there is today. These groundbreaking explorers paved the way for geological surveyors to map the land and uncover the resources below.

Early Surveys of the Athabasca Region

In 1848, John Richardson performed the first geological assessment of the Athabasca Oil Sands (Alberta Geological Survey, 2000). He was able to correlate the layers of oil sands to the Devonian shales observed in New York, successfully dating the oil sands. He also performed extensive microscopic tests on the oil sands to determine that the key component is quartz (Alberta Geological Survey, 2000). John Macoun furthered the geological mapping of the Athabasca Oil Sands in 1875 (Geological Survey of Canada, 1883). As part of the Geological Society of Canada, he was tasked to survey the area with a specific geological perspective. During his journey, he observed many important locations for oil sands and the various regions that they can be extracted from. He noticed that tar sands appeared as he ascended the lower Peace and Athabasca rivers and noted that tar conglomerate became common in 2 feet thick beds in the strata along these banks (Geological Survey of Canada, 1883). One important finding by Macoun was that liquid oil seeped out from the banks and into the streams. There were thin layers of oil on top of the water which indicated that there were large reserves of oil sands beneath the surface (Geological Survey of Canada, 1883). This "ooze" seemed to flow out from the ground and down the slopes to create long, tarred surfaces along the beaches. As he continued to examine the geology of the area, he documented that the oil shales continued along the clearwater river, but dipped beneath the soil as he moved farther away from the river (Geological Survey of Canada, 1883).

Later in 1882, Robert Bell examined the geology and economic significance of the Athabasca River. In his report, he notes the overwhelming abundance of "black petroleum-bearing fine-grained sandstone" which underlies almost all other strata and Cretaceous fossils including gastropods and shells (Bell, 1884). From this, he confirmed Richardson's suggestion that the oil sands were formed in the Devonian age and were trapped in early Cretaceous rocks (Alberta Geological Survey, 2000; Bell, 1884). A similar observation to Macoun was made that when the weather was warm, tar would seep out of the saturated banks along the river. Once the tar was flowing, it was able to collect pebbles and boulders that, when flattened by ice, produced natural asphaltic pavements (Bell, 1884). Bell was one of the first to note the economic significance of petroleum and asphalt. In a report to the Senate Committee, he stated, "The evidence … points to the existence in the Athabasca and Mackenzie valleys of the most extensive petroleum field in America, if not in the world… it is probably this great petroleum field will assume an enormous value in the near future and will rank among [Canada's] chief assets." (Alberta Geological Survey, 2000).

In 1888, Richard George McConnell surveyed the previously unexplored areas between Peace and Athabasca River. McConnell estimated the age of the bituminous sands to the Dakota Formation by correlating lithological and stratigraphical evidence (McConnell, 1893). He credited the Late Cretaceous Western Interior Seaway for creating the oil-rich strata. He also noted that the bituminous sands increased in thickness going down the river, an important consideration for future drilling sites (McConnell, 1893).

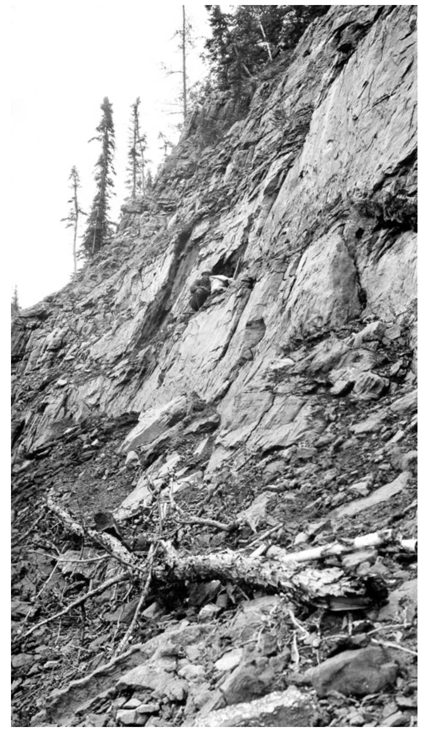


Figure 6.9: *A thin layer of oil sands along a steep outcrop.*

Bell and McConnell had many similar conclusions. They both believed that the petroleum found saturated in the Cretaceous sandstones are derived from the underlying Devonian limestone, evidenced by bituminous-filled cracks and fissures in the limestone (Bell, 1884; McConnell, 1893). Further, they both agreed that the majority of the available petroleum is contained by stratigraphic traps, notably in the crowns of anticlines and domes where oil cannot escape the impervious overlying strata (Figure 6.9).

Initial Recovery Processes and Proposed Uses of the Sands

In his 1882 survey, Bell noted that the tar was covered by an impervious crust of pitch and vegetation (Bell, 1884). Small holes were broken through the crust and the tar was extracted using wooden spatulas. The tar was then sent to the Hudson Bay Company for further analysis. Bell, accompanied by chemist George Christian Hoffmann, determined that approximately 69% of bitumen can be removed from a bituminous sand sample by boiling the sample in hot water (Bell, 1884). He also proposed an alternate method of extraction involving the use of an organic solvent to dissolve the oil and then later distilling the solvent to retrieve the oil. However, this method later proved to be ineffective.

Bell and McConnell hypothesized that the tar sands would be extremely profitable due to their high percentage and abundance of bitumen. Three main uses were proposed by Bell and McConnell for the oil sands: (1) use of the bituminous sands for pavements and roofing, (2) use of separated bitumen for road construction and waterproofing surfaces, and (3) use of bitumen or the bituminous sands as sources of petroleum products (Bell, 1884; McConnell, 1893). These uses, however, were limited by the lack of accessibility to the oil sands region. Bell and McConnell noted that construction of a railway and separation of bitumen from the sands on-site would resolve these issues (Bell, 1884; McConnell, 1893). McConnell particularly emphasized the necessity for drilling the oil sands as the only way to confirm if a high amount of oil is present (McConnell, 1893). He suggested drilling in areas where the bituminous sand is covered by shales, which he predicted would render the oil unable to escape.

First Drillings of the Athabasca Region

Due to McConnell's recommendations, the Geological Survey of Canada started drilling a well at the Athabasca Landing in 1894 (Clark and Blair, 1927). The well was drilled to a depth of 1770 feet before the project was abandoned in 1896, without reaching any oil. Difficulty arose when a much larger than expected depth of overlying, inconsistent strata was encountered (Clark and Blair, 1927). A second boring took place in 1897, 115 miles below the Athabasca landing near the junction of Pelican and Athabasca rivers (Clark and Blair, 1927). As predicted by McConnell, bituminous sand was reached at a depth of 740 feet. Drilling was continued until a depth of 820 feet was reached, at which point a large flow of gas was struck. This caused dangerous working conditions and so drilling ceased until 1898. However, the gas pressure was still extremely high and the project was fully abandoned before achieving its goal of reaching the Devonian limestone, the predicted source of the petroleum (Clark and Blair, 1927).

Figure 6.10: *Workers surveying the oil sands along the bank of a river in Alberta at the beginning of the 20th century.*

Count Alfred von Hammerstein was a German-born entrepreneur who, on route to Yukon to try his luck at the Klondike gold rush, heard rumours of the supposed oil riches of Alberta (Sheppard, 1989). He abandoned his initial plans and, starting in 1906, drilled numerous wells into the Devonian limestone exposures along the Athabasca river. Hammerstein sought to tap into a liquid reservoir of free-flowing oil, which he believed the bituminous sands derived from. Though he did not extract anything of significance, Hammerstein became the first of many private entrepreneurs who attempted to capitalize on the Alberta oil sands (Figure 6.10) (Clark and Blair, 1927).

Early Commercial Uses of the Sands

Sidney Ells, otherwise known as the "father of Alberta bituminous sands", was an engineer of the Canadian Government Department of Mines and a large contributor to the development of the Alberta oil sands. His preliminary examination of the bituminous sands in 1913 refuted the belief that a free-flowing pool of oil exists under the sands (Ells, 1914). He was also the first and only person to create a completed set of topological maps of the bituminous area (Ells, 1914). These maps identified areas of high grade bituminous sand deposits and paid special attention to the commercial considerations of oil sands by noting the locations of impossible river banks, terraced lands, and current and future railheads (Ells, 1914). From 1910 to 1922, Ells drilled 41 wells in the oil sands area to further his research of the sands economic possibilities (Ells, 1926). Though his wells did not have a large significance in regards to oil, his work advanced the understanding of the geology of the area and suitable drilling techniques. Possibly Ells' most notable contribution to the Alberta oil sands was when in 1915, he successfully showed that bituminous sands can be used for pavement construction (Clark and Blair, 1927). Sixty tons of bituminous sands were mined in 1914, transported to Edmonton by dogs, worked into pavement aggregate, and laid on concrete foundation along a 618 yard stretch on Fort Trail (Clark and Blair, 1927). Ells also experimented with different separation techniques to separate bitumen from bituminous soils. The Mellon Institute of Industrial Research in Pennsylvania extended an invitation to Ells in 1915 to allow him to conduct research on hot water separation techniques (Ells, 1926). There, Ells experimented with different temperatures, pressures, and acids, and he was assured that a hot water separation technique should be applicable to the Alberta oil sands (Ells, 1926). His report detailed his findings and included an extensive compilation of different separation techniques utilized throughout Europe and the United States (Ells, 1926). Ells was truly enamored by the oil sands, and even after retirement he continued to promote their commercial development.

The work done by Ells paved the path for Thomas Draper, president of the McMurray Asphaltum and Oil Company, to promote the commercial exploitation of the oil sands for pavement construction (Clark and Blair, 1927). The 1920s proved to be the year of renewed interest in the oil sands by the Canadian government. That year, Ottawa issued Order in Council (OIC) No.1495 that reclaimed all unleased lands with promising deposits of bituminous sands and issued stricter lease regulations requiring applicants to have a feasible process to utilize the bituminous sands (Allan, 1921). In the same year, the Northern Alberta Railway extended to Fort McMurray, thereby creating the transportation necessary for any commercial development to occur (Allan, 1921). Additionally, in 1922, Draper sold 2 carloads of bituminous sand for sidewalking purposes to the city of Edmonton (Clark and Blair, 1927). Later in 1923, the province of Alberta purchased 185 tons of bituminous sands and laid it on 750 feet of roadway on the rural St. Albert trail (Clark and Blair, 1927).

Clark's Separation Technique

Pavement construction was not the primary utilization of the oil sands. Separated bitumen has many more economic utilizations than bituminous sands and were much easier (and far cheaper) to transport than the heavyweight sands. The focus was shifted to developing an effective separation technique that could be easily scaled up for large volumes of bituminous sand. Different separation techniques were created and tested by many individuals with variable degrees of success, but none were able to design a process that was practical for large scale commercial applications.

Karl Clark was a research engineer of road materials and a chemist who perfected and detailed the hot water separation method of bituminous sand in his 1927 report, "The Bituminous Sands of Alberta". He was instructed by the Alberta Scientific and Industrial Research Council to find a promising utilization of the Alberta oil sands. Initially, Clark thought the tar sands could be used to waterproof roads, but in 1922, he concluded that the pavement purposes of the sands were not economically viable due to high transportation costs (Clark and Blair, 1927). Since separated bitumen could be used readily for pavement construction as liquid asphalt and may be converted to a potential motor fuel through a newly popularized "cracking method", Clark redirected his efforts to developing an effective commercial separation technique outlined below (Clark and Blair, 1927).

When bituminous sand is in constant contact with a hot, dilute solution of silicate of soda and is placed in a hot water reservoir with agitation, a complete separation between the sands and the bitumen takes place (Clark and Blair, 1927). Once the agitation ceases, clean, bitumen-free sand settles to the bottom and bitumen collects on the surface in a light froth form. Repeated operation of this process generates more froth and therefore more separated bitumen. This process was found to be extremely effective, with recovered bitumen containing only 10% mineral matter and 20% water content. This process works due to the formation of bitumen emulsions. Treating the bituminous sands with silicate of soda solution results in a water-in-oil (W/O) emulsion in which water droplets are dispersed in a continuous oil phase. The addition of excess hot water causes the inversion of the W/O emulsion to an oil-in-water (O/W) emulsion. Due to the instability of the O/W emulsion, globules of bitumen form and rise to the surface of the water (Clark and Blair, 1927).

Clark's technique was employed in 1925 by the Roads Material Division of the Scientific and Industrial Research Council of Alberta who designed and operated the first separation plant for the Alberta oil sands, the Dunvegan plant, on the outskirts of Edmonton. 500 tons of sand was treated in this plant in 1925 with extremely promising results (Clark and Blair, 1927).

Development of Commercial Oil Sand Plants

In 1927, Robert C. Fitzsimmons founded the International Bitumen Company and began construction of Bitumount, the first commercial plant of the Alberta Oil Sands (Sheppard, 1989). This plant, which used a crude separation technique similar to but less effective than Clark's, was approximately 100 kilometres north of Fort McMurray. Bitumount started by producing 2000 barrels per day in 1931, but once the Great Depression occurred, the plant produced less than 750 barrels per day (Sheppard, 1989). By 1942, Fitzsimmons was in financial debt, and so he sold Bitumount to Lloyd Champion, who renamed the company to Oil Sands Limited. Champion was also unable to maintain the plant, resulting in the provincial government taking full ownership in 1949 and using the space to conduct tests using Clark's seperation technique (Sheppard, 1989). However, the new discovery of oil deposits in Leduc discouraged investors from the Bitumount area, and thus, the plant was abandoned in 1958. Champion later went on to form the Great Canadian Oil Sands company, which is the precursor to SunCor Energy, and one of the main oil sands companies of today (Sheppard, 1989; Suncor Energy Inc., 2017).

The Alberta Oil Sands: Worthwhile Investment or Fuel of the Past?

Alberta's oil sands are the third-largest proven oil reserve in the world (Figure 6.11), spanning the Athabasca, Cold Lake, and Peace River deposits (Natural Resources Canada, 2015). Though the recovery (extraction and separation) methods have evolved in past years, the principles behind these methods have remained constant. The following recovery methods are a staple of Canadian technological innovation: (1) in-situ extraction and (2) open-pit mining (Natural Resources Canada, 2013). In-situ extraction recovers bitumen from great depths very effectively (55-60% bitumen recovered) and accounts for 80% of oil extracted from the sand reserves. The most commonly used in-situ method is Steam Assisted Gravity Drainage (Natural Resources Canada, 2013). Two horizontal wells are drilled, an upper (injection) well and a lower (production) well. The upper well continuously injects steam into the ground which results in bitumen becoming more fluid and able to flow into the lower well. Pumps recover the crude bitumen to the surface where it may be transported directly to an upgrading facility. Open-pit mining, which accounts for 20% of Alberta oil extraction, involves the removal of exposed or near-surface oil sands with shovels, crushing them, and adding hot water (Natural Resources Canada, 2013). The water-oil sand mixture is pumped to an extraction plant where more hot water is added in a separation vessel and the resulting bitumen froth is removed and further refined (Natural Resources Canada, 2013). Both recovery methods use the thermal extraction techniques that Karl Clark perfected in his 1927 report. After the recovery process, the bitumen must be

Figure 6.11: *The modern Athabasca Oil Sands where extraction and separation occurs.*

upgraded into synthetic crude oil (SCO) that can be further refined into diesel and gasoline (Natural Resources Canada, 2013). These processes highlight Canadian advancements in science and engineering.

Today, the oil obtained from the Alberta oil sands are refined and used in a multitude of ways. Products include motor gasoline, diesel fuel (for transportation and electricity generation), heating oil, aviation fuel, heavy fuel oil, lubricating oils, asphalt, and many other products (Natural Resources Canada, 2015).

In addition to the many products the Alberta oil sands have generated, they also have created many new employment opportunities both directly and indirectly. This includes jobs in business, engineering, transportation, and mining (Natural Resources Canada, 2015). Due to the oil sands, Canada is the fifth-largest crude oil producer in the world, generally producing more oil than can be consumed. Thus, crude oil and crude bitumen are one of Canada's largest exports (Statistics Canada, 2017). In 2016, energy products accounted for $1,666.5 million (approximately 13.75%) of total exports (out of $521,127.6 million), with the largest contributor being crude oil and crude bitumen, which accounted for $48,065.3 million (Statistics Canada, 2017). Canada is the leading supplier of energy products to the United States, which strengthens their trading relations (Natural Canada Resources, 2015). It is evident that the oil sands have largely, and positively, impacted the short-term Canadian economy.

While the oil sands have made many important contributions to Canada, there are also many negative implications for the long-term economy and the environment. If Canadians rely too heavily on oil as a source of income for the economy, it could be detrimental in the long run. Dutch disease occurs when a country's economic profitability is solely based on the exports of one resource and it crashes due to increased exchange rates (Pembina Institute, 2013). As the price of oil starts to rise along with the Canadian dollar, this will make oil too expensive for other countries to buy it. When countries stop buying Canada's main export, the economy will not be able to sustain itself and will crash. This can be seen with the oil sands, as they have attributed a large amount of inflation for the Canadian dollar (Pembina Institute, 2013).

The process of extracting and refining bituminous sands releases greenhouse gases (GHGs) and other pollutants into the environment (Charpentier et al., 2009; Leung et al., 2003; Kelly et al., 2010). When compared to the extraction of crude oil, the amount of greenhouse gases produced is much higher, although more intensive and consistent experiments must be done to confirm the exact comparisons in GHG production (Charpentier et al., 2009). Greenhouse gases are known to cause respiratory illnesses and reduce the quality of air. As the oil industry continues to expand, so does the waste that the factories produce. The Environmental Protection Agency outlines a list of priority pollutants potentially resulting from oil extraction that should be monitored. Upon sampling the Athabasca River and Lake Athabasca, the concentrations of the pollutants were very high (Kelly et al., 2010). The samples taken further downstream from tailing ponds showed concentrations of mercury, nickel, chromium, and silver were 8-fold higher than upstream samples (Kelly et al., 2010). There were also higher concentrations of copper, lead, zinc, and additional elements found accumulating in snow samples (Kelly et al., 2010). These pollutants from the oil sands are invading the water system, reducing the quality of drinking water, and increasing the toxicity of the water. This pollution is also detrimental to the health of local organisms in the ecosystem. Some of the acids and salts that are released from the process of extraction and development exert significant effects on the biomass of certain phytoplankton in nearby water systems (Leung et al., 2003). Once the threshold for concentration of these acids and salts in water is reached, there will be impacts on community composition and increased susceptibility to harm (Leung et al., 2003). This disruption to the ecosystem creates an imbalance in nature and can lead to other, more drastic, downstream effects. Overall, the oil sands will provide short-term economic growth, but will destabilize the environment.

New technologies are constantly being developed and tested to address the negative environmental implications of the oil sands. One of the most promising technologies is Nsolv® which ensures a both higher profit return and a lower environmental footprint (Nsolv, 2017).

As new oil sand technologies are developed and alternative sources of fuel are proposed, the future of the Alberta oil sands remains unclear. Canada must make decisions about the oil sands that will ensure sustainability of both the economy and environment.

"There is no question that climate change is happening; the only arguable point is what part humans are playing in it"

-David Attenborough

Chapter 7: Climate Processes

The lifespan of a human being is miniscule in comparison to the age of the Earth. For thousands of years, people have developed different theories concerning Earth's history. Traditions, folklore, and religious beliefs influenced people's perception of Earth's past. Our progression in understanding Earth's climate has developed as people began to explore the world differently. The scientific revolution particularly influenced human views of nature and the universe, and served as a catalyst for diverse research that led to the investigation of climate change.

The concept of an atmosphere surrounding Earth has existed for thousands of years. The first section of this chapter presents how our understanding of the atmosphere has changed over time. As scientists learned about diffraction, they developed a better understanding of light rays and discovered ultraviolet radiation. Other scientists were more concerned with the composition of air itself, discovering oxygen, and subsequently, ozone. These scientists' discoveries have been crucial in the examination of climate change and the devastating effects of pollution.

In our attempt to understand how Earth's climate has changed over time, scientists have discovered the wealth of information that glaciers provide. Society's rejection of Louis Agassiz's glacial theory demonstrates the controversy that has affected scientific discoveries for centuries. As our understanding of glaciers has increased, so has our ability to use glaciers to monitor climate change. Geographic information systems (GIS) and remote sensing methods have transformed the way scientists are able to study glaciers. Regardless of technology, glaciers are viewed throughout history as fundamental indicators of climate change.

Our constant desire to learn how to predict the weather is portrayed through the development of weather monitoring methods and technology. The Industrial Revolution and wars throughout history are described as catalysts for influential climate studies. More recently, a mathematical revolution has improved weather predictions as well as the collection and distribution of weather data. However, there is a need for a new field of mathematics to allow successful long-term weather forecasting that will fundamentally alter future meteorological studies.

Current climate studies would not be possible without the individual contributions of many scientists since the scientific revolution. By amalgamating our understanding of topics ranging from the atmosphere and light to storms and glacial formations, scientists are able to learn more about the climates of the past while comparing them to our current conditions. As scientists develop novel technology and explore the world around us in new ways, we continue to learn more about our Earth's past while developing a plan for a brighter future.

Atmosphere, Ozone, and UV Light in History

What is Ozone?

The ozone layer within Earth's atmosphere is essential for life. Ozone, a pungent, poisonous gas, contributes to creating a habitable climate (an average of 15 degrees Celsius) because it absorbs harmful ultraviolet (UV) radiation from the Sun. Habitable conditions on Earth are decreasing as ozone depletes in the stratosphere, letting more harmful UV radiation through Earth's atmosphere, thereby worsening climate change (Fabian and Dameris, 2016). Ozone forms at the top of the atmosphere and then settles down, accumulating in the stratosphere, which is the second layer of the atmosphere (Hay, 2016). Stratospheric ozone, also called 'good ozone' absorbs ultraviolet radiation that is harmful to organisms on Earth, while also trapping heat, which is key to regulating temperatures on Earth (Hay, 2016).

This all began four billion years ago when oxygen was unavailable and microorganisms lived in oceans, making their own oxygen through photosynthesis (Fabian and Dameris, 2016). It took another three billion years for oxygen concentrations in the atmosphere to reach current levels (Hay, 2016). As populations of microorganisms increased, the remaining free oxygen from photosynthesis accumulated in Earth's atmosphere, and eventually the ozone layer formed, allowing land animals to evolve and biodiversity to rapidly increase (Fabian and Dameris, 2016).

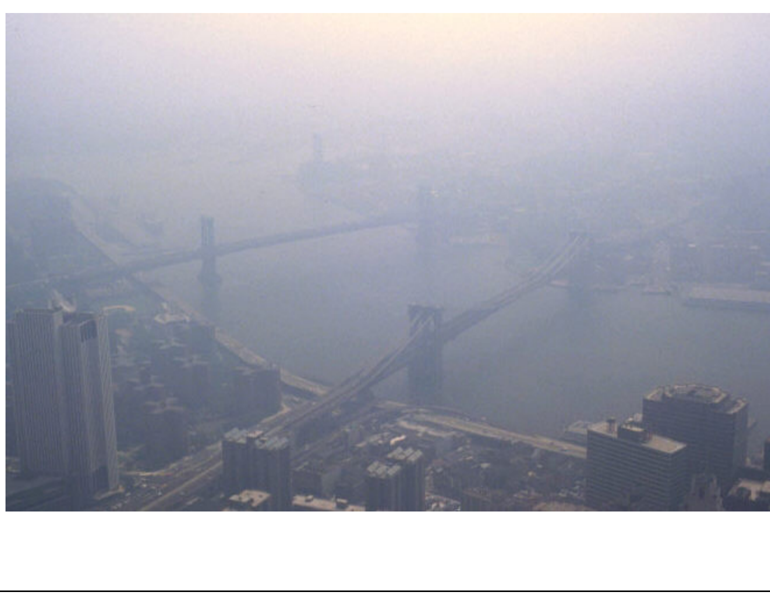


Figure 7.1: *Photochemical smog. The photochemical smog over New York City, USA, generated through the reaction of nitrous oxides or hydrocarbons with solar radiation.*

Ozone forms when oxygen atoms react with oxygen molecules, as shown in Figure 7.2 (Fabian and Dameris, 2016). At normal levels, the ratio of ozone to air molecules is about 15 to 1 billion. However, ozone levels have changed drastically due to human activity, such as industry and car emissions that create photochemical smog, seen in Figure 7.1, which is air pollution that forms when photons from the Sun collide with nitrogen oxides or hydrocarbons (Fabian and Dameris, 2016). Long before ozone was discovered, scientists and philosophers had a general understanding of the atmosphere. Beginning in 6500 BCE, groups around the globe documented their understanding of how air is composed of particles, as well as ideas of how light works (Bag, 2015). These ideas were the groundwork for the modern understanding of how ozone and UV light relate to human-induced climate change.

Early History: What is the Earth's Atmosphere?

The concept of an atmosphere has been prevalent throughout human history, since 6500 BCE. A diverse range of religions, including groups in Japan, Babylonia, and Tibet, all held the idea that an atmosphere exists above Earth (de Visser, 1935; Kingsley, 1994; Bag, 2015). Many religious groups in the east, who lived between 6500 BCE and 500 BCE, considered air to be one of the four elements, the other three being earth, water, and fire. They considered these elements to make up the origin of life (Bag, 2015). Around 3000 BCE, ancient Egyptians worshipped a god named Shu, who embodied the air between the Earth and Sun, analogous to the modern concept of the atmosphere (Wilkinson, 2003). The Rigvedic people of ancient India (6500 BCE to 500 BCE) were a Hindu religious group, who also had a term for the region between the Earth and stars, called *antariksa*, (Bag, 2015). As well, they called the Sun *ragni*, which symbolized wealth and giving (Bag, 2015). Above *antariksa* was heaven, part of an infinitely expansive universe (Bag, 2015). Western cultures also developed the idea of an atmosphere around the same time as Eastern cultures. In ancient Greece, many believed that air was the life force of all living things, being an elemental building block of life (Armstrong, 1967). Empendocles, a fifth century philosopher, was the first in the West to propose that everything was made up of the four basic elements. As well, in ancient Greek philosophy, *aer* was a term used to describe the lower atmosphere, and *aether* was the upper atmosphere above the clouds (Bremmer, 2008).

Many eastern religions, including certain schools of Buddhism and Jainism, accepted the concept that air is made up of particles (Bag, 2015). The fascinations of people living between 6500 BCE and 500 BCE varied widely, as there were also many Indian philosophers who were observing the properties of reflection and refraction of light. In 8th century CE, Annambhatta, who wrote the Sanskrit treatise *Tarka-Sangraha*, which is an explanation of the ancient Indian system of logic and reasoning**,** explained that heat from the Sun was responsible for the change of colour in grass and the ripening of fruit (Bag, 2015). This was a revolutionary idea because it demonstrated people's understanding of the Earth's dependence upon the Sun's energy.

Nicolas de Cusa in the early 1400s made a significant contribution to the modern understanding of the atmosphere, as he was the first person to quantitatively detect water vapour in the air using a hygrometer, which is a device that quantifies humidity (Gaston et al., 2006). de Cusa constructed the hygrometer using a piece of wool that absorbed moisture from the air, and then the change in weight of the wool indicated the degree of water vapour present in the air. He used this to calculate atmospheric humidity (Gaston et al., 2006). This data added to the evidence that the atmosphere is made up of more than one component.

It was not until 17th century AD that studies on the atmosphere progressed, as scientists invented more effective ways for studying gases (Gaston et al., 2006). Johannes Kepler, a German astronomer who lived from 1571 to 1630, was a major contributor who encountered issues of atmospheric refraction when studying astronomical phenomena. In his observations and measurements, he assumed that the atmosphere was homogeneous, composed only of air (Bruin, 1981). Although this assumption was later disproved with the discovery of other atmospheric gases, his discoveries of diffraction were still important to developing the modern understanding of how radiation travels through the atmosphere (Gaston et al. 2006).

The Dispersion of Light

People have observed and documented the occurrence of rainbows since recorded history (Sparavigna, 2012). The rainbow is an excellent example of how light works. In 1st century AD, Lucius Annaeus Seneca, a Roman Latin writer, used glass rods to split sunlight into different colours when light hit the glass obliquely (Sparavigna, 2012; Hine, 2006). During this period, Pliny the Elder, who was a Roman natural philosopher and naval commander, noted the dispersion of light using a stone called Iris, which is modern-day quartz. He observed that when light hit the quartz stone's surface it dispersed, splitting into different colours and creating a rainbow (Bostock, 1855).

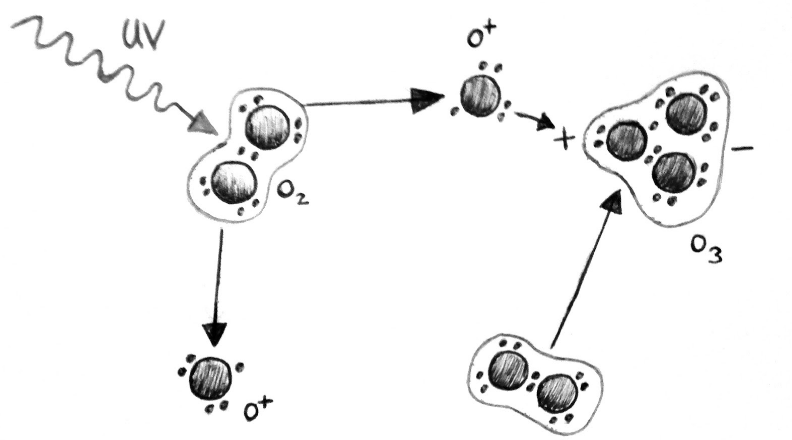


Figure 7.2: *The formation of ozone. A solar ultraviolet photon from the sun splits an oxygen molecule into two oxygen atoms that go on to collide with other oxygen molecules. The oxygen molecules combine with the oxygen atoms to create ozone.*

Rainbows were a fashionable topic among natural philosophers of the seventeenth century (Garber, 2005). Many philosophers, including Rene Descartes and the members of the Society of Jesus, tried to explain how rainbows formed through philosophical interpretations. However, the interpretations by scientists in the field of optics became commonplace instead (Garber, 2005). During the seventeenth century, most scientists came to the conclusion that white light is composed of different coloured light rays (Garber, 2005). Johannes Marcus Marci, a scientist from the Czech Republic, was the first to theorize this idea in 1648, using glass prisms to study the dispersion of white light into its components (Garber, 2005). He concluded that raindrops and prisms decompose light into different colours, and coloured light is part of sunlight, appearing white when altogether (Garber, 2005). Initially, the science community did not readily accept Marci's ideas. Most people believed at the time that glass prisms create coloured light by mixing the sunlight with the glass, and that the mixing was what created the colours. Contradictorily, Marci proposed that the various components of light refract at different angles within the glass (Garber, 2005). As well, Francesco Maria Grimaldi (who coined the term "diffraction"), Robert Boyle, and others scientists had similar ideas, but Marci predates all of them (Grimaldi, 1665; Garber, 2005). Isaac Newton was another key thinker at the time and he contributed a lot to this idea, even publishing a paper about it in 1672 (Newton, 1721). He confirmed Marci's theories with his own findings, publishing them in his book called *Optiks* (Newton, 1721). After Newton's publication, it became widely accepted that the indices of refraction of different rays of light was the mechanism behind rainbows (Garber, 2005; Newton, 1721).

This discovery was a milestone in the discovery of the existence of light beyond the human visual spectrum, and this is what ultimately led to the discovery of UV light.

Ultraviolet Radiation

After the discovery of the diffraction of white light into different components, scientists of the 18th and 19th centuries experimented with the different uses and applications of light diffraction. They primarily used light diffraction to stimulate chemical reactions, observing which rays of light acted as catalysts for reactions. In 1777, Carl Wilhelm Scheele, a Swedish chemist, conducted an experiment in which he soaked paper in a silver chloride solution, and shone white light through a glass prism onto the paper (Draper, 1842). He noted that the light turned the paper a darker colour, indicative that a chemical reaction took place. (Draper, 1842). He did not know why or how this occurred. In 1801, the German physicist Johann Wilhelm Ritter conducted the same experiment, finding that light invisible to the human eye just beyond the violet end of the spectrum was most effective at turning the paper a dark colour. He theorized that there were invisible light rays, naming them "deoxidizing rays", that were stimulating the chemical reaction (Caneva, 2001). The name was changed to "chemical rays" shortly after, and in the 19th century it was changed to "ultraviolet rays". In proceeding years, chemists conducted further experiments to study the effects of ultraviolet light in stimulating chemical reactions.

In 1843, John W. Draper invented a device called the tithonometer for measuring the "chemical force" of UV light, which he called "tithonic rays" (Draper, 1842). In 1802, the scientist William Hyde Wollaston used Newton's discoveries on the spectrum of light to theorize that light was actually made up of distinct bands separated by dark lines, instead of a continuous spectrum (Sandage and Brown, 2004). He built a spectrometer, which was similar to Newton's experimental setup seen in Figure 7.3, but included a lens to enlarge and focus the light onto a screen. He believed that the dark bands were the natural separation between the colours. In 1814, the German physicist Joseph von Fraunhofer mapped out 500 dark bands of light, and these bands were later named "Fraunhofer lines" (Sandage and Brown, 2004). He concluded that the lines could not be intrinsic to the instruments used in his experiments nor be the separation between colours, but were inherent to the sunlight (Sandage and Brown, 2004). What exactly caused the appearance of these lines was unknown at the time, but with them, scientists could then map the spectra of sunlight.

Before the end of WWII, the German scientists Karl-Otto Kiepenhuer and Erich Regener studied solar UV radiation using rockets (Friedman, 1963). They designed a spectrograph that had fluorite optics on a pointing device to keep them directed at the Sun, and American scientists adopted their design after WWII once V-2 rockets were brought to the country (Friedman, 1963). The first successful spectrograph experiment occurred in 1946, and major contributors to spectrograph experiments include: The United States Naval Research

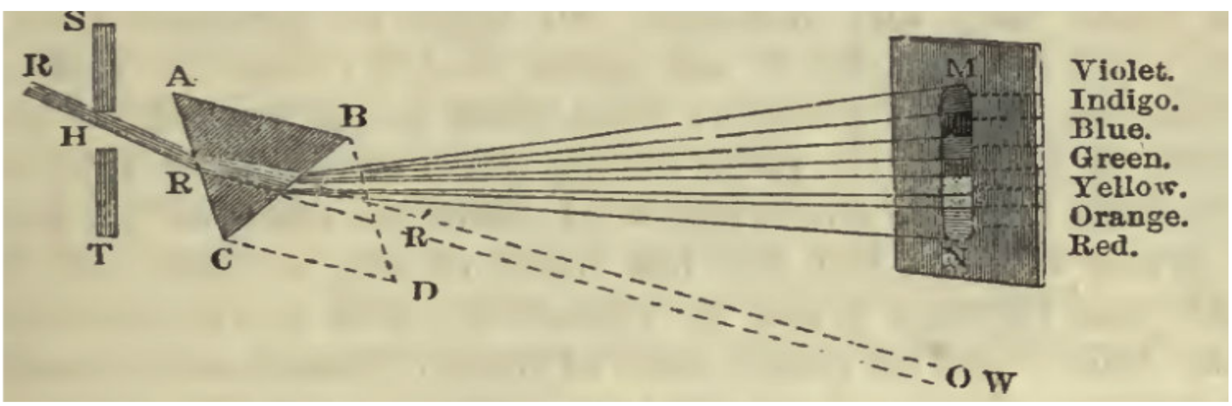


Figure 7.3: *Isaac Newton's diffraction experiment. Sunlight first hits a thin surface with a circular hole constructed, after which it diffracts through a glass prism onto a screen, creating a spectrum of colours.*

Laboratory, Airforce Cambridge Research Laboratories, University of Colorado, John Hopkins Applied Physics Laboratory, and the National Aeronautics and Space Administration (Friedman, 1963).

By 1963, scientists had a clear and detailed understanding of the nature of UV radiation, with reference to the wavelength range of UV rays. Initially, physicists took the best resolution spectrograms above the ionosphere. This included the first high-resolution spectrographic images transmitted by NASA's S-16 satellite solar observatory (Friedman, 1963). On the UV spectrum, three types of UV radiation were categorized in order of increasing wavelength: UV-C, UV-B, and UV-A (Caldwell, 2007).

Late History: From Oxygen to Ozone

The 1770s were a key turning point in the history of discoveries involving ozone and its molecular components. During this period, scientists discovered the molecules that make up ozone and the atmosphere. Joseph Priestley and Carl Wilhelm Scheele both discovered oxygen independently (Fabian and Dameris, 2016). Priestley was an English scientist, philosopher, preacher, teacher, and writer who lived about 100 years ago (Fonda, 1950). He built upon ancient Greek ideas of the four elements, determining that air is not one element, but rather a composition of elements. As well, he is famous for discovering oxygen and its related reactions (Fonda, 1950). Though this seems like a simple discovery, it was revolutionary because it led to the understanding of combustion and oxidation processes (Fonda, 1950).

Priestley wrote unorthodox religious papers about his revolt against the Calvinist church and support for the Unitarian church. He also supported the American and French revolutions that occurred in the 1770s – this was a radical perspective at the time, so eventually he had to flee England (Fonda, 1950). Priestley identified and investigated gases and their properties, discovering oxygen in 1774. Referring to his discovery, he said that oxygen "furnishes a striking illustration that more is owing to what we call chance, that is, to the observation of events arising from unknown causes, than to any proper design or preconceived theory" (Fonda, 1950). In his experiments, Priestley observed that mice lived longer when surrounded by oxygen gas than normal air, and he found that plants could replenish this oxygen (Fonda, 1950). Scheele made similar observations that were published soon after Priestley's findings. In later years, Scheele went on to discover chlorine and nitrogen, and Priestley discovered nitrous oxide, hydrogen chloride, ammonia, sulphur dioxide, and carbon monoxide (Fabian and Dameris, 2016). These scientists were key to paving the way for the discovery of ozone.

The Discovery of Ozone

When ozone was first discovered, society thought it was beneficial towards human health (Fabian and Dameris, 2016). There were even streets called "Ozone Avenue" to attract people to their neighbourhoods (Fabian and Dameris, 2016). Scientists later realized that ozone is poisonous to humans, especially at high levels (Fabian and Dameris, 2016). Christian Friedrich Schönbein was the first to discover ozone as a chemical compound (Gratacap, 1881). In 1840, Schönbein was working in a lab when he discovered a gas that had a unique, pungent smell, and he called it ozone (translating to "smell" in Greek). During this period, the origin of ozone was not known definitively (Gratacap, 1881). Schönbein found the electrolysis of water created a distinct odour, which other scientists initially thought to be the smell of electricity, so Schönbein's results were ignored (Rubin, 2001). Then, Schönbein used a stronger current, and the odour was even more distinct, so he concluded that this odour was from ozone gas (Rubin, 2001). Schönbein said (in a paper he wrote in 1840) that the odour of ozone was similar to that of phosphorus when exposed to air, and phosphorus had identical properties to the ozone produced electrically (Rubin, 2001). The name "ozone" prevailed, despite attempts to change it to "electrified oxygen". Many decades later, ozone was isolated (Rubin, 2001).

Schönbein's nose was the first analytic device for identifying ozone, and today, smell is still a key diagnostic for ozone (Rubin, 2001). Later, scientists created other qualitative methods to test for ozone, the most prominent called a starchiodide test (Rubin, 2001). There are two main quantitative methods for measuring ozone: volumetric methods and spectrophotometry (Tjahjanto, Galuh R. and Wardani, 2012). Robert Bunsen, a German chemist, created a volumetric method for measuring ozone, which was iodometric titration (Tjahjanto, Galuh R. and Wardani, 2012).

In 1920, two physicists named Charles Fabry and Henri Buisson made the first quantitative measurement of ozone thickness (Fabian and Dameris, 2016). During this time, Gordon Miller Bourne Dobson, a British physicist and meteorologist, did systematic measurements with a UV spectrograph of the Earth's ozone layer thickness and seasonal and altitudinal variations (Fabian and Dameris, 2016). In 1926, Dobson implemented six stations with UV spectrographs in various countries to monitor ozone (Fabian and Dameris, 2016). This was the start of a systematic ozone monitoring system, which is still operating today (Fabian and Dameris, 2016). It was from the Dobson network that the main features of Earth's ozone were recorded by the 1960s (Fabian and Dameris, 2016).

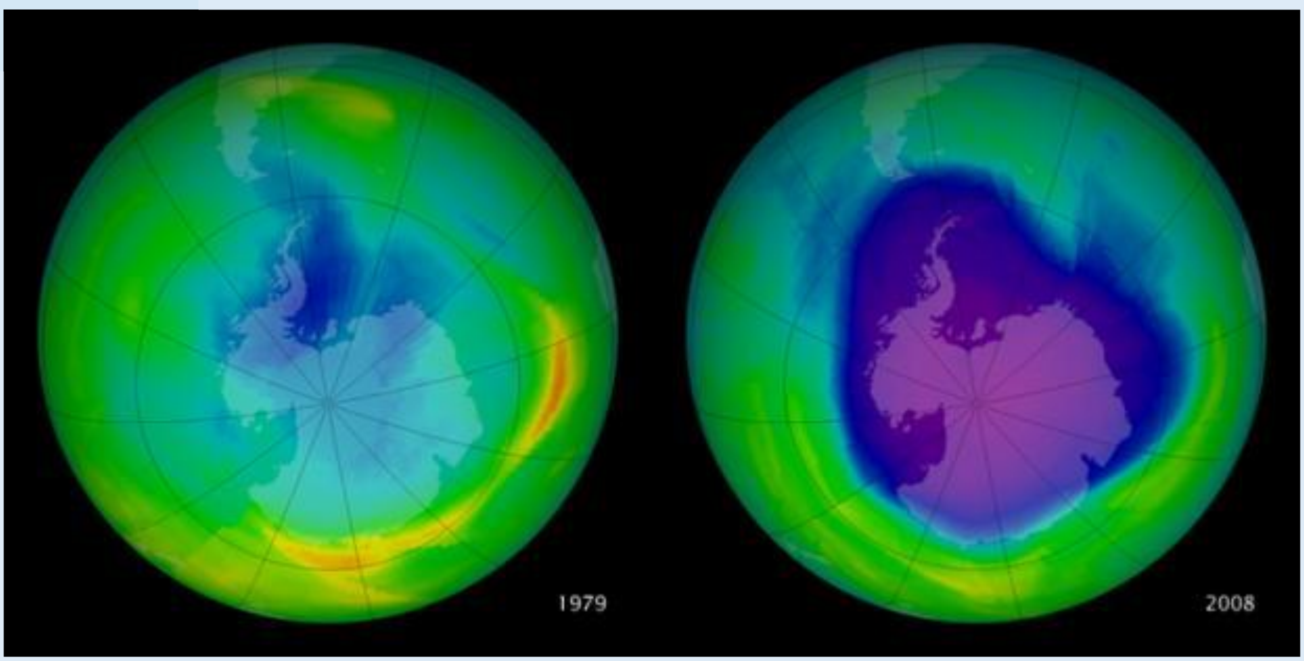
Ozone and Climate Change

In 1971, James Lovelock, an English scientist, environmentalist, and futurist, was on a research expedition in the South Atlantic when he discovered that chloroflurocarbons (CFCs), which are a component of freon in refrigerators and aerosol in spray cans, had been accumulating in the atmosphere since they were created in 1930 (Hay, 2016). It was not until 1974 that a chemistry professor named Sherwood Rowland, at the University of California and his postdoctoral associate, Mario J. Molina, realized that CFCs could be depleting the ozone layer in the stratosphere. They observed that UV light breaks down CFCs, thereby releasing chlorine that goes on to react with ozone, creating chlorine dioxide as the product (Hay, 2016). This reaction depletes ozone. At this time, many other scientists were researching ozone depletion as well.

In 1970 Paul Crutzen, a Dutch chemist-climatologist, determined through his research that agricultural fertilizers were releasing nitrous oxides that were decomposing the ozone back into diatomic oxygen molecules (Hay, 2016). Crutzen wrote a doctoral dissertation in 1973 about the photochemistry of Earth's ozone and the pollution of the stratosphere due to aircraft emissions (Hay, 2016). Measurements of the stratospheric ozone showed that ozone was decreasing at that time (Hay, 2016).

Paul Crutzen was born in Amsterdam in 1958 and as a young adult he worked for the Meteorology Institute of Stockholm University, where he helped with some meteorological projects, specifically running weather prediction models. He eventually got his degree in science, majoring in mathematics, statistics, and meteorology, but he was unable to complete any physics or chemistry courses (Crutzen and Gunter Brauch, 2016). Then in 1965, Crutzen was assigned a position where he helped a scientist from the United States create numerical models of oxygen allotrope distribution in the stratosphere, mesosphere, and lower thermosphere (Crutzen and Gunter Brauch, 2016). After this project, he became more interested in the photochemistry of atmospheric

Figure 7.4: *The ozone hole in 1979 versus ozone hole in 2008. The purple represents the thinnest ozone (most depleted), while the green represents the thickest ozone.*



ozone, specifically the stratosphere, and he began studying the scientific literature on these topics (Crutzen and Gunter Brauch, 2016). He was later awarded the Nobel Prize alongside Frank Rowland and Mario Molina, for their joint research on stratospheric ozone (Hay, 2016).

The stratosphere protects life forms from harmful UV radiation by preventing the radiation from reaching Earth's surface (Fabian and Dameris, 2016). High concentrations of UV radiation negatively affect plants, animals, and other organisms including humans (Fabian and Dameris, 2016). Decreasing ozone layer thickness causes an increase in the amount of UV radiation that reaches the Earth's surface (Fabian and Dameris, 2016).

In 1984, three British Antarctic survey scientists, Joseph Farman, Brian Gardiner and Jonathan Shanklin, demonstrated that ozone levels had dropped to 10% below normal for an Antarctic summer (Hay, 2016). Using Dobson spectrophotometers, they had discovered the ozone hole above the Antarctic, shown in Figure 7.4. (Fabian and Dameris, 2016). On the other side of the Atlantic, Susan Solomon (who worked at the University of Colorado in the 'Cooperative Institute for Research in Environmental Science') was a key scientist in discovering what was causing the depletion of the ozone layer (Hay, 2016). Solomon led expeditions to Antarctica in 1986 and 1987, during which she demonstrated that there was about 100 times greater than normal levels of chlorine dioxide in the atmosphere, indicating a severe reduction in ozone levels (Hay, 2016). The CFC industry was extremely angered when they heard about the movement to ban CFCs, as this ban would put them out of business (Hay, 2016). Many people today arguing that global warming is not caused by human activity are the same people arguing that CFCs were necessary and that increased UV radiation can be thought of as a good thing (Hay, 2016). In the case of CFCs, the majority of people listened to the scientists, and governments and organizations implemented protocols that banned the use of CFCs (Hay, 2016).

In 1987, representatives from 43 nations signed the Montreal Protocol (Hay, 2016). This is an international treaty to phase out the making of substances that deplete ozone, with the goal of protecting the ozone layer (Hay, 2016). Today, the use of CFCs is minimal, which is helping to reverse ozone depletion (Hay, 2016). As the ozone layer has begun to replenish itself, the ozone structure has changed (Hay, 2016). However, holes have continued to form so that the tropopause (boundary between troposphere and stratosphere) has started to become diffuse, affecting the air circulation primarily above Antarctica (Hay, 2016). What the Montreal Protocol neglected to include was nitrous oxide from agricultural fertilizers, which is one of the main ozone destroyers today (Hay, 2016).

The atmosphere acts like a giant greenhouse that lets good radiation through, while protecting life from dangerous UV radiation (Fabian and Dameris, 2016). It also reduces the emissions from surface greenhouse gases, such as carbon dioxide, ozone, nitrous oxide, and methane, thereby reducing the energy lost to space (Fabian and Dameris, 2016). Ozone absorbs solar ultraviolet and infrared radiations. Tropospheric ozone is a greenhouse gas and ozone levels are increasing in the troposphere, contributing to the 'greenhouse effect' (Shindell et al., 2006; Fabian and Dameris, 2016). Ozone in the troposphere is known as photochemical 'smog', as this ozone is so close to the Earth's surface (Shindell et al., 2006). This natural greenhouse effect maintains an average worldwide temperature of 15 degrees Celsius on Earth (Fabian and Dameris, 2016). Human activity, such as burning fossil fuels, deforestation, and agricultural and industrial practices, accentuate the greenhouse effect, which is problematic because it contributes towards Earth's climate changes, which has negative effects for all organisms (Fabian and Dameris, 2016). In the past 100 years, global temperatures have risen by 0.7 degrees Celsius, and they are projected to increase more if greenhouse gas emissions continue without being mitigated (Fabian and Dameris, 2016). Human activity has contributed to huge losses of ozone in the stratosphere and increases in ozone in the troposphere and it is fact that this activity is a major contributor towards climate change (Fabian and Dameris, 2016).

Nineteenth Century Glacial Theory

The nineteenth century marked an era of important scientific discoveries, many of which were not easily accepted because of conflicts with the strong religious beliefs at the time. Among these discoveries was the glacial theory presented by Louis Agassiz. The glacial theory is the concept that ice had once covered large areas of the early Earth. Although it is widely accepted today, the debate of its reality was one of the most argued controversies of nineteenth century science (Macdougall, 2013). From religion, it was believed that boulders on the landscape were transported by huge currents of water and mud from the biblical flood of Noah's time (Imbrie and Palmer Imbrie, 1986). As a result, it took decades of convincing and countless pieces of evidence before the modern understanding of a historical glaciation formed.

Louis Agassiz

Agassiz was a natural scientist who found a deep interest in glaciers following his initial studies in botany and zoology (Figure 7.5). Although he was not the first to recognize glacial features, he is most closely associated as he was the person who gathered the data to develop a holistic theory and published his findings (Lurie, 1988). Agassiz's early research and publications on fossil fish not only established his reputation as a scientist, but also led him to studies on glaciation primarily as evidence for periods of mass extinction (Macdougall, 2013). He believed that a global scale ice age could explain the disappearance of tropical vegetation and organic life in Europe and resulted in the present day enigmatic landscapes. Early in his career, Agassiz worked closely with Swiss geologists Jean de Charpentier and Ignaz Venetz who were among the first to notice that glaciers were a major force of nature (Imbrie and Palmer Imbrie, 1986). He interpreted de Charpentier and Venetz's observations as evidence that a massive polar ice sheet had once covered most of Europe down to the Mediterranean, as well as large parts of North America. Agassiz then began to seek evidence in the form of erratic boulders and glacial scratches in the city of Neuchâtel, Switzerland (Marcou, 1972).

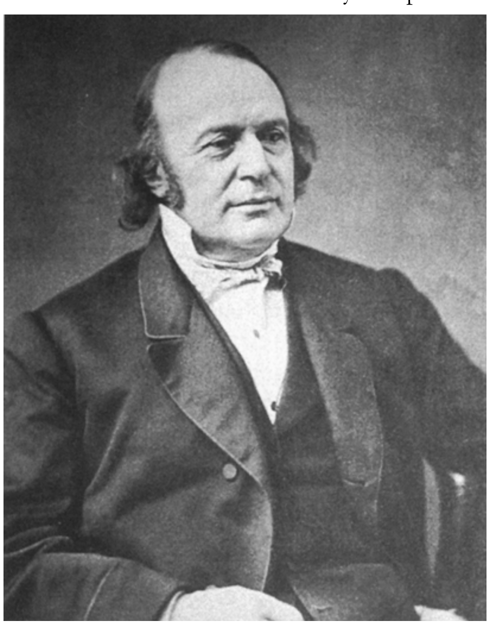


Figure 7.5: *Portrait of Louis Agassiz during his time as an American professor. He was the first to publicly propose the glacial theory in 1837.*

First Address of the Glacial Theory

Agassiz began discussing his ideas about an ice age in front of the Natural History Society of Switzerland in 1837 (Macdougall, 2013). In his address, he noted that early in Earth's history, large areas had been covered with a giant ice sheet and present day glaciers are simply remnants of these conditions (Lurie, 1988). As these masses of ice receded, they left traces of their existences through giant boulders, scratched and polished rocks, moraines, drifts, erratic blocks, and other geological features that appear to be unusual in their modern setting.

In addition, he presented four basic concepts. First, the glacial action in Switzerland that resulted in the erratic boulders and landscape could be understood through observation of the movement of present glaciers (Lurie, 1988). Next, the present heights of the Alps are a result of an upheaval of land, a sudden convulsion that happened under the ice. Following this, he noted that the ice itself was a result of a sudden drop in temperature characterized by the Earth's history of a cyclic climatic pattern. Finally, he stated that ice had not only covered Switzerland, but also large areas of Europe in one vast ice age.

In Agassiz's addresses, he introduced ice as a great geological agent, almost as important as water, and his theory was initially rejected by the most renowned scientists at the time. (Gould, 1901). Regardless, Agassiz published his work in two volumes entitled "Studies on Glaciers" in 1840 which discussed the movement of glaciers and their influence on the environment over which they traveled (Smith and Borns, 2000).

Glaciation in North America

Following his European studies, Agassiz traveled to the United States of America in 1846 to investigate the geology and natural history of North America (Smith and Borns, 2000). Before arriving, he stopped in Nova Scotia, Canada, where he found the same glacial grooves and scratches on the bedrock as those that he found in the Swiss Alps (Macdougall, 2013). These findings were further evidence of the universality of glacial action and supported his theory that much of the Northern hemisphere had once been covered by large ice sheets. He then arrived in Maine where he made similar observations that led him to believe that a large glacier had once covered the entire state to a depth of 2000 metres (Smith and Borns, 2000). Throughout the landscape, Agassiz found roches moutonnees, which are asymmetrical bedrock hummocks shaped by glaciers with a rounded upstream side and a steep downstream side. These, along with the bedrock striae patterns, were clear signs that a widespread glaciation had once occurred.

Agassiz also made important observations in the White Mountains of New Hampshire (Figure 7.6) in 1847. He first noticed that the drift characteristics on the northern side of the mountain were the same as those found on the southern side (Agassiz, 1870). These drifts were distinguished by a clayey or sandy paste with abraded fragments of different rocks impacted within it. Pebbles of all sizes and coarse materials were found throughout the drift grounded together with the clay and sand. He determined that this was a result of compression under great pressure by heavy masses of ice due to the scratches, grooves, and furrows, which are all characteristics of glacial action. Evidence of grinding from advancing glaciers was also found through the diversity of composition and the absence of sorting in the drifts considering today, these traits are only found at the bottom of glaciers. The combination of these observations determined that the deposits could only have been formed under a moving ice mass held between it and underlying rock.

Furthermore, Agassiz noted the presence of moraines. Moraines are loose materials collected along the sides of a glacier which define the margins of the moving mass of ice. Their shape and arrangement are characterized by their accumulation and determine that they were produced by the pressure of a glacier. The movement of the glacier was described as moving northward from the south indicated by a steep southward slope. Agassiz explained that the steeper side of the moraine is always that resting against the glacier while the opposite side is more flat. As the glaciers over the White Mountains melted away, the accumulated water remodelled the moraines and carried off materials to river terraces further down. Using the compilation of evidence that he found in both Europe and North America, Agassiz was able to develop his holistic Ice Age Theory.

Formation of Glaciers

Not only did Agassiz propose his theory of the existence of a global glaciation, but he also studied their formation and structure. These studies were collected in his book *Geological Sketches*, which was the first complete stated theory of a widespread Ice Age to be published in North America (Smith and Borns, 2000). Regarding their formation, he noted that it begins with the freezing of water to ice, which is a precise combination of perfectly regular crystals (Agassiz, 1886). Through the alternating processes of freezing and thawing, the crystals became less regular and merged together. The

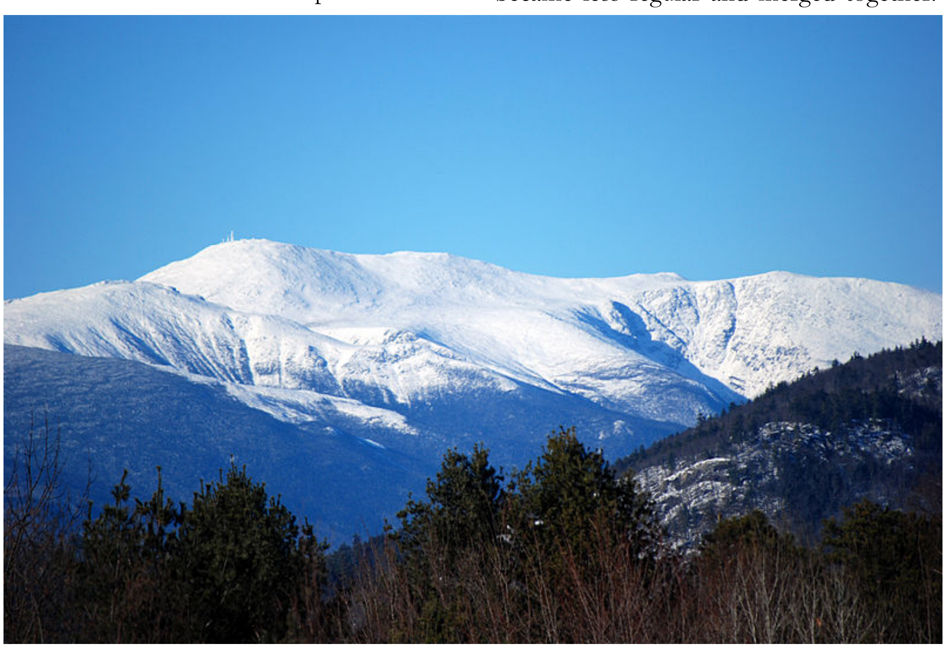


Figure 7.6: *Glaciation on the White Mountains of New Hampshire, United States. Agassiz's studies and observations of the White Mountains provided further evidence of his glacial theory.*

ice however still contained air bubbles which floated upward towards the surface of the ice. During periods of freezing, ice formed below the layer of air bubbles, and resulted in a layer of air between two layers of ice. These alternating beds of various thicknesses eventually blended together to become so thick that it essentially acted as a shelter to the water below it. These are now known as ice sheets.

Glaciers were also classified as land-ice, which were formed by the slow and gradual transformation of snow into ice (Agassiz, 1886). Light and porous snow was penetrated by water and filled with moisture. As the temperature dropped, the water froze and the snow was instead filled with ice-particles. This process continued until the mass of snow changed to an ice-gravel substance where the ice-particles were held together through partial melting and regelation. The whole mass eventually transformed into a compact mass of ice that did not melt from the surface, but disappeared by gradual diminution. This explained the sudden disappearance of icebergs which often crumble and vanish at once instead of slowly dissolving.

Agassiz's Influence

Although Agassiz published numerous observations and evidences supporting his glacial theory, many scientists remained unconvinced as he could not explain why the global scaled glaciation event occurred. One of the driving factors for glaciation was first proposed by the French mathematician Joseph Adhémar in 1842 (Raymo and Huybers, 2008). He went on to propose an explanation for the development of glaciers in that there was a correlation between astronomical forces and ice ages in his publication "*Revolutions de la Mer*" (Woodward, 2014). Adhémar proposed that ice ages occurred when the Earth is in aphelion in which winters lasted a longer time (Woodward, 2014).

James Croll

Years later, Adhémar's research was further expanded upon by a Scottish metaphysicist known as James Croll, shown in Figure 7.7, whose contributions to glacial theory were scientifically advanced for his time (Fleming, 2006). Like Adhémar, Croll believed that secular changes, such as eccentricity and precession, were responsible for climate change, however he also argued that the intensity of solar radiation had an indirect effect in causing glacial epochs (Croll, 1875).

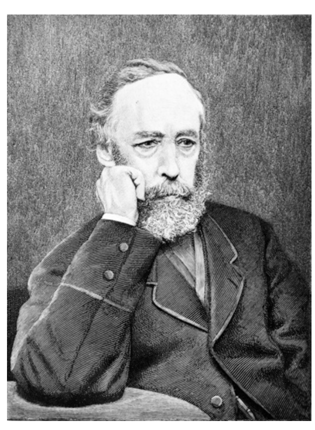


Figure 7.7: *A portrait of the Scottish scientist, James Croll who contributed to Agassiz's glacial theory using physical astronomy.*

From a young age, Croll wanted to understand the principles and laws of science as well as philosophy. By the time he was sixteen, he was knowledgeable in several physical science subjects such as mechanics and electricity (Croll and Irons, 1896). Meanwhile, he did not have an appreciation for geological sciences as he thought that it lacked principles and philosophical method, and was mostly based off of observations and experiments (Croll and Irons, 1896). Ironically however, Croll became known for his calculations in physical astronomy that contributed to glacial theory.

Physical Relation Between Eccentricity and Glacial Epochs

In the nineteenth century, it was believed that climate change resulted from the Earth cooling from its hot origin and that rearrangement of continents caused glacial and interglacial periods (Fleming, 2006). However, Croll rejected this understanding and instead proposed that astronomical forces and the changes in solar insolation intensity heavily were the factors that influenced the climatic conditions on Earth (Croll, 1875). Altogether, he believed that the changes in the precession and eccentricity of Earth's orbit were the underlying causes of extreme climatic conditions (Croll, 1875). He stated that there was an indirect correlation between eccentricity and climate change where periods of high eccentricity adjusted the duration of the seasons, and these cycles were responsible for glacial and interglacial periods. (Croll, 1875). When the Earth was in perihelion, the winters were mild and the temperatures were consistent, whereas in aphelion, the winters were longer and the climate was harsher due to its extended duration (Croll and Irons, 1896). In combination with the albedo effect, this allowed for a greater accumulation of snow and ice in winters (Woodward, 2014). Croll recognized that lighter surfaces have a high albedo effect, in which they reflect more solar light and maintain a cooler environment to expand ice and snow coverage (Woolworth, 2014). In addition, he put forward that the feedback mechanisms of cold and warm currents impacted the Earth's climate change. It was these findings, most notably his proposal on how feedback loops in the environment impacted climatic conditions, that distinguished James Croll as an innovative scientist.

In order to substantiate his theory, Croll took a mathematical approach as he based his theories off of calculations he performed using Leverrier's formula (Croll and Irons, 1896). He calculated the eccentricity of the Earth from the past three million years as well as the next one million years ahead to observe periods when eccentricity was larger than usual (Croll and Irons, 1896). Based off his calculations, he noticed that the theoretical peaks of maximum eccentricity matched with the eras of extreme cold temperatures (Croll and Irons, 1896).

Milanković Cycles

In the 1930s, the Serbian engineer Milutin Milanković expanded upon Croll's work. He argued a slightly different approach in that glaciation occurs in summers, rather than winters as Croll suggested, where the amount of insolation is weaker in the Northern hemisphere due to the orientation of the Earth's spin axis in aphelion (Woodward, 2014). This resulted in less solar insolation, thus the accumulation of snow and ice that eventually develops into ice sheets (Raymo and Huybers, 2008). Through his calculations and understanding of the principles in celestial mechanics, he developed the idea of Milanković Cycles and proposed that glaciation was based upon orbital eccentricity, obliquity, and precession (Woodward, 2014).

Obliquity refers to the amount of tilt the Earth undergoes. At great tilt angles, the Earth would experience colder winters and hotter summers while smaller tilt angles would result in cooler summers and warmer winters (see Figure 7.8) (Woodward, 2014). It was thought that cooler summers were key in building ice sheets as ice and snow would not melt during these seasons and rather accumulate. Next, the precession of equinoxes could greatly influence the climatic conditions on Earth by giving rise to solstices and equinoxes, and causing the changes in seasons (Woodward, 2014). Lastly, orbital eccentricity refers to the orbital path the Earth travels around the Sun. Orbital eccentricity would have a minor influence on the amount of solar insolation that reaches the Earth, however it plays a role determining the axial precession and obliquity (Woodward, 2014).

Disproving Secular Changes of Climate Changes

In the late twentieth century, data from researchers in America and Europe demonstrated that the final glaciations ended approximately ten thousand years ago, which contradicted Croll's theory that suggested it ended eighty thousand years ago (Bol'shakov and Kapitsa, 2011). Furthermore, analysis of oxygen isotope data from deep oceanic waters indicated that precession has minimal impacts on climate change. When this research was announced, Croll and Milanković's theories were not accepted.

Overall, it took several decades since Agassiz's first observations that the glacial theory was fully accepted. Although Croll's work has now been disproved and Milanković's theory did not match with empirical data, their contributions in glacial theory were significant in understanding how astronomical changes can impact conditions on Earth. These studies allowed for further understanding of processes and events in the Earth's past and remains important in studies of the Earth's climate today.

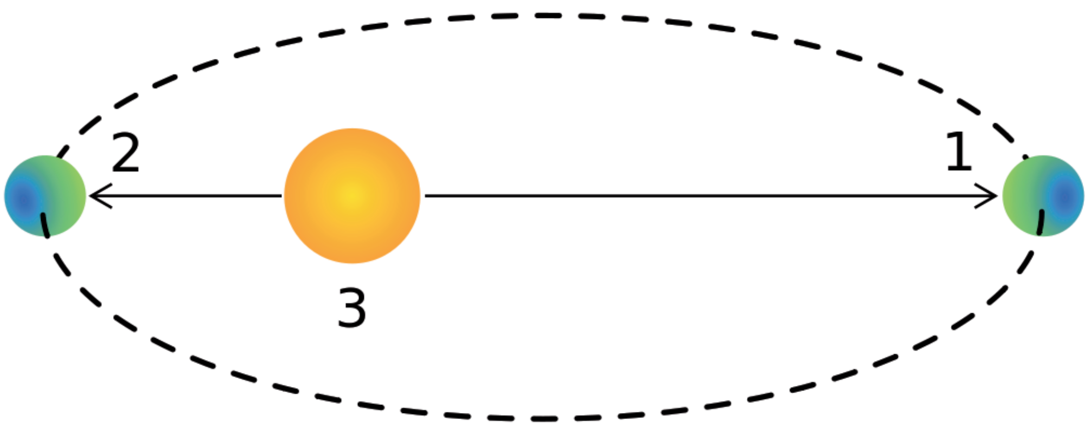


Figure 7.8: *Diagram showing the orbital path of the Earth around the Sun (3). Croll believed that when the Earth was in aphelion (1), the winters were harsher and longer compared to when Earth was in perihelion (2).*

Glaciers as Indicators for Climate Change

One of the best natural indicators of climate change today is the changing volume and geometry of glaciers (Linsbauer et al., 2009). Warmer climatic conditions cause the acceleration of glacier melting in continental regions as shown in Figure 7.9 (Chan, Van Ophem and Huybrechts, 2009). As a result, hydrological systems may be significantly altered due to floods from glacial lakes and sea level rises. There is now a large interest in the worldwide monitoring of glaciers to assess potential natural hazards of flooding activity (Huggel, Kääb, Haeberli and Krummenacher, 2003). For instance, the Swiss Alps are the most densely populated mountainous area and the outburst from glacial melting can cause intense flooding in these communities (Paul et al., 2004). It is predicted that the rates in sea level rising will continue to increase as warmer temperatures will have a disastrous impact on the ice caps and glaciers (Meier et al., 2007).

To predict the water flow paths of melted ice, information on the glacier's topography and estimates of the amount of water stored in the glaciers are required (Linsbauer et al., 2009). In addition, an understanding of the spatial and temporal covariations of glaciers gives an insight into the magnitude of the effects of climate change on large bodies of water and any necessary mitigation measures (Chan, Van Ophem and Huybrechts, 2009). With today's technology, this is most commonly accomplished using remote sensing technology in combination with Geographic Information Systems (GIS) (Huggel, Kääb, Haeberli, and Krummenacher, 2003).

Digital Elevation Models and GIS

Since glaciers often lie in isolated mountainous regions, remote sensing methods are commonly employed to perform glacial surveys (Khalsa et al., 2004). This includes the use of satellite imaging which offers the ability to capture aerial images as well as generate data for digital elevation models (DEM) (Huggel, Kääb, Haeberli and Krummenacher, 2003). DEMs allow for the approximation of the Earth's continuous surface, visual analyses of surface morphology, and calculation of slopes (Frankl, Nyssen, Calvet and Heyse, 2010). In glacial studies, DEMs provide important topological information which can be used for mapping, such as the extents of glacier and moraine surfaces (Kamp, Bolch and Olsenholler, 2005). Data extracted from DEMs can be further processed with spatial analysis software to construct geomorphological maps, calculate glacier volume, and determine elevation changes over time. The wealth of data can then be

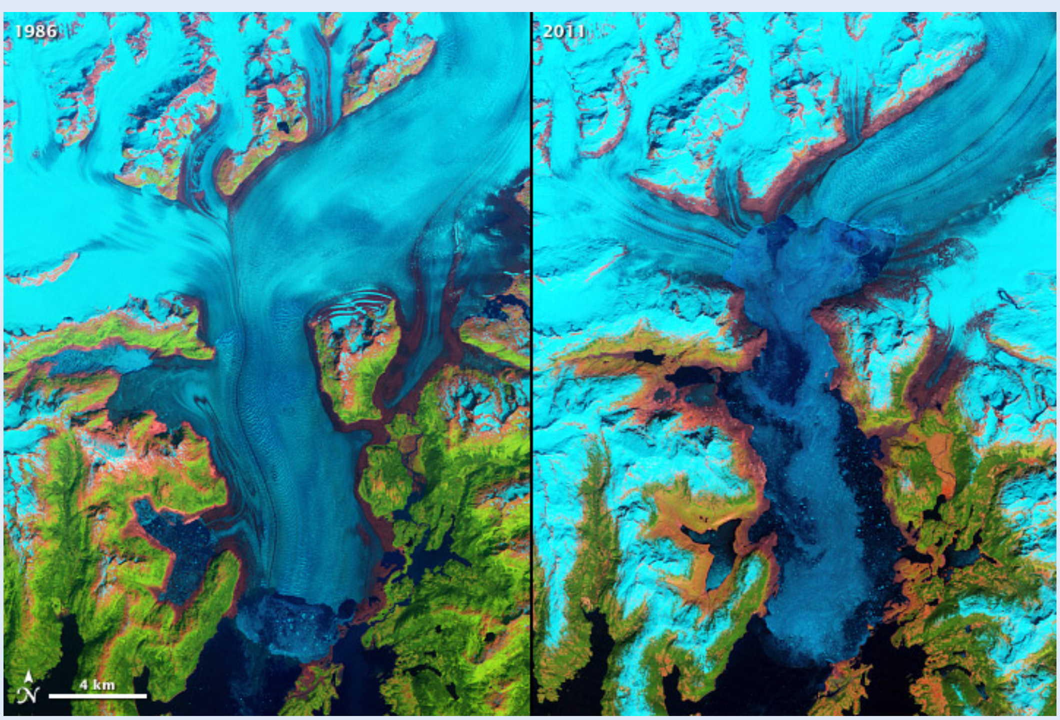


Figure 7.9: *The Columbia Glacier captured by the Landsat satellite showing the retreat of the glacier from 1986 (left) to 2011 (right). Glaciers are visibly sensitive to changes in temperature and thus an important indicator for climate change.*

compiled into a GIS database. GIS is a valuable tool that holds a great potential for efficient data storage, retrieval, and analysis and the use of a database allows for a complete collection of both historical and novel information.

Equilibrium Line Altitude

One of the primary goals in glacier studies is the determination of the total mass balance of a glacier (Khalsa et al., 2004). This is defined as the total gain or loss in mass in a glacier at the end of one hydrologic year. The equilibrium line altitude (ELA) is the elevation at which mass is neither lost nor gained and is commonly used in determining mass balance. The ELA separates a glacier's accumulation zone, the area of snow accumulation, from the ablation zone, the area of net loss in ice mass due to evaporation or melting (Pellitero et al., 2015). This line allows geologists to track changes in the climate, especially the connection between solid precipitation and air temperature. As temperatures rise, greater amounts of ice melts, thus increasing the ablation zone and subsequently, the ELA. On the other hand, when precipitation increases, the accumulation zone increases while the ELA decreases (Cossart, 2011). Currently, there are several methods that can be used to estimate the ELA.

The most widely used technique for ELA estimation is the calculation of the Accumulation Area Ratio (AAR). The AAR is the ratio between the area of the accumulation area to the total area, and assumes that the ratio is constant if the glacier is in a steady state (Pellitero et al., 2015). For modern glaciers, the AAR varies between types of glaciers and climatic regimes, and can be determined using statistical methods and observed data (Ignéczi and Nagy, 2013). Landsat satellite images are used to define snowlines using visible and infrared bands (Chan, Van Ophem and Huybrechts, 2009). This is possible due to the differentiation between the high reflectance of snow and lower reflectance of ice. Defining these areas, along with further statistical calculations allows geologists to determine the AAR of a glacier to give a perspective on the mass balance change (Figure 7.10).

Documenting Glacial Parameters

In the past, glaciers have been studied and measured one by one and the volume was calculated using statistical scaling theories and relationships (Bahr et al., 1997). More recently, techniques involving the analysis of meteorological records and aerial photography have been applied to capture data and create digitized topographical maps (Oerlemans et al., 2005). GIS technology allows the mapping of glaciers to be more efficient in terms of cost and labour (Paul et al., 2002). For instance, software applications are capable of computing glacial parameters such as ELA and slope automatically and accurately (Paul et al., 2002). This is particularly useful when observing larger areas as the process is less time consuming. It is also effective in identifying small changes within smaller glacial areas (Paul et al., 2002).

It has been documented that the rate of sea level rise has been increasing over the past decade as a result of the gradual thinning and rapid retreat of glaciers (Meier et al., 2007). There are also societal and economical concerns associated with the disappearance glaciers and sea level rise.

As Earth's temperature is expected to continue to rise, analyzing the changes glaciers is an accurate method for scientists to use in their climate studies. Applying technologies to geology has advanced science in allowing for more precise measurements that are readily obtained. In the past, some scientists have solely relied on their observations, while others depended on calculations and laws to support their theories. As shown in this application of glaciers as indicators of climate change, scientists have been able to combine historical methods with modern technology as it is necessary to analyze both observations and calculations in order to obtain a holistic view of the subject. Through capturing images of glacial features and creating maps, paleoreconstruction of ice sheets can now be performed to indicate changes in the environment. Overall, keeping record of glacial parameters overtime provides scientists with an abundance of data and statistics that are key to understanding of changes and tendencies from our Earth's past and predicting future trends.

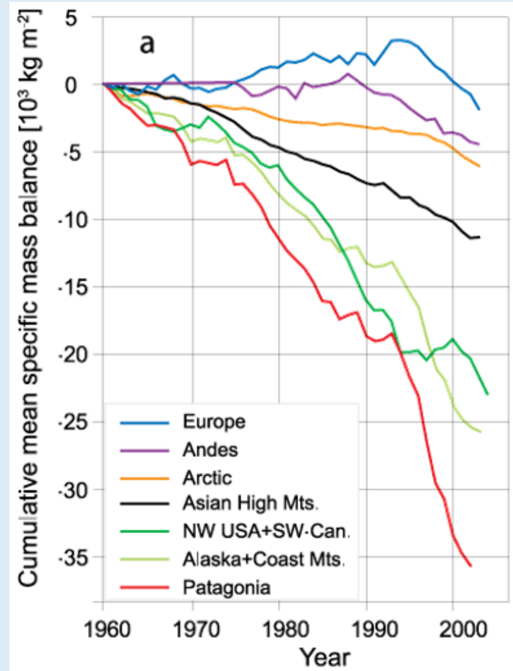


Figure 7.10: *The cumulative mean mass balance of different geographic regions from 1960 to 2000 illustrating the magnitude of climate change in the associated region.*

Meteorology: A Story of War and Discovery

Weather and climate is an integral part of human life. From ancient human civilizations to modern society, we have always attempted to develop tools to help us study and understand and predict weather phenomena. Weather forecasting can influence the decision to take an umbrella to work, or to avoid dangerous sailing conditions for massive cargo ships. Meteorology dates as far back as 380 BC when the Greeks built the magnificent Tower of the Wind (Figure 7.11). Charting of weather began in the British Industrial age and has since evolved into a widespread network of weather information which we process using supercomputers. Our tools for climate investigation are being updated constantly. The catalyst for these advancements in meteorology were often wars. The Crimean War led to the creation of the first weather forecast station in Britain. Similarly, World War I and II initiated the search for upper-atmospheric climatic variables. As we step into the new millennia, meteorology is becoming a more connected field, where tremendous amounts of data are being shared and transferred between different organizations and people everyday. The purpose of studying the history of meteorology is to gain insight on how tools evolved to improve the accuracy of weather forecasts and climate models. Going forward, this could be a useful determinant for whether or not it is feasible to generate better models than those which we possess today.

Figure 7.11: *Tower of the Wind, located in Athens. It is shaped as an octagon, where each wall faces in a Cardinal direction. It had multiple functions, including: a wind vane, a water clock, and a sundial. It is located in the Roman Agora, an ancient marketplace.*

Ancient Meteorology

The word "climate" originates from the Greek word "klima", which denotes regional weather variance based on the slopes of the areas which possess the same latitude with respect to the Earth's axis. The shift from the hunter-gatherer lifestyle to an agricultural society motivated the development of weather forecasting tools and the search for variables which influenced the weather and subsequently, influenced the outlook of their crops (Edwards, 2010).

In ancient Greece, around 380 BC, people did not utilize conventional weather measuring devices. Instead, they were more reliant on observations (Halford and Fish, 2004). People would often connect the behaviour of animals to the weather. This led to the creation of an almanac which recorded all the animal behaviour relevant to weather predictions. Aristotle, an important figure in the scientific community at the time, tried to explain the basis for weather phenomena, instead of trying to seek out a pattern. He theorized that different elements circulated between air, water, and the Earth (Halford and Fish, 2004).

At the same time, the Greeks built weather watching towers in local villages in an attempt to monitor the rainfall, wind direction, and wind speed. These towers would later be used by the Roman Empire, who followed the ancient Greek way of recording the weather. One of the first weather stations, shown in Figure 7.11, stood right in the Roman Agora marketplace, which could have been useful to merchants who at that time, determined when to sell their goods based on the weather (Halford and Fish, 2004).

Figure 7.12: *Aboriginal Canadian legends about weather provide insight into what tools they may have used to predict variation in weather. Stories such as: "Yatth Dene" suggest that the Aboriginal people may have used to the migration of geese to detect the approach of winter.*

The earliest Canadian records of insight into climate came from the Aboriginal people circa 1000 CE (Moses et al. 2013). In order to survive the weather extremes, it was imperative for the Aboriginal people to develop a greater understanding of their surroundings. By definition, they were Canada's first scientists, and their research was collected and dispersed orally through stories. Storytellers were trained for many years to be able to memorize the stories, and repeat them unaltered to the following generations.

Oftentimes these stories about weather were intended to provide spiritual explanations for the occurrence of natural phenomena such as the change in seasons (Moses et al. 2013). Nowadays, a select few of these stories have been translated and converted into written format. Because these stories have been passed on in their original form for so long, they each provide an excellent insight into the historical tools and understanding that went into interpreting climate.

The legend titled "*Yatth Dene*" is a story about a ceaseless winter (Reynolds 1973). In this story, it notes that the geese would not return from the South. This reference shows that the Aboriginal people clearly understood that the behaviour of geese reflected climate. Therefore, it is probable that the geese may have been used as a tool to predict the arrival of winter and spring (Figure 7.12). This would have been a critical observation because it would provide them with information about how their access to certain seasonal resources, such as herbs, may change.

The story: *"Môstos, The Buffalo and Sihkos, The Weasel"* shows that the Aboriginals even made attempts at predicting how severe the winter would be (Reynolds 1973). In this story, a hunter befriends a weasel to hunt down a Buffalo. The weasel managed to kill the buffalo by jumping down its throat and biting off its heart. As the weasel darted out, its left paw prints in the throat of the buffalo which remained on the throats of all other animals to come. It was believed that when men hunted in the fall, they could use the paw marks on the throats of animals to tell whether the winter would be cold or mild.

Conventional instruments of meteorology, such as the barometer, were developed in Europe much later. The early barometer consisted of a thin tube with a pendulum at the bottom (Halford and Fish, 2004). Liquid mercury was used to measure the absolute climate pressure. The first documented barometer was thought to be designed by Torricelli, which the pressure unit torr was named after. In his experiment, he used mercury and found the "weight of the air" using vacuum as a reference. In its earliest iteration, the barometer was a crude instrument that was of little use in predicting temperature. By the end of the 18th century, owning a glass barometer was a status symbol. However, very few people who owned the device actually engaged in meteorology. After Robert Hooke's improvement to the design of the barometer, it was finally useful for predicting immediate temperature changes (Halford and Fish, 2004).

People intuited temperature based on the freezing and boiling of water. As such, the design of the thermometer was inspired by the thermoscope, a device without a scale made by Philo in the Byzantine era which used water as a measurement reference (Halford and Fish,

Figure 7.13: *British Bombardment of the Fortress in Aland Islands during the Crimean war. For both Britain and France, a naval fleet was an important component in their military power. Relying on weather forecasts helped to ensure that these ships did not get caught in the middle of storms and sink.*

2004). Philo constructed the thermoscope in order to conduct an experiment to measure the expansion of air under solar radiation. The thermometer was invented in the 16th century, by Galileo, and used water as a measuring tool. Early thermometers were also barometers, which was a disadvantage because it led to less accurate results. The most highly debated feature of the thermometer was which temperature scale to use, as different producers of thermometers had their own scales which it operated on. Polish-born Dutch physicist Daniel Gabriel Fahrenheit proposed a scale for the thermometer manufactured by himself, which had a fine scale and better reproducibility, and is still used today (Halford and Fish, 2004).

Industrial Revolution

The age of the Industrial Revolution started a new wave of interest in studying climate for navigation, which was important for commerce and military purposes (Halford and Fish, 2004). This was followed by the development of theories for weather phenomena, including a predecessor to the modern storm theory. The Crimean War between Russia and Turkey that started in 1853 also spurred new interest in maritime recording (Troubetzkoy, 2006). Both Britain and France wanted to protect the Middle East by sending fleets through the sea. At the same time, fleets were losing ships to storms. The prediction of weather mainly relied on the marine logs from the ships which had returned to port to warn about stormy seas and wind currents (Figure 7.13). Accurate predictions of the weather relied on existing knowledge of its relation to pressure. This did not do much for amateurs, since they were often confounded by illiteracy (Halford and Fish, 2004).

John Dalton, the founder of the atomic theory, also had interest in hydrology, the study of rainfall and water circulation in the air (Halford and Fish, 2004). In his lifetime, he made more than 200,000 recordings of the weather. Dalton disproved the belief that rivers were fed by mysterious mountain reservoirs, as he provided evidence that precipitation alone could create a river. He also extended on Boyle's theory that air can change in temperature as it expands and compresses. He provided a better understanding of the atmosphere, which stated that air contains water droplets even without the presence of rain, and that warm air can hold more moisture than cold air (Halford and Fish, 2004). In 1821 there was a storm in the state of Connecticut that destroyed houses and forests (Halford and Fish, 2004). William C. Redfield was measuring the falling direction of the wind and found that some trees displayed a pattern which could only be generated if the wind had blown in a circular pattern. He sailed around the eastern seaboard of North America and found that wind blows counter-clockwise around the center of low pressure. This observation, however, was in complete contradiction to the work of a German scientist named Brandes.

Converse to Redfield's claim that wind whirls around a central depression, Brandes asserted that the wind heads towards a central column. James Pollard Espy, a meteorologist from the United States, started an academic war with Redfield which forced meteorologists to take sides. (Halford and Fish, 2004). This debate led to the exploration of wind by various scientists, along with the British Navy. Maury was one such scientist. He set out to take weather recordings at sea aboard a ship called *Falmouth*. With the help from several staff, he was able to travel to various places and start charting the wind. Sometime later, the Crimean War would once again spur interest in weather prediction, especially for storms (Halford and Fish, 2004).

Climate Models

20th Century Meteorology

Even into the 20th century, the motivation for developing climate models was unchanged. Minimizing economic disasters and loss of life from climate and weather variability rested on the reliability and efficiency of meteorology as new technologies and climatic variables presented themselves. Despite all the technological advances made in the previous century, the world had more to learn about the factors which influence the weather. The development of tools to measure these new variables would also prove to be a unique challenge.

On December 17 of 1903, two brothers in North Carolina, Wilbur and Orville Wright, would test one of the first great inventions of the 20th century. Their engine-powered airplane managed to take mankind to new heights. To meteorologists, these planes were indispensable for measuring low altitude atmospheric conditions.

The next leap forward was the design of planes which could serve the military through reconnaissance and direct combat. WWI planes were rather crude in design compared to those which would follow decades later, and most cases of humans losing their lives in these planes were from combat rather than unpredictable weather conditions.

It wasn't until WWII, however, that the demands of planes became much different. The natural defense against anti-air weaponry was the design of new planes which could outrange artillery by flying higher. There was, however, an important weather element which made this strategy very dangerous. Pilots discovered that if they rose to altitudes of 6 to 7 kilometers, they would encounter dangerously strong winds (WMO, 2003). This was mankind's first encounter with jet streams. Soon after came the realization that weather was controlled in part by large-scale atmospheric circulation patterns. The urgent demand for safe air travel accelerated the development of meteorological tools to measure the conditions of the upper atmosphere.

At the dawn of the 20th century, meteorologists were beginning to understand more about the complexities of the Earth's atmosphere. It was concluded that all of Earth's weather systems are contained in the troposphere, which is the lowest layer of the atmosphere (Namias, 1949). It extends from the surface up to an altitude of 10 to 14 kilometers.

At this time, research was being conducted on the physical and chemical properties of the atmosphere (WMO, 2003). This knowledge served as the basis for understanding that the jet stream is made up of high speed eastward winds in the upper troposphere which are formed

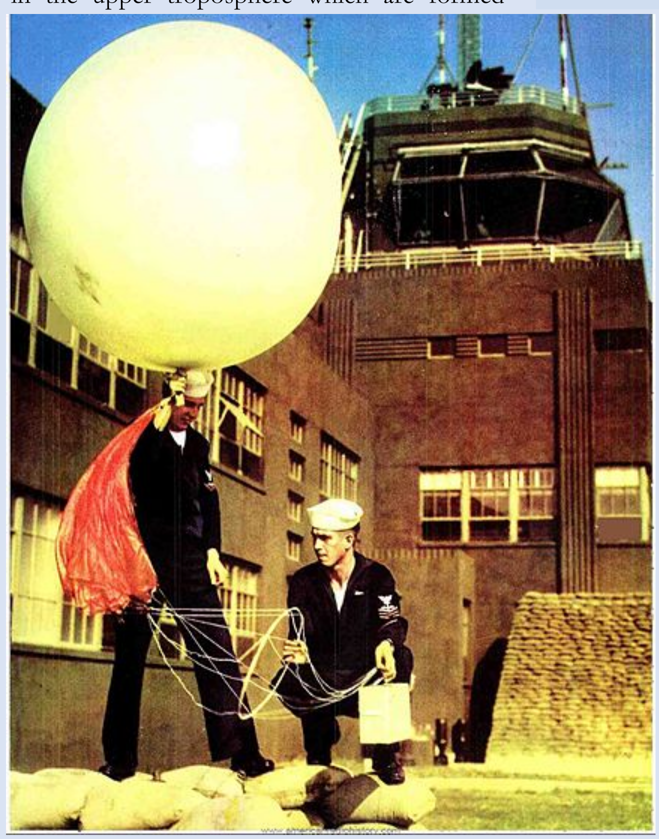


Figure 7.14: *Two US Navy soldiers launching a radiosonde attached to a balloon in 1943. Fighter planes and bombers in WWII oftentimes encountered dangerous weather conditions at high altitudes. By using radiosondes, the military could determine the weather conditions of the upper troposphere and plan flights which would maximize the pilot's safety.*

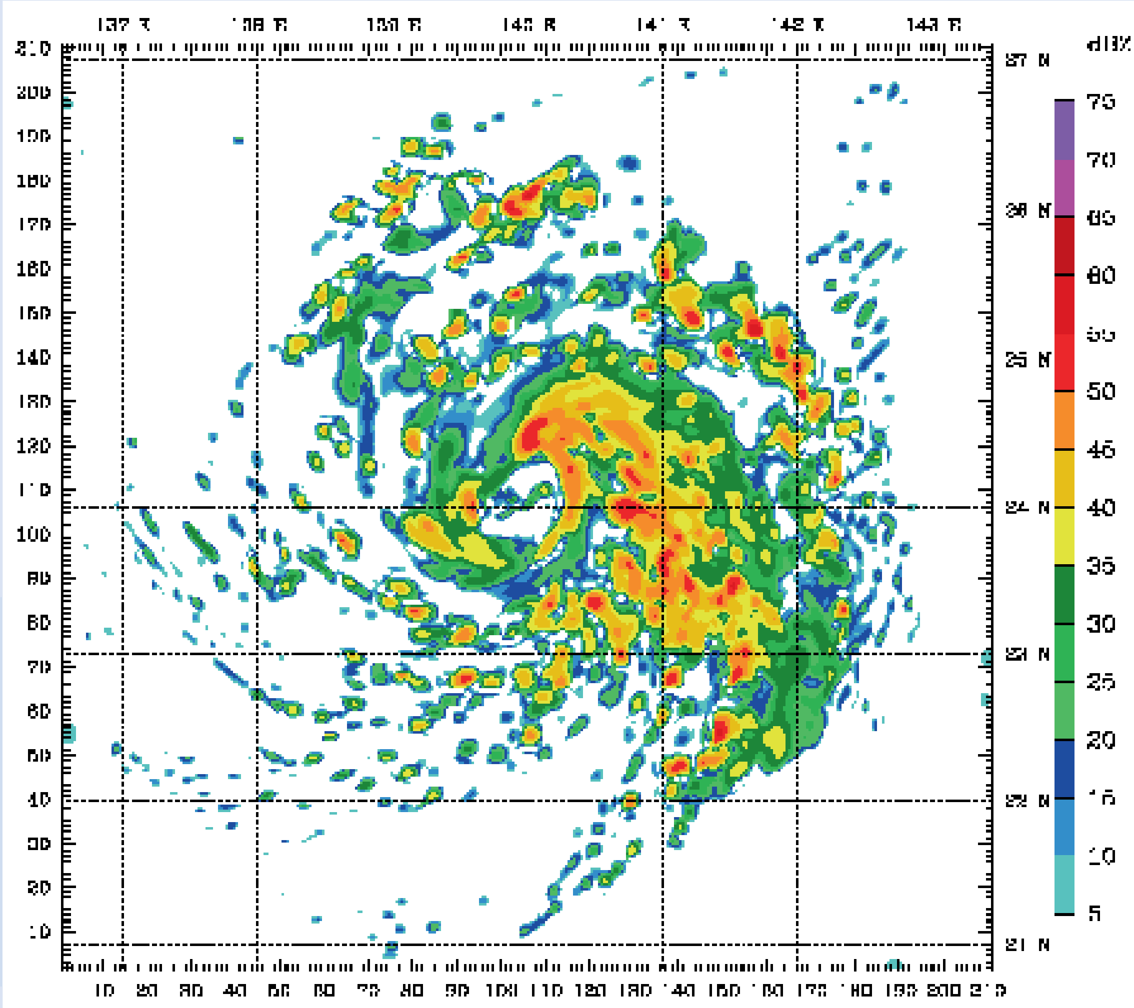


Figure 7.15: *A computer simulation of the Typhoon Mawar in 2005. It is mapped using a grid that spans 3 kilometers. The scale on the right indicates the amount of rainfall where red indicates lots of rainfall, blue indicates light rainfall and white indicates no rainfall.*

from large temperature differences in the atmosphere (Namias 1949).

The radiosonde, shown in Figure 7.14, was created for the purpose of measuring the atmospheric parameters and it can be used to determine the properties of the jet stream for a given location (Elliot 1991). The device is carried into the atmosphere by a large helium balloon and it transmits atmospheric parameters to the ground receiver through radio waves. The radiosonde carries sensors for temperature, pressure, and humidity variables. Once this meteorological data has reached the ground, it can be interpreted for weather forecasting purposes.

The radiosonde itself has seen many design changes over the past century to improve its performance using newly developed technologies. For instance, radiosondes before 1943 used a hair hygristor to measure humidity. This would later be replaced by a lithium chloride instrument because the previous model suffered a tremendous amount of lag in cold temperatures. Oftentimes, the hair hygristor would report large humidity values for higher altitudes, even though it was known at the time that relative humidity decreases with height. The lithium-chloride hygristor left much to be desired, however, and was phased out around 1965 in favour of a carbon hygristor. The principle design flaw with the lithium-chloride hygristor was that it created a small temperature increase in the enclosure due to an exothermic reaction. This would result in a relative humidity slightly lower than that of ambient air.

The history of the design of the radiosonde is important when developing theories for climate variation over time by using a century's worth of data obtained from this device. By improving the design, radiosondes were able to make more accurate and detailed observations. Therefore, it is necessary to take the error of archived meteorological data into consideration when drawing large scale conclusions about climate (Elliot 1991).

21th Century Meteorology

Due to branching ideas about meteorology in the late 1700s, three sub-disciplines emerged: forecasting, dynamical and theoretical meteorology, and empirical statistical climatology (Edwards, 2010). Each, as their name suggests, focused on different aspects of climate and had their own unique approach on studying it. The statistical method became more popular in the 1900s, which was originally thought to be radical due to the extensive calculation and relatively little data collection involved. This is due to the difference between meteorology and other fields which relied more on experimentation than observation. This destined the next revolutionary change in meteorology: the ability to experiment with climate models. This was made possible by the advancement of computers in the 1960s using a crude database of high atmospheric data. Nowadays, the most important simulations in climatology use the Global Circulation Model (GCM). This is also where the three sub-disciplines of meteorology were united. Climate models like GCM allowed climatologists to study the upper atmosphere and experiment with different scenarios such as moving the continents and changing the brightness of the Sun and observe its effect on the Earth and its regional climates (Edwards, 2010).

Meteorology underwent a mathematical revolution in the late 20th century. The efforts of the International Meteorological Organization (superseded in 1950 by the World Meteorological Organization) improved the collection and distribution of weather data tremendously. With this change, the most useful tools for predicting weather became systems of deterministic, nonlinear ordinary differential equations which incorporated meteorological variables such as temperature and wind speed. The preferred method of communicating these solutions is through computer models which are simple enough to be understood by the general population (Figure 7.15).

As the weather simulations become more sophisticated, a disparity between the resolution of climate models and data availability became a new problem (Edwards, 2010). A solution emerged as meteorologists started interpolating and assimilating climate data with computer-generated data (Edwards, 2010).

The transmission and collection of data was also needed for further progression of meteorology. Although satellites and radiosondes had drastically improved the efficiency and vision of weather forecasts, it was difficult to translate the data into usable forms for the forecasting community (Edwards, 2010). In the beginning, the data sent back was distorted and it was difficult to map longitude and latitude on a flat map. The data that was sent back by the satellites were images that could be used to analyze cloud types, and water content. Initially, satellites were not useful to the development of climate data due to its poor resolution. By the late 1990s, satellite resolution had improved enough to be useful in the development of climate models (Edwards, 2010).

With the power of computers, forecasters can incorporate new data into their analysis as it becomes available, making forecasting more flexible. They can also create 4-D weather data by observing snapshots of weather data at different times. This model is astute enough to predict weather events without data sent directly from the region (Edwards, 2010; ECMWF, 2017). For instance, in 1985, the land weather network in North Africa broke down. However, the climate model used by the European Centre for Medium-Range Weather Forecast (ECMWF) was still able to predict a vortex forming above the West Sahara (Bengtsson and Shukla, 1988).

The most significant limitation of computer based methods for weather forecasting and climate models was discovered in 1962 by an MIT meteorology professor named Edward Lorenz. Lorenz discovered from his work with computer models that if he made slight modifications the meteorological variables used as initial conditions, it would considerably alter how the prediction evolved over a long period of time (Lorenz, 1963). This chaotic effect became known as the “butterfly effect”. Lorenz’s conclusion from this effect was that it is unfeasible to generate long-term weather forecasts since the chaotic effects introduced by miniscule rounding errors in data would skew the prediction over time. Even if the means of collecting meteorological data improved in precision tenfold, all computer based weather forecasts will be limited by the butterfly effect.

Therefore, the future of meteorology depends on a new field of mathematics which must emerge to overcome this issue.

"Progress is made by
trial and failure;
the failures are generally a
hundred times more numerous than
the successes; yet they are
usually left unchronicled."

-William Ramsay

Conclusion

The past can hold clues about our future, and in order to unlock the full potential of the planet we live on, it is important to consider what is already known about the history of the Earth. Every single scientist has played a role in shaping our current understanding of this planet. A seemingly endless reservoir of human curiosity has led to incredible discoveries and inventions, all of which have paved the way for future scientists. This book serves as both a narrative and an analysis of historical breakthroughs and the strides that have been taken to arrive at the point where we currently stand in scientific history.

There lies a unifying theme within each of the chapters: no challenge is insurmountable when the pursuit of novel discovery is driven by the innate nature of humans to learn and explore. From the origin of life, to the theories fueled by our inherent curiosity, the number of scientific breakthroughs are constantly on the rise. Technological advancements have greatly facilitated the search for answers to some of Earth's oldest mysteries. Such developments have helped the human race reach the pinnacle of their scientific knowledge, and yet there is still more to come. All the way from the depths of our oceans to the beautiful star-lit mysteries of space that were once just too far out of reach, the search for life itself has become more aggressive than ever. Pursuits like these are what drive the acquisition of knowledge and push modern technology to its full potential. As our level of understanding of the world reaches an all-time high, it is increasingly important to remember the events that brought us to this point. There was a time when some of the greatest theories that we value today were rejected, when sending a man to the moon was completely out of the question, and when expecting to find life a couple hundred metres deep in the ocean was just purely absurd. Evidently, we have come such a long way since then, but the past cannot just remain the past. It should still be put under as much scrutiny as any new piece of evidence. If the periodic reversal of Earth's magnetic poles and the cycle of ice ages in our planet's past are any indication, there should be no doubt that certain phenomena are often predictable. In fact, it is possible that today's questions could be answered by recalling yesterday's events.

There are stories that only time can tell, and many of these begin with the history of the Earth.

References

Abel, O., 1914. *Die Tiere de Furwelt*. Leipzig, Berlin: B.G Teubner.

Abrahams, P., 2010. "Earth Eaters": Ancient and Modern Perspectives on Human Geophagy. In: E. Landa and C. Feller, ed., 2010 *Soil and Culture*. New York: Springer, pp.369-372.

Afnan, S.M., 1958. *Avicenna, his life and works*. London: G. Allen & Unwin.

Agassiz, L., 1870. The Former Existence of Local Glaciers in the White Mountains. *The American Naturalist*, 4(9), pp.550-558.

Agassiz, L., 1886. *Geological sketches*. Boston: Houghton Mifflin.

Agricola, G., Hoover, H. and Hoover, L., 1950. *De re metallica*. New York, N.Y.: Dover.

Ahrens, R., Eswaran, H. and Rice, T., 2002. *Soil Classification: A Global Desk Reference*. CRC Press, pp.5-7.

Alberta Geological Survey, 2000. *Historical Overview of the Fort McMurray Area and Oil Sands Industry in Northeast Alberta*. [pdf] Alberta Energy and Utilities Board. Available at: <http://ags.aer.ca/document/ESR/ESR_2000_05.PDF> [Accessed 18 February 2017].

Alibert, Y. and Benz, W., 2017. Formation and composition of planets around very low mass stars. *Astronomy & Astrophysics*, 598, p.L5.

Allan, J.A., 1921. *Second Annual Report on the Mineral Resources of Alberta*. Edmonton, Alberta: The Legislative Assembly.

Allard, M., Young, D. and Huyen, Y., 1995. Detecting dinosaur DNA. Science, 268(5214), pp.1192-1192.

Allbutt, T.C., 1970. *Greek medicine in Rome; the Fitzpatrick lectures on the history of medicine delivered at the Royal College of Physicians of London in 1909-1910, with other historical essays*. New York: B. Blom.

Allis, R., 2000. Insights on the formation of vapor-dominated geothermal systems. In: *Proceedings World Geothermal Congress*. [online] pp.2489–2496. Available at: <https://www.geothermalenergy.org/pdf/IGAstandard/WGC/2000/R0610.PDF> [Accessed 28 Feb. 2017].

al-Naqib, A. al-Rahman, 2000. *Ibn Sina on Education*. [online] Muslim Heritage. Available at: <http://www.muslimheritage.com/article/ibn-sina-education#section1> [Accessed 26 Jan. 2017].

Anderson, R.N., Boulanger, A., Bagdonas, E.P., Xu, L. and He, W., The Trustees Of Columbia University In The City Of New York, 1996. *Method for identifying subsurface fluid migration and drainage pathways in and among oil and gas reservoirs using 3-D and 4-D seismic imaging*. U.S. Patent 5,586,082.

Anderson, S.P., Glazovky, A.F., 2007. Glaciers Dominate Eustatic Sea-Level Rise in the 21st Century. *Science*. 317, pp.1064-1066.

Anon, 2014. *About | ISSOL*. [online] ISSOL. Available at: <http://issol.org/about/history/> [Accessed 20 Feb. 2017].

Anon, 2016. *Jill F. Banfield*. [online] Earth and Planetary Science. Available at: <http://eps.berkeley.edu/people/jill-f-banfield> [Accessed 21 Feb. 2017].

Anon, 2017. *ANSMET, The Antarctic Search for Meteorites | CWRU*. [online] Caslabs.case.edu. Available at: <http://caslabs.case.edu/ansmet/> [Accessed 28 Feb. 2017].

Anon, 2017. *Argo Canada*. [online] Fisheries and Oceans Canada. Available at: <http://www.meds-

sdmm.dfo-mpo.gc.ca/isdm-gdsi/argo/index-eng.html> [Accessed 27 Feb. 2017].

Anon, 2017. *Environment and Climate Change Canada - Pollution and Waste - Mining*. [online]. Available at: <https://www.ec.gc.ca/pollution/default.asp?lang=En&n=C6A98427-1> [Accessed 28 Feb. 2017].

Anon, 2017. *Foraminifera*. [online] microfossil image recovery and circulation for learning and education. Available at: <http://www.ucl.ac.uk/GeolSci/micropal/foram.html> [Accessed 27 Feb. 2017].

Anon, 2017. *History | ISSOL*. [online] ISSOL. Available at: <http://issol.org/about/history/> [Accessed 20 Feb. 2017].

Anon, 2017. *Ocean bottom deposit collection*. [online] Natural History Museum. Available at: <http://www.nhm.ac.uk/our-science/collections/mineralogy-collections/ocean-bottom-deposit-collection.html> [Accessed 27 Feb. 2017].

Aristotle, 350 BCE. *On the Heavens*. Translated from Greek by J.L. Stocks. Oxford: Clarendon Press.

Aristotle, 1952. Aristotle: Meteorologica. Reprint edition ed. Translated by H.D.P. Lee. London: Harvard University Press.

Armstrong, A.H., 1967. *The Cambridge history of later Greek and early medieval philosophy*. Cambridge University Press.

Arnold, R., Shoba, S., Krasilnikov, P. and Ibanez Marti, J., 2012. *A Handbook of Soil Terminology, Correlation and Classification*. Taylor & Francis, p.340.

Ashby, N., 2002. Relativity and the Global Positioning System. *Physics Today,* 41(5), pp41-47.

Aubet, M.E., 2001. *The Phoenicians and the West: politics, colonies and trade*. Cambridge: Cambridge University Press.

Augustine of Hippo, n.d. *City of God*. Translated from Latin by John Healey, 1610. Edinburgh: John Grant.

Avery, O., MacLeod, C., McCarty, M., 1944. Studies on the Chemical Nature of the Substance Inducing Transformation of Pneumococcal Types: Induction of Transformation by a Deoxyribonucleic Acid Fraction Isolated from Pneumococcus Type III. *Journal of Experimental Medicine,* 79(2), p. 137-158.

Baba, A., Bundschuh, J. and Chandrasekharam, D., 2014. *Geothermal Systems and Energy Resources: Turkey and Greece*. CRC Press.

Bag, A., 2015. Ideas and Researches on Physical Concepts in India. *Indian Journal of History of Science*, 50(4), pp.1-5.

Bahr, D.B., Meier, M.F., Peckham, S.D., 1997. The physical basis of glacier volume-area scaling. *Journal of Geophysical Research*. 102, pp. 20,355-20,362.

Balasubramaniam, R., 2009. On the confirmation of the traditional unit of length measure in the estimates of circumference of the earth. *Current Science*, *96*(4).

Baldwin, M., 1985. Magnetism and the Anti-Copernican Polemic. *Journal for the History of Astronomy*, 16(3), pp.155-174.

Banfield, J. and Marshall, C., 2000. Earth Science and Evolution: Genomics and the Geosciences. Science, 287(5453), pp.605-606.

Barbier, E., 2002. Geothermal energy technology and current status: an overview. *Renewable and Sustainable Energy Reviews*, 6(1–2), pp.3–65.

Barish, B. and Weiss, R., 1999. LIGO and the Detection of Gravitational Waves. *Physics Today*, 52(10), pp.44-50.

Barstow, J. and Irwin, P., 2016. Habitable worlds with JWST: transit spectroscopy of the

TRAPPIST-1 system?. *Monthly Notices of the Royal Astronomical Society: Letters*, 461(1), pp.L92-L96.

Barton, I., 2015. Georgius Agricola's contributions to hydrology. *Journal of Hydrology*, 523, pp.839-849.

Barton, I., 2016. Georgius Agricola's De Re Metallica in early modern scholarship. *Earth Sciences History*, 35(2), pp.265-282.

Basri, G., Borucki, W.J. and Koch, D., 2005. The Kepler Mission: A wide-field transit search for terrestrial planets. *New Astronomy Reviews*, 49(7), pp.478–485.

Beck, R., 2015. Greco-Roman Astrology. *Handbook of Archaeoastronomy and Ethnoastronomy*, pp.1629-1635.

Bednarik, R. G., 1994. A taphonomy of palaeoart. *Antiquity*, *68*(258), pp. 68–74.

Bednarik, R. G., 1997. The earliest evidence of ocean navigation. *International Journal of Nautical Archaeology*, 26(3), pp. 183–191.

Beijing Museum of Natural History, 1979. *Memoirs of the Beijing Museum of Natural History*, 61, pp.51-79.

Bell, J. and Murphey, S., 1859. *A Treatise on Baths: Including Cold, Sea, Warm, Hot, Vapour, Gas, and Mud Baths, Also, on Hydropathy, and Pulmonary Inhalation, with a Description of Bathing in Ancient and Modern Times*. Lindsay & Blakiston.

Bell, R., 1884. *Report on part of the basin of the Athabasca River, North-West Territory*. Montreal: Authority of Parliament.

Bengtsson, L. and Shukla, J., 1988. *Integration of Space and In Situ Observations to Study Global Climate Change*.

Berman, E.R., 1975. Geothermal energy. Energy technology review. United States: Noyes Data Corp.

Berry, A., 1898. *A short history of astronomy*. London: John Murray.

Berry, F.A.F., 1965. *Memorial: Arville Irving Levorsen* (1894-1965). 49(9), pp.1534–1537.

Bird, A.L. and Lamontagne, M., 2015. Impacts of the October 2012 Magnitude 7.8 Earthquake near Haida Gwaii, Canada. *Bulletin of the Seismological Society of America*, 105(2B), p.1178.

Birrell, A., 1999. *The Classic of Mountains and Seas*. London: Penguin Books, p.336.

Blackman, F., 1905. Optima and Limiting Factors. *Annals of Botany*, 19(74), pp.281-296.

Blume, H., 2010. Soils and Soil Pioneers on Stamps. In: E. Landa and C. Feller, ed., *Soil and Culture*. New York: Springer, pp.431-438.

Bol'shakov, V.A., Kapitsa, A.P., 2011. James Croll: a scientist ahead of his time. *Polar Record*, 48(2), pp. 1-5.

Bostock, J., 1855. The Natural History. Pliny the Elder, with Copious Notes and Illustrations.

Bondi, H. and Hoyle, F., 1944. On the mechanism of accretion by stars. *Monthly Notices of the Royal Astronomical Society*, 104, pp.273–282.

Bossu, J.-B., 1963. Jean-Bernard Bossu's Travels in the Interior of North America. Translated by Feiler, Seymour. *Science*, 139(3554), pp.478–479.

Bowler, P., 1989. *Theories of Human Evolution*. Maryland, Baltimore: The John Hopkins University Press, pp.21-74.

Bowler, P.J., 1992. *The Earth Encompassed*. New York: W. W. Norton & Company.

Bragg, L., 1965. The History of X-Ray Analysis. *The Physics Teacher*, 3(7), pp.295-300.

Boyce, J., Pozza, M. and Morris, B., 2001. High-resolution magnetic mapping of contaminated sediments in urbanized environments. *The Leading Edge*, 20(8), pp.886–895.

Brasseur, L., Tamburri, M., Pluedemann, A., 2010. *Sensor Needs and Readiness Levels for Ocean Observing: An Example from the Ocean Observatories Initiative (OOI).* [pdf] Consortium for Ocean Leadership. Available at: <http://www.oceanobs09.net/proceedings/cwp/Brasseur-OceanObs09.cwp.10.pdf> [Accessed 27 February 2017].

Bray, R., 2008. *Environmental Aspects of Dredging.* Leiden: Taylor & Francis.

Bremmer, J.N., 2008. *Greek religion and culture, the Bible, and the ancient Near East* (Vol. 8). Brill.

Brenchley, P., 1985. *Sedimentology*. Oxford [etc.]: Blackwell scientific Publications.

Brevik, E., 2009. *Land Use, Land Cover, and Soil Sciences - A Brief History of Soil Science*. 6th ed. Oxford, UK: Encyclopedia of Life Support Systems (EOLSS), pp.40-65.

Brewster, D., 1831. *The Life of Sir Isaac Newton*. New York: Harper.

Broad, W., 1997. *The Universe Below: Discovering the Secrets of the Deep Sea.* New York: Simon & Schuster Inc.

Bromehead, C., 1948. Ships' Loadstones. *Mineralogical Magazine*, 28(203), pp.429-437.

Brown, R.A. and Kumar, A., 2011. A new perspective on Eratosthenes' measurement of the Earth. *The Physics Teacher*, 49(7), pp.445-447.

Bruin, F., 1981. Atmospheric refraction and extinction near the horizon. *Archive for history of exact sciences*, *25*(1), pp.1-17.

Buffett, B., 2002. Estimates of heat flow in the deep mantle based on the power requirements for the geodynamo. *Geophysical Research Letters*, 29(12).

Buick, R., 1992. The antiquity of oxygenic photosynthesis: evidence from stromatolites in sulphate-deficient Archaean lakes. *Science (New York, N.Y.)*, 255(5040), pp.74–77.

Buick, R., 2008. When did oxygenic photosynthesis evolve? *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, 363(1504), pp.2731–2743.

Buras, A.J., Ellis, J., Gaillard, M.K. and Nanopoulos, D.V., 1978. Aspects of the grand unification of strong, weak and electromagnetic interactions. *Nuclear Physics B*, [online] 135(1), pp.66–92.

Burek, C. and Higgs, B., 2007. *The role of women in the history and development of geology: an introduction*. Geological Society, London, Special Publications, 281(1), pp.1-8.

Burns, R., and Hardy, R., 1930. *Nitrogen Fixation in Bacteria and Higher Plants.* Berlin: Springer Verlag.

Caldwell, M.M., Bornman, J.F., Ballaré, C.L., Flint, S.D. and Kulandaivelu, G., 2007. Terrestrial ecosystems, increased solar ultraviolet radiation, and interactions with other climate change factors. *Photochemical & Photobiological Sciences*, *6*(3), pp.252-266.

Calvin, M., 1989. Forty years of photosynthesis and related activities. *Photosynthesis Research*, 21(1), pp.3–16.

Caneva, K.L., 2001. *The form and function of scientific discoveries* (pp. viii-32). Washington, DC: Smithsonian Institution

Libraries.

Carolina Sparavigna, A., 2013. The Science of Al-Biruni. *International Journal of Sciences*, 1(12), pp.52-60.

Carrigy, 1973. *Guide to the Athabasca Oil Sands Area.* Alberta: Alberta Research.

Cataldi, R. and Burgassi, P.D., 1999a. Flowering and Decline of Thermal Bathing and Other Uses of Natural Heat in the Mediterranean Area, from the Birth of Rome to the End of the First Millennium. In: *Stories From a Heated Earth: Our Geothermal Heritage.* Sacramento, California: Geothermal Resources Council; International Geothermal Association, pp.147–163.

Cataldi, R. and Burgassi, P.D., 1999b. Utilization of Geothermal Resources in Italy from the 11th through the 16th Centuries. In: *Stories From a Heated Earth: Our Geothermal Heritage.* [online] Sacramento, California: Geothermal Resources Council; International Geothermal Association, pp.185–193. Available at: <https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1018276>.

Cataldi, R. and Chiellini, P., 1995. Geothermal energy in the Mediterranean area before the Middle Ages. *International Geothermal Association*, 1995: 1, pp.373–380.

Chamberlin, T.C. and Moulton, F.R., 1900. Certain recent attempts to test the nebular hypothesis. *Science*, 12, pp.201–208.

Chandler, D.P. and Steinberg, D.J., 1987. *In search of Southeast Asia: A modern history*. Honolulu: University of Hawaii Press.

Chan, J., Van Ophem, J. and Huybrechts, P., 2009. Estimation of accumulation area ratio of a glacier from multitemporal satellite images using spectral unmixing. *2009 IEEE International Geoscience and Remote Sensing Symposium*.

Charpentier et al., 2009. Understanding the Canadian Oil Sands industry's greenhouse gas emissions. *Environmental Research Letters.* [e-journal] 4, pp.1-11.

Chela-Flores, J., 2001. *New Science of Astrobiology*. Dordrecht: Springer Netherlands, pp.180-181.

Chu, J., 2016. *Scientists make first direct detection of gravitational waves.* [online] MIT News. Available at: <http://news.mit.edu/2016/ligo-first-detection-gravitational-waves-0211> [Accessed 28 Feb. 2017].

Chyba, C., 2005. Rethinking Earth's Early Atmosphere. *Science*, 308(5724), pp.962-963.

Clark, K.A., and Blair, S.M., 1927. *The Bituminous Sands of Alberta*. Edmonton, Alberta: Authority of the Hon. J. E. Brownlee.

Cook, A., 1998. *Edmond Halley*. Oxford: Clarendon Press.

Cooper, A. and Poinar, H., 2000. Ancient DNA: Do It Right or Not at All. *Science*, 289(5482), pp.1139b-1139.

Copernicus, N., 1976. *On the revolutions of heavenly spheres*. Prometheus books.

Copley, J., 2014. Just how little do we know about the ocean floor? *The Conversation*, [online] Available at: <http://theconversation.com/just-how-little-do-we-know-about-the-ocean-floor-32751> [Accessed 27 February 2017].

Cossart, E., 2011. Mapping Glacier Variation at Regional Scale through Equilibrium Line Altitude Interpolation: GIS and Statistical Application in Massif des Ecrins (French Alps). *Journal of Geographic Information Systems.* 3, pp.232-241.

Costoya, X., deCastro, M. and Gómez-Gesteira, M., 2014. Thermohaline trends in the Bay of Biscay from Argo floats over the decade 2004–2013. *Journal of Marine Systems*, 139, pp.159-165.

Cowles, T., Delaney, J., Orcutt, J., Weller, R., 2010. The Ocean Observatories Initiative: Sustained Ocean Observing Across a Range of Spatial Scales. *Marine Technology Society Jounral*, 44(6), pp.54-64.

Creese, M. and Creese, T., 2006. British women who contributed to research in the geological sciences in the nineteenth century. Proceedings of the Geologists' Association, 117(1), pp.53-83.

Cresswell, J., 2014. *Little Oxford Dictionary of Word Origins*. Oxford University Press, USA.

Croll, J., 1875. *Climate and Time.* New York: D. Appleton and Company.

Croll, J. and Irons, J.C., 1896. *Autobiographical Sketch of James Croll.* London: Edward Stanford.

Crosby, A.W., 2003. *The Columbian exchange: biological and cultural consequences of 1492* (Vol. 2). Greenwood Publishing Group.

Crutzen P.J. and Gunter Brauch H., 2016. *Paul J. Crutzen A Pioneer on Atmospheric Chemistry and Climate Change the Anthropocene.* Mosbach: Springer.

Cuadros, J., Dekov, V., Arroyo, X. and Nieto, F., 2011. Smectite Formation in Submarine Hydrothermal Sediments: Samples from the HMS Challenger Expedition (1872 à 1876). *Clays and Clay Minerals*, 59(2), pp.147-164.

Dalley, S., Reyes, A., Pingree, D., Salvesen, A. and McCall, H., 1998. *The legacy of Mesopotamia*. Oxford: Oxford University Press, pp.107-137.

Darwin, C., 1859. *The Origin of Species*.. London: John Murray.

Darwin, C., 1871. *The Descent of Man*. London: John Murray.

Davidson, J.P., 2000. Fish Tales: Attributing the First Illustration of a Fossil Shark's Tooth to Richard Verstegan (1605) and Nicolas Steno (1667). *Proceedings of the Academy of Natural Sciences of Philadelphia*, 150, pp. 329-344.

Davies, A., 1964. Prince Henry the Navigator. *Transactions and Papers (Institute of British Geographers)*, (35), p.119.

Davis, L., 2009. Mary Anning of Lyme Regis: 19th Century Pioneer in British Palaeontology. Headwaters: The Faculty Journal of the College of Saint Benedict and Saint John's University, 26, pp.96-126.

Davis, T., 1928. Avicennae de Congelatione et Conglutinatione Lapidum. *Journal of Chemical Education*, 5(3), p.371.

Deacon, M., 1997. *Scientists and the sea, 1650-1900: A study of marine science*. Aldershot, Hampshire, Great Britain: Ashgate.

De Vorsey, L., 1976. Pioneer charting of the gulf stream: The contributions of Benjamin Franklin and William Gerard de Brahm. *Imago Mundi*, 28(1), pp. 105–120.

De Baar, H., 1994. Von Liebig's law of the minimum and plankton ecology. *Progress in Oceanography,* 33(4), pp.347-86.

Dekov, V., Cuadros, J., Kamenov, G., Weiss, D., Arnold, T., Basak, C. and Rochette, P., 2010. Metalliferous sediments from the H.M.S. Challenger voyage (1872–1876). *Geochimica et Cosmochimica Acta*, 74(17), pp.5019-5038.

de Saussure, N.T., 1804. *Recherches chimiques sur la végétation*, Paris.

Descartes, R., 1979. *Le Monde: Ou Traité de la Lumière.* Abaris Books.

Desmond, A.J., The Discovery of Marine Transgression and the Exploration of Fossils in Antiquity. *American Journal of Science*, 275, pp. 692-707.

De Visser, M.W., 1935. *Ancient Buddhism in Japan* (Vol. 3). Brill Archive.

De Vitry, J., 1220. *Historia Orientalis*. Translated from Latin by Brother Arnold, 1904. New York: McGraw Publishing Company.

Devlin, A. and Barker, R., 1971. Discovering Photosynthesis. In: A. Devlin and R. Barker, ed., *Photosynthesis*, New York: Van Nostrand Reinhold, pp.1-11.

De Vorsey, L., 1976. Pioneer charting of the gulf stream: The contributions of Benjamin Franklin and William Gerard de Brahm. *Imago Mundi*, 28(1), pp. 105–120.

de Wit, J., Wakeford, H., Gillon, M., Lewis, N., Valenti, J., Demory, B., Burgasser, A., Burdanov, A., Delrez, L., Jehin, E., Lederer, S., Queloz, D., Triaud, A. and Van Grootel, V., 2016. A combined transmission spectrum of the Earth-sized exoplanets TRAPPIST-1 b and c. *Nature*, 537(7618), pp.69-72.

Dietsche, K.-H. and Kuhlgatz, D., 2015. History of the automobile. In: K. Reif, ed., Gasoline Engine Management, Bosch Professional Automotive Information. [online] *Springer Fachmedien*

Wiesbaden, pp.2–7. Available at: <http://link.springer.com/chapter/10.1007/978-3-658-03964-6_1> [Accessed 28 Feb. 2017].

DiPippo, R., 1999. Small geothermal power plants: design, performance and economics. *GHC bulletin*, 20(2), pp.1–8.

Division on Engineering and Physical Sciences., Commission on Engineering and Technical Systems., Aeronautics and Space Engineering Board., and National Research Council, 1995. *Global Positioning System: A Shared National Asset : Recommendations for Technical Improvements and Enhancements*. Washington: National Academies Press, pp.1-18.

Donahue, S., Forristal, D., and Donahue, L., 2013. Detection of soil compaction using seismic surface waves. *Soil and Tillage Research*. 128, April Issue, pp. 54-60.

Draper, J. (1843). XLIX. Description of the tithonometer, an instrument for measuring the chemical force of the indigo-tithonic rays. *Philosophical Magazine Series 3*, 23(154), pp.401-415.

Dreyer, J., 1906. *History of the planetary systems from Thales to Kepler*. Cambridge: University Press.

Duffield, W.A. and Sass, J.H., 2003. Geothermal Energy: Clean Power from the Earth's Heat. U.S. Geological Survey.

Duffin, C.J., Moody, R.T.J., Gardner-Thorpe, C., ed., 2013. *A History of Geology and Medicine*. London: The Geological Society.

Du Tremolet de Lacheisserie, E., Gignoux, D. and Schlenker, M., 2005. *Magnetism*. New York: Springer.

Dutrow, B. and Henry, D., 2011. Tourmaline: A Geologic DVD. *Elements*, 7(5), pp.301-306.

Eckert, M., 2012. Max von Laue and the discovery of X-ray diffraction in 1912. *Annalen der Physik*, 524(5), pp.A83-A85.

ECMWF, 2017. *Data Assimilation | ECMWF*. [online] Ecmwf.int. Available at:

Edwards, K., Bond, P., Gihring, T. and Banfield, J., 2000. An Archaeal Iron-Oxidizing Extreme Acidophile Important in Acid Mine Drainage. Science, 287(5459), pp.1796-1799.

Edwards, P., 2010. *A Vast Machine*. Cambridge: The MIT Press.

Einstein, A., 1905. *On the Electrodynamics of Moving Bodies*. Translated from German by G.B. Jeffrey and W. Perrett, 1923. London: Methuen and Company, Ltd.

Einstein, A., 1916. *The Foundation of the General Theory of Relativity*. Translated from German by A. Engel., 1996. Princeton University Press.

Elder, E., 1982. Women in Early Geology. Journal of Geological Education, 30(5), pp.287-293.

Ellingsen, O., 2002. Method to increase the oil production from an oil reservoir. 6499536.

Elliot, W., Gaffen, D., 1991. On the Utility of Radiosonde Humidity Archives for Climate Studies. *Bulletin American Meteorological Society. 72(10), pp. 1507-1520.*

Ells, S.C., 1914. Preliminary report on the bituminous sands of Northern Alberta. Ottawa: Canada Department of Mines.

Ells, S.C., 1926. Bituminous sands of northern Alberta: Occurrence and economic possibilities. Report on investigations to the end of 1924. Ottawa: Canada Department of Mines.

Emerson, R. and Arnold, W., 1932. A Separation Of The Reactions In Photosynthesis By Means Of Intermittant Light. *The Journal of General Physiology*, 15(4), pp.391-420.

Engelmann, T., 1882. Ueber Sauerstoffausscheidung von Pflanzenzellen im Mikrospektrum. *Pflüger, Archiv für die Gesammte Physiologie des Menschen und der Thiere*, 27(1), pp.485-489.

Engels, F., 1973. *Dialects of Nature*. 7th ed. New York: International Publishers.

Etgen, J., Gray, S. and Zhang, Y. , 2009. An overview of depth imaging in exploration geophysics.

Geophysics, 74(6), pp.WCA5-WCA17.

Fabian, P. and Dameris, M., 2014. *Ozone in the Atmosphere: Basic Principles, Natural and Human Impacts*. Berlin: Springer.

Fagereng, Å. and Toy, V., 2011. Geology of the earthquake source: an introduction. *Geological Society, London, Special Publications*, 359(1), pp.1-16 in Sibson, R., Fagereng, Å., Toy, V. and Rowland, J., 2011. *Geology of the Earthquake Source: A Volume in Honour of Rick Sibson*. London: Geological Society.

Faigler, S., Tal-Or, L., Mazeh, T., Latham, D.W. and Buchhave, L.A., 2013. *BEER analysis of Kepler and CoRoT light curves: I. Discovery of Kepler-76b: A hot Jupiter with evidence for superrotation.*

Feinberg, R., 1988. *Polynesian seafaring and navigation: ocean travel in Anutan culture and society*. Kent: Kent State University Press.

Ferngren, G., 2002. Science and religion. Baltimore, Md.: Johns Hopkins University Press.

Field, Y., Boyle, E., Telis, N., Gao, Z., Gaulton, K., Golan, D., Yengo, L., Rocheleau, G., Froguel, P., McCarthy, M. and Pritchard, J., 2016. Detection of human adaptation during the past 2000 years. *Science*, 354(6313), pp.760-764.

Fisher, D. and Hanson, G., 1951. Revisions in the geology of Saratoga Springs, New York and vicinity. *American Journal of Science*, 249(11), pp.795-814.

Fischer, I., 1975. Another look at Eratosthenes' and Posidonius' determinations of the earth's circumference. *Quarterly Journal of the Royal Astronomical Society*, 16, pp.152-67.

Fitzpatrick, S., 2001. *The Russian Revolution*. Oxford: Oxford University Press.

Fleming, J.R., 2006. James Croll in Context: The Encounter between Climate Dynamics and Geology in the Second Half of the Nineteenth Century. *History of Meteorology,* pp. 43-54.

Folk, R.L., 1965. Henry Clifton Sorby (1826–1908), the Founder Of Petrography. *Journal of Geological Education,* 13(2), pp.43–47.

Fonda, G., 1950. *Joseph Priestley*. The Science Teacher [online] Available at: <http://www.jstor.org.ezproxy.torontopubliclibrary.ca/stable/24139411> [Accessed 25 Feb. 2017].

Foreman-Mackey, D., Hogg, D.W. and Morton, T.D., 2014. *Exoplanet population inference and the abundance of Earth analogs from noisy, incomplete catalogs.*

Foulger, G., 1982. Geothermal exploration and reservoir monitoring using earthquakes and the passive seismic method. *Geothermics*, [online] 11(4), pp.259-268. Available at: <http://journals2.scholarsportal.info/pdf/03756505/v11i0004/259_gearmueatpsm.xml> [Accessed 14 Feb. 2017].

Frankl, A., Nyssen, J., Calvet, M. and Heyse, I., 2010. Use of Digital Elevation Models to understand and map glacial landforms — The case of the Canigou Massif (Eastern Pyrenees, France). *Geomorphology*, 115(1-2), pp.78-89.

Franklin, 1828. *Narrative of a Second Expedition to the Shores of the Polar Sea in the years 1825, 1826, and 1827*. London: Authority of the Right Honourable Secretary of State for Colonial Affairs.

Freely, J., 2010. *Aladdin's lamp*. New York: Vintage Books.

Fridleifsson, I.B., 2003. Status of geothermal energy amongst the world's energy sources. *Geothermics*, 32(4–6), pp.379– 388.

Friedman, G., 1985. History of Geology Relating to Petroleum Exploration. *AAPG Datapages*. [online] Available at: <http://www.searchanddiscovery.com/abstracts/html/1998/annual/abstracts/213.HTM?q=%2BtextStrip%3Ahistory+textStrip%3Asedimentology> [Accessed 15 Feb. 2017].

Friedman, H., 1963. Ultraviolet and X Rays from the Sun. *Annual Review of Astronomy and Astrophysics*, 1(1), pp.59-96.

Fritz, J., 1994. *Around the world in a hundred years: From Henry the Navigator to Magellan*. New York: Scholastic.

Fry, I., 2006. The origins of research into the origins of life. *Endeavour*, 30(1), pp.24-28.

Gallop, 1975. *Plato's Phaedo*. Translated from Greek with commentary by D. Gallop. Oxford: Clarendon Press.

Gamow, G., 1988. *The Great Physicists from Galileo to Einstein*. Dover Publications.

Garber, M., 2005. Chymical Wonders of Light: J. Marcus Marci's Seventeenth-century Bohemian Optics. *Early Science and Medicine*, 10(4), pp.478-509.

Gaston, C., Subramanian, A.C. and Zauscher, M., 2006. The History behind the Discovery of the Earth's Atmospheric Composition. *Science*.

Gellibrand, H., 1635. *A discourse mathematical on the variation of the magneticall needle*. London: Red-crosse.

Geological Survey of Canada, 1883. *Report of Progress - Geological Survey of Canada*. Montreal: Authority of Parliament.

Gerard V. Middleton, 2004. *Early Days in the Life of a Sedimentologist*. [Autobiography] Hamilton.

Gibert, J.P. and Jaudin, F., 1999. Using Geothermal Waters in France: The District Heating System of Chaudes-Aigues from the Middle Ages. In: *Stories From a Heated Earth: Our Geothermal Heritage*. Sacramento, California: Geothermal Resources Council; International Geothermal Association, pp.287–305.

Gilbert, W., 1600. *On the Loadstone and Magnetic Bodies and on the Great Magnet the Earth*. Translated from Latin by P.F. Mottelay, 1893. London: Bernard Quaritch.

Gillon, M., Jehin, E., Lederer, S.M., Delrez, L., de Wit, J., Burdanov, A., Van Grootel, V., Burgasser, A.J., Triaud, A.H., Opitom, C., Demory, B.O., Sahu, D., Bardalez Gagliuffi, D., Magain, P. and Queloz, D., 2016. Temperate Earth-sized planets transiting a nearby ultracool dwarf star. *Nature*, 533(7602), pp.221-224.

Gillon, M., Triaud, A., Demory, B., Jehin, E., Agol, E., Deck, K., Lederer, S., de Wit, J., Burdanov, A., Ingalls, J., Bolmont, E., Leconte, J., Raymond, S., Selsis, F., Turbet, M., Barkaoui, K., Burgasser, A., Burleigh, M., Carey, S., Chaushev, A., Copperwheat, C., Delrez, L., Fernandes, C., Holdsworth, D., Kotze, E., Van Grootel, V., Almleaky, Y., Benkhaldoun, Z., Magain, P. and Queloz, D., 2017. Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1. *Nature*, 542(7642), pp.456-460.

Glasser, O., 2013. *Wilhelm Conrad Röntgen und die Geschichte der Röntgenstrahlen*. Berlin: Springer Berlin Heidelberg.

Glatzmaier, G., 2002. Geodynamo Simulations—How Realistic Are They?. *Annual Review of Earth and Planetary Sciences*, 30(1), pp.237-257.

Glatzmaier, G. and Roberts, P., 1995. A three-dimensional convective dynamo solution with rotating and finitely conducting inner core and mantle. *Physics of the Earth and Planetary Interiors*, 91(1-3), pp.63-75.

Goldstein, B., and Bowen, A., 1983. A New View of Early Greek Astronomy. *Isis,* 74(3), pp. 330-340.

Goodhue, T., 2004. *Fossil hunter*. Bethesda, MD: Academica Press.

Goodman, L.E., 1992. *Avicenna*. Arabic thought and culture. New York: Routledge.

Gordin, M.D., 2012. How Lysenkoism Became Pseudoscience: Dobzhansky to Velikovsky. *Journal of the History of Biology*, [online] 45(3), pp.443–468. Available at: <http://www.ncbi.nlm.nih.gov/pubmed/21698424> [Accessed 20 Feb. 2017].

Gotthelf, A., 2012. *Teleology, First Principles, and Scientific Method in Aristotle's Biology*. [online] Oxford

University Press. Available at: <http://www.oxfordscholarship.com/view/10.1093/acprof:oso/9780199287956.001.0001/acprof-9780199287956> [Accessed 20 Feb. 2017].

Gould, A., 1901. *Louis Agassiz*.

Government of Canada, 2016. *Mapping the Northwest*. [online] Available at: <http://www.bac-lac.gc.ca/eng/discover/exploration-settlement/pathfinders-passageways/Pages/mapping-northwest.aspx#d2> [Accessed February 16 2017]

Govindjee & Krogmann, D., 2004. Discoveries in Oxygenic Photosynthesis (1727–2003): A Perspective. *Photosynthesis Research*, 80(1-3), pp.15–57.

Gratacap, L., 1881. *Atmospheric Ozone for January*, 1881. [online] Available at: <http://www.jstor.org.ezproxy.torontopubliclibrary.ca/stable/2900632-> [Accessed 25 Feb. 2017].

Gray, J. and Steele, J., 2008. Studies on Babylonian goal-year astronomy I: a comparison between planetary data in Goal-Year Texts, Almanacs and Normal Star Almanacs. *Archive for History of Exact Sciences*, 62(5), pp.553-600.

Gray, J. and Steele, J., 2009. Studies on Babylonian goal-year astronomy II: the Babylonian calendar and goal-year methods of prediction. *Archive for History of Exact Sciences*, 63(6), pp.611-633.

Gribbin, J., 2005. *Deep simplicity*. New York: Random House.

Grimaldi, F., 1665. *Physico-mathesis de lvmine, coloribvs, et iride, aliisque adnexis libri duo*. Bononiae: University of Lausanne.

Gross, C., 1993. Hippocampus Minor and Man's Place in Nature: A Case Study in the Social Construction of Neuroanatomy. *Hippocampus,* 3(4), p. 403-416.

Grund, P., 2009. Textual Alchemy: The Transformation of Pseudo-Albertus Magnus'sSemita Rectainto theMirror of Lights. *Ambix*, 56(3), pp.202-225.

Guberlet, M., 1964. *Explorers of the Sea*. New York: The Ronald Press Company.

Gulbekian, E., 1987. The origin and value of the stadion unit used by Eratosthenes in the third century BC. *Archive for History of Exact Sciences*, 37(4), pp.359-363.

Hager, A., 2014. *Encyclopedia of British writers, 16th, 17th, and 18th centuries*. New York: Infobase Publishing.

Haldane, J., 1929. The Origin of Life. *Rationalist Annual*, 148, pp.3-10.

Hale, D., 2013. Methods to compute fault images, extract fault surfaces, and estimate fault throws from 3D seismic images. *Geophysics*, [online] 78(2), pp.O33-O43. Available at: <http://geophysics.geoscienceworld.org/content/78/2/O33> [Accessed 14 Feb. 2017].

Halford, P. and Fish, M., 2004. *Storm warning*. Phoenix Mill [etc.]: Sutton.

Hall, D. and Rao, K., 1999. *Photosynthesis*. 6th ed. Cambridge, UK: Cambridge University Press, pp.22-27.

Hannah, R., 2015. Ancient Greek Calendars. *Handbook of Archaeoastronomy and Ethnoastronomy*, pp.1563-1571.

Hall, M., 1970. *The scientific renaissance, 1450-1630*. Fontana.

Hay, W., 2016. *Experimenting on a small planet*. 2nd ed. Switzerland: Springer.

Healy, J., 1999. Pliny the Elder on science and technology. Oxford: Clarendon.

Heath, 1897. *Archimedes' The Sand-Reckoner*. Translated from Greek with commentary by T.L Heath. Cambridge: Cambridge University Press.

Heath, 1913. *Aristarchus of Samos, the ancient Copernicus ; a history of Greek astronomy to Aristarchus, together* *with Aristarchus's Treatise on the sizes and distances of the sun and moon : a new Greek text with translation and notes*. Oxford: Clarendon Press.

Hedberg, H. D., 1927. The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: A REPLY TO A DISCUSSION BY W. W. RUBEY. *AAPG Bulletin*, 11(8).

Helliwell, J., 2013. Honouring the two Braggs: the first X-ray crystal structure and the first X-ray spectrometer. *Crystallography Reviews*, 19(3), pp.108-116.

Herdman, W., 1923. *Founders of Oceanography and their Work.* [e-book] London: Edward Arnold & Co. Available at: Biodiversity Heritage Library <http://www.biodiversitylibrary.org/item/66796#page/9/mode/1up> [Accessed 27 February 2017].

Herschel, W., 1789. Catalogue of a Second Thousand of New Nebulae and Clusters of Stars; With a Few Introductory Remarks on the Construction of the Heavens. *Philosophical Transactions of the Royal Society of London*, 79, pp.212–255.

Hess, H.H., 1962. History of ocean basins. *Petrologic studies*, 4, pp.599–620.

Higby Schweitzer, M., 2004. Molecular paleontology: some current advances and problems. *Annales de Paléontologie*, 90(2), pp.81-102.

Higuchi, R., Bowman, B., Freiberger, M., Ryder, O. and Wilson, A., 1984. DNA sequences from the quagga, an extinct member of the horse family. *Nature,* 312(5991), pp.282-284.

Himbert, S., Chapman, M., Deamer, D. and Rheinstädter, M., 2016. Organization of Nucleotides in Different Environments and the Formation of Pre-Polymers. *Scientific Reports*, 6(1), p.31285.

Hine, H.M., 2006. Rome, the cosmos, and the emperor in Seneca's Natural questions. *Journal of Roman studies*, *96*, pp.42- 72.

Hippocrates, 1881. *Hippocrates on airs, waters and places*. Translated by E. Littré, J.A. van der Linden, J. Cornarius. and F. Adams. London: Wyman & Sons.

Holmes, C., 2011. *Gulf of Mexico origin, waters, and biota*. College Station: Texas A&M University Press.

Hooke, R., 1664. *Micrographia: or Some Physical Descriptions of Minute Solid Bodies Made with Magnifying Glasses with Observations and Inquiries Thereupon*. London: The Royal Society.

Hopque, Z., 2016. Basic Concept of GPS and Its Applications. *IOSR Journal of Humanities and Social Science*, 21(3).

Horace, 2002. Satires and Epistles. University of Chicago Press.

Hoyle, F., 1960. *The Origin of the Solar Nebula*.

Huggehtt, R., 1998. Soil chronosequences, soil development, and soil evolution: a critical review. *Catena,* 32(3), pp.155-72.

Huggel, C., Kääb, A., Haeberli, W. and Krummenacher, B., 2003. Regional-scale GIS-models for assessment of hazards from glacier lake outbursts: evaluation and application in the Swiss Alps. *Natural Hazards and Earth System Science*, 3(6), pp.647-662.

Hughes, D., 1989. Hipparchus's Spring and Summer and the Ellipticity of the Earth's Orbit. *Journal of the British Astronomical Association*, 99(2), pp.90-94.

Hugill, P.J., 1995. *World trade since 1431: Geography, technology, and capitalism*. Baltimore: JHU Press.

Hutton, C., Shaw, G. and Pearson, R., 1809. *The Philosophical transactions of the Royal Society of London, from their commencement, in 1665, to the year 1800*. London: Printed by and for C. and R. Baldwin.

Huxley, T., 1863. *Evidence as to Man's Place in Nature.* London: Williams and Norgate.

Hyman, T. and Brangwynne, C., 2012. In Retrospect: The Origin of Life. *Nature*, 491, pp.524-525.

Ignéczi, Á. and Nagy, B., 2013. Determining steady-state accumulation-area ratios of outlet glaciers for application of outlets in climate reconstructions. *Quaternary International*, 293, pp.268-274.

Imbrie, J. and Palmer Imbrie, K., 1986. *Ice ages*. Cambridge [Mass.]: Harvard University.

Ingenhousz, J., 1779. *Experiments upon vegetables, discovering their great power of purifying the common air in the sun-shine, and of injuring it in the shade and at night. To which is Joined, A new Method of examining the accurate Degree of Salubrity of the Atmosphere. By John Ingen-Housz, Counsellor of the Court and Body Physician to their Imperial and Royal Majesties, F.R.S. &c. & c.* London: P. Elmsly, in the Strand and H. Payne, in Pall Mall.

Iran Society and Courtois, V., 1956. *Avicenna commemoration volume*. Calcutta, India: Iran Society.

Isern, A., 2006. The Ocean Observatories Initiative: Wiring the Ocean for Interactive Scientific Discovery. *OCEANS 2006*, pp.1-7.

Jacoby, W.R., 1981. Modern concepts of Earth dynamics anticipated by Alfred Wegener in 1912. *Geology*, 9(1), pp.25–27.

Jeans, J.H., 1917. The motion of tidally-distorted masses, with special reference to theories of cosmogony. *Memoirs of the Royal Astronomical Society*, 62, pp.1–48.

Jeffreys, H., 1929. Collision and the origin of rotation in the solar system. *Monthly Notices of the Royal Astronomical Society*, 89, pp.636–641.

Jeffreys, H., 1952. The origin of the Solar System. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 214, pp.281–291.

Jenkins, J.M., Doyle, L.R. and Cullers, D.K., 1996. A matched filter method for ground-based sub-noise detection of terrestrial extrasolar planets in eclipsing binaries: Application to cm draconis. *Icarus*, *119*(2), pp.244-260.

Jennings, J.D., 1978. Ancient native Americans / edited by Jesse D. Jennings. San Francisco: W.H. Freeman.

Jenny, H., 1941. *Factors Affecting Soil Formation.* New York: McGraw Hill Book Company.

Johnson, D. and Hallberg, K., 2005. Acid mine drainage remediation options: a review. Science of The Total Environment, 338(1-2), pp.3-14.

Jones, A., 2002. Eratosthenes, Hipparchus, and the obliquity of the ecliptic. *Journal for the History of Astronomy*, 33(1), pp.15-19.

Jones, A., 2004. A Study of Babylonian Observations of Planets Near Normal Stars. *Archive for History of Exact Sciences*, 58(6).

Jones, A., 2015. Transmission of Babylonian Astronomy to Other Cultures. *Handbook of Archaeoastronomy and Ethnoastronomy*, pp.1877-1881.

Jönsson, K., Rabbow, E., Schill, R., Harms-Ringdahl, M. and Rettberg, P., 2008. Tardigrades survive exposure to space in low Earth orbit. *Current Biology*, 18(17), pp. R729-R731.

Jordan, T.H., Chen, Y.-T., Gasparini, P., Madariaga, R., Main, I., Marzocchi, W., Papadopoulos, G., Sobolev, G., Yamaoka, K. and Zschau, J., 2011. Operational Earhquake Forecasting. State of Knowledge and Guidelines for Utilization. *Annals of Geophysics,* 54(4). [online] Available at: <http://www.annalsofgeophysics.eu/index.php/annals/article/view/5350/5371>.

Kahn, C.H., 2001. *Pythagoras and the Pythagoreans: a brief history*. Indianapolis: Hackett Publishing.

Kamp, U., Bolch, T. and Olsenholler, J., 2005. Geomorphometry of Cerro Sillajhuay (Andes, Chile/Bolivia): Comparison of Digital Elevation Models (DEMs) from ASTER Remote Sensing Data and Contour Maps. *Geocarto International*, 20(1), pp.23-33.

Kane, S.R. and Gelino, D.M., 2012. The habitable zone and extreme planetary orbits. *Astrobiology*, 12(10), pp.940-945.

Kant, I., 1755. *General History of Nature and Theory of the Heavens*. Königsberg: Petersen.

Kaye, T., Falk, A., Pittman, M., Sereno, P., Martin, L., Burnham, D., Gong, E., Xu, X. and Wang, Y.,

2015. Laser-Stimulated Fluorescence in Paleontology. *PLOS ONE*, 10(5), p.e0125923.

Kelly et al., 2010. Oil sands development contributes elements toxic at low concentrations to the Athabasca River and its tributaries. *PNAS* [e-journal] 107(37).

Ke-Qin, G. and Dong, R., 2006. Radiometric Dating of Ignimbrite from Inner Mongolia Provides no Indication of a Post-Middle Jurassic Age for the Daohugou Beds. *Acta Geologica Sinica – English Edition*, 80(1), pp.42-45.

Khalsa, S., Dyurgerov, M., Khromova, T., Raup, B. and Barry, R., 2004. Space-based mapping of glacier changes using ASTER and GIS tools. *IEEE Transactions on Geoscience and Remote Sensing*, 42(10), pp.2177-2183.

Killeen, T., 2010. Ocean Observatories Initiative (OOI): Advanced Research Tools for the Ocean Sciences. *Marine Technology Society Journal,* 44(6), pp.15-17.

Kingsley, P., 1994. Empedocles and his Interpreters: The Four-Element Doxography. *Phronesis*, 39(3), pp.235-254.

Klaver, J., 1997. *Geology and Religious Sentiment.* Leiden: Brill.

Knudsen, B. and Miyamoto, M., 2009. Accurate and fast methods to estimate the population mutation rate from error prone sequences. *BMC Bioinformatics,* 10(1), p.247.

Kölbl, L., 1967. Sedimentology and the petroleum industry. *Sedimentary Geology*, 1, pp.223–234.

Kollerstrom, N., 1992. The Hollow World of Edmond Halley. *Journal for the History of Astronomy*, 23(3), pp.185-192.

Kowalczyk, S., Maslakowski, M., and Tucholka, P., 2014. Determination of the correlation between electrical resistivity of non-cohesive soils and the degree of compaction. Journal of Applied Geophysics. 110 (18) pp. 54-60.

Kritsky, M., 2005. Memoirs of Aleksandr Ivanovich Oparin. *Applied Biochemistry and Microbiology*, 41(3), pp.358-360.

Kunzig, R., 2000. *Mapping the Deep*. New York City: W. W. Norton & Company.

Lal, R., 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, 304(5677), pp.1623-1627.

Lambert, J., Frye, J. and Poinar, G., 1990. Analysis of North American amber by carbon-13 NMR spectroscopy. *Geoarchaeology*, 5(1), pp.43-52.

Langford, J., 1998. *Galileo, science, and the church*. South Bend, Ind.: St. Augustine's Press.

Laplace, P. de, 1796. *Exposition du System du Monde: Paris.* Paris: English translation, HH Harte (1830) The System of the World.

Larson, J., 2001. Greek Nymphs: Myth, Cult, Lore. Oxford, New York: Oxford University Press.

Laseron, C., 1969. *Ancient Australia*. 2nd ed. New York: Taplinger Publishing Company, p.14.

Lazcano, A., 2010. Historical Development of Origins Research. *Cold Spring Harbor Perspectives in Biology*, 2(11), pp.1-16.

Leeder, M., 1998. Lyell's Principles of Geology : foundations of sedimentology. *Geological Society, London, Special Publications*, 143(1), pp.95-110.

Leick, G., 2003. *The Babylonians*. London: Routledge.

Leung et al., 2003. The ecological effects of naphthenic acids and salts on phytoplankton from the Athabasca oil sands region. *Aquatic Toxicology* [e-journal] 62(1), pp.11-26.

Levenson, T., 1997. *Measure for measure*. Oxford [u.a.]: Oxford Univ. Press.

Lewis, M., Clark, W. and Ambrose, S.E., 1997. *The Journals of Lewis and Clark*. Revised edition ed. Boston: Mariner Books.

Ley, W., 1948. *The lungfish, the Dodo & the Unicorn*. New York: Viking Press.

Li, J., Lockley, M., Bai, Z., Zhang, L., Wei, Q., Ding, Y., Matsukawa, M. and Hayashi, K., 2009. New bird and small theropod tracks from the Lower Cretaceous of Otog Qi, Inner Mongolia.

Lindow, J., 2002. *Norse Mythology: A Guide to Gods, Heroes, Rituals, and Beliefs*. Oxford: Oxford University Press.

Linsbauer, A., Paul, F., Hoelzle, M., Frey, H. and Haeberli, W., 2009. The Swiss Alps Without Glaciers – A GIS-based Modelling Approach for Reconstruction of Glacier Beds. *Proceedings of Geomorphometry*.

Lippiello, E., Marzocchi, W., de Arcangelis, L. and Godano, C., 2012. Spatial organization of foreshocks as a tool to forecast large earthquakes. *Scientific Reports*, 2, p.846.

Lister, M., 1699. *A journey to Paris in the year 1698*.

Logsdon, T., 1998. *Orbital Mechanics: Theory and Applications*. New York: John Wiley & Sons.

Lorenz, E.N., 1963. Deterministic nonperiodic flow. *Journal of the atmospheric sciences*, 20(2), pp.130-141.

Lund, J.W., 1993. Spas and Balneology in the United States.

Lund, J.W., 1999. Historical Impacts of Geothermal Resources on the People of North America. In: *Stories From a Heated Earth: Our Geothermal Heritage*. Sacramento, California: Geothermal Resources Council; International Geothermal Association, pp.451–477.

Lund, J.W. and Boyd, T.L., 2016. Direct utilization of geothermal energy 2015 worldwide review. *Geothermics*, 60, pp.66– 93.

Lurie, E., 1988. *Louis Agassiz, a life in science*. Baltimore: Johns Hopkins University Press.

Lyell, C., 1863. *Geological Evidences of the Antiquity of Man*. London: John Murray.

Lyttleton, R., 1960. Dynamical calculations relating to the origin of the solar system. *Monthly Notices of the Royal Astronomical Society*, 121, pp.551–569.

MacDonald, M., Ragozzine, D., Fabrycky, D., Ford, E., Holman, M., Isaacson, H., Lissauer, J., Lopez, E., Mazeh, T., Rogers, L., Rowe, J., Steffen, J. and Torres, G., 2016. A dynamical analysis of the Kepler-80 system of five transiting planets. *The Astronomical Journal*, 152(4), p.105.

Macdougall, J., 2013. *Frozen earth*. Berkeley: University of California Press.Mackenzie, A., 1911. *Voyages from Montreal through the continent of North America to the frozen and Pacific oceans in 1789 and 1793, with an account of the rise and state of the fur trade*. Edition 2. Toronto: Courier Press.

Magiels, G., 2010. *From Sunlight to Insight : Jan IngenHousz, the Discovery of Photosynthesis*. Brussels: ASP-VUB Press, pp.65-68.

Magill, F., 2003. *Ancient World*. London: Routledge.

Marcou, J., 1972. *Life, letters and works of Louis Agassiz*. Farnborough: Gregg.

Martin, W. and Russell, M., 2003. On the origins of cells: a hypothesis for the evolutionary transitions from abiotic geochemistry to chemoautotrophic prokaryotes, and from prokaryotes to nucleated cells. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 358(1429), pp.59-85.

Martin, W., Baross, J., Kelley, D. and Russell, M., 2008. Hydrothermal vents and the origin of life. *Nature Reviews Microbiology*, 6(1), pp.805-814.

Matek, B., 2016. 2016 Annual U.S. & Global Geothermal Power Production Report. *Geothermal Energy Association*, p.36.

Maury, M.F., 1850. *Wind and current charts*. US Hydrographic Office.

Maury, M.F., 2003. *The physical geography of the sea and its meteorology*. North Chelmsford: Courier Corporation.

Maxwell, J.C., 2010. On physical lines of force. *Philosophical Magazine*, 90(1).

Mayer, J.R., 1845. *Die organische Bewegung in ihrem Zusammenhange mit dem Stoffwechsel*, Heilbronn.

Mayor, A., 2001. *The first fossil hunters*. Princeton, NJ [u.a.]: Princeton Univ. Press.

Mayor, A., 2005. *Fossil Legends of the First Americans*. Princeton: Princeton University Press, pp.1-25.

Mayor, A., 2007. *Fossils in Native American Lands Whose Bones, Whose Story? Fossil Appropriations Past and Present*. [ebook] Washington, D.C: Stanford University, pp.2-5. Available at: <https://web.stanford.edu/dept/HPS/Mayorwhosebones.pdf> [Accessed 22 Feb. 2017].

Mayor, M. and Queloz, D., 1995. A Jupiter-mass companion to a solar-type star. *Nature*, 378(6555), pp.355-359.

McCall, A., 1931. The Development of Soil Science. *Agricultural History Society*. 5,(3), pp. 43-56.

McConnell, R.G., 1893. Report on a portion of the district of Athabasca, comprising the country between Peace River and Athabasca River, North of Lesser Slave Lake. Ottawa: Geological Survey of Canada.

McCrea, W., 1960. The Origin of the Solar System. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 256(1285), pp.245–266.

McCrea, W., 1988. Formation of the Solar System: Brief review and revised protoplanet theory. In: S.K. Runcorn, ed., *The physics of the planets: Their origin, evolution and structure*. Chichester: John Wiley and Sons, p.421–439.

McGinnis, J., 2010. *Avicenna*. Great medieval thinkers. Oxford: Oxford University Press.

McGrail, S., 1991. Early sea voyages. *International Journal of Nautical Archaeology*, 20(2), pp. 85–93.

McLeish A., 1986. *Geological Science*. Cheltenham: Thomas Nelson and Sons Ltd.

McMenamin, M., 2007. Ammonite fossil portrayed on an ancient Greek countermarked coin. *Antiquity*, 81(314), pp.944-948.

Mead, G., 1923. Scientific Method and the Moral Sciences. *The International Journal of Ethics*. 33, (3), 229-247.

Meier, M.F., Dyurgerov, M.B., Rick, U.K., O'neel, S., Pfeffer, W.T., Anderson, R.S., Anderson, S.P. and Glazovsky, A.F., 2007. Glaciers dominate eustatic sea-level rise in the 21st century. *Science*, *317*(5841), pp.1064-1067.

Melvold, K., De Ruyter de Wildt, M., Van De Wal, R.S.W., 2005. Estimating the contribution of Arctic glaciers to sea-level change in the next 100 years. *Annals of Glaciology*. 42, pp.230-236.

Menon, C., 1932. *Early astronomy and cosmology*. London: G. Allen & Unwin Ltd, pp.113-130.

Merrill, R., McElhinny, M. and McFadden, P., 1998. *The Magnetic Field of the Earth*. San Diego: Academic Press.

Mertz, W., 1981. The essential trace elements. *Science*, 213(4514), pp.1332-1338.

Middleton, G.V., 1973. Johannes Walther's Law of the Correlation of Facies. *Geological Society of America Bulletin*, 84(3), pp.979–988.

Middleton, G.V., 1978. Sedimentology, history. In: *Sedimentology, Encyclopedia of Earth Science*. [online] Springer Netherlands, pp.1032–1047. Available at: <http://link.springer.com/referenceworkentry/10.1007/978-1-4020-3609-5_186> [Accessed 24 Feb. 2017].

Middleton, G.V., 2005. Timetable of Petroleum Geology. [online] Available at: <http://archives.datapages.com/data/phi/v6_2005/middleton.htm> [Accessed 26 Feb. 2017].

Middleton, G., 2009. Sedimentology and Oil: what was the historical connection? [Review] Hamilton.

Miller, C. ed., 2013. *Atlas of US and Canadian Environmental History*. Routledge.

Miller, S. and Urey, H.,1959a. Origin of Life. *Science*, 130(3389), pp.1622-1624.

Miller, S. and Urey, H., 1959b. The Formation of Organic Compounds on the Primitive Earth. *Science*, 130(3370), pp.245-251.

Mills, S., Fabrycky, D., Migaszewski, C., Ford, E., Petigura, E. and Isaacson, H., 2016. A resonant chain of four transiting, sub-Neptune planets. *Nature*, 533(7604), pp.509-512.

Moffat, J., 2008. *Reinventing gravity*. New York: HyperCollinsPublisher.

Moody, C., 1955. The American Petroleum Institute's Geological Research Program. *Tulsa Geological Society Digest*, [online] 23, pp.86-88. Available at: <http://archives.datapages.com.libaccess.lib.mcmaster.ca/data/tgs/digest/data/023/023001/86_tgs230086.htm?q=%2BtextStrip%3Aproject+textStrip%3A51> [Accessed 14 Feb. 2017].

Moscati, S., 2001. *The Phoenicians*. New York: IB Tauris.

Moses, D., Goldie, T., Ruffo, A., 2013. *An Anthology of Canadian Native Literature in English*. Oxford: Oxford University Press.

Namias, J., Clapp, P., 1949. Confluence Theory of the High Tropospheric Jet Stream. *Journal of Atmospheric Sciences, 74(3).*

Narrien, J., 1833. An Historical account of the origin and progress of astronomy. London: Baldwin & cradock.

Nasr, S., 1993. *Introduction to Islamic Cosmological Doctrines*. New York City: SUNY Press.

National Aeronautics and Space Administration, 2013. *Kepler: About the Mission*. [online] Available at: <https://kepler.nasa.gov/Mission/QuickGuide/> [Accessed 26 Feb. 2017].

National Aeronautics and Space Administration, 2014. *NASA's Kepler Mission Announces a Planet Bonanza, 715 New Worlds*. [press release] 26 February 2014. Available at: <https://www.nasa.gov/ames/kepler/nasas-kepler-mission-announces-a-planet-bonanza> [16 February 2017].

National Aeronautics and Space Administration, 2016. *Kepler's Small Habitable Zone Planets*. [press release] 10 May 2016. Available at: <https://www.nasa.gov/mission_pages/kepler/multimedia/images/keplers-small-habitable-zone-planets> [23 February 2017].

National Aeronautics and Space Administration, 2017. *Chronology of Mars Exploration*. [online] Available at: <https://history.nasa.gov/marschro.htm> [Accessed 27 Feb. 2017].

National Aeronautics and Space Administration. 2017. *How many exoplanets has Kepler discovered?*. [online] Available at: https://www.nasa.gov/kepler/discoveries [Accessed 20 Feb. 2017].

National Aeronautics and Space Administration Exoplanet Archive, n.d. *Exoplanet and Candidate Statistics*. [online] Available at: <http://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html> [Accessed 21 February 2017].

Natural Resources Canada, 2013. *Oil Sands Processes*. [online] Available at: <http://www.nrcan.gc.ca/energy/oil-sands/5853> [Accessed February 26 2017].

Natural Resources Canada, 2015. *Energy Markets Fact Book*. [pdf] Government of Canada. Available at: <http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/files/pdf/2014/14-0173EnergyMarketFacts_e.pdf> [Accessed February 26 2017].

Natural Resources Canada, 2016. *Seismic zones in Western Canada*. [online] Earthquakes Canada. Available at: <http://www.earthquakescanada.nrcan.gc.ca/zones/westcan-en.php> [Accessed 17 Apr. 2017].

Newton, I., 1728. *The Principia: Mathematical Principles of Natural Philosophy*. Translated from Latin by B. Cohen and A. Whitman. 1999. London: University of California Press.

Newton, I., 2010. *Philosophiæ Naturalis Principia Mathematica*. Lightning Source Inc.

Newman, W., 2014. Mercury and Sulphur among the High Medieval Alchemists: From Rāzī and Avicenna to Albertus Magnus and Pseudo-Roger Bacon. *Ambix*, [online] 61(4). Available at: <http://www.tandfonline.com/doi/abs/10.1179/1745823414Y.0000000004> [Accessed 1 Feb. 2017].

Nimmo, F., Price, G., Brodholt, J. and Gubbins, D., 2004. The influence of potassium on core and geodynamo evolution. *Geophysical Journal International*, 156(2), pp.363-376.

Norman, A., 1968. *Advances in agronomy*. New York: Academic Press, pp.5-8.

Norman, R., 1269. *The Newe Attractive, Showing the Nature, Propertie, and Manifold Vertues of the Loadstone: With the Declination of the Needle, Touched Therewith, Under the Plaine of the Horizon*. Translated from Latin by S. Chapman and J. Bartels, 1940. London: Oxford University Press.

Nsolv, 2017. *Technology Overview – The Nsolv Process.* [online] Available at: <https://www.nsolv.ca/technology/> [Accessed February 27 2017].

Oerlemans, J., Bassford, R.P., Chapman, W., Dowdeswell, J.A., Glazovsky, A.F., Hagen, J.O., Melvold, K., de Ruyter de Wildt, M. and Van de Wal, R.S.W., 2005. Estimating the contribution of Arctic glaciers to sea-level change in the next 100 years. *Annals of Glaciology*, *42*(1), pp.230-236.

Ojha, L., Wilhelm, M., Murchie, S., McEwen, A., Wray, J., Hanley, J., Massé, M. and Chojnacki, M., 2015. Spectral evidence for hydrated salts in recurring slope lineae on Mars. *Nature Geoscience*, 8(11), pp.829-832.

Okada, H. and Kenyon-Smith, A., 2005. The Evolution of Clastic Sedimentology. Edinburgh: Dundedin Academic Press.

Oldroyd, D., 1988. Darwinian impacts. 2nd ed. Kensington, Australia: New South Wales University Press.

Oldroyd, D.R., 1996. *Thinking about the Earth: A History of Ideas in Geology*. Harvard University Press.

O'Neil, W., 1986. *Early astronomy: From Babylonia to Copernicus*. Sydney: Sydney University Press, pp.67-108.

Oparin, A., 1953. *The Origin of Life*. 2nd Ed. Originally Translated from Russian by S. Morgulis., 1938. New York: Dover Publications.

Orgel, L., 1998. The origin of life—a review of facts and speculations. *Trends in Biochemical Sciences*, 23(12), pp.491-495.

Pääbo, S., 1985. Molecular cloning of Ancient Egyptian mummy DNA. Nature, 314(6012), pp.644-645.

Pakendorf B., Stoneking, M., 2005. Mitochondrial DNA and human evolution. *Annual Review of Genomics and Human Genetics, 6,* p. 165-183.

Parkinson, B., 2003. *An Interview with Dr. Bradford W. Parkinson.* Interview by...Steven Storm. [magazine] Quest: The History of Spaceflight Quarterly. April 1 and June 4, 2003.

Partington, J., 1937. Albertus Magnus on Alchemy. *Ambix*, 1(1), pp.3-20.

Paul, F., Kaab, A., Maisch, M., Kellenberger, T., Haeberli, W., 2002. The new remote-sensing-derived Swiss glacier inventory: I. Methods. *Annals of Glaciology.* 34, pp.355-361.

Office of the Press Secretary. 2000. *Improving the Civilian Global Positioning System (GPS).* Press release, 1 May 2000.

Paul, F., Kaab, A., Maisch, M., Kellenberger, T., Haeberli, W., 2004. Rapid disintegration of Alpine glaciers observed with satellite data. *Geophysical Research Letters.* 31(21).

Pausânias, 1898. Pausanias's Description of Greece, tr. with a commentary by J.G. Frazer. Translated by J.G. Frazer. London Macmillan.

Pedersen, O., 1996. *Early physics and astronomy*. Cambridge: Cambridge University Press.

Pellitero, R., Rea, B., Spagnolo, M., Bakke, J., Hughes, P., Ivy-Ochs, S., Lukas, S. and Ribolini, A., 2015. A GIS tool for automatic calculation of glacier equilibrium-line altitudes. *Computers & Geosciences*, 82, pp.55-62.

Pembina Institute, 2003. *Booms, busts, and bitumen: The economic implications of Canadian oil sands development.* [pdf] Equiterre. Available at: <http://www.equiterre.org/sites/fichiers/booms_busts_and_bitumen_-_the_economic_implications_of_canadian_oilsands_development.pdf> [Accessed February 25 2017].

Pentland, D., 1985. *The Akshee Indians*. Manitoba: University of Manitoba.

Peregrinus, P., 1269. *The Letter of Petrus Peregrinus on the Magnet A.D. 1269*. Translated from Latin by Brother Arnold, 1904. New York: McGraw Publishing Company.

Pettijohn, F., 1975. Sedimentary Rocks. 3rd ed. New York, NY: Harper and Row.

Phalen, W., 2014. *How the telegraph changed the world.* Jefferson: McFarland.

Pickrell, J., Coop, G., Novembre, J., Kudaravalli, S., Li, J., Absher, D., Srinivasan, B., Barsh, G., Myers, R., Feldman, M. and Pritchard, J., 2009. Signals of recent positive selection in a worldwide sample of human populations. Genome Research, 19(5), pp.826-837.

Pipes, R., 1969. *Revolutionary Russia*. Garden City, N.Y.: Anchor Books.

Planavsky, N.J. et al., 2014. Evidence for oxygenic photosynthesis half a billion years before the Great Oxidation Event. *Nature Geoscience*, 7(4), pp.283–286.

Poinar, H., Schwarz, C., Qi, J., Shapiro, B., MacPhee, R., Buigues, B., Tikhonov, A., Huson, D., Tomsho, L., Auch, A., Rampp, M., Miller, W. and Schuster, S., 2006. Metagenomics to Paleogenomics: Large-Scale Sequencing of Mammoth DNA. Science, 311(5759), pp.392-394.

Poincare, H., 1900. The Theory of Lorentz and The Principle of Reaction. Translated from French by S. Lawrence. *Archives néerlandaises des sciences exactes et naturelles,* 5(2), pp.252-278.

Prentice, A.J.R., 1978. Origin of the solar system. *The Moon and the Planets*, 19(3), pp.341–398.

Priestley, J. and Hey, W., 1772. Observations on Different Kinds of Air. *Philosophical Transactions of the Royal Society of London*, 62(0), pp.147-264.

Pronzato, R., & Manconi, R., 2008. Mediterranean commercial sponges: over 5000 years of natural history and cultural heritage. *Marine Ecology*, *29*(2), pp. 146–166.

Pruvost, M., Schwarz, R., Correia, V., Champlot, S., Braguier, S., Morel, N., Fernandez-Jalvo, Y., Grange, T. and Geigl, E., 2007. Freshly excavated fossil bones are best for amplification of ancient DNA. *Proceedings of the National Academy of Sciences*, 104(3), pp.739-744.

Rabinowitch, E., 1971. An unfolding discovery. *Proceedings of the National Academy of Science*, 68, pp.2875–2876.

Rahmstorf, S., 2003. Thermohaline circulation: The current climate. *Nature*, *421*(6924), pp. 699–699.

Rafferty, K., 2000. Geothermal Power Generation A Primer on Low-Temperature, Small-Scale Applications. [online] Available at: <http://citeseerx.ist.psu.edu/viewdoc/citations;jsessionid=AAA3A7ED0E0CFF4C0A1FA0

63457D3DAE? doi=10.1.1.600.9869> [Accessed 28 Feb. 2017].

Randall, J., 1960. *Aristotle*. New York: Columbia University Press, pp. 28.

Raup, D. and Sepkoski, J., 1982. Mass Extinctions in the Marine Fossil Record. *Science*, 215(4539), pp.1501-1503.Raven, P., Johnson, G., Mason, K., Losos, J. and Singer, S. (2016). *Biology*. New York, NY: McGraw-Hill Education.

Raymo, M.E., Huybers, P., 2008. Unlocking the mysteries of the ice ages. *Nature.* 451, pp. 284-285.

Raymond, S., Barnes, R. and Mandell, A., 2008. Observable consequences of planet formation models in systems with close-in terrestrial planets. *Monthly Notices of the Royal Astronomical Society*, 384(2), pp.663-674.

Reyment, R.A., 1991. Johannes Walther (1860–1937). Terra Nova, 3(2), pp.221–223.

Reynolds, M., Paul, M., 1973. *Legends of Déné*. Saskatoon: Saskatchewan Indian Cultural College.

Richter, C.F., 1935. An instrumental earthquake magnitude scale. *Bulletin of the Seismological Society of America*, 25(1), pp.1–32.

Rikitake, T., 1983. *Earthquake Forecasting and Warning*. United States: Center for Academic Publications Japan/Tokyo.

Roberts, C. M., 2003. Our shifting perspectives on the oceans. *Oryx*, 37(02). pp. 166-177

Roberts, L., 1989. Disease and death in the New World. *Science*, 246(4935), 1245–1247.

Rochberg, F., 2000. Scribes And Scholars: The Ṭupšar Enūma Anu Enlil. *In the Path of the Moon*, 6, pp.237-256.

Roemmich, D., John Gould, W. and Gilson, J., 2012. 135 years of global ocean warming between the Challenger expedition and the Argo Programme. *Nature Climate Change*, 2(6), pp.425-428.

Roemmich, D., Johnson, G., Riser, S., Davis, R., Gilson, J., Owens, W., Garzoli, S., Schmid, C. and Ignaszewski, M., 2009. The Argo Program: Observing the Global Oceans with Profiling Floats. *Oceanography*, 22(2), pp.34-43.

Rogers, J. and Santosh, M., 2004. *Continents and supercontinents*. New York: Oxford University Press.

Rosing, M. and Frei, R., 2004. U-rich Archaean sea-floor sediments from Greenland – indications of >3700 Ma oxygenic photosynthesis. Earth and Planetary Science Letters, 217(3-4), pp.237-244.

Roger Walker, R., 1973. Mopping Up the Turbidite Mess. In: Evolving Concepts in Sedimentology. Baltimore and London: The Johns Hopkins University Press, pp.1–30.

Rozwadowski, H., Van Keuren D., 2004. *The Machine in Neptune's Garden: Historical Perspectives on Technology and the Marine Environment.* Sagamore Beach: Science History Publications.

Ruben, S., Randall, M., Kamen, M. and Hyde, J., 1941. Heavy Oxygen (O^{18}) as a Tracer in the Study of Photosynthesis. *Journal of the American Chemical Society*, 63(3), pp.877-879.

Rubey, W.W., 1927. The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: DISCUSSION. *AAPG Bulletin*, 11(6).

Rubin, M., 2001. *The History of Ozone. The Shonbein Period, 1839-1868*. [online] Available at: <http://www.scs.illinois.edu/~mainzv/HIST/bulletin_open_access/v26-1/v26-1%20p40-56.pdf> [Accessed 25 Feb. 2017].

Rudwick, M.J.S., 1976. *The Meaning of Fossils*. 2nd ed. New York: Science History Publications.

Rudwick, M.J.S., 1997. *Georges Cuvier, Fossil Bones, and Geological Catastrophes*. London: University of Chicago Press.

Russell, E., 1910. The effect of earthworms on soil productiveness. *The Journal of Agricultural Science.* 3(3), pp. 246-57.

Russell, H.N., 1935. *The Solar System and its Origin*. New York: The Macmillan company.Sachs, A. and

Hunger, H., 1996. *Astronomical diaries and related texts from Babylonia: Volume IV*. Vienna: Østerreichischen Akademie der Wissenschaften.

Russell, P.E., 2001. *Prince Henry 'the Navigator': a life*. New Haven: Yale University Press.

Rydin, A.R., 2011. *Le Verrier's 1859 Paper on Mercury, and Possible Reasons for Mercury's Anomalous Prevession.*

Ryskin, G., 2009. Secular variation of the Earth's magnetic field: induced by the ocean flow?. *New Journal of Physics*, 11(6).

Sachs, A., 1974. Babylonian Observational Astronomy. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 276(1257), pp.43-50.

Sachs, J., 1862. Über den Einfluss des Lichtes auf die Bildung des Amylums in den Chlorophyllkornern. *Botanische Zeitung*, 20, pp.365–373.

Samaan, A., 2013. *From a "race of masters" to a "master race"*. Charleston, S.C.: CreateSpace.

Sandage, A. and Brown, L., 2004. *Centennial history of the Carnegie Institution of Washington*. Cambridge: Cambridge University Press, pp.50-54.

Satkoski, A., Beukes, N., Li, W., Beard, B. and Johnson, C., 2015. A redox-stratified ocean 3.2 billion years ago. Earth and Planetary Science Letters, 430, pp.43-53.

Sauer, T., 2004. Albert Einstein's 1916 Review Article on General Relativity. *Einstein Papers Project.*

Schlegel, C. and Weinfield, H. eds., 2006. *Theogony: And, Works and Days*. University of Michigan Press.

Schlesinger, R., 2007. *In the wake of Columbus: the impact of the New World on Europe, 1492-1650*. Wheeling: Harlan Davidson.

Schmidt, O., 1944. A meteoric theory of origin of Earth and planets. *Comptes Rendus (Doklady) Academie des Sciences de l'URSS*, 45, pp.229–233.

Seager, S. and Sasselov, D.D., 2000. Theoretical transmission spectra during extrasolar giant planet transits. *The Astrophysical Journal*, 537(2), p.916.

Sears, M. and Merriman, D., 1980. *Oceanography, the past*. Berlin: Springer-Verlag.

Segalstad T., 2008. *Glimpses from the history of mineralogy and the Geological Museum in Oslo*. International Geological Congress, Natural History Museum, University of Oslo.

Segalstad, T.V., 2010. *Glimpses from the history of mineralogy and the Geological Museum in Oslo*. [online] Available at: <http://folk.uio.no/tomvs/minerals/geo4910/Mineralogy-Geomus-Oslo.pdf.>.

Sénébier, J., 1782. *Mémoires physico-chimiques sur l'influence de la lumière solaire pour modifier les êtres des trois règnes de la nature et surtout ceux du règne végétal*. Genève: Chirol.

Shapiro, B., 2013. Ancient DNA. In: Losos, J.B., Baum, D.A., Futuyma, D.J., Hoekstra, H.E., Lenski, R.E., Moore, A.J., Peichel, C.L., Schluter, D. and Whitlock, M.C., eds. 2013. The Princeton Guide to Evolution. Princeton: Princeton University Press. pp.475-481.

Sheehan, W., 1996. The Planet Mars: A History of Observation and Discovery. University of Arizona Press.Sighart, J., 1876. Albert the Great of the Order of Friar-Preachers. London: R. Washbourne.

Shepard, F.P., 1955. New Methods of Identifying Sedimentary Environments. *SEPM Journal of Sedimentary Research*, [online] Vol. 25(2). Available at: <http://archives.datapages.com.libaccess.lib.mcmaster.ca/data/sepm/journals/v01-32/data/025/025002/0155.htm?q=%2BtextStrip%3Aproject+textStrip%3A51> [Accessed 14 Feb. 2017].

Shephard, B. and Stewart, H., 1972. *CHALLENGER sketchbook*. Philadelphia, Pa: Philadelphia

Maritime Museum.

Sheppard, M.C. ed., 1989. *Oil Sands Scientist - The Letters of Karl A. Clark 1920 - 1949*. Edmonton, Alberta: The University of Alberta Press.

Shindell, D., Faluvegi, G., Lacis, A., Hansen, J., Ruedy, R. and Aguilar, E., 2006. Role of tropospheric ozone increases in 20th-century climate change. *Journal of Geophysical Research*, 111(D8).

Smith, D. and Borns, H., 2000. Louis Agassiz, the Great Deluge, and Early Maine Geology. *Northeastern Naturalist*, 7(2), pp.157-177.

Smith, P., 1968. Pre-gilbertian conceptions of terrestrial magnetism. *Tectonophysics*, 6(6), pp.499-510.

Smith, P., 1970. The beginning of experimental studies of magnetism in Europe. *Earth-Science Reviews*, 6(1), pp.A11-A18.

Smith, P., 2012. Soils and climate change. *Current Opinion in Environmental Sustainability*, 4(5), pp.539-544.

Snellen, I.A.G., de Kok, R.J., Le Poole, R., Brogi, M. and Birkby, J., 2013. Finding extraterrestrial life using ground-based high-dispersion spectroscopy. *The Astrophysical Journal*, *764*(2), p.182.

Soane, B., and van Ouwerkerk, C., 1994. Soil Compaction in Crop Production. Amsterdam: Elsevier Science.

Solounias, N. and Mayor, A., 2004. Ancient References to the Fossils from the Land of Pythagoras. *Earth Sciences History*, 23(2), pp.283-296.

Sparavigna, A.C., 2012. The play of colours of prisms. *arXiv preprint arXiv:1207.3504*.

Spitzer, L., 1939. The dissipation of planetary filaments. *The Astrophysical Journal*, 90, pp.675–688.

Srinivasan, M., 1996. *Physics for Engineers*. New Delhi: New Age International.

Statistics Canada, 2017. CANSIM, table 228-0059. Available at: <http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/gblec04-eng.htm> [Accessed 25 February 2017].

Steele, J., 2003. Planetary Latitudes in Babylonian Mathematical Astronomy. *Journal for the History of Astronomy*, 34(3), pp.269-289.

Steele, J.M., 2006. Greek influence on Babylonian astronomy?. *Mediterranean Archaeology and Archaeometry*, *6*, pp.153-160.

Steele, J., 2007. Celestial Measurement in Babylonian Astronomy. *Annals of Science*, 64(3), pp.293-325.

Steele, J., 2014. Babylonian Observational and Predictive Astronomy. *Handbook of Archaeoastronomy and Ethnoastronomy*, pp.1855-1862.

Steinicke, W., 2005. Einstein and the Gravitational Waves. *Astronomische Nachrichten*, [online] 326(7). Available at: <http://www.hs.uni-hamburg.de/DE/GNT/events/pdf/steinicke05.pdf> [Accessed 28 Feb. 2017].

Steno, 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 J.G. Winter., 1968. New York: Hafner Publishing Company, Inc.

Steno, N. and Winter, J.G., 1968. The prodromus of Nicolaus Steno's dissertation concerning a solid body enclosed by process of nature within a solid. *Contributions to the history of geology*. New York, NY: Hafner Pub. Co.

Stewart, J., 2011. *Exploring the history of hyperbaric chambers, atmospheric diving suits and manned submersibles: the scientists and machinery*. Bloomington: Xlibris Corporation.

Stocks, J.L., 1922. *Aristotle's De caelo*. Translated from Greek with commentary by J.L. Stocks. Oxford: Clarendon Press.

Strangway, D., 1970. *History ofthe earth's magnetic field*. McGraw-Hill Inc.

Stroik, T. and Putnam, M., 2013. *The structural design of language*. Cambridge: Cambridge University Press.

Stukeley, W., 1752. *Memoir of Isaac Newton's Life*. Reprint 2004. London: Royal Society Library.

Suggs, R.C., 1960. *The island civilizations of Polynesia* (Vol. 304). New York: New American Library.

Suncor Energy Inc., 2017. *History*. [online] Available at: < http://www.suncor.com/en-CA/about-us/history> [Accessed February 20 2017].

Swinton, W., 1966. *Giants past and present*. London: Hale.

Taghavifar, H., and Mardani, A., 2014. Effect of velocity , wheel load and multipass on soil compaction. *Journal of the Saudi Society of Agricultural Science*, 13(1), pp.57-66.

Tankha, V., 2006. *Ancient Greek philosophy*. Delhi: Pearson Longman.

Teagle, D., Ildefonse, B., 2011. Journey to the mantle of the Earth. *Nature News and Comment*, [online] Available at: <http://www.gm.univ-montp2.fr/spip/IMG/pdf/Teagle_MoHole-X335_Nature_2011.pdf> [Accessed 27 February 2017].

The Holy Bible: King James Version, 1999. New York: American Bible Society.

Theophrastus., Richards, J. and Caley, E. (1956). *Theophrastus on stones*. Columbus, Ohio: Ohio State University.

Thomas, R., Schaffner, W., Wilson, A. and Pääbo, S., 1989. DNA phylogeny of the extinct marsupial wolf. Nature, 340(6233), pp.465-467.

Thomson, C., 1877. *The voyage of the 'Challenger.' The Atlantic a preliminary account of the general results of the exploring voyage of H.M.S. Challenger during the year 1873 and the early part of the year 1875*. London: Macmillan and Co.

Thomson, K., 2000. Huxley, Wilberforce and the Oxford Museum. *American Scientist*. 88(3), p. 210-213.

Thorne, K. and Weiss, R., 2016. *A Brief History of LIGO | Caltech*. [online] The California Institute of Technology. Available at: <http://www.caltech.edu/content/brief-history-ligo> [Accessed 28 Feb. 2017].

Torrens, H., 1995. Mary Anning (1799–1847) of Lyme; 'the greatest fossilist the world ever knew'. The British Journal for the History of Science, 28(03), pp.257-284.

Troubetzkoy, A., 2006. *A Brief history of the Crimean war*. London: Robinson.

Tyndall, J., 1905. *Fragments ofscience*. [online] New York, P.D. Collier. Available at: <https://archive.org/details/fragmenoscien02tyndrich> [Accessed 20 Feb. 2017].

Tyson, G., Chapman, J., Hugenholtz, P., Allen, E., Ram, R., Richardson, P., Solovyev, V., Rubin, E., Rokhsar, D. and Banfield, J., 2004. Community structure and metabolism through reconstruction of microbial genomes from the environment. *Nature,* 428(6978), pp.37-43.

United Nations, 1994. *General Assembly*. [pdf] United Nations. Available at: <http://www.unccd.int/Lists/SiteDocume ntLibrary/conventionText/conv-eng.pdf > [Accessed 10 April, 2017].

Unwin, R., 1995. A Provincial Man of Science at Work: Martin Lister, F.R.S., and His Illustrators 1670-1683. *Notes and Records of the Royal Society*, 49(2), pp.209-230.

US Census Bureau, D.I.S., 2017. International Programs, World Population. [online] Available at: <https://www.census.gov/population/international/data/worldpop/table_population.php> [Accessed 27 Feb. 2017].

Van Helden, A., 1999. *Catalogue of early telescopes*. [Firenze]: Giunti.

van Niel, C., 1932. On the morphology and physiology of the purple and green sulphur bacteria. *Arch Mikrobiol*, 3(1), pp.1-112.

Van Wagoner, J., Posamentier, H., Mitchum, R., Vail, P., Sarg, J., Loutit, S., and Hardenbol, J., 2012. An Overview of the Fundamentals of Stratigraphy and Key Definitions. *The Society of Economic Paleontologists and Economists*. Publication 42, pp.39-45.

Vincent, P. et al., 2014. Mary Anning's Legacy to French vertebrate palaeontology. Cambridge University Press, 151(1), pp.7-20.

von Weizsäcker, C.F., 1944. Über die Entstehung des Planetensystems. *Zeitschrift fur Astrophysik*, 22, pp.319–355.

Waggoner, B., 2001. Molecular Palaeontology. *Encyclopedia of Life Sciences*.

Wald, C., 2015. Forensic science: the soil sleuth. *Nature*, 520(7458), pp. 422-4.

Wang, C., 2002. Detection of a recent earthquake fault by the shallow reflection seismic method. *Geophysics*, [online] 67(5), pp.1465-1473. Available at: <http://library.seg.org/doi/abs/10.1190/1.1512791> [Accessed 14 Feb. 2017].

Warkentin, B., 2006. *Footprints in the soil*. Amsterdam: Elsevier Science, pp.22-290.

Warner, C. and Bednarik, R.G., 1996. Pleistocene knotting. *History and science of knots*, *11*, p.1.

Warn, F., 2000. *Bitter Sea: the real story of Greek Sponge Diving*, South Woodham Ferrers: Guardian Angel Press.

Weber, L., 2002. Georgius Agricola (1494-1555): Scholar, Physician, Scientist, Entrepreneur, Diplomat. *Toxicological Sciences*, 69(2), pp.292-294.

Weinburg, S., 2015. *To Explain the World: The Discovery of Modern Science*. New York: HarperCollins Publishers.

Wenk, H. and Bulach, A., 2016. *Minerals*. Cambridge: Cambridge University Press, p.10.

Whitney, M, and Cameron, F., 1903. *The Chemistry of Soils as Related to Crop Production*. Washington: Government Printing Office.

Wilkinson, R.H., 2003. *The complete gods and goddesses of ancient Egypt*. Thames & Hudson.

Williams, F.L., 1963. *Matthew Fontaine Maury, scientist of the sea*. New Brunswick: Rutgers University Press.

Wilmshurst, J. M., Hunt, T. L., Lipo, C. P., & Anderson, A. J., 2011. High-precision radiocarbon dating shows recent and rapid initial human colonization of East Polynesia. *Proceedings of the National Academy of Sciences*, *108*(5), pp. 1815–1820.

Witze, A., 2013. Marine science: Oceanography's billion-dollar baby. *Nature News*, [online] Available at: <http://www.nature.com/news/marine-science-oceanography-s-billion-dollar-baby-1.13803> [Accessed 27 February 2017].

Witze, A., 2016. Massive ocean-observing project launches – despite turmoil. *Nature News*, [online] Available at: <http://www.nature.com/news/massive-ocean-observing-project-launches-despite-turmoil-1.20031?WT.mc_id=TWT_NatureNews> [Accessed 27 February 2017].

WMO, 2003. *Climate into the 21st Century*. Cambridge: Cambridge University Press.

Woodward, J., 2014. *The Ice Age: A Very Short Introduction*. New York: Oxford University Press.

Woolfson, M., 1964. A capture theory of the origin of the Solar System. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 282(1391), pp.485–507.

Woolfson, M., 2000. The origin and evolution of the solar system. *Astronomy and Geophysics*, 41(1), p.1.12-1.19.

Woolfson, M., 2007. *The Formation of the Solar System: Theories Old and New*. London: Imperial College Press.

Wu, Z., Chen, Q., Barosh, P., Peng, H. and Hu, D., 2013. Stress rise precursor to earthquakes in the Tibetan Plateau. *Natural Science*, 05(08), pp.46-55.

Wyckoff, D., 1958. Albertus Magnus on Ore Deposits. *Isis*, 49(2), pp.109-122.

Xing, L., Mayor, A., Chen, Y., Harris, J. and Burns, M., 2011. The Folklore of Dinosaur Trackways in China: Impact on Paleontology. *Ichnos*, 18(4), pp.213-220.

Yang, H., Golenberg, E. and Shoshani, J., 1996. Phylogenetic resolution within the Elephantidae using fossil DNA sequence from the American mastodon (Mammut americanum) as an outgroup. *Proceedings of the National Academy of Sciences*, 93(3), pp.1190-1194.

Yang, Y., Yokobori, S. and Yamagishi, A., 2009. Assessing Panspermia Hypothesis by Microorganisms Collected from The High Altitude Atmosphere. *Biological Sciences in Space*, 23(3), pp.151-163.

Yilmaz, O., 2001. *Seismic Data Analysis.* 2nd ed. Society of Exploration Geophysicists, pp.1-24.

Zhen, S., 1961. Records on Fossil Vertebrates in Ancient Chinese Literature. *Vertebrata PalAsiatica*, pp.370-373.

Zhang, Y., 2002. Long Tracing for Dinosaur Tracks. *Explorations of Nature*, 1, pp.25-28.

Zuckerkandl, E., Pauling, L. Molecular disease, evolution, and genetic heterogeneity. In: Kasha, M., Pullman, B. 1962. *Horizons in Biochemistry.* New York: Academic Press. pp.189-225.

Zvelebil, M., 2009. *Hunters in transition: Mesolithic societies of temperate Eurasia and their transition to farming.* Cambridge: Cambridge University Press.

Image Credits

Chapter 1

1.1: The Mesopotamian Region. Wikimedia Commons, Goran Tek-en, 2014.

1.2: A Sculpture of Aristorle. Wikemedia Commons, Jastrow, 2006.

1.3: A portrait of Vasily Dokuchaev. Wikimedia Commons, 19th century.

1.4: Soil compression from external load. Wikimedia Commons, Blonder, 1984.

1.5: Theophrastus (Teofrasto Orto botanico). Wikimedia Commons, Tato Grasso, 2007.

1.6: The Alchemist in Search of the Philosophers Stone. Wikimedia Commons, Joseph Wright of Derby, 1771.

1.7: Georgius Agricola: Vom Berg- und Hüttenwesen. Wikimedia Commons, Angie, 1556.

1.8: A Divining Rod. Wikimedia Commons, Cassier's magazine, 1891.

1.9: Water powered mine-hoist. Wikimedia Commons, Hoover H., and Hoover L, 1555.

1.10: Zeolite. Wikimedia Commons, Thomas Splettstoesser, 2015.

1.11: Avicenna. Wikimedia Commons, 2008.

1.12: Ghaznavid Empire. Wikimedia Commons, Ahmed Hafez, 2007.

1.13: Moraine Lake. Wikimedia Commons, Gorgo, 2005.

1.14: Types of faults. Wikimedia Commons, 2013.

1.15: Haida Gwaii map. Wikimedia Commons, Shaundd, 2013.

Chapter 2

2.1: An example of a Babylonian observational. Wikimedia Commons, Daderot, 2014.

2.2: A greek copy of Aristarchus of Samos's notes. Wikimedia Commons.

2.3: The TRAPPIST-1 system. Wikimedia Commons, NASA, 2017.

2.8: Scientific observations from the Kepler… National Aeronautic and Space Administration, William Borucki, 2009.

2.9: A Marble Bust with Aristotle. Bust of Aristotle. Wikipedia, Marie-Lan Nguyen, 2006.

2.10: A depiction of a cannonball launched into orbit imagined by Newton in the Principia. (Background modified). The effects of centripetal force. A Treatise of the System of the World, Isaac Newton, 1728.

2.11**:** The LIGO interferometer that detects gravitational wave. The two "Fabry-Pérot cavity" arms stretch and contract to measure the effects of gravitational waves. (Background modified). LIGO's interferometer. Simplified. Wikipedia, Menner, 2016.

2.12: A Directional Spoon. Wikimedia Commons, 2006.

2.13: Mercator's World Map. Wikimedia Commons, Wilhelm Krucken, 2012.

2.14: Copernican Heliocentric Diagram. Wikimedia Commons, Copernicus, 1543.

2.15: Outer Core Convection. Wikimedia Commons, United States Geological Survey.

Chapter 3

3.1: A portrait of Charles Darwin. Wikimedia Commons, Elliot &Fry, 1874.

3.2: Darwin's drawings of different forms. Wikimedia Commons, Darwin, 1845.

3.3: Drawings of different primate skeletons. Wikimedia Commons, Benjamin Hawkins, 1863.

3.4: A portrait of Thomas Huxley. Wikimedia Commons, Lock & Whitfield, 1880.

3.5: A double-stranded DNA helix. Wikimedia Commons, Jerome Walker, 2007.

3.6: Image of Loius Pasteur. Wikimedia Commons, Félix Nadar, 1878.

3.7: Alexander Oparin and Andrei Kursanov. Wikimedia Commons, Pavel Troshkin, 1938.

3.8:Stromatolites in Glacier National Park. MO. Wikimedia Commons, P. Carrara, 1982.

3.9: Image of Friedrich Engels. Wikimedia Commons, 1879.

3.10: Image of Lysenko with Joseph Stalin. Wikimedia Commons, 1935.

3.11: Map of Hydrothermal Vents on Earth. Wikimedia Commons, DeDuijn, 2016.

3.12: Artist's rendition of the British scientist. Wikimedia Commons, Rembrandt Peale, 1801.

3.13 Light microscope image of chloroplast. Wikimedia Commons, Thomas Geier, 2000.

3.14: Calvin working in the Lawrence. Lawrence Berkeley Laboratory Collection, 1962.

3.15: Stromatolites deposited during the Cambrian. Wikimedia Commons, Michael C. Rygel, 2005.

Chapter 4

4.1: *Hipparion* skull. Wikimedia Commons, Deng Tao, 1872.

4.2: An extremely well preserved *Mammuthus Primigenius*. Wikimedia Commons, Nandaro, 2013.

4.3: Very well preserved three-toed dinosaur footprint. Wikimedia Commons, Greg Willis, 2009.

4.4: Fossil of *Mammut americanum*. Wikimedia Commons, Momotarou, 2012.

4.5: William Smith. Wikimedie Commons, Hugues Fourau, 1837.

4.6: A bull Indian Elephant. Wikimedia Commons, N. Naseer, 2008.

4.7: An artist's rendition. Kunstformen der Natur, Ernst Haeckel, 1904.

4.8: Nicolaus Steno's sketch. Canis Cachariae, Nicolaus Steno, 1667.

4.9: Sketch of Nicolaus Steno. Famous Danish Men and Women, modified by J.P. Trap, 1868.

4.10: Cuvier's illustrations. Cuvier's 1799 paper, George Cuvier, 1799.

4.11: Illustration of the wooly mammoth. Brockhaus and Efron Encyclopedic Dictionary, 1890—1907.

4.12: Lyme Regis cliffs. Wikimedia Commons, Michael Maggs, 2007.

4.13: Drawing of the skull of Temnodontosaurus. Philosophical Transactions of the Royal Society, Everard Home, 1814.

4.14: Autograph letter from Mary Anning. Wikimedia Commons, Mary Anning, 1823.

4.15: Stained glass window. Wikimedia Commons, Ballista, 2006.

4.16: Acid mine drainage. NASA, Carol Stoker, 2002.

Chapter 5

5.1: Artist depiction of a Kraken. Wikimedia Commons, R. Ellis, 1994.

5.2: Map of Phoenician trade routes. Wikimedia Commons, 2010.

5.3: Detailed current diagrams sketched by Matthew Fontaine Maury. American Geographical Society Library Digital Map Collection, 2010.

5.4: The Bathysphere. Flickr, Mike Cole, 2009.

5.5: Station locations within the OOI. Wikimedia Commons, 2007.

5.6: Tools used by the Challenger crew. Wikimedia Commons, J.J. Spry, 1877.

5.7: Globigerina. Wikimedia Commons, Hannes Grobe, 2011.

5.8: Pumice. Wikimedia Commons, Norbert Nagel, 2011.

5.9: Watercolour rendition of the H.M.S Challenger. Benjamin Sheppard, 1873.

5.10: Releasing an Argo float. Elizabeth Crapo, 2010.

Chapter 6

6.1: Asclepiades of Bithynia. Wikimedia Commons.

6.2: Bust of Pausanias. Wikimedia Commons, Paolo Monti, 1969.

6.3: Ancient Petroglyphs. Wikimedia Commons, Scosme.

6.4: Porcelain Vase with Iron Oxide Glaze. Wikimedia Commons, 1722.

6.5: Hot Water Geothermal Diagram. Wikimedia Commons, Wendell A. Duffield, John H. Sass, 2003.

6.6: Nicolaus Steno Portrait Derivative. Wikimedia Commons, 2012.

6.7: Stratigraphic Trap Diagram. Wikimedia Commons, 2014.

6.8: Seismic Survey Depiction. Wikimedia Commons, Nhwit, 2012.

6.9: Workers surveying the oil sands along the bank of a river in Alberta at the beginning of the 20th century. Wikimedia Commons, circa 1900-1930.
6.10: A thin layer of oil sands along a steep outcrop. Wikimedia Commons, Provincial Archives of Alberta, 2007

6.11: The modern Athabasca Oil Sands where extraction and separation occurs. Wikimedia Commons, Howl Arts Collective, 2008.

Chapter 7

7.1: Photochemical Smog. Wikimedia Commons, Dr. Edwin P. Ewing, 1988.

7.2: The Formation of Ozone. Original work, Mila Gillis-Adelman, 2017.

7.3: Isaac Newton's diffraction experiment. The life of Sir Isaac Newton, David Brewster, 1836.

7.4: The ozone hole in 1979 versus the ozone hole in 2008. Wikimedia Commons, NASA, 2008.

7.5: Portrait of Louis Agassiz. Wikimedia Commons, 2005.

7.6: Glaciation on the White Mountains. Wikimedia Commons, Barrison, H, 2009.

7.7: Portrait of James Croll. Wikimedia Commons, 1897

7.8: Diagram showing the orbital path of the Earth. Wikimedia Commons, Foresman, P.S, 2011

7.9: The Columbia Glacier. NASA/USGS. 2013.

7.10: The cumulative mean mass balance. Wikimedia Commons, NOAA, 2010.

7.11: A Tower of the Wind located in Athens. Wikimedia Commons, Andreas Trepete, 2008.

7.12: Photo of Canadian Geese. Flickr, Robert Linsdell, 2014.

7.13: British Bombardment of the Fortress in Aland Islands during the Crimean war. Wikimedia Commons, drawn by E. T. Dolby.

7.14: This photo depicts two US Navy soldiers launching a radiosonde attached to a balloon in 1943. Wikimedia Commons, American Radio History, 1943.

7.15: A computer simulation of the Typhoon Mawar in 2005. Wikimedia Commons, Wikipedia user Atmoz, 2005.

Other

Page i-ii: Iceland Mountain Range. Original Work, Connor MacLean, 2016

Glossary & Index

Agronomy 6
The science of producing and using plants for food, fuel, fibre and land reclamation.

Albedo 29, 132
The amount of solar energy that is reflected from a planet back into space.

Alchemy 11, 12, 38
An early form of chemistry that was based on transmuting metals, primarily into gold.

Allele 55
A variant form of a gene.

Anthropogenic 14, 59
Anything resulting due to human activity.

Anticline 112, 117
An arch-shaped fold in stratified rock.

Aphelion 132, 133
The point in an orbit of a planet or object that is the furthest from its star.

Astrology 28
The study of celestial objects in order to predict future events.

Biodiversity 70, 95, 124
The variety of organisms in a habitat or ecosystem.

Biogenesis 56
The production of new living organisms or living matter by pre-existing organisms.

Biosphere 63, 66, 92
The section of the Earth and its atmosphere that supports living organisms

Biostratigraphy 113
The study of fossils and their use in dating rock formations

Bitumen 116-121
A black, viscous, liquid or semi-solid form of petroleum which can be found naturally or refined from distillation.

Botany 10, 130
The study of plants.

Carbonization 19
The process in which an organic substance is converted into a carbon or carbon-containing residue.

Cartography 91-92
The study and practice of making maps.

Climate 124, 128, 132-141
The weather conditions that generally occur in an area over a long period of time.

Crystallography 10-15
The study of the arrangement of atoms in crystalline structures.

Delta 110, 113-114
A landform created by the deposition of sediment where a river enters slow moving or stationary water.

Diagenesis 75
The change of sediments or existing sedimentary rocks into new sedimentary rock.

Entropy 47
A thermodynamic quantity representing the degree of disorder or randomness of a system.

Epoch 58, 132
A period of time.

Earth Science 4, 14, 16-20, 113
The science of the constitution of and the processes that occur on Earth and its atmosphere.

Exoplanet 28-29, 34-35
Any planet that orbits a star outside of our solar system.

Facies 113-114
A character of a rock bed expressed by its formation, composition, and fossil content.

Fault 19-21, 115
A fracture or discontinuity in a volume of rock where significant movement has occurred.

Foraminifera 98-99, 113
A single-celled planktonic animal with a perforated chalky shell.

Geocentrism 37, 45
The belief that the Earth is the centre of the universe.

Geology.....................................8, 10, 18-19, 35, 50, 57, 70, 78, 82, 84-87, 108, 112-118, 130, 135
A division of Earth science that focuses on the Earth, the rocks that compose it, and the processes through which it changes over time.

Geomicrobiology 86
The study of the interactions between microorganisms and earth materials.

Geomorphology 150
The study of physical features on Earth and their relation to its geologic structures.

Genome 55, 80-81, 87
The complete set of genes or genetic material in a cell or organism.

Globigerina Ooze 94, 98-100
A chalky deposit that occurs on the ocean bed consisting mainly of the shells of foraminifera.

Heliocentric 30, 36-38, 45
The accepted model in which the Sun is the centre of the solar system.

Hummock 131
A small mound above the ground.

Lenticular 30-31
An adjective that describes a formation with a lens-shaped cross-section.

Lignite 116
A soft, brownish coal that contains traces of plant structures.

Lithology 111
The study of physical characteristics of rocks.

Metallurgy 11, 15
The study of the physical and chemical properties of metallic elements.

Metaphysics 10, 16, 18
A branch of philosophy concerned with the fundamental nature of reality.

Meteorology.............................19, 104, 107, 128, 136-141
The study of the processes that occur within the atmosphere, primarily focused on forecasting the weather.

Mineralogy 10-15
The study of minerals.

Mohorovic Discontinuity 94
The boundary between the crust and the mantle of the Earth.

Natural Selection 51, 53-54, 56, 79-80
The process whereby organisms that are more suited to their environment survive to produce more offspring and pass on their genetic material.

Oceanography 90, 93
The study of the ocean.

Paleontology 50, 52, 70, 72, 74-82, 85-86, 111
The study of fossils.

Pedology 4, 6, 8-9
The study of the chemical and physical properties of soils.

Perihelion 132-133
The point in the orbit of a planet or object in which it is closest to to its star.

Permineralization 19
The process of fossilization in which mineral deposits form an internal cast of an organism.

Petrification 19
The process in which organic material becomes a fossil through replacement by minerals.

Petrography 112-113
The branch of science concerned with the description and classification of rocks.

Petrology 111-112
The branch of science concerned with the origin, small-scale structure and composition of rocks.

Phylogenetics 55, 75, 80-81
The study of the evolutionary relationships between organisms.

Planetesimal 31, 34
A precursor to planets formed from dust, rock and other space materials.

Polymath 16, 77
A person of wide-ranging knowledge.

Pyroelectricity 10
The ability of materials to generate temporary voltage when heated or cooled.

Sedimentology 13, 72, 110-114
The study of sediments and the processes which create them.

Semiconductor 10
A substance that gains the ability to conduct electricity by the addition of impurities or temperature effects.

Stratigraphy 19, 51, 78, 80, 84, 111-113
The study of the order of strata and their relative position to one another.

Stratum 50
A layer or series of layers of rocks.

Transmutation 11, 20, 52
The process of changing from one substance into another.

Zoology 130
The study of animals and their behaviour.