History of The Earth

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Earthrise taken by Apollo 8 crewmember William "Bill" Anders on December 24, 1968 (Christmas Eve), at mission time 075:49:07 (16:40 UTC), while in low orbit around the far side of the Moon. This photograph shows the Earth rising for the third time above the lunar horizon.

Foreword

Curiosity, exploration, open-mindedness, opportunity, and *adaptation*. These are not just empty words – they are good descriptors of the many authors of this book whom I have encountered. It was the year 2017, as I was finishing my final year of a bachelor's degree in the geosciences, I was given the privilege to mentor and assist in the teaching of this cohort of students. These newly welcomed university students were beyond their years and immediately, had some sense of drive and a refreshing perspective in learning. In essence, it was uncommon for all students to have been exposed to detailed studies in the geosciences earlier in their education since it already encompassed integrated subjects. It was from that realization and impression that I hoped to mentor and immerse them with me in this journey of the Earth Sciences.

My experience in the geosciences started around a similar stage whereby, that desire to explore and discover was ignited on a field course to Iceland. Studying glaciers, volcanoes, cryovolcanoes, ecological environment, and Icelandic culture during this time was an opportunity of a lifetime that truly changed my perspective on how I can potentially and positively influence/contribute to the community as a whole. I applied this experience in my teaching and although I didn't expect everyone to have the same passion that I had, I strived for each, individual student to at least connect, relate, and develop an appreciation of the complexity of processes shaping our Earth.

Now, as I delve into the industry of planetary exploration and education, I see that some people focus on looking out into the cosmos and the sky but often times, they forget to look down at where they are currently standing. Before exploring the skies and the stars, humanity first explored Earth. This book truly encompasses the various pathways that scientists, voyagers, storytellers, and historians took in order to preserve and shape the Earth's current narrative.

As we take the pulse of our planet looking from above, history continues to write itself and new technologies/discoveries have yet to be documented. Setting the stage for studies about our planet for future generations to come, this book is not only a part of Earth's history, but it is also a part of *our history*.

We are more than just a pale blue dot.

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Introduction

This book contains a collection of articles written by students in the Integrated Science program at McMaster University. The articles delve further into both the history of the earth and the history of science, aiming to use one to help further our understanding of the other. The topics stretch the range of human exploration, chronicling changes in our understanding of the earth and its processes. Each article is structured in a way that first shares an aspect of science history and human exploration. Science is not just a timeline of names and theories, but a pursuit to fully understand. It is the story of questions; with the history of science, we hope to share not just this story, but that of everyone who has helped both ask and answer them. Each of the topics in these articles is then further examined with a modern lens. Each early question acts as a springboard to multiple new ones, creating a cyclical process of new questions and answers. The modern sections share a snapshot of the current work that was initiated by the original questions, sharing how our knowledge has changed since its first discovery.

Each article in this collection represents the diverse interests of students in an interdisciplinary program; the combination of such unique backgrounds helps to create a wholistic view of science on and about the planet. Alongside each of the Integrated Science courses taken by students of the program, many chose to specialize in a specific discipline, using their electives to further their understanding in this area. The passion that is common among all students is that of scientific exploration and learning. How can we ask important questions, and how can we find answers to them? This uniting factor is also the glue that pulls each article together to form the collection. Science is not a series of isolated parts, but instead a constantly expanding web; it is only with this knowledge that we can answer the never-ending questions. We hope that these articles inspire you to continue to ask questions and to honour the stories of the people who have helped answer them.

Chapter 1: Volcanic Processes and the Internal Earth

The Earth is not simply static; it is an amazingly active and dynamic environment. In a perpetual state of building, breaking, melting, and reshaping, our planet is constantly changing itself through natural cycles and processes. Many of these processes result from activities occurring below the surface, in the internal earth, and were thus inexplicable to humankind for centuries. Despite this barrier, human civilizations have continuously strived to explain these mysterious events and get a glimpse into the secrets of the wondrous world we live on. In this chapter, we will explore one of Earth's most dramatic natural phenomena: volcanic eruptions. Focusing on historical perspectives, we will look at how influence from mythology, religion, and science has played a role in our perception and comprehension of these events. We will also see how advancements in science have allowed humans to explore the previously uncharted waters of the deep subterranean world. Lastly, one of the remarkable discoveries regarding the inner earth will be highlighted, a discovery made by one of the first female geophysicists.

Historical Perspectives Regarding Volcanism

Introduction

Throughout the age of human civilization, the laws that have governed the way *homo sapiens* have been ever changing with the acquisition of knowledge. For many years in the past, ancient religious beliefs set forth by books such as the Holy Bible were widely accepted as humans lacked the ability and to challenge what has been practiced and presented for hundred years (Suran, 2010). With growing curiosity for explanatins fte unknown came tirst for knowledge, setting into action the questionment of religious beliefs and an ever evolving field of science.

Figure 1.1. Vulcan, the Greek God of Fire. The Greek myth of Vulcan states that he occupied a workshop underneath Mount Etna as a blacksmith, making weapons and tools for battle within the fiery depths of the volcano .

The Earth is no stranger to volcanism, which has been recorded in Earth's rich geological history as a vital component of the formation and evolution of life and earth as we know it (Lunine, 2006). It is only natural that curiosity of the contents and functions of volcanoes brewed alongside(Negro et al., 2013a). From this, civilizations began to provide reasoning for such tragedies, initially through ancient mythology and religion, and later through critical observation skills.

Foundations from Greek Mythology

Mount Etna, located in Italy, sparked the interest of humans throughout history. Accounts for eruptions of Mount Etna have been present in ancient literature since 1500 BCE (Negro et al., 2013b). Two primary Greek myths help describe the action of Mount Etna, dating back from 500-400 BCE (Adkins and Pollard, n.d.). One myth claims that the Greek God of sky and thunder, Zeus, conquered the monstrous serpent-like giant Typhon by trapping him under the mountain, casting him to the underworld (Belmont, 2016; Pyle, 2017). Typhon periodically lost his temper, spewing fire from the thousands of dragon heads that made up his body, thereby producing an eruption (Belmont, 2016). The second myth describes Mount Etna as the workshop for Vulcan, the Greek God of Fire, seen to the left in Figure 1.1 (Precourt, 2014). As a blacksmith and craftsman, Vulcan held his fiery workshop in the mountain (Editors of Encyclopaedia Britannica, 2019). Together, these myths interpreted the origins of violent eruptions from Mount Etna in Ancient Greece (Negro et al., 2013b).

The Impact of Christianity

The rationale and reasoning behind volcanic activity was variable with the spread of human civilization and the divergence of religious beliefs. The eruption of the volcano Eldgjá in Iceland is a prime example of such. The Vikings believed it to be a purposeful act from Christian gods set forth to convert recently settled Vikings and Celts to Christianity (Bodkin, 2018; Katz, 2018). This eruption, which happened in the early tenth century, occurred after the settlement of the Vikings and Celts, practicing Paganism, in Iceland (Bodkin, 2018). Ancient texts describe the event to have resulted in blood-red skies, harsh winters, a weakened sun, climactic abnormalities, human and livestock mortality and severe drought (Bodkin, 2018). The Voluspá, a poem written in approximately 961 AD, describes how the Pagan God Odin prophetizes the end of the Pagan Pantheon as the rearing of "a monstrous wolf that will swallow the Sun" and with replacement by a singular god (Katz, 2018). As theorized by historians and supported in Icelandic history, the conversion to Christianity happened within this time, linking it to the outcomes of the eruption (Katz, 2018).

Challenging Religious Beliefs

While the beliefs of religious institutions sufficed for centuries, the accumulation of observation based facts helped produce a more logical picture for the natural disasters associated with volcanism (Pyle, 2017). It was not until the approach of the 19th century that explorers began to accumulate data and observations regarding the composition, formation and action of volcanoes, deviating from the foundational myths and religious beliefs that has governed human knowledge in the past (Pyle, 2017). This accompanied general exploration of the natural world and came with the amalgamation of small scale experiments and observations by natural scientists around the world. The ultimate progression of knowledge can be attributed to the sharing, revising and testing of theories put forth by early natural scientists (Pyle, 2017).

Building a Definition

Some of our earlier, more descriptive, definitions of volcanoes can be found in dictionaries, such as in Samuel Johnson's 1755 book, *A Dictionary of the English Language*. Johnson defined volcanoes by their historical and mythological context: "When the Cyclops o'er their anvils sweat, From the volcano's grofs eruptions rife, and curling sheets of smoke obscure the skies" (Johnson, 1755). However, Johnson also included objective observations of a volcano: "A burning mountain. Navigators tell us there is a burning mountain in a island, and many volcano's and fiery hills" (Johnson, 1755). This definition indicates the presence of beliefs of supernatural powers associated with volcanism. Nonetheless, it was still observed and noted that volcanoes and islands are often associated. The correlation with the natural world was representative of a movement away from supernatural explanations (Johnson, 1755).

Johnson's definition lead the way into a time when natural scientists began to play a bigger role in explaining observations. Knowledge of combustion and fire was developing, which illuminated theories about the inner mechanics of Earth (Pyle, 2017). Scientists began to spawn better informed theories through implementation of the scientific method.

Setting the Stage for Science

During the 19th century, geology was still an emerging science, yet interest was fluorishing in volcanism (Pyle, 2017). This may be attributed to volcanic activity at Mount Vesuvius, located in Italy, at the beginning of the century. There were no volcanoes in the British Isles, and the volcanic fields in France, Germany and Spain had lain dormant for centuries (Pyle, 2017). Western European scientists, who were the main proponents of volcanic research, had to travel to Italy and beyond to obtain primary data (Pyle, 2017).

Prior to these great explorations, scientists theorized about the nature of volcanoes based on recent advances in chemistry (Pyle, 2017). This began in 1790, when Scottish chemist James Hall systematically melted rocks to observe their cooling process (Pyle, 2017). Hall found that fast cooling produced glassy rocks, but slow cooling the melt would transform into a 'stony' crystalline mass (Pyle, 2017).

Volcanism and the Geologic Cycle

Hall's findings were a signal to others about the nature of Earth's interior. This included Scottish geologist, James Hutton, pictured in Figure 1.2, and his friend and mathematician, John Playfair (Pyle, 2017). Hutton theorized that the Earth had a fluid centre with vapour that carried heat to shallow subterranean reservoirs or to the surface as a volcano erupts (Playfair, 1802). This coincided with Hall's research because it was explanatory of eruptions (Playfair, 1802). A central heat at above 30^{o} of Wedgewood's Pyrometer, an arkane temperature scale, would keep the lava in liquid form within the Earth, which would then solidify in either of the ways Hall described, dependent on its transportation to the surface (Playfair, 1802). Hutton's theories about central heat and volcanism were just one piece of the puzzle for his grand geological cycle.

Figure 1.2. An oil painting of James Hutton by Sir Henry Raeburn in 1776.

Hutton was a proponent of uniformitarianism, in which changes in the earth's crust during geological history resulted from the action of continuous and uniform processes (Editors of Encyclopaedia Britannica, 2018). With his field work in Scotland, Hutton came to think that modern processes, such as his observed erosion on the Scottish coast, transportation and deposition of sediments, and even volcanism, had their past recorded in the rocks (Editors of Encyclopaedia Britannica, 2001).

On the note of volcanism, Hutton proposed that, while rocks were broken down through erosional processes, new rock formations were produced through volcanism (Editors of Encyclopaedia Britannica, 2018). The internal heat of the Earth brought new rock to the Earth's surface (Editors of Encyclopaedia Britannica, 2018). Mineral and metallic veins in the strata and liquids expelled by volcanoes, for example, indicate that beneath the surface is a region of molten minerals and metals (Rossetter, 2018). This was explanatory of why volcanoes are presently extant only in particular areas. The number of mountains thought to be extinct volcanoes is clear evidence that they were formed, and therefore may form again, in any location (Rossetter, 2018). This attested to the universality of this subterraneous region of molten matter, and also to the generality of the cause of consolidation and uplift, as part of the geological cycle (Rossetter, 2018).

Many of Hutton's ideas were encapsulated by himself, but also his close friend John Playfair. Hutton's ideas are known through Playfair's *Illustrations of the Huttonian Theory of the Earth* (1802) (Pyle, 2017). Playfair described Hutton's ideas about volcanism as the following: "the centre of the globe was a fluid melted mass, with vapour carrying heat to shallow subterranean reservoirs of 'whinstone and basaltes', or erupting as lava at the surface" (Playfair, 1802). This definition is notably vastly different from Johnson's mid-18th century definition, indicating the presence of a relatively rapid conversion from religious to science based beliefs (Johnson, 1755; Dean, 1983). Despite the domination of religious explinations for centuries, this evolution of the definition of volcanism is a clear indication of the evolution of knowledge.

A Chemical Theory for Volcanism

Simultaneously, chemical advances led some scientists in other directions. Significant discoveries were made by Humphry Davy in 1808 (Pyle, 2017). He discovered the elements sodium, potassium, calcium and magnesium through electrochemical experimentation (Davy, 1828). In addition, Davy was able to isolate many Alkaline Earth metals, including magnesium, calcium, strontium and barium (Davy, 1828). Because these reactive metals are always found in combination with oxygen at the earth's surface, Davy proposed if they are found in pure form it would cause chemical reactions that would produce the effect of subterranean fire (Davy, 1828).

This discovery was highly revered due to his high standing in the scientific circles of London and as a founding fellow member of the Geological Society of London (Pyle, 2017). As director of the Royal Institution, he impressed crowds using a volcano modelled from clay, packed with potassium metal. Adding water to the potassium led to violent explosions that caused lava to flow down the sides of the model volcano (Pyle, 2017).

It was not until 1814 when Davy had the opportunity to observe a live volcano. He climbed Mount Vesuvius and examined the crater and the stream of lava within (Davy, 1828). He wrote, "the crater emitted so large a quantity of smoke, with muriatic and sulphurous acid fumes, that it was impossible to approach it except in the direction of the wind; and it threw up every two or three minutes showers of red hot stones" (Davy, 1828). The following year, Davy was convinced that "the origin of Volcanoes from the action of Water on the metallic bases on the Earth" (Davy, 1828).

It was at this time when a true scientific process was utilized. Davy's ideas were formulated and receieved, but he had yet to present conclusive proof as opposed to limited qualitative observations. Further testing was necessary to ensure that Davy's chemical theory was legitimate. He would have to prove that there were traces of pure unreacted in the lavas where they first erupted (Pyle, 2017).

Davy eventually published his book, *On the Phaenomena of Volcanoes*, in 1928, in which he conceded that none of the chemical causes assigned for volcanic fires can be true (Davy, 1828). The idea of combustion of mineral coal could not be true because its combustion under the surface could never produce violent and extensive heat and, furthermore, it was scarcely possible that carbonaceous matter, if such a cause existed, should not be found in the lava (Davy, 1828). In addition, the theory where the action of sulphur on iron is the cause of volcanic fire, could not be true because the heat produced by the action of sulphur on the common metals is inadequate (Davy, 1828). Lastly, Davy's theory of reactive metals were disproved by his own later observations on Mount Vesuvius (Davy, 1828). If it were true then some of the oxidized substances should have been found in the lava, and combustion should have increased upon the substances coming into atmospheric contact. However, Davy observed no such phenomena (Davy, 1828).

Hence, Davy concluded that the theories derived from "thermometrical experiments on the temperature of mines and of sources of hot water, render it probable that the interior of the globe possesses a very high temperature" were correct and explained why volcanoes existed (Davy, 1828). Although Davy was ultimately incorrect, Davy's field work and experimentation were still a step in the direction of modern science. In any case, the theory of the global nucleus as a hot, fluid matter, grew to be the prevailing theory as scientists conducted further explorations of volcanism (Davy, 1828).

Further Explorations of Volcanism

Meanwhile, Alexander von Humboldt, a German naturalist and explorer, began publishing his own ideas on volcanism in 1823 (Pyle, 2017). He had visited volcanoes in Europe and Latin America and was interested in describing the macroscopic workings of Earth's interior (Pyle, 2017). Humboldt recognized Davy's theory, but was more convinced of a subterranean heat source as a source of volcanism, which was supported by his own observation that deep mines were warmer than the air outside (Humboldt, 1845).

Humboldt's work had an advantage over many before him. While other scientists produced theories on known physical concepts or explored no further than their homeland, Humboldt travelled to far regions of the Earth (Kellner, 2019). In addition to visiting Mt. Vesuvias in Italy, he travelled to South America where he made great strives in the understanding of the Andean volcanoes concerning the role played by eruptive forces and metamorphosis in the history and ongoing development of the Earth's crust (Kellner, 2019). He also described the formation of soils on volcanoes and its effect on plant growth, as seen in Figure 1.3 (Humboldt, 1845). His exceptional travels are acclaimed by even Charles Darwin, who referred to Humboldt as "the greatest scientific traveler who ever lived" (Egerton, 1970). Darwin's respect for Humboldt was demonstrated by his own journey on the Beagle three decades later, when he brought a copy of Humboldt's seven-volume travel narrative (Smith, 2013). Humboldt also had a distinctive scientific mindset that likely attributed to his success. He believed the only way to understand the world was to look at it as a whole, using all the physical sciences together, instead of breaking everything down into isolated. Humboldt wrote, "knowledge and comprehension are the joy and justification of humanity" (Humboldt, 1845).

In addition to reiterating the plutonist view in his life's work, *Kosmos* (1845), Humboldt also described the formation and occurrence of volcanoes. For example, while observing the Andes he noticed that volcanoes are not distributed randomly; they occur in long chains (Humboldt, 1845). Furthermore, Humboldt theorized that volcanoes occurred in areas where rock is fractured due to events like earthquakes. Violent shaking would allow magma to more easily rise from subterranean caverns to the surface, feeding the explosive volcanoes in the Andes (Humboldt, 1845).

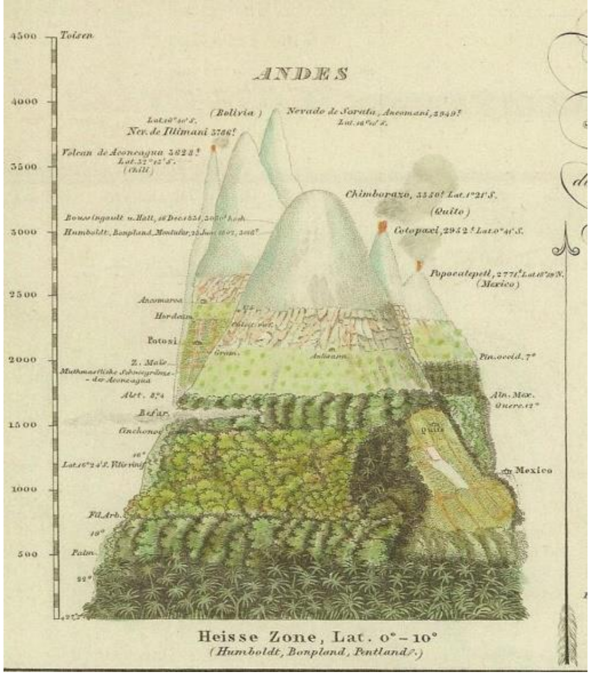

Figure 1.3. An image from the Berghaus Atlas, of which Humboldt was a contributor, that describes the variation of plant growth along the Andes.

Humboldt's prediction about the nature of volcanoes was mostly accurate by modern standards, but it would not be for over a century later until ideas about volcanism and the Earth's interior were properly synthesied Marshak, 2013). Over the remainder of the 19th century, the main point of contention was the nature of Earth's depths and its internal heat. By the conclusion of the nineteenth century, it was the scientific concensus that the Earth's interior was hot and that volcanoes were associated with fire (Pyle, 2017). Ideas concerning the presence of supernatural beings and religious implications of the human race were abandoned as being rational, making was for observation based conclusions (Pyle, 2017).

The continuation of human knowledge makes significant advances beginning in 1960, when plate tectonic theory set up a new framework for connecting the convection of earth's interior and surface expressions of volcanism.

Modern Mechanisms and Components of Volcanoes

An Inside Look at a Volcano

The contents of volcanoes are ultimately what people all around the world associate them with. Volcanoes contain hot, molten rock, known as magma when within Earth's interior, and as lava once it has reached the surface (Geiger, Barker and Troll, 2017). Volcanism today is understoofd in terms of plate tectonics, magma composition and geological significane.

Plate Tectonics

Modern understanding of volcanism on Earth is supported by the processes associated with plate tectonic theory, originally proposed by Alfred Wegener as Continental Drift (Marshak, 2013). This theory states that Earth has a rigid outer layer, known as the lithosphere, that overlies a plastic, partly molten, layer called the asthenosphere (Marshak, 2013). The lithosphere consists of seven very large continental and oceanic plates, six or seven regional plates, and many smaller ones, as seen in Figure 1.4 (Encyclopedia Britannica, 2011). The geographical link between plate tectonic boundaries and the presence of volcanoes provides an avenue for the study of volcanoes, an area previously scientifically underdeveloped (Marshak, 2013). The movement of the plates within the lithosphere, being convergent, divergent or lateral, were thought to be responsible for volcanism as volcanoes are mainly found near plate margins (Marshak, 2013).

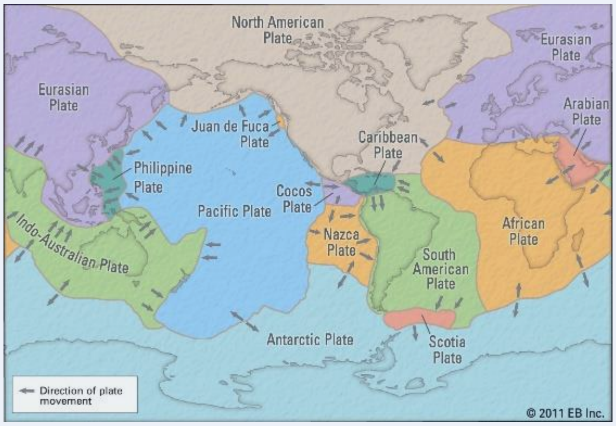

Figure 1.4. A visual depiction of the continental and oceanic plates of Earth.

Specifically, convergence of continental and oceanic plates is associated with volcanism (Murck et al., 1996). Oceanic plates are typically denser and subduct beneath continental plates at convergent boundaries. As a result, water subducts with the oceanic plate (Murck et al., 1996). The friction from the subduction produces heat, thereby melting continental plate **material and mixing it with the oceanic plate** material and the water (Murck et al., 1996). **The heat and the mix of more and less volatile ingredients causes changes in density and pressure, which causes the mantle to partially melt. The melted contents violently rise to the surface as magma, causing an eruption.** This is why volcanism is prominent on continental-oceanic boundaries, such as the Pacific Ring of Fire (Murck et al., 1996).

Understanding Magma

Magma is molten rock, containing a hot liquid base (known as the melt), molten minerals, dissolved gases, and a mixture of common elements. Silicon and oxygen are the most abundant elements found in magma, expressed as silica, SiO_2, molecules, which make up the backbone of most rocks (Miller, 2016). There are three main categories of magma, classified by varying chemical compositions, differences in gas content, viscosity and temperature (Cassidy et al., 2018). While the melting temperatures of different types of rocks and minerals vary, it is notable that greater water content and greater pressures, lower the melting temperatures of rocks and minerals, resulting in greater quantities of molten rock along subduction zones at oceanic plate boundaries, and areas deep within the Earth (González-Cataldo, 2016). There are three main classifications for magma, as follows:

Felsic Magma

Having a high silica content of around 70%, felsic magma has a high viscosity and contains the highest levels of dissolved gases (Cassidy et al., 2018). Felsic magmas are associated with violent and destructive eruptions as gasses becomes trapped and escape when pressure builds rendering think explosive action, forming rhyolite and dacite (Caryl, 2014).

Intermediate Magma

With a lower silica and gas content than felsic magma, intermediate magmas typically build up pressure below the surface of the Earth and explode in violent eruptions, cooling to form andesite. Intermediate magmas are mostly erupted from volcanoes found in continental volcanic arcs, such as the Andes Mountains (Caryl, 2014).

Mafic Magma

The magma with the lowest viscosity contains less than 50% silica, making it less viscous with lower gas content than the other two types (Cassidy et al., 2018). Eruptions of mafic magmas are fluid and flow quickly with little flow resistance, cooling to form basalt. Mafic magmas have a higher content of elements such as magnesium and iron, making mafic rocks heavier, denser and darker in colour (Caryl, 2014).

Composition of Earth

All three types of magma are associated with different types of eruptions and igneous products that make up the Earth's crust. It is notable that the crust is merely the uppermost part of the Earth and that magma typically originates from the region below the crust known as the mantle (Jordan, 1979). Being hot and bouyant, magma is able to penetrate weak zones in the crust, ultimately producing volcanic eruptions and introducing lava to the surface of the earth (Miller, 2016).

Mechanics of Volcanism

An eruption begins with an accumulation of gas-rich magma, which causes emissions of steam and gas from openings on the surface of the Earth, known as vents. This is often associated with small earthquakes generated by the rising plug of dense, viscous magma oscillating against a sheath of more-permeable magma (Decker and Decker, 2006).

Magma rises to the Earth's surface in different forms. For example, magma may emerge as a thin and fluid lava, which then flow continuously, or it may shoot straight up in glowing fountains or curtains. Magma rises due to the magma having a lower density than the surrounding solid rocks from which it is formed, thus rising to the surface (Decker and Decker, 2006). The weight of the overlying rocks adds additional pressure, which is proportionate to depth, such that the pressure decreases as the magma ascends. Pressure also controls the amount of gas that magma can dissolve. The amount of dissolved gas and the viscosity of the magma are influential in determining the properties and explosiveness of the eruption (Murck et al., 1996).

For example, nonexplosive, or effusive, eruptions, are associated with low viscosity, mafic magmas and low dissolved-gas content (Marshak, 2013). At first, the explosion may seem violent as the gas bubbles rise rapidly upwards. If the magma rises quickly enough, a rapid decrease in pressure will occur which can create a spectacular fountaining of lava. However, when the fountaining ceases, hot, fluid lava emerging from the vent flows rapidly downslope (Murck et al., 1996). In contrast, explosive eruptions are characterized by high viscosity magma, usually andesitic or rhyolitic (Marshak, 2013). As the magma moves upward towards the surface, the pressure decreases and allows dissolved gases to expand and escape explosively. The higher the viscosity, the more difficult it is for the gas to form bubbles and the greater the chances of a violent eruption (Murck et al., 1996). For example, the viscous magma may collect pockets of gas. As pressure increases, the gas will eventually be realeased as a violent explosion, allowing lava to be expelled from an opening in the crust (Marshak, 2013).

Dangers Associated with Eruptions

While the flow of lava itself can be detrimental to human civilization and established vegetation, it is now well understood that volcanic ash and pyroclastic debris are equally as dangerous due to the physical characteristics of each. (Zuskin et al., 2007). Volcanic ash is composed of microscopic fragments of glass-like material which is ejected into the atmosphere, and can be thick enough to block out light from the sun and cover nearby surroundings. Ash also becomes a health hazard as the small fragments can pierce and clog the alveoli, leading to severe breathing issues (Longo and Longo, 2013). Pyroclastic debris is a blanket term used to describe materials ejected from a volcano during eruption, including ash, large pieces of rock known as lava blocks and small pieces of rock known as lapilli (Adams, 2013). Together, these pose a threat to surrounding environments as they are hot, fast moving and unstoppable (Mastrolorenzo et al., 2010).

Figure 1.5. The eruption of Eyjafjallajökull, located in Iceland, shows the extent of the resultant ash plume.

Volcanism on earth is not new, yet our evolution of knowledge has been rapid. Modern technologies and research, in combination with historical observation has built a significant understaning of volcanim and its impact on human civilizations (Pyle, 2017).

Mt. Vesuvius and the History of Volcanology

One of the most astounding phenomena in nature is volcanism: the processes of molten rocks erupting onto the surface of the earth and creating volcanic debris (ScienceDirect, 2019). Ideas on the causes of volcanism are presented in ancient Roman mythology, in theories of philosophers, and the modern field of volcanology (Bullard, 1962). As such, here we will dive into the history of volcanology, its important figures, and its geological significance, using the infamous Mount Vesuvius as our muse.

Figure 1.6. Google Earth map depicting Mount Vesuvius and its surroundings (Google Earth Pro, 2018).

Mount Vesuvius (*above*) is arguably the most scientifically important volcano in history, as accounts of its activity and observations of the incidents that surround its prominent eruptions led to the development of volcanology (Dean, 2017). Vesuvius, a stratovolcano located 11 kilometres south of Naples, Italy (Dean, 2017), showed no signs of volcanic activity in the first century BC and was reported by ancient writers to have been covered by vineyards growing on its exceptionally fertile soils (Hull, 1892). Yet, it is most famous for its violent eruption on August 24th 79 AD (Hull, 1892; Bullard, 1962). From its central crater rose a cloud of pyroclastic debris that dispersed into the sky dropping layers of 300-degree centigrade ashes and lapilli on Earth's surface, burying the Roman town of Pompeii and its inhabitants (Hull, 1892; Leafloor, 2015).

The impact of Vesuvius, however, began long before this in 63 AD when earthquakes began to cause damage to the cities surrounding the volcano, including distant Naples (Hull, 1892). When Vesuvius finally erupted, its effects spanned 16 radial miles from its focus and destroyed, not only Pompeii, but also the lesser-known cities of Herculaneum, which was flooded with lahars, and Stabiae, which, like Pompeii, was buried by volcanic ash. Vesuvius erupted again in 472 AD to cover all of Europe with a thin dusting of volcanic ash. Since 1500 AD it has erupted another 56 times. This frequency of eruptions afforded prominent volcanologists of this period opportunities to study this wonder; research that paved the way for modern volcanology (Hull, 1892).

The Beginnings of Geomythology

Some of the first descriptions of volcanic activity were presented in Roman myths (Bullard, 1962). It was believed that volcanoes were suspicious and dangerous, making their investigation a wicked act. Nonetheless, volcanism astounded ancient Romans leading them to include this phenomenon prominently in their mythology (Bullard, 1962). Mount Vesuvius, specifically, was thought to be an entrance to the underworld (Lill, 2015) where giants lived, accounting for the loud noises, shaking, and spewing that occasionally occurred around the volcano (Leafloor, 2015). Its violent eruption in 79 AD, however, was equated to divine vengeance against the sin and immorality of the citizens of Pompeii (Lill, 2015). In this era, it was believed that if humans became hubris about their importance, the gods would remind them of their place in the hierarchy of beings (Leafloor, 2015), making the Romans believe these violent volcanic eruptions were their punishment (Lill, 2015). Another explanation for Vesuvius's great eruption, as recorded in frescos (plaster wall paintings) on Pompeian walls (The National Gallery, 2019), was that volcanic eruptions were natural processes the gods had created to teach humans caution, courage, and common sense in the face of danger (Lill, 2015). These geo-mythological fields of thought were most prominent prior to the common era (Connors, 2015).

Greek Philosophers and Scientific Thought

Volcanism's continued presence prior to and during the common era led Greek philosophers to formulate more scientific explanations of these phenomena from the fourth century BC and onwards (Bullard, 1962). It is important to recognize, however, that the ancient Greek views remained rooted in idealism, rather than deductive reasoning, as the collection of facts and close observation of scientific phenomena was unusual in the first millennium. Plato, Aristotle, and Strabo were among the most influential philosophers who attempted to provide scientific explanations of volcanism (Bullard, 1962).

Plato (ca. 427 - 347 BC), the earliest of these philosophers (Bullard, 1962), believed volcanism was the result of subterranean lava found in reservoirs (Hull, 1892) and that winds inside the Earth caused the violent eruptions of this lava (Kavanagh, Engwell, and Martin, 2018). This idea was supported by Aristotle (ca. 384 - 322 BC), who described volcanism to result from 'pent-up' winds trapped in subterranean channels catching fire due to the presence of sulphur and coal (Bullard, 1962). Aristotle was the first to document some outcomes of volcanism, noting that earthquakes and volcanoes occasionally led oceans to be converted to lands and vice versa (Hull, 1892). Finally, Strabo (ca. 63 BC - 21 AD), a self-taught geographer, expanded on these ideas, noting that Italian land had felt more violent earthquake vibrations before volcanic eruptions occurred (Bullard, 1962). These observations led him to conclude that volcanoes acted as a sort of safety valve for the subterranean winds described by Plato and Aristotle, that allowed the escape of trapped wind, fire, and other matter, reducing the magnitude and frequency of earthquakes in these regions (Hull, 1892; Bullard, 1962).

Pliny the Younger

Pompeii, a city located only two kilometres southeast of Mount Vesuvius's base, was first founded by Oscans. Later it became settled by the Greeks during the 8th century BC, followed by the Etruscans in the 7th century, then the Samnites near the end of the fifth (Jashemski, 2019). By the third century BC, Pompeii was conquered by the Romans after the Samnite war, where its beautiful landscapes and fertile land gained popularity as a trade region and resort town, with exquisite food and wine (Dobran, 2006). Looks, however, can be deceiving. Strabo, who had been examining the rocks of Vesuvius's summit documented the presence of a dormant volcano, Vesuvius, in close proximity to the town (Sigurdsson, 1999). Although the cities surrounding Vesuvius had been living peacefully for many centuries, this quiet, unspoken treaty between the people and Vesuvius began to change in 62 AD. It was at this time that Vesuvius began to stir once again, resulting in earthquakes that caused great damage to Pompeii and Herculaneum (Jashemski, 2019). This year also marked the birth of a certain individual who would experience the awakening of Mount Vesuvius firsthand and live to tell the tale; undoubtedly advancing our knowledge of Vesuvius and volcanism and impacting many generations to come. This individual was Pliny the Younger.

Figure 1.7. Oil painting of Pliny the Younger and his mother in Misenum, completed by Angelic Kauffmann in 1785.

Pliny the younger was born in Como, Northern Italy in 62 AD, into a wealthy, aristocratic family *(right)* (Sigurdsson, 1999). Unfortunately, his father died soon after his birth, and he was adopted by his uncle, Gaius Plinius Secundus, commonly known as Pliny the Elder (Sigurdsson, 1999). Pliny the Elder was the most important reporter of Roman science at the time, known for writing one of the first scientific encyclopedias, *Historia Naturalis*, which had a lasting influence on European scholars until the scientific revolution (Sigurdsson, 1999). Pliny the Younger was raised in Como and Rome by his mother and uncle, and experienced many earthquakes originating from Vesuvius, an occurrence that was quite normalized. When another earthquake occurred in 63 AD Nero, the Roman emperor at that time, continued a concert he was giving, seemingly unalarmed (Zilinga de Boer and Sanders, 2002).

At this time volcanism was still considered to be something supernatural and thought to be primarily caused by subterranean winds. This belief was supported by the Aetna poem and ideas put forth by Lucius Annaeux Seneca following the initial quake of 62 AD (Sigurdsson, 1999). The Aetna poem, a Latin poem of unknown authorship written between

63 and 79 AD, described the causational relationship wind had with volcanic heat and led to the proposition that violent earthquake motions were due to winds being absorbed from the atmosphere into the peaks of mountains, as well as rock fall events that occurred within earth (Hine, 2015). Seneca made similar deductions in his book about natural philosophy, *Quaestiones Naturales* in 62 AD, with the additional proposition that subterranean winds rushing through sulfur and flammable substances created frictional heating, setting the fuels on fire (Geikie, 1910). He also observed plagues often followed bouts of volcanic activity, noticing the death of hundreds of sheep after the initial quake of 62 AD. He attributed these plagues to death-carrying elements that lay within the earth, released by poisons from the internal fire. These elements were believed to pollute the clean atmosphere, leading to disease in those who breathed them, with increased vulnerability for organisms who had their heads close to the ground, such as sheep (Sigurdsson, 1999).

Growing up, Pliny the Younger immersed himself in studies of rhetoric and was taught Latin by Quintilian, one of the most influential authors of the time who made important contributions to educational theory and literary criticism (Sigurdsson, 1999). This education would have a great impact on his writing, including his personal letters documenting his life events. Another important character in his life was his vastly travelled, greatly inquisitive uncle, for whom he had deep respect (Encyclopedia Britannica, 2019).

Figure 1.8. Painting depicting Vesuvius' eruption and the umbrella pine-shaped cloud by George Julius Poulett Scrope in 1822.

In these years, there was not much concern regarding Vesuvius, though, this all changed on the morning of August 24th 79 AD with the great Vesuvian Eruption that buried Pompeii. The events surrounding this eruption were meticulously documented by Pliny the Younger in a letter written 25 years later to his friend, the historian Cornelius Tacitus (Younger, 1936). On this fateful morning Pliny the Older was stationed at his home in Misenum, when he noticed clouds of unusual size, that had the shape of an umbrella pine, filling the sky (*left*). Drawn by his curiosity, Pliny the Elder immediately ordered a ship to move closer to the eruption and observe this phenomenon originating from Mount Vesuvius, while Pliny the Younger, only seventeen at that time, decided to stay in Misenum to finish his studies. Little did Pliny the Elder know, he likely should have followed his nephew's example. Nonetheless, as he was leaving he received a message that changed the nature of his journey. The message came from Rectina, the wife of his friend Tascius, who lived at the base of Mount Vesuvius (Younger, 1936). As Pliny the Elder approached the mountain, ashes and lapilli were falling hotter and thicker, forcing his ship to change course and head for Stabiae instead. Pliny the Younger noted that although it was daytime, it was dark and the smell of sulphur was permeating the area. By midnight there were intense shocks vibrating the area. This was later discovered to be caused by the collapse of the eruption column, resulting from decreased pressure in the magma chamber as lava erupted at the Earth's surface (Sigurdsson, 1999). Pliny the Younger, who observed from afar, noted that lava flows ignited the vegetation and habitat. As the day progressed the flames and smell of sulphur intensified, and unfortunately, his uncle met his inevitable death while resting in his friends house where he collapsed, likely due to excessive fume inhalation (Younger, 1936).

This account of Vesuvius's eruption in 79 AD is the most detailed first-hand account written found to date, and although it may have been exaggerated by Pliny the Younger, served as an important aid for future studies of this eruption. Unfortunately, this is as far as Pliny the Younger's exploration on volcanoes went. He began practicing law shortly after his uncle's death and attainined high administrative posts by becoming a praetor and consul (Encyclopedia Britannica, 2019).

William Hamilton

After Pliny the Younger's detailed description of the events that occurred at Vesuvius in 79 AD, the field of volcanology was essentially left untouched from the Dark ages into the Renaissance era until Sir William Hamilton published *Observations on Mt. Vesuvius, Mt. Etna, and Other Volcanoes in 1774* (Bullard, 1962). This was the first of Hamilton's many significant contributions to modern volcanology (Bullard, 1962). Hamilton's appointment as an English ambassador to the British Envoy of Extraordinary and Plenipotentiary at the Court of Naples in 1764 brought him into close proximity of Mount Vesuvius, with which he was immediately enthralled (Bullard, 1962; Sleep, 1969). He became one of the most knowledgeable students of volcanoes in the 18th century, (Thüsen, 1999) recording Vesuvius's eruptions and observing volcanic phenomena as a hobby until 1800 when he left Italy (Sleep, 1969). Hamilton *(right)* was a self-taught volcanologist and was not confident in his ability to explain natural philosophy (Dean, 2017). Yet he published accounts of important Vesuvian eruptions in 1766, 1767, 1770, and 1779 (Dean, 2017), allowing philosophers of the era to interpret his observations and generate official theories (Wall, 2004). His enormous contributions to a new way of studying volcanology afforded him the title of the first volcanologist (Wall, 2004).

Hamilton's approach to geological and volcanological studies was unique (Sleep, 1969). While most volcanologists of the 18th century were metaphysical philosophers who were heavily influenced by the church and relied on the feelings and intuitions of others to generate hypotheses, Hamilton was obsequious in his own observation to confirm others' beliefs. Rather than studying from afar and making what he believed to be uneducated guesses, Hamilton was one of the first investigators of volcanism to pursue his own data collection and observation in a more Baconian, or deductive, way. He would not formulate findings into hypotheses until he had gathered an enormous amount of evidence. Importantly, he was one of the first scientists to break free from the Church's metaphysical views, putting him on a pedestal with other famous natural philosophers, such as Guettard, Desmarest, and Leonardo da Vinci, for laying the foundations for the observational approach of modern geology. Since Hamilton's theories and methods were unorthodox for the time, it was surprising that society so easily accepted his views. This is likely related to the accuracy of his observations, and his use of indisputable evidence and reasoning in the presentation of his works (Sleep, 1969).

Hamilton's first-hand accounts of Vesuvian eruptions and observations of the surrounding geology were of great importance to modern volcanology (Hull, 1892). Not only did these experiences lead him to many important conclusions about the processes behind volcanism, but they also provided a platform for the development of theories by other natural philosophers and a new way of communicating geological ideas. Hamilton was the first to use drawings, diagrams, and paintings to effectively communicate geological phenomena supporting his observational approach to science (Hull, 1892). This began in the form of his own hand-drawn pen-and-ink sketches of the Vesuvian crater throughout the Vesuvian eruption of 1767 (Hull, 1892), but led to him commissioning an artist named Peter Fabris to paint the scenes he wanted the world to see (Wall, 2004). Together they developed a system in which geologic strata and temperatures were represented by specific colours to effectively communicate the environmental changes that occurred over the course of volcanic eruptions (Hamilton, 2012). Their images inspired other geologists to follow Hamilton's approach to the study of geologic phenomena and draw what they saw so others could better understand their findings (Hamilton, 2012).

Figure 1.9. Oil painting of Sir William Hamilton completed by George Romney in 1784.

This extensive research led Hamilton to discover various volcanological phenomena around Mount Vesuvius, contributing to a better understanding of volcanism and the principles it followed (Thüsen, 1999). His proposition that volcanic activity extended far back into history evolved after visiting the Pompeian archaeological excavations in April 1872, where he discovered a 10-foot deep area of exposed sediment with alternating layers of lapilli and volcanic dust (Thüsen, 1999). This indicated to him that a multitude of eruptions had occurred (Hull, 1892), where dense tephra ejected from the volcano settled into a layer on top of which volcanic ash lay (Thüsen, 1999). He also found that Vesuvius had three crater-cones within one another that seemed to grow and change after each eruption (Thüsen, 1999). In a 1786 letter to his colleague, Sir Joseph Banks, Hamilton explained that with each eruption, flowing lava seemed to cool on the flanks of Mount Vesuvius, gradually changing the volcano's form. This observation, along with fractured limestone he discovered in the region, led Hamilton to further conclude that volcanism was a constructive force (Thüsen, 1999), an idea that was contrary to common opinion at the time. He proposed that all of Naples had been created by volcanoes when the seafloor was broken and lifted as a result of earthquakes and volcanic activity (Thüsen, 1999). Consequently, he rejected the idea that volcanoes were burning coal (Thüsen, 1999). Instead, a lava source more deeply rooted in the earth produced tremors as the molten rock escaped (Hamilton, 1786; Thüsen, 1999). This was an enormous contribution to the theory of volcano formation.

Hamilton was not satisfied with simply observing active volcanoes, however, and on April 12th, 1766 walked up to the lava spewing from an erupting spatter cone on the flanks of Vesuvius (Wall, 2004). He ran an impromptu experiment in which he threw large stones at this flow with all his force, noticing the stones did not make an indentation in the liquid which seemed to flow quickly, much like water, despite its apparent viscosity. After the lava cooled, he obtained samples that were later sold to the Natural History Museum in London *(above)* (Wall, 2004). Further analysis of these rock samples allowed Hamilton to make conclusions on the origins of basalt (Sleep, 1969). He stated in 1776 that basalt was 'merely' lava, suggesting its origins were purely volcanic. This discovery, though seemingly trivial, had great importance in the 18th century as geologists of the time commonly debated the origins of rocks. Some argued that rock formation occurred in aqueous environments, while those who believed in uniformitarianism agreed that rocks formed due to intense heat, pressure, and igneous fusion. Since Hamilton came to the same uniformitarian conclusion that Desmarest had in 1774, other geologists became convinced by Hamilton's drawings and notes and eventually accepted his idea of volcanic origins (Sleep, 1969).

Figure 1.10. Samples of stone and volcanic matter collected from Mount Vesuvius by Hamilton and depicted in a coloured etching by Peter Fabris in 1776.

Perhaps the most important contribution William Hamilton made to geology and volcanology was his *Campi Phlegraei* or *Fields of Fire*. This is a published account of all the letters he had written during the 1760s and 1770s to the Royal Society in London documenting his volcanological observations and Vesuvius' eruption cycle (Wall, 2004; Hamilton, 2012). Published originally in 1776, and again in 1779 with a supplement, this document discussed all-natural volcanic phenomena occurring in Southern Italy at the time (Wall, 2004), allowing future geologists, including de Saussure, Dolomieu, Hutton, and Lyell to not only understand antiquity (Sleep, 1969), but also to build on his theories (Lill, 2015). It has also been said that *Campi Phlegraei*, which remains the standard point of reference for virtually all volcanological pursuit (Thüsen, 1999), was the most trustworthy account of historical and scientific phenomena at Mount Vesuvius (Sleep, 1969).

Sir William Hamilton, a man originally untrained in natural history (Thüsen, 1999) has become one of the most notable contributors to volcanology of the 18th century (Sleep, 1969). Though he chose to restrict his theories to only those he could extensively prove, his meticulous observation, Baconian data collection, in-depth accounts, and samples of the volcanic activity of Vesuvius were essential to the beginning of volcanology (Sleep, 1969). He provided future geologists with a platform for further progress (Sleep, 1969).

Interpreting Eruptions and Volcanological Monitoring

Interpreting the Vesuvian Eruption of 79 AD

Advances in the field of volcanology have greatly improved our current understanding of the events that occurred during the eruption of 79 AD at Mount Vesuvius. With the use of both historical and geological evidence, including study of deposits accumulated during the eruption, as well as the extensive documentation of the event, Sigurdsson, Cashdollar and Sparks (1982) deduced that the eruption was characterised by two major phases. The first phase was the Plinian phase, which lasted for approximately 18 hours. During this phase pumice fell south of the volcano as a result of a high eruption cloud, which settled into a well-bedded uniform layer. Dense fragments of limestone and pre-existing volcanic rocks found within this layer indicates that some of the materials originated from the walls of the volcanic pipe during the eruption (*below*). This layer reaches thicknesses of up to 2.88 metres in Pompeii, thought its thickness is variable and decreases exponentially as the distance from Vesuvius increases (Sigurdsson, Cashdollar and Sparks, 1982).

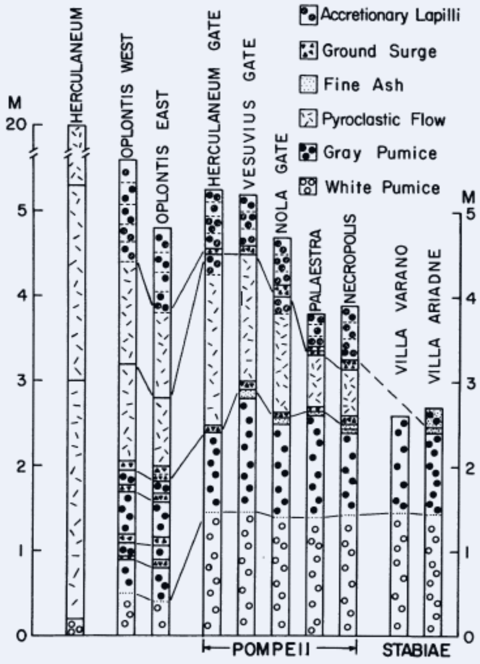

Figure 1.11. Stratigraphy of deposits of AD 79 west and south of Vesuvius, note specifically the Pompeiian sites. Produced by Sigurdsson et al., 1982.

The second phase of the eruption, referred to as the Pelean phase, was characterized by nuée ardentes, hot ash avalanches that swept down the south and west flanks of the volcano. This activity is confirmed by the presence of a thin ground surge deposit composed of well-sorted limestones, dense volcanic rocks and brick or roof tiles (Sigurdsson, Cashdollar and Sparks, 1982). The presence of building debris indicates that this was a very powerful surge, attributed to a nuée ardente, rather than an air fall which would not produce sufficient force to transport these types of debris.

Overlying this layer, there are fine-grained, poorly sorted flow deposits that contain minor rock fragments and occasional pieces of building debris. This composition and structure indicates deposition from a pyroclastic flow, a hot, chaotic avalanche of pumice, ash and gas that flowed down the flanks of the volcano and buried areas of Pompeii. Pyroclastic flows form localized, un-bedded deposits which fill valleys and depressions tens of meters in thickness. In Pompeii, the pyroclastic flow is overlain with a second ground surge deposit 10 to 20 centimetres in thickness, with fragments of limestones and pre-existing volcanic rocks, indicating a second nuée ardente occurred (Sigurdsson, Cashdollar and Sparks, 1982).

Finally, there is a fine-grained ash deposit with pea-sized accretionary lapilli, resulting from the final explosive activity of the eruption. This deposit is gray in colour, and 60 to 70 centimetres thick. The lapilli, which are spherical ash pellets, are the dominant feature of this sedimentary deposit and indicate the presence of water during deposition, since they are formed in eruption clouds as ash particles aggregate onto falling water droplets. This lapilli layer is also well-bedded and fine grained, suggesting that the explosion could have occurred following heavy rainfall, which entered the volcanic vent (Sigurdsson, Cashdollar and Sparks, 1982).

Volcanological Monitoring

Tragedies such as these have motivated advances in volcanic monitoring techniques. Vesuvius has been closely monitored after its' first volcanic observatory was founded during 1841; it remains one of the most dangerous volcanoes in the world due to its' explosive eruptive style and proximity to a densely populated society (Giudicepietro, et al., 2010). Current monitoring systems employ seismological, geodetical and geochemical observations (Giudicepietro, et al., 2010). Geochemical monitoring employs chemical analyses of minerals in air and water that relate to changes in volcanic activity. One example of geochemical monitoring is the study of the composition of groundwater surrounding the volcano due to their long residence time in volcanic areas. During the process of degassing magma releases large amounts of volatiles into the atmosphere. Depending on the solubility of these volatiles may then dissolve into groundwater and become transported by groundwater to various water sources(Federico, et al., 2004). An example of a volatile of interest would be Helium, specifically the ratio of isotopes He-3 and He-4. Increased ratio of He-3/He-4 isotopes is a result of increased crustal helium which indicates pressure build-up and increasing rock failure. Increased ratio of these isotopes were observed for six months prior to an earthquake that occurred at Vesuvius, October 1999 (Federico, et al., 2004). With these developments in volcanic monitoring techniques, society has been able to better predict and prepare for these catastrophic events.

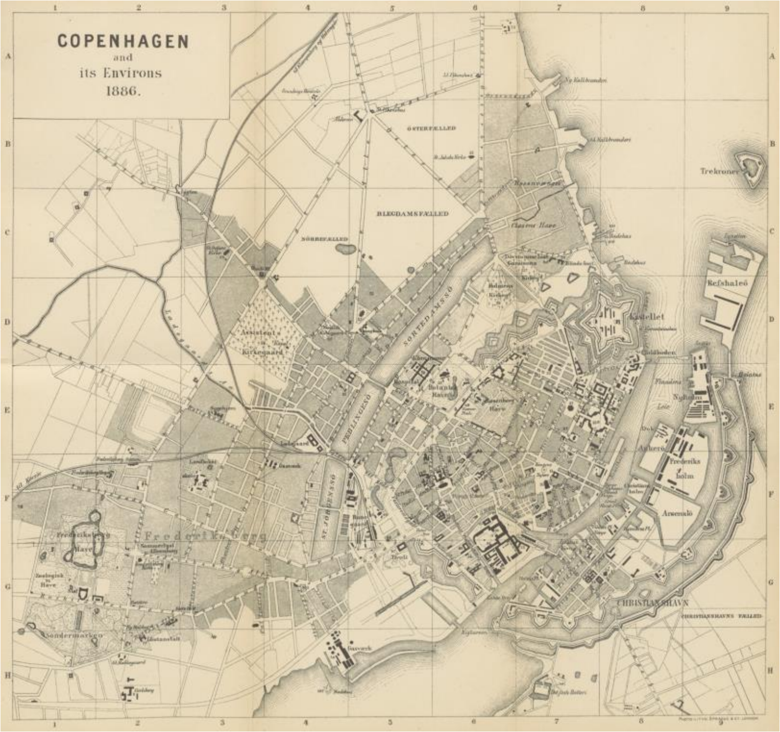

Figure 1. Map of Copenhagen at the time of Inge Lehmann's birth. She grew up in Østerbro, the area North of Sortedams Sø.

Inge Lehmann

Throughout the history of mankind, thoughts on the composition of the inner earth have varied immensely. In the late 17th century, Edmond Halley proposed that the Earth was hollow. This idea was already present in much folklore but was disproven definitively by Charles Hutton in 1778 (Griffin, 2012). The works of Athansius Kircher in *Mundus Subterraneus* predicted that the Earth had a central fire and a network of smaller lava-filled chambers, underground lakes and fountains, as well as passages and channels where water and lava circulate and occasionally come to the surface as springs or volcanoes (Griffin, 2012). Thomas Burnet proposed that the Earth was both like an egg, with the crust being the shell and the watery interior abyss being the yolk, and like an onion, with orbits of shells (Griffin, 2012).

Although it is a science fiction novel, many ideas about the Earth's interior came from Jules Verne's *Journey to the Center of the Earth*. He makes it seem as though it is possible to travel to the Earth's deep interior through an extinct volcanic crater (Debus, 2006). While the characters in the book believed that the centre of the Earth was very hot (specifically 195,000˚C) they explain that they won't experience elevated temperatures as they approach the base of the Earth's crust, due to Humphry Davy's geochemistry and chemical oxidation theory of volcanic eruption. He thought that metallic veins existed in reactive alkaline cores under volcanoes, which would react violently in a volcanic eruption when in contact with water (Debus, 2006). This theory also complies with the idea of a steadily cooling Earth.

Later, Richard Dixon Oldham analyzed seismic waves from several earthquakes, which allowed him to conclude that the Earth has a large, liquid, metallic core. Geophysicists at this time also believed that each layer of the inner Earth was separated by abrupt density changes that they called "discontinuities" (Davidson, 1936). This was the theory that had been upheld until the time of Inge Lehmann's birth.

Early Life and Aspirations

Inge Lehmann was a Danish mathematician and scientist, responsible for making one of the most ground-breaking discoveries in the field of seismology and geophysics (Hjortenberg, 2009). Her upbringing and primary schooling sparked her passion for science and aided her in avoiding much of the adversity and prejudice that numerous female scientists in the early 20th century endured. Many of Lehmann's early life experiences and encounters led her to her eventual career as a seismologist and served as inspiration for her scientific discoveries (Carlowicz, 2018).

Inge Lehmann was born to Alfred Georg Ludvig Lehmann and Ida Sophie Tørsleff on May 13, 1888, and was raised in Østerbro, a relatively wealthy district just north of central Copenhagen (see Figure 1) (Rafferty, 2015). She came into a family of fairly high standing; many of her ancestors were priests, barristers, politicians, and engineers (Bolt, 1997). Her great-grandfather was the Governor of the National Bank, her grandfather laid down the first Danish telegraph line, and her father was the first professor of experimental psychology at Copenhagen University (American Museum of Natural History, n.d.). Several of the women in her family were unconventionally prominent as well; her cousin Anne Lisbeth Groes became Danish Minister of Trade and Industry, and both Anne and her mother, Singe Andrea Tørsleff, were active advocates for women's rights (Rafferty, 2015).

At this point in time, Denmark, and Copenhagen in particular, was known for being progressive, especially when it came to women's rights. The Dansk Kvindesamfund (Danish Women's Society), was founded in 1871 and worked to grant women rights that would improve their educational, social, and financial position. Through resilience and determination, they made many advances, securing more women's rights than most other parts of the world at this time (Bolt, 1997). In 1875, women won the right of admission to university, allowing them to compete with men for high-level jobs and increase their status and pay (Fiig and Siim, 2007). This also enabled them to contribute to academic fields, from which they had previously been omitted. Women were granted the right to vote on June 5, 1915, when the 1849 Danish Constitution was largely revised (Danish Cultural Heritage, n.d.). With newly strengthened political citizenship, over 12,000 Danish women marched to Amalienborg Palace, where they handed to King Christian XI a letter notably missing the word "thank" (Fiig and Siim, 2007). This movement marked the end of the fight for parliamentary enfranchisement and reinforced that they did not owe gratitude for their right to vote, as voting was not a gift but their civil right. Growing up, Lehmann was unaware of these political proceedings, however she benefited greatly from the developing egalitarianism that ensued.

When Lehmann was growing up in Denmark, schools were not run by the government; liberalization and privatization characterized their education system. This meant that whomever chose to open a school had the right to teach the students in the way they best saw fit, and wealthier members of society were expected to provide their children with an education that would suit their future needs (Larsen, 2018). Lehmann had the fortune of attending a unique private school founded and run by Hanna Adler, an aunt of Niels Bohr (Hjortenberg, 2009). The school was called Fællesskolen, meaning "shared school", and it was the first coeducational school in Denmark (Lehmann, 1987). At Adler's school, no differentiation based on sex or social status was tolerated and students were taught all subjects, including needlework and rugby, regardless of gender (Hjortenberg, 2009). Lehmann stood out from her classmates academically, and her math teacher often gave her special problems to solve individually (Bolt, 1997). Her parents disapproved of this, viewing her grades as proof she was not smart enough for extra work. Lehmann later remarked however, "They could not be expected to understand, I suppose, that I should have been stronger if I had not been so bored with school work" (Lehmann, 1987). It was during these early years that Lehmann discovered her aptitude for mathematics, her avidity for science, and her appreciation for impartiality. Decades later, she wrote in an obituary for Adler "we were not burdened by the prejudice which makes life difficult for so many people" (Carlowicz, 2018). Inge Lehmann's schooling at Fællesskolen was indubitably a major contributor to her abilities, ambition, and sense of equality that continued to guide her throughout her life.

In July 1906, she passed the university entrance exam with distinction of the first class and entered the University of Copenhagen to study mathematics (Carlowicz, 2018). Unbeknownst to her at the time, this was a great accomplishment as, despite the fact that they now had the right, many women still struggled to obtain admission to universities (Watts, 2013). Transitioning from her open-minded Fællesskolen was difficult, for Lehmann soon realized that not many people were of the opinion that everyone should be treated equally, regardless of sex or social standing. Looking back, she has recalled that because "no difference between the intellect of boys and girls was recognized," at Adler's school, it "brought some disappointment later in life when [she] had to recognize that was not the general attitude" (Bolt, 1997). She continued her studies at Newnham College in Cambridge, then returned home to Copenhagen due to stress and exhaustion from overworking (Carlowicz, 2018). She worked at an actuary's office for several years, gaining considerable training in computations that would prove to be useful years later (Rafferty, 2015). In 1920 she graduated from the University of Copenhagen, having completed her candidata magisterii degree in physical science and mathematics (Hjortenberg, 2009).

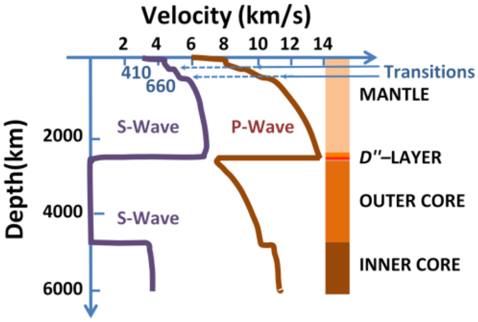

Figure 2. A comparison of the velocities of S- and P-seismic waves through the layers of the inner Earth.

Seismography

Although Inge Lehmann had only experienced a distant earthquake at the age of 15 or 16, her memory of the floor moving in a slow and shaky way, and the fact that the epicentre to this earthquake was never found incited her curiosity and interest in the field of seismology (Lehmann, 1987). She entered this field and found her passion for it in 1925 when she began working for Niels Erik Nörlund, the director of Gradmaalingen, a geodetic institution responsible for measuring the meridian arc in Denmark (Lehmann, 1987). N. E. Nörlund was very attentive to details and demanded that they use the best existing seismographs in ideal locations (Lehmann, 1987).

"I began to do seismic work and had some extremely interesting years in which I and three young men who had never seen a seismograph before were active installing Wiechert, Galitzin-Wilip and Milne-Shaw seismographs in Copenhagen and also helping to prepare the Greenland installations." – Inge Lehmann (Bolt, 1997)

Through her assistance with this endeavour, she learned that the earth's interior composition could be determined through the observation of seismograms and was immediately enthralled (Lehmann, 1987). This newfound interest led her to study seismology independently, and in the summer of 1927, she had the opportunity to visit several seismic stations around Europe (Lehmann, 1987). One notable trip was a month-long stay with Professor Beno Gutenberg in Darmstadt, where he gave her much of his invaluable time and help (Lehmann, 1987). He had previously used recordings of distant earthquakes to estimate the depth of Earth's core to be 2900 km, which is very close to the current estimate of 2885.3 km (Bolt, 1997). During her time abroad, she was also permitted to attend a meeting of the International Geodetic and Geophysical Union, which was unusual for someone of her position. There they discussed seismic curves with little success; the time curves calculated by each of the seismologists were different, possibly due to the inaccuracy of observations (Lehmann, 1987). This disparity motivated her future study of the accuracy of the seismograph stations. She determined that, although the stations were not perfectly accurate to begin with, there were other problems. The seismograph stations were all located within relative proximity to one another, so it was difficult to acquire an accurate overall picture (Lehmann, 1987). While this made it challenging to accurately determine travel times, it did give the benefit that the slope of the time curves could be determined, especially if the epicentre was a fair distance from the group of seismic stations (Lehmann, 1987).

After having passed an examination in geodesy at the University of Copenhagen, Inge Lehmann served as the chief of the seismological department of the Royal Danish Geodetic Institute from 1928 to 1953 (Bolt, 1997). In this role, she maintained the three seismographic observatories in Denmark and was responsible for instructing and communicating with the caretakers assigned to each station (Bolt, 1997). It was also her duty to interpret the seismograms and publish each station's measurements, a task that developed her unequalled knowledge of seismic wave patterns. Although she was given very little assistance with her duties and was discouraged from doing her own research, she did not let this stop her and would conduct her scientific work during her little spare time (Carlowicz, 2018).

The Discovery

There are two main types of seismic waves that travel through the Earth as a result of earthquakes: P-waves and S-waves. P-waves, also called primary waves or compressional waves, move in a back-and-forth motion in the direction of propagation (Ammon, 2019). They can travel through solids and liquids at speeds up to 14 kilometres per second, which is faster than other types of waves (Ammon, 2019). S-waves, also called secondary waves or shear waves, travel like elastic waves and arrive at seismic recording stations later, due to their slower velocity of up to 8 kilometres per second (see Figure 2) (Ammon, 2019). They can only move through solids, a key characteristic that allows seismologists to determine whether layers of the earth are solid or liquid. For example, if P-waves are recorded but S-waves are not, this means that there must be a layer of liquid between the epicentre of the earthquake and the seismic recording station. The way these waves are refracted is essential to determining earthquake epicentres and the boundaries between layers of the inner Earth (Ammon, 2019).

Given her experience with seismic waves, it seems as though if anyone were to discover the truth about the Earth's core using seismographs and geophysics, it would be Inge Lehmann. The discovery started in 1929, when an earthquake near New Zealand generated seismic waves that were detected by the seismographs of the Royal Danish Geodetic Institute. Lehmann observed this seismic data and noticed that the waves did not propagate through the Earth as predicted by the accepted theory at the time (American Museum of Natural History, n.d.). This theory, proposed by Richard Dixon Oldham, postulated that the Earth's interior was comprised of a large liquid core, surrounded by a viscous mantle, which was covered by a solid crust (Encyclopaedia Britannica, 1998). The results seen by Lehmann on the seismograms could not be explained using Oldham's theory. Several P-waves were recorded by seismographs located in what is known as the 'shadow zone': a region where P-waves would not have appeared if the core was one molten layer (see Figure 3). This inconsistency with the current theory prompted Lehmann to hypothesize that the waves had traveled into the core some distance before being deflected by a previously unknown boundary. Lehmann wrote in her biographical notes, 'The most important result arrived at was that the presence of a distinct inner core was required for the interpretation of some phases recorded at great epicentral distances' (Bolt, 1997).

Lehmann's deduction was based on her keen examination and analysis of the waveforms recorded and could have easily been overlooked by someone who lacked her experience. At this time, scientific instruments and methods of recording data were rarely standardized, making it extremely difficult to compare data collected at more than one station (Lehmann, 1987). After years of interpreting the readings from the three seismographs under her care, Lehmann had developed a remarkable ability to visually calibrate data recorded on different seismograms. By eye, she would correlate analogous waveforms, allowing phases to be matched clearly and minimizing the readout error on wave arrival times. Her interpretation of this data was the foundation of a 1936 paper in which she theorized that Earth's centre consisted of two parts: a solid inner core surrounded by a liquid outer core, separated by what has come to be called the Lehmann Discontinuity (Carlowicz, 2018).

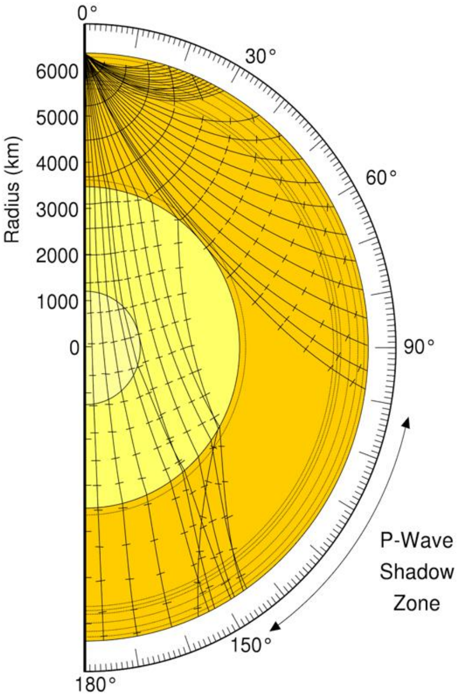

Figure 3. P-wave shadow zone assuming Lehmann's postulations regarding the Earth's interior composition. This shadow zone is smaller than Oldham's theory would have predicted.

Later Life

Inge Lehmann's contributions to the world of seismology and geophysics did not end with the publication of her most famous finding; in fact, the majority of her work was done afterwards (Bolt, 1997). While at the Danish Geodetic Institution she wrote and published 35 papers, the contents of which extended far beyond her discovery of the inner core (American Museum of Natural History, n.d.). Her 1952 paper on cyclones and the relationship between microseismic events, which she had experienced in Greenland, helps us to predict these deadly storms before they occur (Hjortenberg, 2009). She played a large role in the development of the European Seismological Commission and in the foundation of the International Seismological Centre. Even after her retirement in 1953 from the Royal Danish Geodetic Institute, she continued to work from her home in Denmark, as well as overseas in the US and Canada (Hjortenberg, 2009). Lehmann was an active participant in the International Union of Geodesy and Geophysics meetings, especially when it came to discussions of time curves, for which she had great enthusiasm. A seismic array station on the Greenland Ice Cap was named The Inge Lehmann Station in her honour and was used for Blue Ice: a cooperative project between Denmark and the US (Hjortenberg, 2009). Lehmann wrote her last paper, *Seismology in the days of old,* in 1987 at the age of 99 and died peacefully on February 21, 1993 at the age of 104 (Rafferty, 2015).

Before passing, Lehmann donated the entirety of her estate to a fund that offers a travel scholarship to either a psychologist or geophysicist. The fund is now managed by the Danish Academy of Sciences and Letters (Hjortenberg, 2009). In 1996, a Danish children's book was written about her by Jensen and Pedersen after an earthquake had recently occurred in Copenhagen. The book described how Inge Lehmann found the earthquake wonderful, even though it may have been frightening (Hjortenberg, 2009). Also, in 1996, the American Geophysical Union presented for the first time the Inge Lehmann Medal, awarded every other year for 'outstanding contributions towards the understanding of the structure, composition and/or dynamics of the Earth's mantle and core' (Hjortenberg, 2009).

Modern Perspectives on the Inner Earth

The theory of the presence of a solid inner core that Inge Lehmann proposed still holds today, and it was in fact confirmed by Freeman Gilbert and Adam M. Dziewonski in 1970 (Rousseau, 2013). In 1993, it had been established that the inner core was crystalline (Anderson, 2002). We now know not only that the Earth's inner core is solid and crystalline, but we also know its composition and the events that led to its formation.

An Explanation of the Theory

If the interior of the Earth was homogenous, seismic waves that result from earthquakes would travel in straight lines through the Earth at a constant speed of approximately 10 kilometres per second (Rousseau, 2013). This is not observed in practice, which means that the Earth's interior must not be uniform.

Inge Lehmann proposed that there were three distinct areas in the Earth's interior: the mantle, which can be divided into the upper mantle and the mantle, the outer core and the inner core (see Figure 4) (Rousseau, 2013). Boundaries between these areas cause seismic waves travelling through the Earth's interior to change speed and be refracted based on differences in density between the media (Rousseau, 2013). The paths of different waves differ depending on the angle at which they depart; for example, some waves may have a straight path if they pass no boundaries between layers of the Earth's interior, while others may be reflected or refracted multiple times. The paths of waves will bend inwards when moving from the mantle to the outer core, then inwards again when moving into the inner core, where waves also move at a higher speed (Rousseau, 2013). The opposite is true when the waves move in the other direction.

Seismic waves continue to be a primary method of investigation into the composition and properties of the inner Earth. They can also be used to determine the epicentre of an earthquake (Rousseau, 2013). Since the approximate speeds and reflection and refraction patterns observed in each layer of the inner Earth are now known, they can be used to calculate the distance to the epicentre from several seismic stations (Rousseau, 2013).

Earth's Beginnings

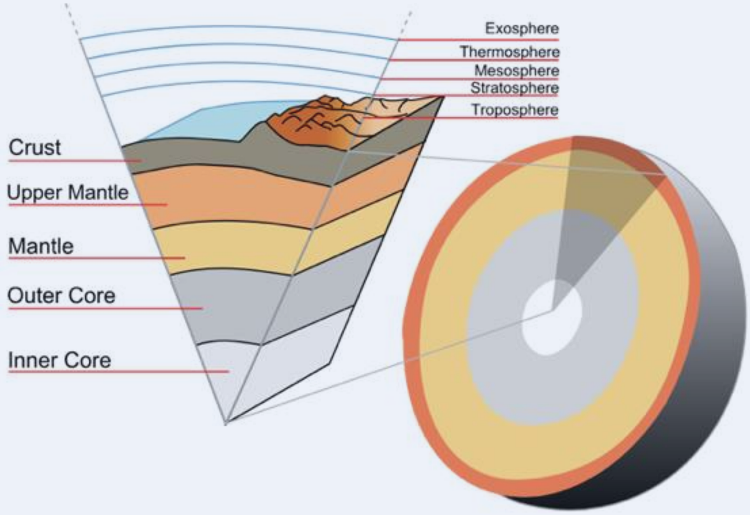

Figure 4. A cross-sectional diagram of the Earth's interior, demonstrating the layers of the inner Earth as we know them today.

The Earth, along with the rest of our solar system, formed during the Big Bang, but the solid inner core did not form until later; it was likely formed 1-1.5 billion years ago (University of Liverpool, 2015). Researchers have discovered that there was a sharp increase in the strength of Earth's magnetic field at this point, which likely indicates that that solid iron was present in the Earth's centre (University of Liverpool, 2015). The solid inner core was formed by the outer molten core cooling, which it has gradually been doing at a very slow rate since the creation of our planet (University of Liverpool, 2015). The core solidifies from the centre outwards, and since increasing pressure results in a higher melting temperature, and since accretion can cause increases in pressure, the core can pressure-freeze when the Earth reaches a certain size (Anderson, 2002). Earth's magnetic field comes from the motion of the liquid iron alloy in Earth's outer core, so when the iron started to "freeze" and become the inner core, the magnetic field experienced a sharp increase in strength due to the greater relative proportion of buoyant, lighter, non-metallic elements in the outer core (University of Liverpool, 2015). A growing inner core is necessary to fuel the dynamo that exists today, and the inner core continues to grow at a rate of approximately one millimetre per year (Anderson, 2002).

The Composition

The inner Earth has four main divisions. The outermost layer is the crust, which varies in thickness between 25 to 70 kilometres under continents and from about 5 to 10 kilometres under oceans (Andrei., 2016). Beneath the crust is the mantle, which contains dense silicate rocks and extends to a depth of approximately 2900 kilometres (Andrei., 2016). The mantle can also be broken up into two layers: the upper and lower mantle. Even deeper is the outer core, which extends from about 2900 to 5150 kilometres into the Earth (Andrei., 2016). Finally, the inner core spans the innermost part of the earth from 5150 to 6276 kilometres (Andrei., 2016).

The Earth's core is mainly made of iron (~85%), along with nickel (~5%) and other lighter elements including oxygen, carbon, sulfur and silicon (Badro et al., 2014). Of these, silicon, sulfur and carbon are known to be soluble in iron in all conditions, while oxygen is less soluble at low pressures (Badro et al., 2014). The speed at which seismic waves travel through the core of the Earth is proof that it must be lighter than pure iron (Badro et al., 2014). The inner core and outer core have a density jump of approximately 4.5%, which is explained in part by the fact that the inner core is solid while the outer core is liquid, and partially by the presence of more light elements in the outer core than the inner core (Badro et al., 2014). Because of the outer core's low viscosity and inability to transmit shear waves, it is usually considered to be completely molten (Anderson, 2002).

Another interesting aspect of the Earth's inner core is its anisotropy. Anisotropy is the quality of exhibiting a property that has different values when measured along different axes (Song, 2015). The inner core can be further divided into the inner-inner core (IIC) and the outer-inner core (OIC), each of which comprises about half the radius of the inner core. This division is based on their anisotropic properties. The outermost part of the inner core is almost isotropic, but compressional waves, or P waves, have variations in their speed according to their orientation in the IIC (Wang and Song, 2018). Specifically, seismic waves travel slowest when propagating along a path that is approximately 45° from the equatorial plane in the IIC (Wang and Song, 2018). The variation of seismic wave speeds due to orientation can be greater than variations caused by changes in temperature and composition (Anderson, 2002). Furthermore, seismic attenuation, or the energy loss experienced by seismic waves as they propagate through the Earth, differs between the two layers of the inner core; as the depth into the inner core increases, seismic attenuation decreases, especially within 600 kilometres of the centre of the Earth (Wang and Song, 2018). The near-equatorial anisotropy of the IIC and the North-South anisotropy if the OIC can be explained by the preferred alignment of anisotropic iron crystals, which may have been created during the solidification of the core or from solid-state convective flow within the inner core (Wang and Song, 2018).

Inge Lehmann made many contributions to our current knowledge of seismology and geophysics. Her discoveries are the basis for our modern understanding, and her resilience and passion for science and discovery made her stand out as one of the most notable women in scientific history.

Chapter 2: Influence of Ancient Society and Mythology on Science

For as long as we know, humans have been trying to understand the world that we live in. In early times, a primary resource for this understanding came from religious texts and mythology; if we could not explain something about the world, there would be a story or legend that could explain it adequately. We now know that many of these myths are not true based on scientific evidence. However, mythology has had an enormous impact on science. Not only has it provided preliminary theories and explanations for processes and features of the world, but it provided an interest in understanding why things are the way they are and sparked a passion for discovery. This ultimately became what we know as science today. It is clear that we have always been searching for explanations about what we observe around us, and only the way we reach these explanations has changed. This chapter will explore the connections between mythology and science. Particularly, it will focus on the lost city of Atlantis, the flood myth, the development of the fields of geology and paleontology, and the origins and explanations of asbestos.

Finding Atlantis

Origin of the Atlantis Myth

The myth of Atlantis is a story that has fascinated humanity for thousands of years. It describes a tale of how a once magnificent city, home to a god-like civilization, met its demise through a mysterious and tragic plunge into the ocean (Gill, 1980). Though a famous narrative in popular culture, not many people know of its origins: *Timaeus* and *Critias*, two books written by the ancient Greek philosopher Plato (ca. 429 - 347 B.C) (Gill, 1980). Plato lived in ancient Greece, a civilization that bordered the Mediterranean Sea, which led out into the Atlantic Ocean through the pillars of Heracles (Gill, 1980). Beyond those pillars, according to Plato's text, is where Atlantis once stood, acting as the connection towards the "true ocean" and "true continent" (Figure 2.1) (Gill, 1980). Atlantis is described as a great naval power with extensive influence that narrowly conquered all enemy countries in one fell swoop (Gill, 1980). The narrator then goes to praise Atlantis to be the symbol of military power, courage, and virtue. However, the Atlanteans lost a war to the Athenians, and the other countries were able to regain control of their own land. He then continued to state that, tragically, within the span of a day, violent earthquakes and floods caused Atlantis to sink into the ocean (Gill, 1980). The remains of Atlantis consist of all but a shoal of mud that prevents people from going past the pillars of Heracles, towards the true continent (Gill, 1980).

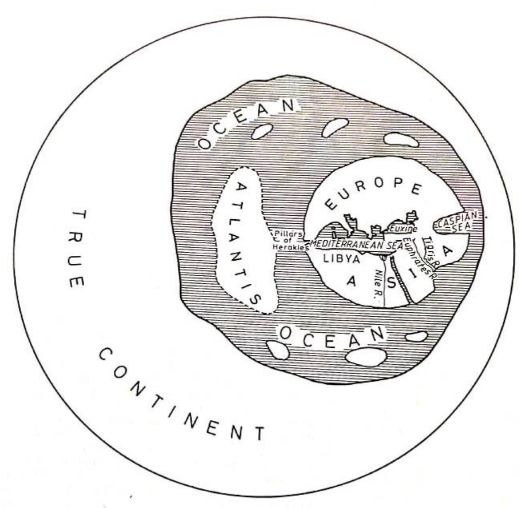

Figure 2.1. Plato's view of the world in relation to Atlantis. The world known to the ancient Greeks were surrounded by an ocean, which is bordered by the true continent (Gill, 1980).

After this introduction, Plato then goes to describe the city of Atlantis in detail. In the beginning, the only inhabitants of Atlantis were a couple with a daughter who was a beautiful maiden (Plato, 2008). Poseidon, the God of the Sea, fell in love with her and together they birthed five sons who later became the kings of Atlantis (Waterfield, 2008). Poseidon reshaped the island into rings of alternating land and water, with the center full of the most fertile land (Figure 2.2) (Waterfield, 2008). On this land, Poseidon created two springs, one hot and one cold, that allowed many different fruit and vegetables to grow from the fertile soil (Waterfield, 2008). Aside from this treasure, the island was home to countless exotic creatures, the soil was littered with precious gems, and the country grew rich trading with neighbouring nations (Waterfield, 2008). Within its citadel, Atlantis also had a magnificent palace with a temple made of gold and silver and a roof of ivory, dedicated to Poseidon (Waterfield, 2008). In all other parts of the palace, the walls, pillars, and floor were coated with orichalcum (Waterfield, 2008).

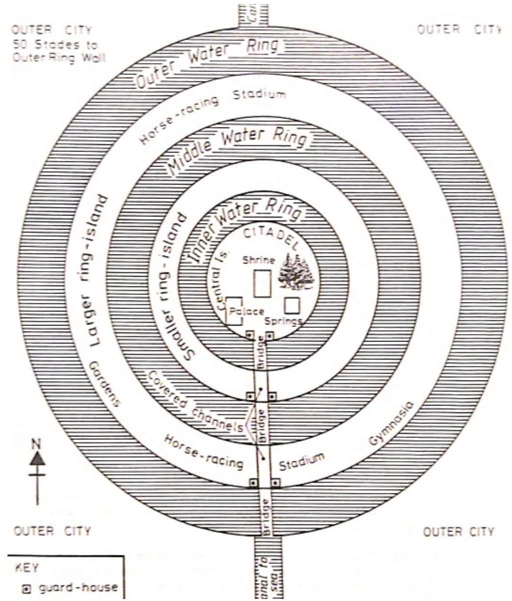

Figure 2.2. Illustration of Plato's description of Atlantis' central city, which is surrounded by rings of land and water.

The rest of Atlantis was a level plain surrounded by impressive mountains (Waterfield, 2008). The plains were used for horse tracks and stadiums, while the mountains were home to many wealthy citizens and wild animals (Waterfield, 2008). Soon, the country grew to great success under the ruling of powerful and fair kings (Waterfield, 2008). And soon after, Plato's text abruptly ends.

Interpretations of Plato's Story

Even during Plato's time, scholars debated whether his accounts were factual or fabrications. Aristotle, one of Plato's pupils, assumed that Atlantis is fictitious and served as a political allegory (Gill, 1980). Aristotle pointed out that, even within Plato's text, there were explicit parallels drawn between Atlantis and Plato's concept of an "ideal state" (Gill, 1980). On the other hand, geographers at that time like Posidonous and Strabos regarded the story of Atlantis as factual (Gill, 1980). More recent theories suggest that the Atlanteans were actually ancient Minoans as they shared similar lifestyle (Gill, 1980). Others casted doubt on this theory, arguing that the chronology did not match. Nonetheless, clearly humanity has been fascinated by the legend of Atlantis since the age of ancient Greece. The obsession with the search for Atlantis had undoubtedly incentivized many scientists to develop new theories and understandings of the possibility for Atlantis to exist or for it to just simply be a legend.

Lemuria

The search for Atlantis began around the time when Darwin arrived at his conclusions on the evolution of species, but before Wegener could propose Pangaea. A geologist named Phillip Sclater wrote an article about the evidence for a land bridge connecting Asia and Africa (Sclater, 1864). The Bering Strait land bridge, for example, was a strip of land allowing the passage of humans to North America from Eurasia (National Park Service, 2018). Sclater proposed a new land bridge, naming this land "Lemuria" after the Lemur fossils he found scattered over both Africa and Asia. These fossils, he postulated, would be great evidence supporting his theory of land bridges and a once connected world (Sclater, 1864). The first piece of evidence Sclater provided was that similar groups of fauna and flora must occupy similar geographical areas (Sclater, 1864). He pointed out that this is a constant rule and that if there existed land far apart that was similar ecologically, one must come up with another rule to satisfy the aforementioned given rule. This makes logical sense, in that a palm tree for example, will not grow in the Arctic, but only in certain warm tropical climates. Madagascar was one of these exceptions that he decided must satisfy the rule (Sclater, 1864). It would make sense that Madagascar, located close to Africa (Figure 2.3), would represent similar fauna and flora to those of African origin. This, however, is not the case. In fact, with regards to the study species, the lemur, there are approximately eight unique types located solely on Madagascar, and not on either Africa nor India (Sclater, 1864). Specifically, these lemurs had a unique dental structure not present in the lemurs in Africa and India. This, along with other clues involving species located in Madagascar and not Africa or vice versa, led Sclater to a multitude of conclusions. He decided that it is probable that Madagascar was never a part of Africa. However, he also mentioned that the presence of lemurs on both land masses suggests that some of Africa must have once been part of Madagascar (Sclater, 1864). He also concluded that Madagascar and some surrounding islands, due to their strange collection of organisms, must have remained separated from other land masses for a long period of time (Sclater, 1864). Finally, he reached the conclusion that there must have existed some sort of landform connecting Madagascar to India which would allow for the similarities to occur between these locations. He proposed that this land eventually broke off into many islands, of which some connected with Africa, while some remain islands today. He ended by exclaiming that this old landmass should be called Lemuria (Sclater, 1864).

Figure 2.3. A map showing the distance and relationship between Africa and Madagascar

Is Atlantis a Land Bridge?

The development of the concept of the land bridge of Lemuria led to many conclusions regarding the mythological land of Atlantis. Not long after Sclater proposed Lemuria, two books were written by a scientist named William Scott-Elliot; *The Story of Atlantis* and *The Lost Lemuria.* In this, Elliot reminds readers that it is generally recognized that the land that we walk on was once seafloor while the current seafloor was once continental (Elliot, 1904). It was a generally accepted theory at the time that land masses sank and rose, allowing the concept of land bridges to be fully supported. Using this evidence, Elliot supports the claim that Atlantis may have been as Lemuria was: a sunken land bridge connecting most of the world together. Elliot provides five pieces of evidence clearly proving that Atlantis must have existed. The first is that with the mapping of the sea floor by American and British gunboats, a great ridge in the mid-Atlantic was found. Surrounding this ridge is much volcanic debris. Conclusively, this is thought to have been a sunken island with volcanoes. A man named Starkie Gardner generated the opinion that this must be sufficient evidence for a land connecting the British islands to a larger continent and that the islands are simply the highest elevation points on this now sunken continent. Secondly, there are many locations on varying continents where similar fauna and flora are to be found. The general theory was that all plants and animals originated in one location. If this was to be so, how was it that fossils of similar species were to be found on multiple different continents? His explanation was that there must have existed some landform which brought together all of these separate continents. Then, Elliot moves onto the differences in human complexion. On Atlantis, it was thought that men of every colour lived together in peace. This would then explain how Native Americans have such a wide range of complexion if Atlantis were to have existed and connected different regions. Religion too provides great evidence for a once connected continent. When voyaging to different parts of the world, the Spanish found that the similarities between new religions and their own were striking. In fact, the religions were almost identical. Natives worshiped crosses and feared a serpent creature while *God* (translated) was a common name for their deity. Even baptism was practiced by many nations. There existed a long list of puzzling similarities between religions found across oceans. Finally, Elliot summarizes observations and recordings from ancient writings. He refers to Aelian, who wrote about a "great continent" across the ocean, and Marcellus, who recorded the idea of islands where natives all had a recollection of a greater island that once governed them all. He finally directly references Plato's Atlantis story, stating records of an island located through the pillars of Hercules which contained a large civilization. All of this evidence clearly points to a larger continent which once connected lands that has since been separated. He explains that this could logically be Atlantis since all of his evidence appears to point to this conclusion. However, was this a conclusion that was drawn from unbiased evidence or was it one that was fabricated intentionally by finding evidence with the purpose of proving Atlantis's existence? Eventually, Elliot concludes that Atlantis has since sunk into the ocean during a "Great Submergence". With the knowledge of Lemuria and land bridges at the time, this is a completely logical conclusion. Clearly, Atlantis was once there and has since become the ocean floor. This would be difficult to prove in that time, as undersea exploration did not reach a substantial level until the 1960s (PBS, 1998). Elliot further attempts to approximate the location of Atlantis by providing maps of the world over the course of 900,000 years. The first map shows where Atlantis may have lain 1 million years ago, based on Plato's story and the understanding at the time of land bridges and sinking continents. As a key, all of the following maps show dry land in red, the remains of Lemuria in blue and an outline of the world as it is now in black.

In the first map (Figure 2.4), Atlantis was thought to be a great continent, connecting many lands together and encompassing most of the world. Fragments of Lemuria, as well as a Hyperborean continent (a large Northern continent in Greek mythology (Shnirelman, 2014)) are shown in blue. This map represents when Atlantis was at its peak before submerging into the sea.

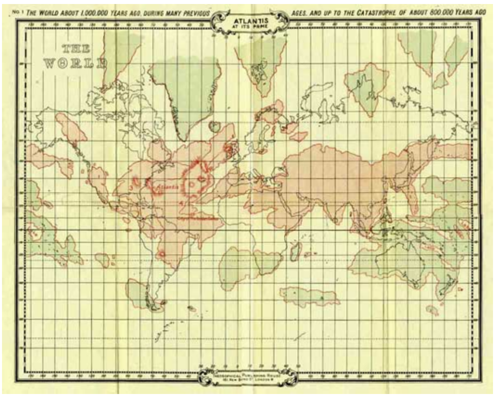

Figure 2.4. The first map made by Elliot showing Atlantis at its prime

The second map (Figure 2.5) shows the world after the "Great Submergence" thought to have occurred 800,000 years ago and separated Atlantis from other continents. Atlantis has greatly decreased in size and is now separated from North America. Lemuria is still shown in blue but the area is substantially smaller.

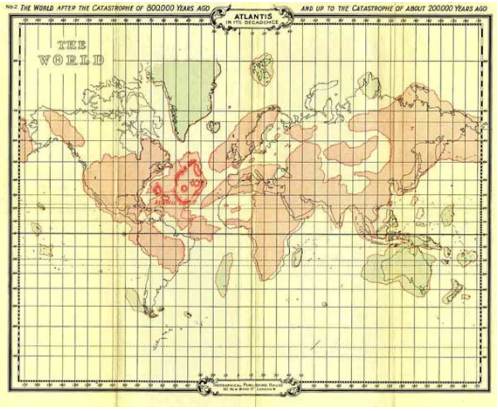

Figure 2.5. The second map showing Atlantis after its fall

The third map (Figure 2.6) shows the world after yet another catastrophe occurring 200,000 years ago. Atlantis has now split in two, resulting in islands Ruta and Daitya. It appears that Egypt has submerged and other small changes are evident, but relatively unimportant.

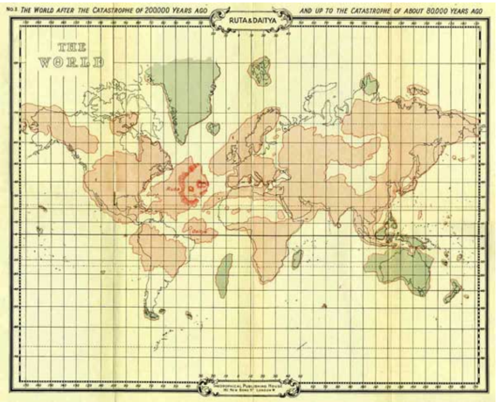

Figure 2.6. The third map after Atlantis split in two.

The fourth and final map (Figure 2.7) shows the world after a large and important event 80,000 years ago. It is unclear what this event was or thought to be, but its consequences are clear in the map. Daitya has sunk almost completely while Ruta's remains consist only of small islands, including one named Poseidonis. This island finally sank in 9564 BC. At this time, the Sahara desert was on the bottom of the ocean.

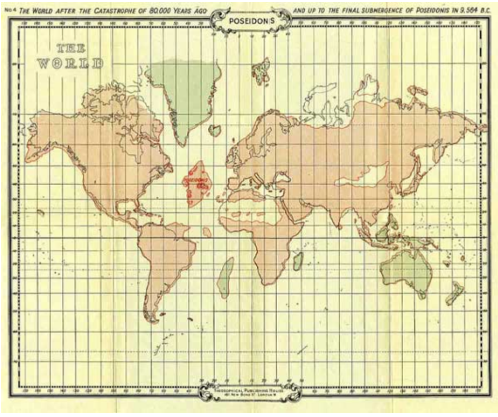

Figure 2.7. The fourth map after most of Atlantis has sunk.

These conclusions provided seemingly strong evidence for Atlantis being a potential land bridge, connecting much of the world together and having sunk in the recent past (Elliot, 1896). Using the evidence which was considered to be accurate in the 1800s, these conclusions have no repercussions or imperfections.

Ignatius Donnelly

Ignatius Donnelly (1831-1901), born in Philadelphia, served as a congressman and studied law (Minnesota Legislative Reference Library, n.d). He appeared to be fascinated with mythological stories and published several books dedicated to providing evidence to prove that those myths were true (Minnesota Legislative Reference Library, n.d). Of course, he was inspired by Plato's accounts of Atlantis and set out to find evidence of its existence (Donnelly, 1882). Part of his theories were also inspired by Sclater's Lemuria and the land bridge concept (Donnelly, 1882). The fruition of his work was a book he published in 1882 titled *Atlantis: The Antediluvian World.*

During the time that Donnelly wrote and published his book, the world of geology was influenced by the land bridge theory proposed by Sclater and Charles Lyell's *Principles of Geology*, as Donnelly had made citations to both works. Within the first few pages of the text, it was clear that Donnelly thought Atlantis was indisputably real. He even stated that the stories of the Garden of Eden (Christian), Asgard (Norse), and the Elysian Fields (Greek) were all inspired by this great civilization. As Plato referred to Atlantis as having fertile land that grew a great variety of vegetation and supported many exotic animals, Donnelly thought that Atlantis is the perfect inspiration for these mythical gardens. The first evidence that Donnelly explicitly used was that the sinking of Atlantis is the origin of the flood myths found through many different religious texts, such as the Genesis. He argues that the similar mutual accounts indicate that such an event had occurred, in which land had sank below the sea. Donnelly was also a supporter of the land bridge theory. When the myth stated that Atlantis "extends as far as the pillars of Heracles" and when Donnelly noted the similar language structures between Western and Eastern countries, he theorized that Atlantis might have once been a land bridge that connected America and Europe. His argument was further supported by how Plato mentioned Atlantis as being the bridge to the "true continent".

Donnelly then sought to prove that Earth is capable of such instantaneous and dramatic changes. He first used the volcanic eruption in Iceland in 1783 as an example, where a single eruption was able to create a new island with high, soaring cliffs. Before a day had elapsed, the island had sunken again, leaving only a reef of rocks breaking the surface of the ocean. Donnelly (1882) draws the parallel between this event and its striking similarities to the muddy shoal that was said to have formed when Atlantis sunk. Moreover, he wanted to demonstrate that the catastrophe that befell Atlantis was entirely plausible.

Perhaps one of the most seemingly convincing evidence that Donnelly provided for the possibility of the sinking of Lemuria and Atlantis is through the analysis of the geology in Pennsylvania. He stated that the alternating strata between coal and slate in Pennsylvania is an indication of repetitive rising and lowering sea levels (Donnelly, 1882). The coal layers were deposited when land was above sea level, where the carbon from terrestrial vegetation were deposited and eventually formed coal. On the other hand, the slate layers, which were originally shale, were likely deposited in a marine environment (Donnelly, 1882). This led Donnelly (1882) to hypothesize that the land was submerged underwater during certain periods of time. As this geological pattern stretched for thousands of square miles, Donnelly (1882) then argues that it is completely possible for large land masses such as Lemuria and Atlantis to experience a similar fate of sinking into the oceans. He proposes that remnants of the mountaintops in Lemuria can still be seen in the form of the Australian Archipelago. Similarly, the Dolphin's Ridge, a part of the mid-oceanic ridges, was once part of the mountains that bordered Atlantis, as mentioned in Plato's story (Donnelly, 1882).

In a sense, Donnelly's theory is not completely lacking in scientific accuracy. He was correct in noticing a pattern in marine and non-marine depositions. For instance, coal is usually deposited from peat formation, which occurs in the swampy areas of continental environments (McCabe, 1984), whereas hale is typically deposited in deep marine environments (Plummer, 2007).

However, his theories were soon disputed with the emergence of the Continental Drift theory, that offered a different explanation to many of Donnelly's arguments.

Plate Tectonics

In 1910, geologist Alfred Wegener observed the similarity of the coastlines on Brazil and Africa. Wegener, at the time, disregarded his observations since he presumed that any implications from this finding were too improbable. A year later, however, Wegener came into contact with evidence collected by previous scientists on the paleontological similarities between Brazil and Africa. From this, he began researching the possibility of continental drift (Wegener, 1924). He made further connections and published his findings in a book entitled "The Origin of Continents and Oceans". Published in 1915, Wegener proposes that the continents used to all sit together as one supercontinent. He named this continent "Pangaea" meaning "all-lands" (Weil, 1997) (Figure 2.8). At this time, many geologists were convinced that land masses could rise and sink, so naturally, Wegener's theory was not widely accepted (Saigeetha and Banyal, 2005). Another common theory at the time was the Contraction Theory (Wegener, 1924). This theory states that, like an apple rotting, the Earth shrunk as it cooled and therefore, the surface cracked. Such as there are ridges on a rotting apple, mountains also formed on Earth in a similar fashion (Wegener, 1924). This could not, however, explain the different ages of mountain ranges. So, Wegener proposed his displacement

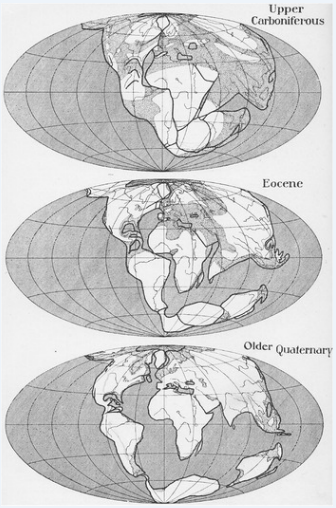

Figure 2.8. Wegener's diagram of the supercontinent Pangaea and its subsequent breakup.

theory, or as we know it, continental drift. Wegener found much evidence to back up his theory in order to convince his peers. The land bridge which was proposed in the 1800s by Sclater was to account for the similarities in fauna and flora in distant locales. Wegener, however, saw this consistency in vegetation and life as evidence for his supercontinent (Wegener, 1924). Clearly, if all of the continents were once together, fauna and flora alike could have easily traveled between what is now two largely separated continents (Wegener, 1924). As well, Wegener brought up the coal deposits in the Antarctic, which Donnelly had used to suggest evidence for the existence of Atlantis earlier. Coal requires a warm climate and vegetation to deposit (McCabe, 1985). For this to occur, the Antarctic must have once been much closer to the equator. On top of this, Wegener explained that his theory could account for ideas that past theories neglected to. With continental drift theory, Wegener proposed the idea of orogeny through the collision of plates (Wegener, 1924) instead of the previously mentioned Contraction Theory. These pieces of evidence seemed substantial, but Wegener was unable to account for other questions asked by scientists at the time. He suggested that Pangaea had originated near the South pole and had drifted upwards towards the equator (Saigeetha and Banyal, 2005). He believed that the spinning force of the Earth cause continents to drift away from the poles. However, this was proven false when others found that the force caused by the spinning Earth was not strong enough to move continents. As well, Wegener proposed that the continents moved by crashing through the seafloor (Wegener, 1924). Since Wegener was unable to provide evidence for the force that caused continents to drift, his theory, which we now know is correct, was unfortunately ignored.

It was not until the 1960s that geoscientists discovered the mechanism for the motion of drifting plates, solidifying Wegener's theory in the minds of every doubter. In the mid 1900s, a man named Harry Hess was studying and mapping out the seafloor as part of his naval duty (Weil, 1997). In 1962, Hess proposed the concept of seafloor spreading. This theory said that hot magma could push apart plates and cause them to break apart from other parts of continents. This would give a promising mechanism for Wegener's theory of continental drift (Weil, 1997).

Once Hess provided a potential and plausible mechanism for the theory, it simply needed substantial proof. This was provided later in the 1960's with the discovery of mid-oceanic ridges. These ridges held evidence for a spreading oceanic plate. On either side of the ridge were records of changing poles. The geomagnetic properties of the ocean showed bands of reversing polarity (Figure 2.9). These bands were identical on either side of the ridge, proving that the ocean floor was spreading outwards from the center of the ridge (PBS, 1998).

Using the theory of plate tectonics, we have now been able to construct more accurate maps of the past world, both recent and distant. Around the time during Elliot's first map; 1 million years ago, the world appeared as in Figure 2.10.

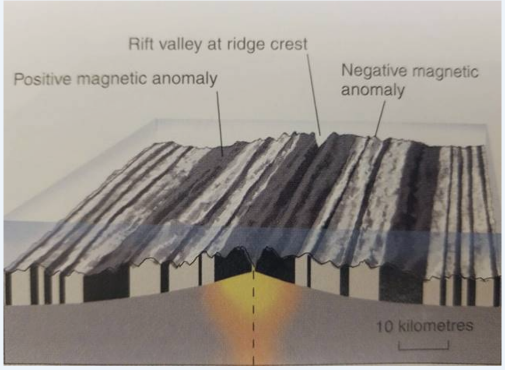

Figure 2.9. A diagram showing how magnetism changes and radiates out from mid-ocean ridges

As one can see, this is identical to our world now. The rate at which our continents shift is much slower than the rate initially thought that continents sank by. Therefore, there does not exist land bridges which have now sunk. With rising sea levels, it is possible that we will lose some landmass over the years, however it will not occur at the rate initially thought without severe consequences being recorded in other locations.

Unfortunately for Atlantis, what we know today does not merit a sinking landmass. Changing sea levels, however and the plate tectonic theory allow us to identify different mechanisms for which a landmass could have disappeared and left no trace of its people on our Earth today.

Figure 2.10. A figure showing what the world looked like 1 million years ago.

17th Century Geology and Paleontology

Paleontology as a modern field lies on the line between biology and geology, as it is the study of fossils, which are both past life, and products of geological processes. However, the nature of fossils was not always known. When the history of the emergence of any scientific field or new discovery is studied, it becomes rather apparent, that various spatial and temporal factors become of great influence. Societal hierarchies, culture, religion, wealth… All of these and more, emerge as "rate-limiting steps" to which new discoveries are made, new theories are accepted, and new fields of research are progressed. Within this section, the focus is directed towards the progression of paleontology and geology, and how they moved towards modern fields of science throughout the 17th Century.

At this point in time, the study of fossils was largely concerned with what fossils might be, as it was not generally accepted that they were past life. Much of early paleontology was concerned with determining what fossils were, and not what life or processes they may have represented. The theories ranged for fossils from giant humans, to rocks growing in solids. However, one consistent fact about most scientists of this era was belief in the flood, of which often guided their discussion and reasoning with their findings. As a result, many of the theories in 17th century paleontology were centered around proving the flood. The chapter will shed light upon the effect of religion on the science of the era, and more specifically, it will explore how the Biblical story of Noah's Ark both led to hindrances and progression of the fields. Furthermore, it will examine the works of some of the leading scientists at the time, and analyze the quality of science being done, and the effects that various temporal and spatial influences may have had on them. Finally, the chapter will conclude with some of the modern theories of Paleontology, and potential existing local evidence of the flood from Noah's Ark.

Thomas Burnet's *The Sacred Theory of Earth*

In the 1680's Thomas Burnet published his four books titled The Sacred Theory of Earth. These sparked a lively debate for the next couple of decades about the proper connection between physical hypotheses and the Genesis creation beliefs. Despite this debate about the validity of the theories present within the books, it was well agreed upon that Burnet's style made his theories seem plausible (Poole, 2008). The start of Burnet's first book describes his reasoning for investigating the origin of things. He describes in this book what he already knows about the origin of the world, since this is what he will base his further investigation on. During this section he states that the Earth arose from "Chaos" around 6000 years before the time of his writing. In this section, he states that one of his goals is to understand the changes that have already happened to earth since its creation, and the changes that are going to happen before the end of days (Burnet, 1719). Although Burnet was working inside a flawed set of assumptions his intensions were valid. He desired to infer information about previous states of the planet from the current state. He also wanted to understand enough about why the planet changed to predict what might happen next. With the biblical view of the time, one of the widely accepted events was Noah's flood from Genesis 6:9. This was one of the fixations of Burnet as it was a large geological event he could look for evidence of. The initial consideration for Burnet was the amount of water that would be necessary to cover the world everywhere in water. To determine if the was possible, Burnet made a rough estimation of the amount of water that would be necessary to completely cover the earth, and settled on around 8 times the amount of water available from the oceans (Burnet, 1719). In his writing Burnet admitted that this was a conservative estimate, and that the quantity of water necessary could be even greater. Regardless, it was his conclusion that there is nowhere near enough water on the Earth's surface to explain the Great Flood. The result of this discovery did not lead Burnet to question his beliefs concerning the flood however, instead he looked further into scripture for a possible solution to the issue of the shortage of water. Based on this he considered that water could have come from inside the earth, and from the forty days of rain that were said to have occurred. Based on observations of past rainfall records, Burnet concluded that only about one one-hundredth of the water could have come from the forty days of rain. He also rejected the theory that water had come from inside the Earth because it was contrary to experience. This led to only two options for Burnet to explore; that either there was water added to the earth from heaven for the duration of the flood, or that human accounts of the sacred history were inaccurate (Burnet, 1719). It is an interesting departure of Burnet to suggest that sacred text may not be accurate, although he doesn't go so far as to directly dispute it he does put the idea out there. Therefore, although employing some flawed assumptions, he did execute some methodology of a scientist, through calculation and experience. Motivated by the Great Flood, Burnet torqued the wheels of early geology.

Nicolas Steno's *Prodromus*

Steno, in the fields of geology and paleontology, was an extremely significant individual that made important contributions to the advancement of both fields. Like many early scientists or naturalists as they are sometimes called, Steno was interested in many aspects of the natural world, was intrigued by the unanswered questions of his time, and was influenced by his society. In addition to his contributions towards geology, Steno performed dissections of many specimens while working as a Royal Anatomist and is well known for his work in brain anatomy and discovery of the *ductus stenosis*, a salivary duct. He also, became deeply involved in religion, later working as a theologian rather than a scientist and becoming ordained a priest (Lærke and Andrault, 2018). It will become apparent, that religion and societal beliefs played a significant role in dictating the direction of Steno's life and scientific career.

In terms of his geological and paleontological contributions, Steno's famous work, *The Prodromus to a dissertation concerning solids naturally contained within solids* (referring to the English version Steno published with Henry Oldenburg in 1671) encompasses his main contributions to the fields. However, before exploring *Prodromus*, it is imperative for one to understand the stature of Science at the time. Solving the problems of Nature through scientific observation was not a commonplace practice in the mid 1600s. Contrarily, the concept that knowledge about Nature granted to man by God and protected by the Church was the general belief, and the Genesis flood was accepted as fact. In attempt to challenge the flood, Italian philosopher Giordano Bruno provided evidence of a change to land and sea distribution, and was consequentially burned at the stake (Steno, 1916).

Figure 2.16: Drawing of Nicolas Steno, renowned priest and philosopher

Onwards, despite the characteristics of his era, Steno begins *Prodromus* by addressing the question as to why we can observe marine objects at a great distance from the sea (Steno, 1671). In doing so, he is referring, of course, to fossils. At the time, the origin of fossils was unknown. Indeed, a popular belief at the time was one that coincided with Neoplatonism, it being that fossils grew in the ground to resemble the life on the Earth (Mallat, 1982). Steno never appears to take this view, he states "no Man will easily determine the place of production, who knows not the manner of production; all discoursing of the manner of production will be to no purpose, if a certain knowledge be not had of the nature of matter" (Steno, 1671). It is for this section of the book that Steno is often credited with the discovery of trace fossils. However, in this statement, Steno appears to wish to understand more, or in other words, he wants to learn the associated processes rather than about the fossils themselves (Lærke and Andrault, 2018). Steno goes on to explain his understanding of this process with his 3 propositions which are, summarized: 1. Solids such as rocks, bones, and shells were already solidified when they contacted fluid Earth matter in order to leave an imprint or be included in the resulting solid, 2. If a solid is to share the surface and internal composition of another solid, then the manner and place of production are alike, 3. A Solid produced by the Laws of Nature is produced from a fluid (Steno, 1671). Despite the lack of data and research at the time, one can appreciate the degree of accuracy within some of these statements. Steno's first proposition explains mold and cast fossils in that they are often involved with rock matter not yet lithified. The other two also contain a certain degree of logic to them, although both call for improvement and revision they are a great start. For example, rocks tend to appear similar in surface and interior composition when formed due to the same processes when it comes down to grain size, ripples, or chemical composition, however, the rocks may have been spatially and temporally separated when formed. In addition to the study of fossils in *Prodrimus*, Steno goes on to make significant geological observations. It was in this publication, that the modern principles of original horizontality, superposition, and lateral continuity are first stated. Steno states superposition for the first time, claiming, "At what time there was formed any bed, the matter incumbent on it was all fluid, and by consequence, when the lowest bed was laid, none of the upper bed was extant" (Steno, 1671). He goes on to discuss the horizontal nature of beds, as well as that they continue laterally in all directions, until reaching a discontinuity or slowly disappearing. Therefore, modern principles of geology and paleontology were formulated by a man whom lived almost 400 years ago.

There is a reason however, for Steno's successes compared with philosophers of his time. Steno represented the rise of the modern scientific method. Although the majority of his experiments were in anatomy rather than Earth sciences, there is a quote that appears numerous times within *Prodromus*. Steno states a certain topic of inquiry and analyzes it through stating that it "answers neither reason, nor experience" (Steno, 1671). Therefore, he observed the processes around him, before relying on reason and stayed away from preconceived societal beliefs. However, it is unfortunate that this method did not remain present through the entirety of his work. Near the end of *Prodromus*, Steno attempts to explain that his conclusions do not refute that of the Genesis Flood (Steno, 1671). Not many years later, Steno would abandon science and become priest and theologian. In 1710, Gottfried Wilhelm Leibniz wrote in his *Essais de théodicée* that Steno "was a great anatomist, and very well versed in the natural sciences, but unfortunately he abandoned research and turned from a great physicist into a mediocre theologian" (Lærke and Andrault, 2018).

Johann Beringer's Fake Fossils

Around the time of Steno, there was much interest surrounding these slowly emerging fields of geology and paleontology. Many intellectuals of the era wrote on, and proposed theories to describe processes and the appearance of fossils. One of these individuals was the German physician Johann Beringer, whom became victim to one of the largest hoaxes in the history of science (Mallat, 1982). In 1725, Beringer published a book called the *Lithographiae Wirceburgensis,* and within it (in this text, referring to the 1963 University of California press English translation by Jahn and Woolf), he explains his findings pertaining to his studies surrounding fossils, and attempts to account for their origin (Beringer, 1963). Before investigating his findings, let it be known that Beringer published his book during a period in which the concerning fields were undergoing rapid change, classical theories became under scrutiny, and new methods of stone classification were constantly arising (Beringer, 1963). Religion still played a critical societal and philosophical role. Specifically, Beringer's introduction to *Lithographiae Wirceburgensis* suggests that he "was inclined toward the [Genesis Flood] theory, this being one of the several theories much favored by scholars".

Figure 2.17: three specimens of the false fossils discovered by Johann Beringer

Proceeding, the hoax begins with the fossils Beringer found in Würzberg. As the Chair of History at the University of Würzberg, Beringer was envied by some professors and students (Mallat, 1982). Thus, they attempted to flaw his studies by carving out fossils, and burying them in his region of study for him to find. In *Lithographiae Wirceburgensis*, upon finding the fossils he states, "for by a singular stroke of Divine Providence… a mountain which I had frequently examined in the past but never scrutinized very closely, revealed a treasure" (Beringer, 1963). Within the book, he does make some accurate statements, concerning how rocks can contain ancient remnants of species and display their characteristics, and that rocks may arise from biota, but biota may not arise from rocks. However, some of his fossils (as they are carved) are unlike any known specimens of his era, however he is quick to classify them as "exotic figures of insects obviously from other regions… and other heretofore unknown species" (Beringer, 1963). Some of the fossils he finds even resemble celestial bodies. In attempt to explain these, he turns not to science, but to reason, of which is clearly under heavy societal and religious influence. He makes remarks such as "God has entrusted me", that possibly "they derive from relics of the Flood", and that this is a "new object, previously unknown to the devotees of natural science" (Beringer, 1963). Therefore, despite the fact that he does ask questions about fossils, he never employs any scientific methods to attempt to validate them. However, it can also be argued that it could not have been expected of him to anticipate trickery of this sort.

Eventually, in 1726, Beringer would realize the fallacy of the stones. In attempt to buy the published copies of *Lithographiae Wirceburgensis,* he would send himself into poverty (Beringer, 1963). He would also go on to take legal action against those who wronged him to try to regain credibility, and would win the case (Mallat, 1982). This entire historical event signifies the importance of the scientific method. Unlike Steno, Beringer did not attempt to observe or experience a process that could lead to the emergence of such fossils. While he did reason, he attempted to use his preconceived beliefs to explain the origins of his discovery. Therefore, in the absence of execution of quality science, one of the greatest hoaxes in scientific history emerges as the product.

William Whiston and A new Theory of Earth

In the 17th Century, the investigation of the Earth primarily fell to people belonging to one of three main groups. These were the religious clergy, medical practitioners and gentleman of leisure (Porter, 1978). It was to the religious clergy that William Whiston belonged. Whiston among other early members in the field at this time were not known for generating the most ideal empirical evidence, as they were tied to much religious controversy (Porter, 1978). At the end of the 17th century Whiston published his book *A New Theory of Earth*, in which he claims to prove the Genesis story by making use of philosophical reason. In his book, Whiston asserts that the Earth started as a comet, as a comet's atmosphere has similar properties to the ancient chaos expected in early Earth (Whiston, 1696). One of the biggest questions in geology has always been: how did the earth form, and how has it changed since it was formed? Whiston had some logical arguments to support his theory, one being that comets have roughly the same relative atmospheric size as Earth. However, the issue with his ideas were that they were generated with the goal of proving the genesis story, and not with finding the most likely explanation for the natural world. One of the topics of discussion in this theory is the eccentricity of Earth's orbit. In the theory, one of Whiston's reasons for the assumption that the orbits were initially circular is that, human use of planets would benefit from circular orbits (Whiston, 1696). This argument stems from a heavy reliance on the Bible as the absolute truth, because this argument only makes sense, if you assume that the planets were designed to be of use to humans. Whiston like many other religious geologists of the time, spends a lot of time and effort trying to prove and explain the Flood. One of Whiston's arguments that came out of necessity of his flood belief, was that the land area of earth is found on the surface of deep and large areas of water. In his book he stated that the reason for this argument was that without the superposition of land onto subterranean fluid, the notion of the Flood would be simply inexplicable (Whiston, 1696). This, to someone who believes in the Flood would seem like a simple rational argument, since the Flood's occurrence is not in question, there must be some natural phenomenon to explain the Flood. This is an example of a man of science who was logical and intelligent, however since his initial assumptions had no basis of evidence, the results of his study and reason were skewed. Some arguments within the theory are more damaging than this however, and are based entirely on religious history. Since this book was presented as a comprehensive theory encompassing the geological history of Earth, it should have included some geological evidence, however some arguments did not. The explanation for Earth's stratigraphy from Whiston's perspective came down to initial placement during the creation and the Flood, which unfortunately prevented him from looking further into its meaning, and seeing what he could deduce (Whiston, 1696).

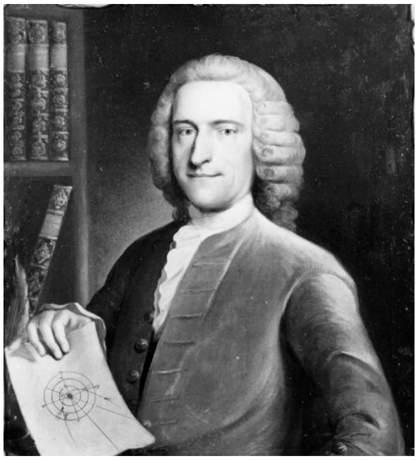

Figure 2.18: Artistic rendition of William Whiston, author of the well-respected at the time, new theory of earth. His work represented popular beliefs for the history of the Earth.

Flood Geology

Despite the fact that the Genesis Flood is no longer a universally accepted belief among scientists, it is still the topic of some research and interest. The research however is no longer looking for evidence of a global flood, it is more directed towards the search for a flood that could be the one of reference in the Genesis story. The possibility of a real large-scale flood seems plausible, due to the widespread theme of flood beliefs in religions originating from areas around the Black Sea.

Figure 2.19: Map of Black Sea region. The area of the principle investigation for biblical flood analogs in the current day. Chosen for its proximity to origin centers of religions with a flood belief and its potential for a catastrophic flood.

Recent investigations to seek evidence of a rapid flooding event in the Black Sea region were stimulated by a Russian-American expedition in 1993. This expedition involved the collection of geological samples in the region where the flood could have occurred (Ryan et al., 2003). There are actually two suggested floods that may have occurred in the Black Sea region; the earlier, dating back to the late Pleistocene, and the later placed within the early Holocene (Yanko-Hombach, Gilbert and Dolukhanov, 2007).

The Late Pleistocene flood

There are several lines of evidence that support the late Pleistocene flood hypothesis and the Great Flood story. The Tarkhankutian basin located inside the margins of the black sea, is an area that was shown to have brought salt water into the Pontic basin another precursor the black sea in the area, resulting in an increase in salinity, to about 8-11%, as well as brining salt water marine organisms into the basin (Yanko-Hombach, Gilbert and Dolukhanov, 2007). During the last glacial maximum, the connection between the Pontic basin and the Sea of Marmara was interrupted. As a result of this the level of the Tarkhankutian Sea dropped to around 100 meters below its current level. The sea then rose rapidly to about 20 m below its current level, between 17 and 11 ky BP (before present). Based on the current geological evidence, this is the most likely flood to have been the stimulus of the Genesis Flood story reported in religious texts; however, archeological findings do not indicate that societies were affected greatly by this event (Yanko-Hombach, Gilbert and Dolukhanov, 2007).

Geological methods for examining past floods

A wide range of methods can be used to determine information about past flooding events, methods that are geological, and/or biological. One characteristic of large-scale flooding events is their ability to move large amounts of sediment that eventually ends up in river drainage basins (Schneuwly-Bollschweiler, Stoffel and Rudolf-Miklau, 2013). Flood deposits have a distinct sedimentology, which is characterized by a nearly pure terrestrial mineral composition, and a low organic content. The organization of sediment within these flood deposits typically involves an upward fining of grain size as a result of diminishing flow velocities as the flood wanes. These deposits are easily identified by determining a decrease in grain size from bottom to top within the sediment stratigraphy. Total organic carbon can be measured to determine the organic content, and magnetic susceptibility can be compared with the surrounding environment (Schneuwly-Bollschweiler, Stoffel and Rudolf-Miklau, 2013). After flood layers have been identified, other information about the flood that created them can be determined. Another important factor to determine is the time frame in which the sedimentary layer was created, both how long ago, and over what period of time. The period over which the deposition occurred is especially valuable as it allows for the rate of sediment deposition to be calculated (Schneuwly-Bollschweiler, Stoffel and Rudolf-Miklau, 2013). The main method for dating these sediments is radioisotope dating, more specifically radiocarbon dating of the trapped terrestrial organic matter. For this method to work, remains of terrestrial microorganisms must be identified in the sediment layers. This is the case because the level of radioactive decay of the carbon must isolated from atmosphere in order to accurately determine the age. Marine organisms could integrate old carbon from the water, which would give an age estimate that is older than the actual age. It is also important to note that more often than not, flood layers contain little organic matter. The age of the flood layer is determined using the age of the layer above and below by the principle of superposition (Schneuwly-Bollschweiler, Stoffel and Rudolf-Miklau, 2013). In addition to understanding the frequency and magnitude of floods, seasonality can also offer some interesting information. This information could allow for more conclusions to be drawn about past environmental conditions from the flood record for example higher flood frequency associated with thunderstorms in the summer (Schneuwly-Bollschweiler, Stoffel and Rudolf-Miklau, 2013). Unfortunately for the search for specific flood events, the selection of the lake is important for the efficacy of studying the flood record. The first important factor is a good understanding of the lakes depocenter, this makes floods where the shape of the lake has changed much harder to study. The next factor in the ability to study floods in a given lake, is the geomorphic indications that surround the lake. These factors include a relief in the catch area in order to erode material for transport. An area of evident inflows, that ideally are only active during an extreme event, and the presence of delta structures at major areas of influx (Schneuwly-Bollschweiler, Stoffel and Rudolf-Miklau, 2013). This can cause particular problems when the goal is to look for evidence of one specific flood, instead of finding an area ideal for the study of flood geology. The way flood layers are dated is also an issue when searching for a specific flood like the one that may have been incorporated in the Genesis story. This is an issue because one can't search around a given time frame but rather the flood record can be examined, and then the time period can afterwards be determined. Thus, it is not possible to pinpoint a certain date. Overall, much can be learned about an environment from the geological study of floods, however it is only effective in some areas, and in some contexts.

Figure 2.20: An artistic rendition of Noah's Ark from the Genesis story of the Great Flood. An influential belief in the progression of geologic theory.

Asbestos Through Time: The Inextinguishable Mineral

Ever since the emergence of modern humans, there have been a number of pivotal moments shaping the development of the species. While some of the most monumental cultural events include the shift from nomadic lifestyles to sedentarism, as well the age of enlightenment and scientific revolution, arguably the most important moment precedes all of this, with the ability to control fire. For generations, the beauty and utility of fire has mesmerized people, bringing about countless innovations. Moreover, the human fascination with fire, and nature as a whole, led to the discovery and harnessing of inimitable resources. One such resource with a close connection to fire is the mineral asbestos.

Figure 2.21: The fibrous mineral chrysotile, a type of asbestos.

As a naturally occurring mineral, asbestos refers to a group of fibrous hydrated silicates (Pira et al., 2018). These minerals are further organized into two subgroups: the serpentine and amphibole. The most prevalent type of asbestos, in the form of chrysotile, a white magnesium silicate, is classified under the serpentine group (Pira et al., 2018). Similarly, variegated asbestos such as crocidolite and amosite, blue and brown asbestos, respectively, as well as anthophyllite, fall under the amphibole group for their characteristically strong mechanical properties (Pira et al., 2018). While structurally different, the thermal inertness of asbestos minerals is attributed to their distinctly high melting points (Kusiorowski et al., 2012).

Ancient Origins

The earliest known use of asbestos dates as far back as 4,500 years ago, in eastern Finland (Garfinkel, 1984; Ross and Nolan, 2003). At this time, communities around Lake Juojärvi fortified pottery and cooking utensils with anthophyllite (Ross and Nolan, 2003). However, the use of asbestos in strengthening materials was not exclusive to the Finnish, as many regions of Scandinavia and Russia incorporated asbestos in ceramics and other objects as early as the Stone Age, extending well into the Iron Age (Ross and Nolan, 2003).

During the classical period of the Mediterranean, asbestos deposits were prevalent throughout the region of Mount Troodos in Cyprus (Ross and Nolan, 2003). The asbestos mines of the surrounding villages Pelendria and Apsiou, some 25 km southeast of Mount Troodos, were uncovered by unknown travellers of the 16th century (Ross and Nolan, 2003). While the exact location of the asbestos deposits has since been lost, it was known that asbestos was extracted and played a role in the manufacturing of materials (Ross and Nolan, 2003).

Perhaps the first detailed documentation of asbestos use originated from ancient Greece. The ancient Greek historian Herodotus commented on the use of asbestos in cremation cloths in 456 BC and a myriad of other clothing articles such as hats and shoes, as well as its more widespread use in lamp wicks throughout the 5th century (Garfinkel, 1984; Ross and Nolan, 2003). Theophrastus, a pupil of Aristotle, who lived between 372-287 BC is credited with providing a more comprehensive description of the natural appearance and properties of asbestos in his treatise *On Stones* (Ross and Nolan, 2003). In addition to proposing a classification system based on rock heat exposure and magnetism, as well as elaborate documentation of various gemstones, Theophrastus noted that a stone, presumably asbestos, can be set ablaze when doused in oil, but remains unscathed when all of the oil has burned away (Caley and Richards, 1956; Ross and Nolan, 2003). Moreover, Theophrastus describes the mystifying rock as resembling rotten wood, an observation that has brought about contentious interpretations about the true subject being referred to. It is believed that he was instead discussing lignite, a low quality coal that may often appear brown and fibrous (Caley and Richards, 1956). Interestingly, due to the naturally high water content of lignite, it will not burn even after being covered with oil; in order to ignite, it must first be dried out completely (Caley and Richards, 1956).

While Theophrastus' exact field methodologies are unknown, understanding the location he surveyed, Scapte Hyle, provides strong evidence he was not in fact describing asbestos, as the area was not known to harbour the mineral. However, that is not to say that the fireproof properties of asbestos were unknown to him; the coastal city Karystos, adjacent to Athens, was a known source of asbestos (Caley and Richards, 1956), and Theophrastus' journeys through the largest city would undoubtedly lead him to come across the mineral's uses.

Another prominent figure to mention the asbestos from Karystos was the Greek geographer Strabo (Ross and Nolan, 2003). As an avid traveller, Strabo chronicled many of his expeditions and observations of the world in his *Geography* (Ross and Nolan, 2003). Thought to be written over the course of Strabo's life, *Geography* is comprised of a total of 17 books that were finished by approximately 23 AD (Pothecary, 2007). Book 10 of the work mentions how a stone woven into towels and other matted fabrics is simply tossed into a fire for cleaning (Strabo, 1928; Ross and Nolan, 2003). Based on the location of the source material, it was aptly named the "Karystian stone" (Ross and Nolan, 2003).

In a similar way, the etymology and cultural implications of asbestos can be traced to ancient Rome. Pliny the Elder, an acclaimed Roman naturalist living from 23 to 79 AD, wrote the book *Natural History* shortly before his death (Ross and Nolan, 2003). Within this work, Pliny the Elder revisits the established Greek word "ἀσβεστος," the origin of the term "asbestos," by transliterating it into the Latin "asbestinon" (Ross and Nolan, 2003). The noun specifically refers to the fire-resistant cloth utilized during royal cremation traditions, but also found in the sacred fire of Vesta, as kindling (Ross and Nolan, 2003). As such, asbestos was often associated with status and sanctity. In the form of a shroud for cremating, the fireproof asbestos would cover only the ashes belonging to kings; in this way, it served as a distinguishing article, separating royal bodies in communal burial pyres (Laufer, 1915).

Initially, however, the Greek usage of asbestos differed based on context; as a noun, it referred to the mineral calcium carbonate, or lime, whereas it also meant inextinguishable or unquenchable in its adjectival form (Ross and Nolan, 2003). It is interesting to note that Pliny may not have fully known the geology of asbestos, contrasting the Greek understanding of the mineral. In fact, Pliny the Elder speculated that the woven asbestos material originated from foreign, exotic desert plants in India, where he may have unknowingly attributed the name of asbestos to other similar looking rocks (Ross and Nolan, 2003).

From the influence of the Roman Empire, asbestos also emerged in the East. Transitioning from the selective ownership of the Roman elite, asbestos became a commercial commodity traded with China (Laufer, 1915). Early records from the Han period, at the turn of the third century, describe how fireproof asbestos clothing was a novelty for nobles of the Han dynasty (Laufer, 1915). Furthermore, this incited inquest into the origins of the mineral, primarily through the scope of Taoist philosophy. The prevailing belief of the time was that its unmatched properties were the result of varying forces of nature. Namely, this encompassed the ideas that asbestos was the fibre of a plant, as well as the hair of an animal that inhabits volcanoes (Laufer, 1915).

Figure 2.22: A renaissance depiction of the salamander being prodded at the centre of a fire.

Throughout time, a defining characteristic of asbestos is its innate resistance to fire. Beyond its records in ancient Greek and Roman civilization, asbestos was a source of fascination during the Middle Ages. With the inception and rise of alchemy, asbestos was quickly incorporated into a narrative of mythology, particularly within the medieval lore of the salamander (Bulfinch, 1913; Ross and Nolan, 2003). As the Chinese had first alluded, the notion that asbestos was the fur of a mythical creature was cemented by oral accounts and fables of the fire-extinguishing salamander (Laufner, 1915). Although these ideas were not grounded in empirical scientific data, this understanding of asbestos is reflective of the theory-based approach that shaped the knowledge of the world at that time. More robust methods to studying asbestos emerged later, such as in the work *The Textbook of Mineralology*, by 16th century German mineralogist Georgius Agricola. Noting the physical properties of the mineral in immense detail and comparing its taste to that of other compounds like alum (Agricola, 1955), Agricola helped to establish a more objective scientific attitude towards the study of asbestos.

Industrial Prominence

Asbestos has had many uses throughout the modern era as well, and was predominantly used for its strength and resistance to fire. For example, Benjamin Franklin had an asbestos purse, and Pope Pius IX used the mineral as fireproof paper (Dodson and Hammar, 2005). Although the time or place of origin of asbestos prevalence was not formally documented, it was during the early 1800s that the use of asbestos became more common (Dodson and Hammar, 2005).

Figure 2.23: An advertisement showing an asbestos-insulated laundry iron.

The heat resistance, among other useful qualities such as structural integrity and flexibility drove the widespread use of asbestos during the Industrial Revolution (Virta, 2006). The relatively modern asbestos industry began in Italy, when a textile company used the mineral to produce simple items such as fabric and string. During this time, industrialization motivated rapid innovations, which included ways to take advantage of asbestos that was relatively scarce and new to industry (Virta, 2006). Building materials made from asbestos were a significant application of the mineral, as their use became a new method for structural insulation and mechanical fireproofing. For example, asbestos was included in wall paints and wall materials with the intention of fire safety (Virta, 2006).

The growing demand for asbestos inspired the search for asbestos deposits across the world as Italy, the main supplier and the other countries that supplied asbestos did not have sufficient output (Virta, 2006). Abundant deposits of asbestos were found, primarily in Canada, Russia, and South Africa, which quickly became the major suppliers of asbestos.

As time passed, the availability of asbestos and newer technology allowed for the mass production of asbestos materials and products. A significant invention by the Austrian Ludwig Hatschek in 1907, involved a machine that produced thin sheets containing asbestos, which vastly increased manufacturing efficiency (Virta, 2006). The products made using this machine also dramatically increased the asbestos demand as it provided a means for cheap, fireproof building materials. Another significant advance was a process to mass produce asbestos piping that led to common asbestos use in water supply. It was during this time that the automobile industry was growing and asbestos was included in car parts.

Although asbestos as a mineral was not extensively studied (partially due to the lack of geochemical studying methods during the time), asbestos commonly played a role in advances in technology and industry. By 1958, there were approximately 3000 different documented applications for asbestos, where it was honored as a "boon to humanity" and "faithful servant of mankind" (Virta, 2006). During the early 20th century, asbestos was widely celebrated for its many contributions and worldwide demand was at an all-time high (Virta, 2006). Although the World Wars and the Great Depression caused asbestos production to wane, post-war reconstruction and recovering economies worldwide caused peak production (Virta, 2006). The influence of asbestos in the modern era made it a truly prominent material for industrial innovation.

The Link to Disease

It was during the mid 20th century that the "magic mineral" was revealed to be dangerous (Virta, 2006; Bartrip, 2003). Historically, disease and shortened life spans among asbestos miners has been speculated, however the adverse effects were first documented in a medical article in 1924, appearing in the British Medical Journal (Bartrip, 2003). In the report, pathologist William Cooke wrote about a case study conducted on a woman who worked in an asbestos factory and died of fibrosis and tuberculosis (Bartrip, 2003). This article sparked interest and motivation for other health researchers and more case studies were published. Thomas Oliver, a physician, introduced the term "asbestosis" in the late 1920s to describe lung diseases associated with asbestos particles (Bartrip, 2003).

In the 1930s, suspicions arose regarding a link between lung cancer and asbestos exposure, however it was largely disbelieved, likely due to its reputation as an important mineral as well as its prevalence and countless applications (Bartrip, 2003). Sponsored research within the asbestos industry found that tumors could be induced in mice with asbestos exposure, but as a result of their interests the studies were never made public (Greenberg, 1999). Experiments were conducted on different levels of biological organization such as the cellular, tissue, organ, and organism level (guinea pigs and mice) (Greenberg, 2017). Data was also collected on the mortality rates of asbestos workers, yet were kept hidden and unanalyzed (Greenberg, 1999).

In 1953, the Turner Brothers Asbestos Company requested that the physician Dr. Richard Doll study the mortality data on asbestos workers in order to address allegations of the possible carcinogenic properties of asbestos (Greenberg, 1999). Research continued and in 1955, Doll determined a direct causation between asbestos and lung cancer, where statistical data showed substantially higher rates of lung cancer in the workers compared to the average population (Bartrip, 2003; Greenberg, 1999). Against the wishes of the industry, Doll daringly published his findings, however the effects of his publication were unexpectedly minor (Greenberg, 1999). The relevance of the study was greatly unappreciated, and legislation did not respond until the mid 1970s (Greenberg, 1999). Compensation to asbestos workers and their families were only considered 25 years after Doll's publication, and they were very strict. Even in the late 1900s, there was a strong resistance from the asbestos industry, as asbestos was considered indispensable (Virta, 2006).

However, public opposition of asbestos use started having a significant effect on asbestos production (Virta, 2006). Fear of the potentially harmful effects of asbestos caused a decrease in asbestos demand, and liability issues started to arise (Virta, 2006). Many lawsuits were filed by asbestos workers and their families encouraging manufacturing companies to use alternative minerals or substances in their products (Virta, 2006).

Figure 2.24: A group of asbestos workers in 1976 protesting Babcock and Wilcox, an industrial technology developing company.

Modern Policy and Medical Geology

Advancements in countless fields, including medicine, geophysics, and mineralogy are inextricably linked to the current breadth of understanding surrounding asbestos. In many ways, the novelty of asbestos as merely a natural source for functional products now renders the mineral as the epitome of cautionary industrial practice. Nowadays, asbestos harvesting and manufacturing is largely avoided, and the use of alternatives to asbestos is common practice to prevent its many adverse effects on public health (Luus, 2007).

Health Implications

In the early to mid 1900s, the majority of the medical research on asbestos was sponsored by the industry itself and was suppressed to preserve their reputation and business (Virta

2006). However, after Doll's courageous publication, more medical research was conducted and more data were published (Virta 2006). Similarly to the tobacco industry, doubt remained even after proven links to disease and cancer were established. The effects on human health are difficult to study because asbestos-related diseases generally take many years to develop (National Cancer Institute, 2017) . Modern research in the 21st century is continuously conducted to assess the danger of asbestos. With modern medicine and biochemistry, studying the causation of asbestos-related diseases now involves more evidence-based approaches. Although the majority of asbestos research is still based on data surrounding human exposure and disease/cancer rates, researchers are able to both theoretically and experimentally study the exact association between asbestos and lung diseases.

Figure 2.25: The lung tissue of an individual afflicted with asbestosis.

In 2010 researchers at the University of Hawaii discovered that when asbestos fibers kill cells, they cause the release of a protein that promotes tumor growth. These findings were the first medically established process describing the carcinogenic properties of asbestos (University of Hawaii, 2010). Even more significant, is that these findings can potentially lead to the prevention and treatment of asbestos diseases such as mesothelioma (University of Hawaii, 2010). This discovery was possible because of the modern understanding of physiology, cellular functions, and mutagens (University of Hawaii, 2010).

Asbestos is also categorized as a pollutant, and environmental researchers monitor asbestos levels in nature as well as in the air looking for relationships between lung disease incidence rates and the presence of asbestos (Pira et al., 2018). Because asbestos is present in many of the products that still exist today, efforts are made to reduce exposure and replace asbestos with inert and safe alternatives (Pira et al., 2018). In addition, data are much more easily obtainable on varying populations with different levels of asbestos exposure and are constantly being analyzed (Kang et al., 2013). The majority of asbestos use occurred in the late 1900s and so the latent nature of the disease has caused its high incidence rates to peak at the present time (National Cancer Institute, 2017). Statistical evidence is used today to predict and establish numerical relationships between factors such as dosage and mortality rates, as well as time of exposure and disease incidence rates (Kang et al., 2013).

It was not until the 1980s that action was taken in the United States to control asbestos use (Selby, n.d.). The Asbestos Hazard Emergency Response Act of 1986 (AHERA) and the Asbestos Ban and Phase-Out Rule (ABPR) were issued in an attempt to protect the public from asbestos exposure by asbestos removal in schools and banning the marketing of asbestos including the manufacturing, importation, and sale of asbestos or asbestos-containing products (Selby, n.d.).

The ABPR was highly resisted by the asbestos industry, as the opposition claimed that the ban would result in economic issues surrounding loss of jobs and damaging the trade market (Selby, n.d.). After a lawsuit filed by the asbestos company Corrosion Proof Fittings against the Environmental Protection Agency, the ban was overturned; however, some items remained on the banned list (Selby, n.d.). Spray-based asbestos products and several paper and flooring products were banned due to the potential for exposure to humans, but more significantly new uses of asbestos were prohibited (Selby, n.d.). This stopped the expansion of the asbestos market by limiting its applications.

Presently, asbestos is strictly banned in only a few countries including Canada and the UK. In the United States there are a few limitations on its use, but asbestos is freely imported and circulated within the market (Selby, n.d.). Motivated by the economy and private business, opposition to asbestos control renders the future for regulation in the US to remain unclear (Selby, n.d.). Based on self-interest, it is entirely possible that the asbestos industry will continue to withhold negative research findings from the public as it has done in the past.

Geochemistry

Since the identification of the role of asbestos in triggering disease, an increasing area of focus revolves around its particular mineralogical and geochemical properties. In essence, these scientific fields help to better characterize asbestos and describe its potential biological ramifications. For example, the crystal habit, or the external shape formed by asbestos fibres, is called asbestiform (Institute of Medicine, 2006). These minerals typically consist of long, yet thin fibres, contributing to their ability to be woven and separated (Institute of Medicine, 2006). By understanding the way these fibres form in nature, the various chemical and physical interactions of asbestos and its environment may also be elucidated.

Studies investigating the soils containing asbestos and certain mining practices have made the connection between the mineral form and detrimental effects on human health. (Ngozi-Chika et al., 2014; Bloise et al., 2017). For example, mineral dust formed by natural erosive processes or due to common rock extraction techniques, such as sandblasting, may be transported considerable distances to end up in a variety of new locations. This was the case in 1991, when small amounts of asbestos were found in Libby, Montana in vermiculite deposits, a mineral with commercial applications ranging from insulation to kitty litter (Lee et al., 2008; Ngozi-Chika et al., 2014). Consequently, workers of the local mine exhibited health problems consistent with asbestos exposure, leading to investigations into the natural abundance of asbestos in geological formations (Lee et al., 2008).

Similarly, a study in the Basilicata region of Southern Italy on the environmental exposure to soils containing asbestos showed that the presence of toxic trace elements could also be a factor in assessing biological effects. Soil in that area is rich in the asbestos mineral tremolite, along with clay minerals, quartz, and others. In addition, it is rich in the metamorphic rock serpentinite, which is formed by the aggregation of several serpentine minerals, and weathers readily into an inhalable dust (Bloise et al., 2017). The discovery of high amounts of Fe-Cr oxides in chrysotile and nickel in tremolite in the soil indicate that heavy metal impurities in the structure of the asbestos contribute to severe cytotoxicity (Bloise et al., 2017). The pervasiveness of these toxins and fine asbestos fibres also suggest that human activity facilitates the formation of the harmful dust (Bloise et al., 2017).

An interesting extension of the geochemistry of asbestos is its role in primitive geological processes and formations. Serpentinization, a process whereby mafic and ultramafic rocks are hydrolyzed and metamorphosed primarily into serpentine, has been studied as a source of energy in the early formation of the Earth (Preiner et al., 2018). Occurring along subduction zones, serpentinization is highly exothermic and releases hydrogen gas as a byproduct (Holm et al., 2015; Preiner et al., 2018). This has been associated with the formation of deep ocean hydrothermal vents for as long as 4 billion years, and ultimately early anoxic atmospheric conditions of the planet (Holm et al., 2015; Preiner et al., 2018). These recent insights have helped to better explain one facet of the deep-rooted history of asbestos. It is through modern techniques and scientific principles that the connection of asbestos to the workings of the Earth is made clear.

Future Outlooks

Asbestos has played a significant role in societies around the world. Humanity has been making use of asbestos for millenia, exploiting its fire resistant properties and strength for countless innovations throughout the ages (Virta, 2006).

Our understanding of asbestos has demonstrated the evolution of science since ancient times. The human approach to the unknown and the control of knowledge has changed dramatically over time. The applications of asbestos progressed together with science. As human knowledge expanded, advances in geology and other natural sciences allowed for a better understanding of the inextinguishable mineral and it became a prominent material in modern industry. Scientific advances did however reveal the harmful effects that asbestos exposure has on human health, yet with asbestos so ingrained as a material in our soceity there are many complications with controlling it. Scientific repression by the asbestos industry has hindered progress in health research and awareness. Although unethical, intellectual repression still exists.

While action has taken place in a few countries to control and inhibit asbestos use, most countries still allow production. The conflict of interests between the economy and public health is undoubtedly complex. However, hopefully ethical decisions guide those with power to end the suffering and extinguish asbestos from modern society.

The Flood Myth and the Science it Influenced

For most of antiquity up until the modern day, the narrative of a massive flood covering the Earth has been a key part of cultural and religious understanding. In fact, the flood myth has attracted more attention than any other cultural story (Dundes, 1988). A specific example of such a flood myth is the Judeo-Christian deluge. In this story, God tells one man, Noah, and his family to build an ark and gather up the animals to the ark to purge the world of mankind to rid the evil they had become in the eyes of the Lord (Figure 2.11) (The Bible, Genesis. 6). God sends a flood with 40 days of rain, after which Noah receives an olive branch from a dove, signaling the presence of dry land, and Noah begins a new lineage of man (The Bible, Genesis. 7-9).

Figure 2.11. The Great Flood has consistently remained of constant interest for artists such as this example of The Deluge *by Joseph Turner, famous for beginning the Apocalyptic Sublime (Turner, 1805).*

While this story has been passed down through the ages, it appeared in a unique and new light after a new discovery made by an avid Assyriologist, George Smith, in 1872 (Dundes, 1988). Hidden in a tablet covered in thick deposits, Smith discovered a far older, extremely similar version of the Flood Myth from Mesopotamia. Sadly, Smith's passion would also lead to his demise; in an attempt for further exploration, he travelled to Aleppo, Syria in the most extreme summer months and quickly died of dysentery (Dundes, 1988).

By translating this text, Smith revolutionized the understanding of the Flood Myth because not only was the narrative contained in one the most influential books of all time, the Bible, it also lay within one of the most ancient books of all time, *The Epic of Gilgamesh* (Bates, 2010).

Literalists argued that this proved the existence of the deluge, a mass flood, as multiple sources recorded its occurrence, whereas refuters claimed that the Chaldean account provided evidence that it was simply local mythology of the region (Gould, 1987). Whatever the argument, his discovery provoked a great interest and exploded the study of the comparative mythology of the Flood Myth throughout the world, and no one can deny the profound influence of the Flood Myth on the scientific understanding of how the world has formed throughout history.

Flood Mythologies Across Cultures

While many people may be familiar with the biblical narrative of the flood, flood mythologies traverse vast cultures across the ancient world. One flood myth originating in Kenya depicts a Supreme God known as En-Kai who wished to put an end to humanity's sinful ways (Lynch and Roberts, 2010). En-Kai chose to save one righteous man named Tumbainot and his family. Similar to the Biblical account, Tumbainot was told to build a boat, and with him, bring animals of each type along with his family. When Tumbainot, his family, and all the animals got on the boat, En-Kai sent rains that flooded the Earth. When the rains ended, Tumbainot tested for dry land by sending out birds. Upon confirming the end of the flood, Tumbainot returned to land with his family and animals, and re-established the world. While it is clear that this particular story shares remarkable similarities with the Biblical account, albeit with some minor differences, it is yet another case of a cultural memory of a flood.

There appears to be a collective recollection of mass flood events across global culture. One example of an ancient African flood mythology relates a story about a pot of water (Lynch and Roberts, 2010). This particular myth from Tanzania depicts a pot of water that never went dry. One important rule surrounding the pot of water was to never touch it. A woman, curious about the consequences, touched the pot. Upon violating the rule, the pot then shattered. The water spilled out, flooding the world and drowning everything (Lynch and Roberts, 2010).

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Flood myths are abundant and central to ancient Chinese traditions as well (Birrell, 1997). Currently there are two collections of Chinese flood mythologies: classical northern Chinese mythology, and the modern folklore of the south. There is no one flood mythology of the ancient Chinese people, rather multiple diverse stories (Birrell, 1997). One example of a classical ancient Chinese flood myth from the Huai-nan Tzu texts (Figure 2.12) of 139 BCE retells the tale of the goddess, Nu Kua, who saved the world from a catastrophic flood. This myth is estimated to have been written around 139 BCE. In the story, the world is plagued by fire and mass flood. Nu Kua uses her skills in metallurgy and animal communication to bring order to the universe, thereby ending the flood (Birrell, 1997).

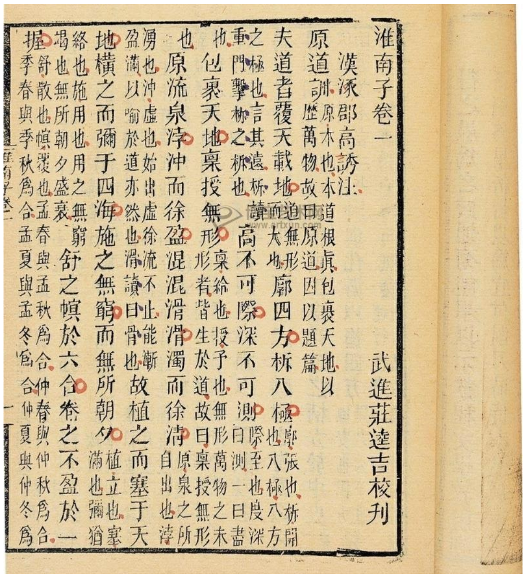

Figure 2.12. Excerpt from the Zhang edition of the Huai- nan Tzu texts.

淮南子卷一　武進莊逵吉校刊

漢涿郡高誘注

原道訓（原本也本道根眞包裹天地以歷萬物故曰原道因以題篇）

夫道者覆天載地（道無形而大也）廓四方柝八極（廓張也柝開也八極八方

之極也言其遠柝讀重門擊柝之柝也）高不可際深不可測（際至也度深自測一曰書

也）包裹天地稟授無形（稟給也授予也無形萬物之未形者皆生於道故曰稟授無形

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湧也沖虛也始出虛徐流不止能漸盈滿以喻於道亦然也滑讀曰骨也）故植之而塞于天

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絡也施用也用之無窮竭也無所朝夕盛衰）舒之幎於六合卷之不盈於一

握（舒散也幎覆也孟春與孟秋爲合仲春與仲秋爲合季春與季秋爲合孟夏與孟冬爲合仲夏與仲冬爲）

According to Mayan and Aztec folklore, there existed a previous world that had been destroyed by a flood (Taube, 1993). As is evident by sheer instances of cross-cultural flood mythology, the idea of a great flood destroying humanity is not unique to the well-known Biblical tale, and it is not unique to one culture. Whether the reason behind this global recollection be cross-cultural spreading of ideas, an actual flood event, or perhaps a combination of both, there is no denying the strong cultural influence of flooding, as aquatic disaster plays a significant role in the human experience.

Diluvialism

At the cusp of the Enlightenment, the field of geology was experiencing an explosion of new evidence and methods to better understand the makings and workings of the world. With new information came new ideas, proposals, and hypotheses of how the world came to be, many of which were outlandish and naïve (Gould, 1987). Before then, the main resource people had was their understanding of the world from religious scripts, many of which have detailed and specific information on the world's creation (Gould, 1987).

In Europe, still having limited sources of information on the beginnings of the Earth, scientists could for the first time investigate the natural evidence while staying firmly rooted in the scriptural understanding (Gould, 1987). At this time, those who examined the Earth's past for evidence of religious events firmly believed in the Augustinan ideal that the natural world could only expose and not refute divine truths (Rappaport, 1997). From a geological standpoint, the most tantalizing element of major world formation was the Great Flood. Unlike most miracles recorded in religious tradition, a worldwide flood would have left a significant record on the geological record and could potentially be supported or falsified through evidence found literally beneath their feet.

From these conclusions, several theories were grounded upon diluvialism, the attribution of a Great Flood as a foundational part of the formation of the Earth's landscape (Rappaport, 1997). One of the earliest of theses diluvial theories arose from Thomas Burnet, an English theologian and scientist, studying first at Cambridge and then joining the church as a chaplain (Baker, 2018). In 1681, he published *The Sacred Theory of the Earth*, a proposal on the Earth's cosmogony that was founded on a rational explanation of spiritual events (Figure 2.13). Burnet believed Creation's natural laws could carry out the will of God, and God did not miraculously intervene except in the very beginning of creation (Baker, 2018). In his theory, the Earth had been ordered into concentric layers of increasing density by depth, to which during the Great Flood, the crust had ruptured, giving way to water underneath that flooded the world and gave rise to the mountains and valleys visible today (Gould, 1987). He came to this conclusion after calculating that the volume of water on the Earth. He lamented its inaccuracies as he had insufficient maps. After determining uses an estimate of the ocean's depths and area of the oceans, he concluded it could not possibly result in a global deluge. Instead, he proposed that the water must have come bursting from within the Earth (Gould, 1987). Isaac Newton, already famous by this time, was a firm supporter, and they discussed in letters this theory at length with Newton proposing that some of the features of the Earth had been defined before the flood (Gould, 1987).

However, Burnet was not without critics. Herbert Croft, Bishop of Hereford, greatly criticized Burnet for his lack of acceptance of divine intervention rather than natural cause to the Flood (Rappaport, 1997). Others greatly disliked Burnet's disregard for certain evidence, such as the fossil record (Rappaport, 1997). Indeed, it would only two centuries later that Charles Lyell, a key critic of catastrophism such as that proposed by Burnet, would call Burnet's work free indulgence of his imagination (Gould, 1987). Archibald Geike, the well-known geologist, would also call it "speculation" that had "run so completely riot" that it could not even be called science itself (1905).

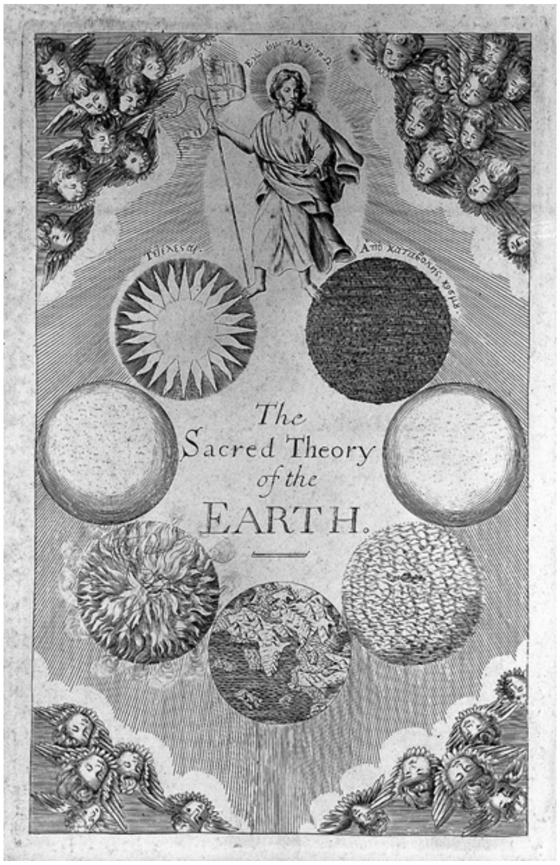


Figure 2.13. The cover of the Sacred Theory of the Earth demonstrating Burnet's Theory visually. Similar to a clockwork motion, his theory begins with chaos, then smooth Earth, then the deluge, modern Earth directly opposite from the Christ figure, which inscribed above his crown dictates Christ as the Alpha and Omega, both the beginning and then end. The Sun to the left of Christ shows the final rapture.

In response to the apparent lack of fossil discourse in the diluvial hypothesis, John Woodward took it upon his own to suggest his own theory (Van Helden, 1995). Woodward proposed that the flood had dissolved the Earth's solid surface with the densest material settling on the bottom and the lighter material on top (Rappaport, 1997). While he did concede that such a flood must have been miraculously induced, his method explained how marine fossils had deposited all over the world regardless of modern-day terrain.

William Winston, another English scientist (Snobelen, 2004), built on these initial ideas in his *A New Theory of the Earth*. In his book, he proposed that the flood water could have occurred from the tailings of a comet, which they had just discovered was water at the time (Rappaport 1997). He concluded that the fossil record could have been shifted over time, contrasting the mechanism that Woodward had so eloquently proposed. However, challenges to the idea continued to be presented. Some argued against his ideas, citing the inability of water to dissolve rock. Despite this, Woodward's ideas had firmly taken hold and would be discussed, built upon, and edited for the next fifty years (Rappaport, 1997).

Neptunism and Plutonism

Neptunism is a geological theory first proposed by Abraham Gottlob Werner (Jenkins, 2016), who lived from the years 1749-1817 (Master, 2009). The theory of Neptunism holds that rocks originated in Earth's early oceans often attributed to the Flood, and is named after Neptune, the Roman god of the sea (Master, 2009). The opposing theory of the time was Plutonism, which attributes volcanoes and igneous intrusion to Earth's rock formation, rather than the ancient oceans (Coleman, Mills and Zimmerer, 2016).

One major and influential proponent of Neptunism was Robert Jameson, a professor of natural history from 1804 to 1854 at the University of Edinburgh in Scotland (Jenkins, 2016). Jameson studied for two years under Werner (Master, 2009). While teaching at the university, he influenced many prominent natural scientists, such as Charles Darwin (Jenkins, 2016). Interestingly, Darwin and Jameson would later be on opposing sides of the Neptunism-Plutonism debate (Master, 2009). In 1808, Jameson founded the Wernerian Natural History Society in Werner's honour (Master, 2009).

Upon studying the rock components of the ocean floors, Moro, a Venetian scientist of natural history proposed that the oceans were formed by volcanic activity underwater (Arrhenius and Bonatti, 1965). He contributed to the idea that Earth's early oceans had dissolved salts, which is what allowed aquatic life forms to develop (Arrhenius and Bonatti, 1965).

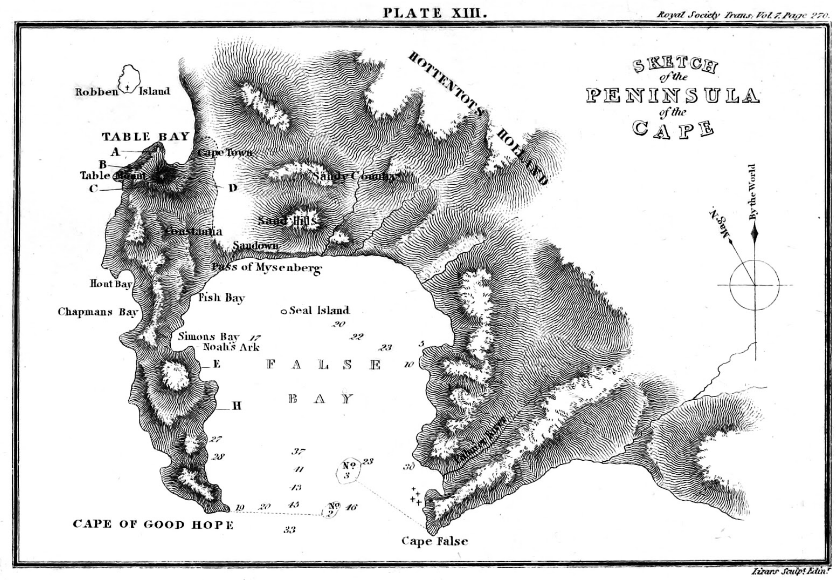
Neptunism versus Plutonism, a Case in Point

One example of the rivalry between Neptunism and Plutonism can be analyzed in the study of the Cape Granites (Figure 2.14), a group of granitic rocks located in South Africa, in the Western Cape Province (Master, 2009).

While Neptunism was first proposed by Jameson, Plutonism was established by James Hutton of the University of Edinburgh in 1788 (Master, 2009). Like Jameson, Hutton had disciples and his own school of thought. Notably, a chemist and geologist named James Hall, his son, Basil Hall and a professor named John Playfair were among his supporters (Master, 2009). Basil Hall was a sailor and noted that a naval life served as the perfect medium for studying geology, as it allowed for vast travel to natural sites, not easily accessible by land. Similar to his father, Basil hall was an advocate of Plutonism (Master, 2009). On one particular voyage, Basil Hall explored the Cape Granites of South Africa. It was on this investigation that Basil Hall noted features of the granitic group of rocks indicating intrusion. Playfair, Abel, and Hall argued that the granitic rock was of intrusive igneous nature, as opposed to possessing marine origins (Master, 2009).

Jameson argued against the Plutonian explanation of Playfair, Abel, and Hall (Master, 2009). He concluded that their Plutonian explanation was unsatisfactory and argued that the rocks of the Cape crossed into each other, much like sandstone and limestone (Master, 2009).

The two camps had different views on the temporal order of the rock layers present in the Cape (Master, 2009). According to Neptunian views, the rocks formed out of mineral crystallizations of Earth's ancient flooded seas, with the granite layer first being deposited, followed by the slate and greywacke, and then sandstone. According to the Plutonian view, the slate was first deposited horizontally, but heated and gradually slanted as granite intruded from beneath the crust (Master, 2009).



It was concluded by Professor Roderick Noble in 1870 that the mountain structure was most likely formed by granitic intrusion, supporting the claims of the Plutonians (Master, 2009). Most of this debate took place in the Victorian times of the United Kingdom. This time period valued a clear winner and loser in a debate, giving little esteem to compromise and collaboration of opposing ideas (Master, 2009).

Figure 2.14. Map of the Cape of Good Hope in South Africa, by Playfair and Basil Hall, published in the Royal Society of Edinburgh.

The Tsunami: A Modern Water Disaster

While no global flood has been evidently recorded in the geological record, floods immense in scale and height, but not quite on par with the Biblical flood, occur frequently in the modern era the form of tsunamis. Tsunamis are large, powerful, and instantaneous; they causing huge damage to an area by raising the immediate sea level (Bryant, 2014).

Tsunamis can be induced by a wide range of factors whether it be meteorological, seismic, volcanic, or meteorite impact. Meteorological tsunamis are generated by the movement of typhoons and massive atmospheric pressure jumps and tend to occur in hurricane hotspots (Bryant, 2014). It would appear that the meteorological cause of tsunamis is most similar to the Biblical account as it occurs at the same time as extensive rains and stormy weather (The Bible, Genesis. 7:12); however seismic events are the far more common causes of tsunami. Seismic tsunamis are produced by earthquakes typically formed at plate boundaries (Bryant, 2014).

There are three key types of faults that give rise to a tsunami: dip-slip vertical faults, strike-slip vertical faults and thrust faults on dipping planes, all of which are faults characteristic of subduction zones (Bryant, 2014). A vertical fault has no hanging wall, instead the adjacent rock surfaces are separated perpendicularly (Fossen, 2010). In a strike-slip vertical fault, displacement is horizontal relative to the Earth surface, whereas with dip-slip faults, the force of displacement is aligned with the dip direction of the fault, which must be vertical. With a thrust fault, the rock that lies above the fault plane rises upwards (Fossen, 2010). All of the largest tsunamis on record have been due to earthquakes created by movement on thrust faults (Joseph and Joseph, 2011). When this movement occurs under water, the uplift generates a gravity wave that travels through the ocean (Figure 2.15). Generally, these movements occur when the cold oceanic part of the lithosphere sinks underneath coastal crust (Becker and Faccenna, 2009), most actively occurring along the subducting boundaries of the Pacific plate.

Tsunamis induced by rockfalls and rockslides may be more localized but generate immense waves. Areas such as Alaska and British Columbia are particularly at risk from rockfall-generated tsunamis due to the presence of steep fjord walls, and have recorded wave heights of up to 50 m (Joseph and Joseph, 2011). Triggered by a land earthquake, the tsunamis tend to be propagate in two directions: upslope and parallel to the rockfall. In a similar fashion, the collapse of a volcanic caldera can also induce a tsunami, removing large amounts of rock debris from steep caldera walls and rapidly displacing water in the caldera. In addition, a violent pyroclastic flow from a volcano can displace large volumes of sea water, generating a ferocious tsunami such as the one induced by the infamous eruption of the Krakatau volcano (Latter, 1981). Volcanic eruptions can also create tsunamis via shallow submarine eruptions, causing low amplitude tsunamis.

While tsunamis in modern times may very well not cover the same expanse as the mythological flood they are still immense: just a few meters of crustal movement can create a wave that affects thousands of square kilometers of coastline.

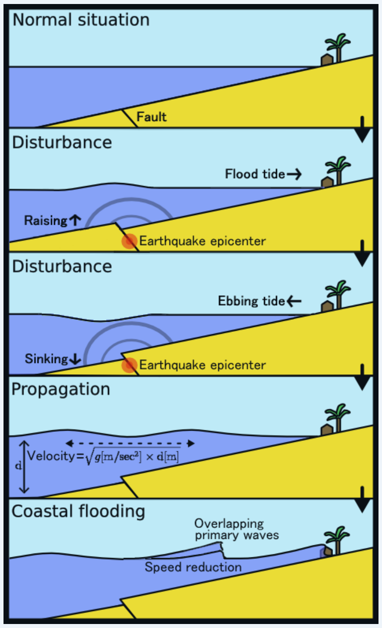


Figure 2.15. A vertical fault produces an earthquake. This earthquake can either raise or sink the sea floor. This disturbance results in a flood tide and ebbing tide. The waves, initiated by the disturbance, travel at a speed that is a function of the distance to the surface and the Earth's gravitational force. Eventually, the wave travels and hits the coastal surface, potentially causing extensive damage (Liekens 2004).

Predicting Great Floods

While there has been a considerable amount of research and effort described in the previous sections trying to detect a great flood in the past and how that might have influenced the way the world looks today, a great effort is spent on trying to detect tsunamis that occur in modern times (Bryant, 2014). Tsunamis are rare events, most requiring both shallow seismic activity and a magnitude of greater than 6.3 (Roger and Gunnell, 2012). However, it is very difficult to predict tsunami strength and impact solely on seismic magnitude. Fault structure, water depth, coastal configuration and direction of energy propagation are all significant controls on the height of a tsunami, regardless of magnitude (Joseph and Joseph, 2011).

The task of tsunami prediction is uniquely challenging, as geoscientists must predict the height, time of a arrival, and location of a tsunami as correctly and quickly as possible (Bernard and Robinson, 2009). Currently, tsunami are predicted via three main technologies: Deep-ocean Assessment and Reporting of Tsunamis (DART), cabled observatories, and differential GPS buoys, however DART technology is the most widespread of them all (Percival et al., 2018; Kawaguchi et al., 2013. The DART technology work by having a seafloor barometer, which measures pressure differences caused by waves as small as a centimetre every 15 seconds (González et al., 1998). The pressure information is then sent to a floating surface buoy via an acoustic communication, which then transmits the signal to a satellite, which relays it to tsunami warning centers (González et al., 1998). This is regularly transmitted every 5 hours and in the case of a tsunami detected, the system will override and transmit the signal with less than a three minute delay. Several of these recording stations are combined and geophysically modelled to predict time and wave amplitude at a variety of region to warn areas of particular risk.

Chapter 3: Discovery and Understanding Through Human Exploration

Curiosity is part of human nature. We seek to explore, to understand the world around us. We are constantly chasing answers to our questions. There was once a time where people had no true idea of what the Earth looked like, or what a map was. People believed that the Earth was at the centre of the universe. Our knowledge of climate change would not be the same without understanding how ice ages and global cooling cycles occur. Continental drift and our entire understanding of geologic processes are built upon the discovery of mid-ocean ridges. Human exploration takes grit and true determination. This chapter explores the lives of four incredible people, and the invaluable contributions they have made to science. From the ancient Greeks to the woman on the sidelines of world war II, these are some of the incredible people who have helped enhance our discovery and understanding through exploration.

Hecataeus of Miletus

Before the sixth century BCE in Greece, most ideas had been based on faith and spread by rich aristocrats of the time. These aristocrats claimed Homeric heroes as their ancestors, but these beliefs were being challenged (Encyclopaedia Iranica, 2019). At the turn of the sixth century BCE, merchants began expanding their influence on the world. The new ruling class was less tied to tradition, and started to come up with novel ideas not based on tradition, but rather on empirical thought and concrete evidence (Encyclopaedia Iranica, 2019). People like Anaximander of Miletus, Heraclitus of Ephesus, and Thales of Miletus around this time were considered to be the first philosophers, and their critical attitude towards tradition landed them a place in history as the first Western Scientists (Lendering, 2019).

Figure 3.1. Map of Greece and Turkey, with the location of Miletus marked in red.

This was the world Hecataeus was born into. Not much about his life is known, but he is best known for his work regarding a series of two books and a map of the known world. The book was called *Periodos Ges* (Circuit of the Earth) and was split into two parts - one concerning Europe and the other concerning Asia (Pearson, 1939).

As was prevalent in his time, Hecataeus was interested in challenging commonly held beliefs, which make up Greek mythology as we know it today. He attempted to reduce these stories to order to pinpoint a chronology of the past. In Hecataeus' words: "I write as I think true, for the stories of the Greeks are many and ridiculous in my opinion" (Braun, 2004). One belief that he sought to challenge was that of the 12 Labours of Heracles, specifically the geography of some of the stories. For his tenth labour, Heracles was challenged to drive the cows of Geryones from an island Erytheia, off the coast of Epirus, to Mycenae, on the mainland (Frazer, 2019). According to Hecataeus, the king Geryones did not live on an island, but rather on the mainland, making the task much more trivial (Braun, 2004). This is an example of Hecataeus' start as a geographer of the time, and soon others followed suit in reducing improbable features of myths, and using rationalism to dull the excitement of fables (Braun, 2004).

Greece at the time of Hecataeus

Hecataeus was born around 550-560 BCE in Miletus, a small Greek city on the western coast of the Anatolian peninsula (Figure 3.1) (Herodotus, 1920). Miletus was a Greek city that was conquered by Cyrus the Great in 574 BCE, and had been under Persian rule since then. Late in Hecataeus' life in 499 BCE, the ruling tyrant of Miletus, Aristagoras, led a revolt of the surrounding Ionian cities against the Persian Empire (Pearson, 1939). Hecataeus, by that time an upstanding citizen with a considerable reputation, tried in vain to persuade the cities against such a revolt (Herodotus, 1920). The revolt ended in 493 BCE with the Ionian states surrendering to Persian rule once again, but the events succeeding the revolt would bring about the Greco-Persian wars, which ended in 449 BCE, after Hecataeus had died in 476 BCE (Pearson, 1939). It was in this tumultuous political climate that Hecataeus travelled the Mediterranean and wrote his books.

Herodotus

Much of our knowledge of Hecataeus and other early Greeks comes from Herodotus, often known as the "father of history." All that remains of Hecataeus' work is mere fragments, meaning that most of the information we get about his work and his life comes from other sources. Herodotus' *Histories* has survived mostly intact, proving a wealth of information. Herodotus was born in 484 BCE, during the Greco-Persian wars. Most of his book is concerned with retelling the history of the war and the events surrounding it (Herodotus, 1920). It is the methods which he used to create his book that give him his title as the father of history. He was the first to use a systematic method of investigation to create a historical narrative, often piecing together works from different Greeks such as Hecataeus (Neville, 1977). Both Hecataeus and Herodotus were alive at the same time, although Hecataeus was an old man when Herodotus was a child. It is Herodotus' mentions of Hecataeus' work that help us piece together the impact Hecataeus had on geography and history. Herodotus simultaneously provides an insight into the books that Hecataeus wrote and a commentary on the work (Herodotus, 1920). One must be very careful to separate the two to determine what Hecataeus actually wrote, and what

Herodotus thought of his work.

Hecataeus' map

Before Hecataeus, Anaximander of Miletus created a map of the known world (Harley and Woodward, 1987). Hecataeus' map was based off of Anaximander's map and therefore bears similarities to it (Figure 3.2). Hecataeus' improvements made the map better, and his map and geography skills remained the best and most accepted until after Alexander the Great's conquests, despite being ridiculed by successors (Thomson, 1948). The idea of round continents surrounded by an circumfluent ocean was ridiculed by Herodotus and later philosophers such as Aristotle and Plato, and they warned against trusting relative distances on the map (Bunbury, 1883). When Hecataeus was making his map, he relied heavily on mathematical and ethnographic symmetry and balance, and mixed fact and fiction (Thomson, 1948). His idea that Europe and Asia were the same size was heavily criticized, as others thought that Europe had to be bigger than Asia, which future maps, such as the one made by Herodotus, show (Bunbury, 1883). His improved world map was done on a material called pinax, which is described by some as a wooden panel that could be written or painted on, but Herodotus speaks of it as a bronze tablet with the map engraved on it (West, 1991).

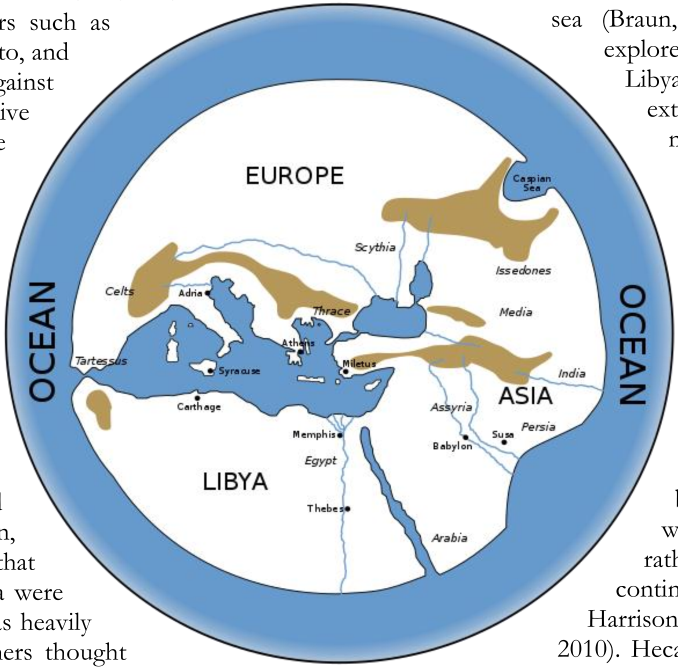


Figure 3.2. A reconstruction of Hecataeus' map, originally published by Edward Bunbury in 1883. The map is generated from descriptions given in Periodos Ges *and from other authors, such as Herodotus.*

Hecataeus, like Anaximander before him, put Delphi, in Greece, at the centre of the world. This was the accepted idea at the time, as Delphi was an important place for the Greek religion, as it was where Apollo's oracle resided (Bunbury, 1883). The idea of placing important religious areas at the centre of the world did not end with the Greeks, even as predominant religions shifted. In the middle ages, where Christianity was common, most maps had the city of Jerusalem at the centre of the world (Lukermann, 1961). Herodotus, while agreeing with some aspects of Hecataeus' map, such as Delphi being the centre, disagreed with Hecataeus and all others who saw the Earth as exactly round, with the ocean forming a border around it (Bispham, Harrison and Sparkes, 2010). The round Earth, encircled by Oceanus, the Greek personification of the ocean, was an idea originating from Homeric poems (Homer, 1914).

Hecataeus' travels allowed him to create a more accurate map than Anaximander. He explored Egypt and the Nile River extensively, and as a result the Nile delta is more accurate on Hecataeus' map, and the river is thinner, more akin to a river as opposed to a sea (Braun, 2004). He also explored the coast of Libya (modern Africa) extensively, and his map was the first to illustrate the coast in Libya, including the Psyllic Gulf, called the Gulf of Sidra today. Although Hecataeus' map illustrated the regions of Libya, Hecataeus believed that Libya was part of Asia, rather than its own continent (Bispham, Harrison and Sparkes, 2010). Hecataeus can also be credited with the definite and map-like arrangements of the inner zones of the gulf (Bunbury, 1883; Pearson, 1939).

Periodos Ges and *Genealogies*

Hecataeus created two books in his lifetime, *Periodos Ges* and *Genealogies*. It is the former that is concerned with his reputation as a geographer, while *Genealogies* is Hecataeus' account of history (Lendering, 2019). It is often thought that *Periodos Ges* is a written description of Hecataeus' map, although it is not clear which work was created first (Bunbury, 1883). It should be noted that Hecataeus was one of the first Greeks to question the idea that myth was actual fact, although he did generally record myths more than true history (Thomson, 1948). *Periodos Ges*, his other work, was concerned with descriptions of the world, and was divided into two books: one about Europe, and the other, Asia.

Although *Periodos Ges* was considered to be an account of geographical information about different locations, it also contains information on the culture, customs and manners of the people living there (Bunbury, 1883; Pearson, 1939; Harley and Woodward, 1987). It also contained information about the flora and fauna of the area, as well as the climate. It is believed that locations in Hecataeus' books and other Greek works at the time were a recording of the names of places and people in the order in which they appear to a coastal voyager on a boat, with a view to providing practical information for travelers (Bunbury, 1883). Modern historians would be able to use the order of the books as a map to where Hecataeus travelled and where he believed locations were in relation to each other. Due to the lack of surviving fragments of the book, however, much of the information that could have been gained from this is lost. The common Greek idea at the time was that the world was divided into two continents: Europe and Asia (West, 1991; Bispham, Harrison and Sparkes, 2010). *Periodos Ges* is split into two books, implying that Hecataeus believed the same, especially as descriptions of Egypt and Libya are found in the Asiatic book.

Figure 3.3. Satellite image of Egypt showing the fertile lands around the Nile River, compared to the dry, infertile land in the rest of the area.

Hecataeus supposedly travelled extensively to create *Periodos Ges.* Interestingly, there is only records of Hecataeus in Egypt, and it therefore cannot be confirmed that he actually travelled anywhere else himself, rather than receiving records from others who visited (Bunbury, 1883). In Egypt, the Nile River fascinated the Greeks. One thing that particularly interested the Greeks was the overflowing of the Nile, which deposited fertile muds to produce rich harvests in an otherwise rainless land (Figure 3.3). The river is what made the land livable and usable, and the regular flooding, especially during the dry season, confused the Greek travelers (Thomson, 1948). The Egyptians priests had no explanation for the constant overflowing and just accepted it, but the Greeks sought to explain it with reason, as they could not do without theories (Heidel, 1935). Two prevailing ideas were that the flushing came from heavy rains dropped by the winds on the Ethiopian mountain or from snow melting on the same mountain (Heidel, 1935; Thomson, 1948). Herodotus believed that the sun moved further away in summer and evaporated the river less.

Hecataeus' legacy

Hecataeus had a tendency to mix myth with geography, often giving etymological stories steeped in myth when describing a location. The best example of this is in Egypt. When describing the country, Hecataeus gave an account of Menelaus and Helen (main characters in Homer's *the Iliad*) in Egypt, not Troy (Heidel, 1935). The true story of the Trojan War is a mystery, as even Homer admits that there is another version than the one he told. When Herodotus recounts the story of the Trojan War, he chooses not to retell Homer's version, for which there is no evidence, but instead travelled to Egypt, where there is a temple with an unusual dedication, and priests who tell the story of Paris and Helen becoming shipwrecked in Egypt where Menelaus finds them, rather than returning to Troy (Neville, 1977). This quiet rebellion against Homer is a key moment in the development of history, and may have even made history as we know it possible. It is very likely that Herodotus was drawn to Egypt and the story of Menelaus and Paris there due to Hecataeus' account.

Another important legacy of Hecataeus' work is the idea of conceptual units. Before Hecataeus, there was no clear division between continents other than being separated geographically (Lukermann, 1961; Bispham, Harrison and Sparkes, 2010). After his time, Europe, Asia, and Libya became separate conceptual units, with their own geography as well as different people with different customs and beliefs (Harley and Woodward, 1987). Using his knowledge of the world gained by writing *Periodos Ges*, Hecataeus improved upon Anaximander's map, adding to the legacy of mapmaking.

Hecataeus was part of a group known as the "logographers," a group of individuals that concerned themselves with historiography and chronicling the world around them. The logographers, mostly hailing from Ionia, were the predecessors of Herodotus, and therefore the predecessors of history (Pearson, 1939). The work that they created drove the recording of history and geography forward and influenced Herodotus' adaption of a historical method. Hecataeus, consequently, can not only be considered to be a predecessor of the history of cartography and geography, but of history itself.

21st Century Maps

Over the past 2500 years, we have learned a lot about what the world looks like. While Hecataeus' map may not have been entirely accurate, he was still instrumental in driving the science of cartography forward. Today, we have many different ways of representing the Earth, including paper maps, Google maps and Google Earth, and geographic information systems.

Map of the world

Over the course of history there have been many different methods used to map the world, but the most common nowadays is with the use of satellite imagery, and satellites have also been used to confirm that the Earth is elliptical (Malling, 1992). An upgrade to satellites was the use of laser and doppler to compute accurate distances on the Earth's surface (Malling, 1992). Cartography and modern map making have been assisted by computer-assisted design, Geographic Information Systems (GIS), and Global Positioning Systems (GPS) (Ehrenburg, 2016).

GPS is particularly helpful for cartographers, surveyors and map makers to make precise geographic coordinates for features on Earth's surface. It has become the most useful tool for land and field surveying, and has been adapted for use in cars, boats, and phones, among other things (Ehrenburg, 2016). The use of GPS has also increased the speed at which geographic information can be obtained, taking minutes or hours (Ehrenburg, 2016) as opposed to years, as was the case in Hecataeus' time.

Google Earth and Google maps

Launched in 2005, Google Earth is a free piece of software that brings satellite imagery of our planet onto computers (Yu and Gong, 2012). The satellite images are mapped onto the globe, and the images can be zoomed in to provide much higher detailed images (Lisle, 2006). It also allows users to change their viewing angle, opening up more possibilities than the traditional birds-eye view of other maps (Lisle, 2006). It can show three dimensional projections of geographic landforms, giving a very realistic overview of the geography of an area, and not limited to two dimensions, as flat maps are (Lisle, 2006). Google Earth also allows users to do a 'mash-up,' where images can be overlain to provide relevant information (Goodchild, 2007).

Google Maps provides a similar service, in that it gives users a geospatial information platform upon which the general public can read, write, alter, store, test, represent, and present information in ways that they desire and in formats and environments they understand, despite not being experts in GIS (Miller, 2006). It has similar functions to Google Earth, in that it allows users to see information about certain areas including pictures, street maps, and information about popular locations, through its integration with Google's search engine (Miller, 2006).

Geographic Information System

Geographic Information System (GIS) is a system designed to store, capture, and analyze geographic and spatial data. GIS relies on the ability to specify locations on the Earth's surface, using coordinates such as longitude and latitude or the Universal Transverse Mercator (UTM) system (Goodchild, 2007). GIS has many uses, including archaeology, hydrology, and mineral resource mapping (Goodchild, 2007). The roots of GIS are buried in cartography, as GIS could not have been developed without knowledge of maps and the way they are created.

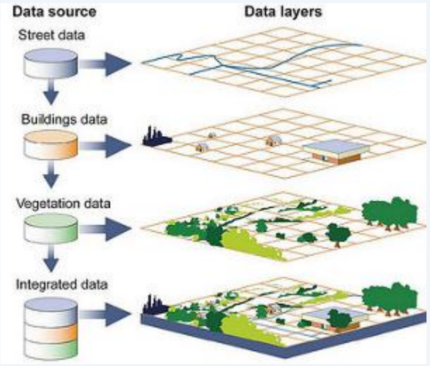


Figure 3.4. An example of how layers of raster and vector data can be complied on top of each other to generate images that can be useful.

Two different data types are used in GIS, vector data and raster data (Auerbach, 2018). Vectors can exist in three ways: as a point, a line, or a polygon. Raster data is a high-resolution image comprised of a grid of pixels. Vector data is much simpler than raster data. Overlaying these data points over a map can allow scientists to compute spatial analysis, map topography, and look for natural resources (Figure 3.4) (Auerbach, 2018).

Thanks to Hecataeus and his work, we have developed many different ways of exploring and describing the earth around us. Cartography, geography, and history are greatly influenced by Hecataeus' map and books. Although we now understand exactly what the Earth's surface looks like, technologies and techniques such as GIS are being created and refined to help us learn even more about the world around us.

Galileo Galilei

Galileo Galilei (1564-1642) is a, if not the, central significant figure of the Scientific Revolution of the 17th century (Figure 3.5). His work has had infinitely many impacts on modern science. He aided in establishing the modern scientific method and made many contributions to the fields of mathematics, astronomy and physics (Machamer, 2017). Additionally, he is known for having come to science's defence when the Catholic Church was a large and influencing power, attempting to cease the progress of science (Waters, 2018). Galileo devoted his life to learning about the sciences and developing knew theories. Additionally, he made it a point to stand up for what he believed in and what he thought was important. His dedication to science has made him one of the most important scientific historical figures.

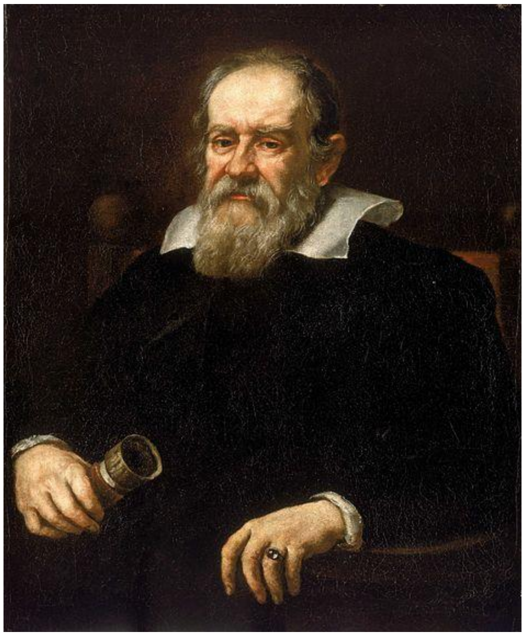


Figure 3.5. A portrait of Galileo Galilei.

Brief Biography

In order to appreciate his discoveries, it is vital to understand Galileo Galilei's background and life. He was the first of seven children, born to a relatively noble Florentine family (Waters, 2018). He was home-schooled by his father with the help of a tutor, until he entered the University of Pisa in 1581 as a medical student. His studies did not fully captivate his interest and he found himself conducting various scientific and mathematical experiments in his spare time (Waters, 2018). A sole year into his studies, he discovered the isochronal movement of pendulums by observing a chandelier in the Pisa cathedral. He performed a set of experiments to validate this discovery. Five years after enrolling in the University, Galileo retired from his medical studies and returned home without a degree in 1586 (Waters, 2018). He then acquired a position as a lecturer of mathematics in 1589 at the University of Pisa, with the help of some friends. Later, his friends once again aided him in looking for another position and he was placed as the chair of mathematics at the University of Padua (Waters, 2018). In Padua, he met his wife and had three children (Machamer, 2017). Although the University of Padua offered him professorship for life around the year 1610, Galileo rejected the offer and instead returned to Florence to become the grand duke's chief philosopher and mathematician (Waters, 2018). In Florence, he flourished and gained continental recognition through various publications and the invention of his telescope. In the subsequent years, he garnered a hateful following and began an opposition with the Church, which believed that his publications were blasphemous in nature as a result of his support for the Copernican model of the solar system (Waters, 2018). This opposition led to Galileo being sentenced to house arrest for the rest of his life (see *The Galileo Affair*). The years after his condemnation brought some trouble to Galileo: his favourite daughter died in 1634 and he became blind in 1637. Despite his house arrest, his fame did not waiver and many famous scientists – such as Thomas Hobbes – travelled hundreds of kilometers in order to meet Galileo. Unfortunately, he died under house arrest in 1642 (Waters, 2018).

Galileo's life was not without merit. He has caused a lasting impact on various scientific disciplines, such as geodesy.

Galileo and Natural Motion

During his time as the mathematics chair at the University of Pisa (1589-1592), Galileo composed both an essay and a dialogue on motion, neither of which were published until these manuscripts were discovered and translated (Drabkin, Drake and Galileo, 1960). His studies within these essays focused primarily on the effects of weight on movement, inertia and the motion of free fall, with the goal of disproving a number of Aristotle's postulates using scientific reasoning rather than assumption and experience (Drabkin, Drake and Galileo, 1960). In particular, Galileo argued against Aristotle's explanation of projectiles; it was originally believed that the acceleration of the projectile at the end of its path was a result of a shift in air molecules. In essence, the philosopher proposed that the falling object created a void behind it as it fell and that air particles rushed to fill said void, applying a pushing force to the back of the object and accelerating its motion (Drabkin, Drake and Galileo, 1960). Galileo did not agree with this view, and instead began to describe the force of gravity, stating that the object will lose the effects of the upwards force and instead be overcome by an alternative downwards force as it neared the ground (Drabkin, Drake and Galileo, 1960). He failed, though, to describe what this force is, but continued to experiment with weight and acceleration using inclined surfaces (Drabkin, Drake and Galileo, 1960).

In 1630 he began compiling "*Discorsi e dimostrazioni matematiche intorno a due nuove scienze*", and by 1638 it was published (Drake and Galileo, 1973). This work saw new insights into the elusive concept of gravity, and it was here that he described the acceleration of free fall. As translated by Stillman Drake, Galileo observed that:

> … *the degree of swiftness acquired in the first and second little parts of time [after descent of the object has begun] is double the degree that the moveable acquired in the first little part; and the degree that it gets in three little parts of time triple…*

In this, he essentially described the acceleration of an object due to the force of gravity, discovered to be at a rate of 32 ft/s^2 ($9.8 m/s^2$) (Drake and Galileo, 1973). This was achieved through numerous experiments involving the development of ratios between speeds and distances of balls rolling down various inclines (Drake and Galileo, 1973). He described the law of acceleration in free fall, as well as explained that the acceleration of an object is not dependent on mass but rather its resistance (Drake and Galileo, 1973). These writings catalogued a cohesive and chronological account of his findings, made useful by their detail and logic.

Galileo and Heliocentricity

Though evidence to prove that the Earth was round had first been established in 500 B.C. by Pythagoras, the theory was deemed incorrect by the Catholic Church and science as a whole took a step backwards (Greene, 2017). The 17th century was a time of Catholic reign (see *The Galileo Affair*) and the flat Earth theory was the popular estimation of our planet's shape (Greene, 2017). In essence, it was biblical belief that the Earth was the centre of the universe, with the sun and other planets orbiting around it in close proximity; further, the flat shape explained the location of heaven above and hell below, as detailed in the Bible (Greene, 2017).

Galileo's interest in astronomy was facilitated by his creation of a telescope in 1609 (Figure 3.6; Drake and Galileo, 1973). He first used the instrument to study the Moon and observed that rather than being a smooth orb, the Moon had a terrain similar to Earth's (Green, 2017). This was determined using his training as an artist, which helped identify that the causes of the shadows he had seen on the surface of the Moon were mountains (Green, 2017). This started to alter his view on Aristotelian astronomy, and he realized that bodies in the solar systems may be formed in similar ways to Earth (Greene, 2017).

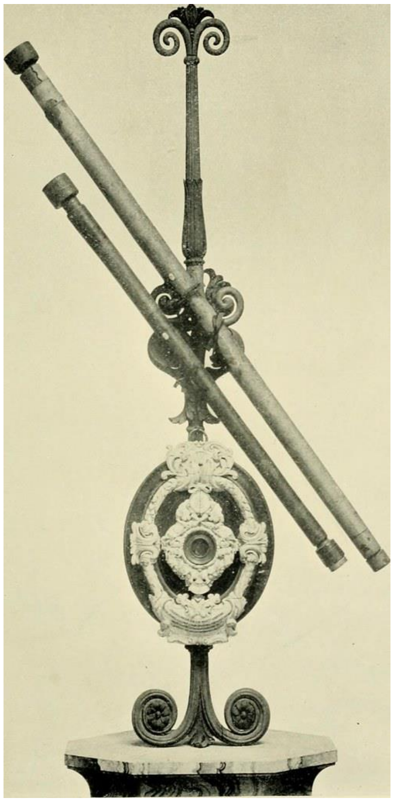


Figure 3.6. A depiction of Galileo's telescoscope which he used to observe the moons of Jupiter.

Following this discovery, Galileo turned his attention to Jupiter where he noted the presence of four orbiting bodies, coined the Medicean Stars (Greene, 2017). A former student of Galileo's speculated that if the Copernican model were true, then Venus should exhibit phases similar to the moon. If the Ptolemaic model (geocentric) were true, then Venus should only have crescent phases. The contrast in phases is attributed to the differing orbits around the different celestial bodies (Greene, 2017). Galileo focussed his perspicillum on Venus. After careful observation, the collected data clearly supported the Copernican model of the solar system, since a half-moon-type phase had been observed (Greene, 2017). This discovery had implications in both the determination of longitude, as well as became further proof for the Copernican system. The Ptolemaic system was the chief theory at the time as it supported the Bible's belief in the flattened Earth hypothesis (Greene, 2017). Galileo inspired a change in thought surrounding the structure of the solar system, and he was able to defend both the Copernican hypothesis from a scientific and biblical perspective (Greene, 2017).

Galileo, Newton and the Field of Geodesy

Galileo's work in both motion and astronomy opened doors to a number of new disciplines in science. Born the year that Galileo died, Sir Isaac Newton (1642-1727) was considered to be at the forefront of the scientific revolution. His contributions to physics and mathematics are immeasurable, and his work on motion and the universal law of gravitation have played a significant role in numerous fields of science (Figure 3.7; Westfall, 1979). Interestingly, a number of his theories were based on the work of Galileo; Newton further investigated his work on forces to better understand dynamics, and also studied his dialogues on free fall (Westfall, 1979). He pieced together the work of Copernicus (1473-1543), Galileo and Kepler (1571-1630) to develop his theory of universal gravitation (1687) which states:

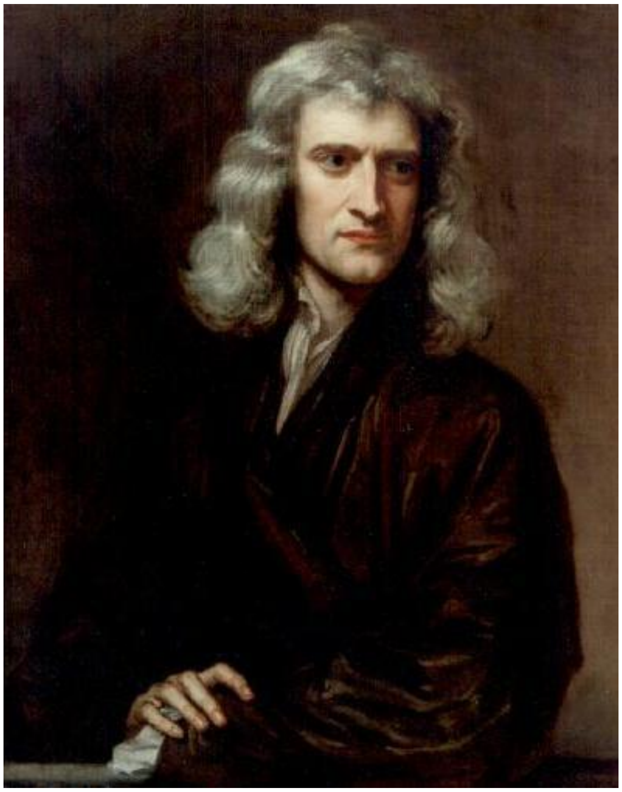


Figure 3.7. Oil portrait of Sir Isaac Newton.

Every particle attracts every other particle in the universe with a force proportional to the product of their masses [or] inversely proportional to the square of the distance of their centers.

Furthermore, Galileo's strong belief in the Copernican system, as well as his work to support it, prompted scientists to study the shape of the Earth (Westfall, 1979). This, alongside the principles of the gravitational field in which Galileo experimented on and Newton proposed, became the basis of a new field of Earth science: geodesy. As originally defined by F.R. Helmert (1843-1917) in 1880, the field is focused on the mapping and measurement of the Earth, including its gravity (Zhiping, Yunying and Shubo, 2014). Though some geodetic principles had been discovered and studied as early as third century B.C., the field experienced its true beginnings in the 17th century when Christiaan Huygens (1629-1695) used Newton's findings on gravity to propose a more detailed model of the Earth's shape (Zhiping, Yunying and Shubo, 2014). Almost 60 years later, A.C. Clairaut (1713-1765) used gravimetry to further assess Earth's shape and the two became the pioneers of the field (Zhiping, Yunying and Shubo, 2014).

Measurements of arc length by a number of scientists in the 18th century helped refine the data of Huygens (Zhiping, Yunying and Shubo, 2014). He had believed that the Earth was an oblate spheroid flattened at the poles, but rather it was found that it was an ellipsoid flattened at its poles, proved by the proportional increase in meridional arc per degree with increasing latitude (Zhiping, Yunying and Shubo, 2014). This is not entirely true, as ellipsoidal shapes cannot account for the topography of the Earth, and so the concept of a geoid ensued. This was accomplished through the development of the Stokes integral in 1849 by Sir G.G. Stokes (1819-1903), which examines the surface of the Earth using terrestrial gravimetric results. The resulting surface was coined the geoid by Johann Benedict Listing (1808-1882) in 1873 (Zhiping, Yunying and Shubo, 2014). These findings branched off into the field of gravimetric geodesy, using Galileo's work as their guidance.

Geodesy and the Composition of the Earth

The use of acceleration due to gravity to deduce both the mass and structure of the Earth also became a large part of geodesy by the late 18th century, when Cavendish (1797-1810) determined the value of *G*, the gravitational constant (Ducheyne, 2011). His experiments involved pendulums, and they were based on the Galilean studies of acceleration in free fall. In this, he hoped to determine the density of the Earth (Ducheyne, 2011). Using the value of *G*, he was able to calculate the mass of the Earth, and from that he found that the average density of the Earth was higher than that of the rocks at the surface of the Earth (Zhiping, Yunying and Shubo, 2014). Interestingly enough, over a century ago, Galileo had described the behaviour of light and heavy objects and their tendencies to travel to specific places (i.e. heavy things go to the centre while light things are found outside) with respect to mechanics and motion (Drabkin, Drake and Galileo, 1960). He had believed that the denser the object, the smaller the space it occupies and therefore, the less dense, the more space it occupies (Drabkin, Drake and Galileo, 1960). In fact, he draws a parallel to Earth and Air in his writing, and goes on to essentially explain the fundamental principles of Cavendish's discovery:

> … *the form of the earth caused its matter to be compressed in a very narrow space… But in a sphere the spaces become narrower as we approach the center, and larger as we recede from the center...*

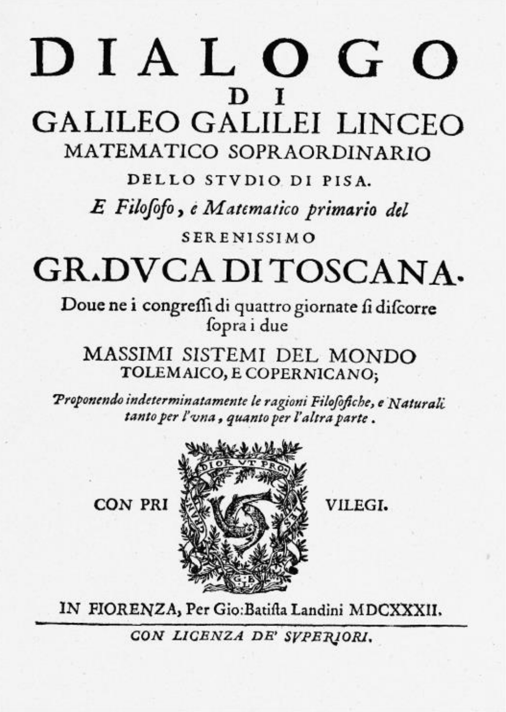
This is essentially describing the concept of differentiation of the Earth; that the denser matter will reside at the core, and increasingly get less dense as one reaches the surface (Walters and Reidar, 2004). This has become a principle understanding in the field of Earth sciences and without it, the current understanding of geology and geodesy would be limited.

Galileo and the Catholic Church

The twenty-year battle between the Roman Catholic Church and Galileo Galilei is now commonly known as the Galileo Affair (Gingerich, 1982). The Galileo Affair caused Galileo to abandon the rules of science that had been set in his time in order to determine a new set of rules, which are still used to this day.

In 1543, when Copernicus first published "*De revolutionibus orbium coelestium"*, there was no strong piece of evidence that could completely support the heliocentric model of the solar system (Gingerich, 1982). Decades later, it was Galileo that was able to provide this evidence by carefully observing the four moons of Jupiter and the phases of Venus using his perspicillum.

Following this discovery, Galileo changed his quiet support of the heliocentric hypothesis (Gingerich, 1982). Galileo's stance quickly gained popularity. Shortly after, Galileo was asked to defend his view that the Bible raises no objections to the Copernican system. Galileo provided a thorough analysis which he addressed to the Grand Duchess Cristina in a letter (Gingerich, 1982). The analysis stated that the Bible and the heliocentric model did not conflict. His letter to Duchess Cristina was circulated throughout society and Church officials condemned the Copernican model as a result of its growing popularity (Gingerich, 1982). In essence, the Church was preventing individuals from stating opinions or hypotheses that may conflict with the Church's teachings. The Church then recalled Copernicus' De revolutionibus and amended it so that its contributions to accurate time-keeping were kept, but any mention of the heliocentric model was removed (Gingerich, 1982). Following the recall, Galileo was cautioned against publicly and blatantly supporting the Copernican system by the pope. Galileo respectfully followed the caution and was sent away peacefully. He followed the Church's request for seven years. Then, a new - more liberal - pope was elected: Maffeo Barberini (Gingerich, 1982). However, Barberini maintained the Church's position that Galileo should remain neutral when speaking about the potential model of the solar system. Soon after, Galileo attempted to write a neutral dialogue which spoke of the Ptolemaic and the Copernican models. Unfortunately, his work titled "*Dialogo sopra i due massimi sistemi del mondo, tolemaico e copernicano*" was deemed far from neutral by the public and his enemies (Figure 3.8). Following this incidence, the pope was made aware of when Galileo had first been cautioned to remain neutral and silent (Gingerich, 1982). Reminded of this event, the pope was furious! In 1633, Galileo was ordered to go to Rome immediately, despite the fact that it was an arduous journey for the determined scientist, who was now 70 years of age (Gingerich, 1982). In Rome, he was accused of disobedience. The annotated script of Galileo's caution was never notarized and the pope who had ordered his neutrality had died. Thus, in court, the caution had no meaning (Gingerich, 1982). The case was held for a few months, until the pope decided to interrogate Galileo once again. He entered the following statement into the Book of Decrees:



DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filoſofo, e Matematico primario del
SERENISSIMO
GR.DVCA DI TOSCANA.
Doue ne i congreſſi di quattro giornate ſi diſcorre
ſopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filoſofiche, e Naturali
tanto per l'vna, quanto per l'altra parte.

CON PRI VILEGI.

IN FIORENZA, Per Gio:Batiſta Landini MDCXXXII.
CON LICENZA DE' SVPERIORI.

Figure 3.8. Frontispiece and title page of Galileo's work: "Dialogo sopra i due massimi sistemi del mondo, tolemaico e copernicano", Galileo's incriminating work.

Galileo Galilei… is to be interrogated concerning the accusation, even threatened with torture, and if he sustains it, proceeding to an abjuration of the vehement suspicious of heresy before the full Congregation of the Holy Office, sentenced to imprisonment…

Galileo, threatened with torture, succumbed to the pope and stated:

I do not hold and have not held this opinion of Copernicus since the command was intimated to me that I must abandon it. I am here to submit, and I have not held this opinion since the decision was pronounced, as I have stated.

A final document stated that there is nothing more to be done. This document was signed by Galileo Galilei.

The years following his trial were not facile. He was sent back to his home in Arcetri where he remained under house arrest and died in 1642 (Gingerich, 1982).

Galileo's Impact on the Field of Geodesy

Evidently, Galileo Galilei was a man who was incredibly devoted to science and to his work. He sacrificed his entire life to science and has since caused infinitely many impacts on the scientific community and its developments. Although his main area of work was physics and mathematics, he also made a large impact on Earth sciences. His contribution to the development of the modern scientific method and to the development of the field of geodesy has been invaluable. We will explore these topics further in the pages to come.

Galileo and the Modern Scientific Method

The scientific method is the process by which scientists attempt to discover accurate and consistent new information about some aspect of the universe (Dziak, 2018). Galileo Galilei was one of the six founding fathers of science and of the scientific method (Betz, 2011). His work followed the general outline of the scientific method: he employed a hypothesis (or study question), observed and analyzed the results of an experiment and then developed a conclusion based on said experiment. The scientific method is now fundamental in the way modern scientists design and perform scientific studies. Sciences of the Earth have followed suit, of course, and Earth scientists employ the scientific method in their studies. Take, for example, the glacial sedimentologist, Carolyn Eyles. She is both a renowned and appreciated glacial sedimentologist and professor at McMaster University. One of the studies she was a part of used architectural element analysis to delineate and analyze the internal sedimentary architecture of the Tiskilwa Formation (Slomka et al., 2015). This study began with the task of determining the sedimentary heterogeneity and architecture, and depositional history of till in order to create more accurate three-dimensional models of the sediments' facies geometry, fluid flow pathways and contaminant migration routes. The published study outlines the methods used in the study, such that the study could be re-conducted by any scientist. The authors also analyzed the results and provided a conclusion which can be further applied to the architectural analysis of till sheets and provide insight to groundwater flow pathways through till (Slomka et al., 2015). As one can see, this study evidently applies the scientific method. The scientific method has provided an unbiased framework for all science experiments in all fields, including Earth sciences and has made an enormous and lasting impact on the way all scientists undergo endeavours in their field.

Modern Applications of Geodesy

Galileo's work on gravity and geodesy has impacted the field's progression in the modern age (Zhiping, Yunying and Shubo, 2014). It has expanded to have implications in multiple areas of science; in particular, it helps support the launch and missions of space craft. Generally, precise surface coordinates for both tracking stations and launch areas, as well as use of accurate geodetic coordinate systems, is required for successful mission of the spacecraft. Further, data on the gravitational field and the gravitational parameters of the area surrounding the measured surface points are required (Zhiping, Yunying and Shubo, 2014). These data are important for tracking the crafts as they travel through space (Zhiping, Yunying and Shubo, 2014). Knowing the topography and accurate coordinates of several locations on Earth is incredibly important in order to also determine the location of space crafts and survey their status. In this way, the Earth sciences have made a very large impact on the astronomical community.

NASA's Space Geodesy Project uses a number of different systems to determine a number of Earth's geodetic properties (NASA, 2019).

Figure 3.9. Very Long Baseline Inferometry antenna found in Ny-Ålesund.

These systems include Very Long Baseline Inferometry (VLBI), Global Navigation Satellite Systems (GNSS) and the Doppler Orbitography and Radio-Positioning by Integrated Satellite (DORIS) Systems (Figure 3.9; NASA, 2019). These are used to appropriately determine the coordinate systems required for tracking of spacecraft; this is done by defining the Terrestrial Reference Frame (TRF), which provides the fundamental baseline data for all space and Earth based geodetic observations.

This project has had an immense number of impacts on the understanding of Earth processes, including the dynamic nature of Earth's surface in relation to tectonic processes (NASA, 2019).

Louis Agassiz and the Ice Age Theory

At the beginning of the 19th century, geologists across Europe believed glaciers were a phenomenon specific to high altitudes and latitudes, with no role in geological processes. However, by the end of the century, many considered glaciers to be a significant and powerful factor in the formation of modern landforms and superficial deposits, largely due to the work of Louis Agassiz. Although Agassiz was not the first to propose a glacial theory or the even first to postulate the idea of an Ice Age, his name is widely associated with both of these elements. This was because of Agassiz's unparalleled desire to advance the sciences and more importantly, his reputation as a naturalist. Nevertheless, there is no doubt that Agassiz's work in glaciology advanced our understanding of glaciers popularized the field for scientists around the world.

Glaciology before Agassiz

Several geologists were making important observations of glaciers in the early 19th century before Agassiz entered the scene. Ignaz Venetz was one of the pioneers of glaciology who studied glacier landforms in southern Switzerland and made the first analyses of climate-glacier-landscape interactions (Macdougall, 2013). He worked with Jean-Pierre Perraudin, who was a mountain guide in a small Swiss town and had vast knowledge pertaining to the alpine terrains of the Val de Bagnes, a nearby valley. He was the first to develop the basis of an Ice Age in 1815 when he estimated that moraine ridges and scratched rocks over tens of kilometres away from active glaciers displayed a period when the glaciers were much larger (Carozzi, 1966).

Jean de Charpentier was another geologist who began to study glaciers in the Rhone Valley of France in 1818 and was the first to see a clear relationship between the elevation of erratic blocks and the vertical patterns of rock walls smoother by glaciers (Macdougall, 2013). He also concluded that rocks below erratic blocks bore signatures of glacial contact and were smooth while rocks above erratic blocks were not worn smooth since they were above the glacier surface (Finnegan, 2004). Venetz and Perraudin's research provided a method to determine the length and width of glaciers by use of the terminal and lateral moraines and Charpentier found a way to estimate the vertical height of an ancient glacier (Finnegan, 2004). Finally, another important figure was Jens Esmark of Denmark, who believed that large glaciers in northern Europe created moraines and caused the movement of large erratic rock (Macdougall, 2013). Overall, Venetz and Perraudin, Charpentier, and Esmark arrived at similar conclusions regarding glaciers in Europe while investigating different geographic areas. Therefore, the foundation for the theory of an Ice Age was laid but not widely known. These great geologists lacked someone who would bring glacial theory into the spotlight and spark the massive field of glaciology.

Early Life

Jean Louis Rodolphe Agassiz was born on May 28, 1807, in village of Môtier in French-speaking Switzerland (Guyot, 1878). Agassiz was a bright student who loved the sciences from a young age. The first words he wrote in his memorandum from his final year of preparatory study were that he wished "to advance in the sciences", despite his parents' pressure to become a medical doctor (Lurie, 1966). In an effort to please his parents, Agassiz first went to school in Zurich, Switzerland, and then in Munich, Germany to obtain his medical degree in 1826 (Figure 3.10). However, along the way, Agassiz's many professors continuously sang

Figure 3.10. A lithograph of Louis Agassiz from the early to mid-19th century by Antoine Sonrel.

their praises for his talent in the natural sciences and expressed their hopes that he would help them with their work (Lurie, 1966).

Agassiz's study of Fossil Fishes

Agassiz discovered a passion for studying fish fossils, stating that fish were creatures that represented the entire history of nature itself (Lurie, 1966). While working relentlessly in the field in addition to taking several paleontology classes and completing his medical degree, Agassiz gained many connections in Munich who further intensified his desire to make a living as a scholar. He also met his wife, Cécile Braun, at this time (Irmscher, 2013). His study of fossil fishes also took him to Vienna before he returned to his hometown in Switzerland, which, to him, felt extremely confining. Thus, he decided to head to the National Museum of Natural History in Paris, the centre for European science in 1831.

In Paris, Agassiz impressed Georges Cuvier, one of the great naturalists at the time, with his research in fossil fish and was given permission to work in Cuvier's laboratories at the national museum (Woodward, 2014). Despite the difference in status between the two men, Agassiz thought of Cuvier as a competitor; he boldly wrote letters to his mother saying that, with the access to the fossils that Cuvier had given him, he had a chance of completely beating Cuvier out in the field of fossil fishes (Irmscher, 2013). Cuvier taught Agassiz many concepts that would allow him to go on and conduct his own investigations; he showed him how to reconstruct fragmentary fossil remains according to the principle of correlation of parts and how to overall infer details from the past using current evidence (Lurie, 1966). Something of utmost importance that Cuvier ingrained in Agassiz was the theory of catastrophism. This idea, coupled with the predominantly Christian society that Agassiz lived in, cemented his views on the cause of all aspects and changes within paleontology and geology (Lurie, 1966).

Discovering the field of Glaciology

Returning to Neuchatel, Switzerland in 1832, Agassiz was content to settle down into a life of writing his research. Agassiz's son Alex was born in 1835, and he was cherished by Agassiz despite his withering marriage. Money was not scarce in the household, but Agassiz insisted on hiring multiple assistants to help his work, which restricted personal spending to only bare necessities much to his wife's protests (Lurie, 1966). In his attempt to publish with maximum efficiency, Agassiz even asked his wife to sketch figures for his own work (Figure 3.11).

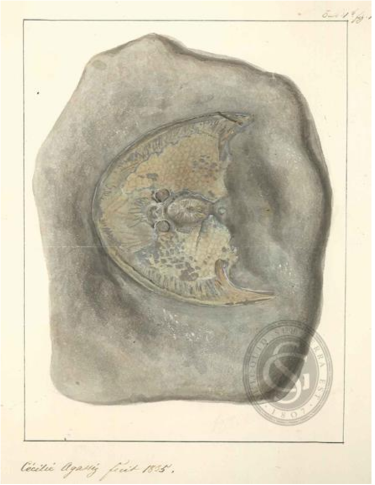


Figure 3.11. The head of an Early Devonian fossil fish, Cephalaspis lyelli*, drawn by Cécile in watercolour in 1835.*

Completely focused on his research and furthering his career in science, Agassiz immediately accepted when his friend, Jean de Charpentier, invited him to Bex, France to discuss the possibility of glaciers as an explanation for the then unexplained geological features (Lurie, 1966). Charpentier showed Agassiz how to read signs of ancient ice, such as polished bedrock, degraded moraines, and hanging valleys in the Rhone Valley of Bex, and explained how glacial theory may be the reason that moraines and erratic blocks were present in the Alpine regions of Switzerland. Seeing the ideas postulated by Charpentier in person began to change Agassiz's view on glacial theory (Woodward, 2014).

Soon after in 1837, Karl Friedrich Schimper, a friend of Agassiz's from Munich, published a poem called "Die Eiszeit Ode", which directly translates to the "Ice Age Ode". The poem mentions Schimper's beliefs that large parts of the world were once covered in ice in "world winter" periods, which may have been the first record of the idea of an Ice Age (Brockhaus and Schimper, 1838). Unfortunately, scientific reception to the poem was limited because of its exaggerated tone and complex metaphors (Irmscher, 2013). However, this poem triggered Agassiz to begin his own research in the Swiss Alps on signs of glaciation.

Within the same year, Agassiz claimed that Ice Ages occurred in cycles, with the most recent during the Pleistocene epoch, and ice had covered the world from the North Pole to the Mediterranean and Caspian seas in front of the Swiss Society of Natural History (Knight, 2011). He called upon the knowledge he gained from Cuvier and Charpentier, stating that the glaciers of the present were remnants of the glacial events of the past and that recession of glaciers left key features such as scratched and polished rocks and giant boulders. While he acknowledged the work of Schimper and other geologists in front of the Society, he emphasized that his conclusions followed common sense and that anyone would have naturally arrived at his conclusions regardless of prior knowledge about glaciology (Lurie, 1966). Although the core of an Ice Age's existence was not Agassiz's idea, he did add in his original hypothesis that glaciation occurred in series over time, and there were likely many Ice Ages before the most recent one in the Pleistocene epoch (Lurie, 1966).

Religious Motivations of Glaciology

There was resistance to the ideas Agassiz presented, in part because a common theme in the 19th century was attempting to reconcile Scripture with science, with Diluvialism as the most popular concept. Diluvialism applies religious beliefs to explain the natural world, using scientific hypotheses as a medium. Diluvialists stated that the biblical flood shaped the landscape and was the cause of the extinction catastrophe Cuvier believed in (Fick, 1973). Similarly, Agassiz defended special creationism, in which the Divine Being recreated species after the extinction event. His glacial theory supported his beliefs that the animals did not evolve or migrate. As well, the landscapes in question did not fit with the known characteristics of floods; the large swaths of unsorted, unstratified material would have been somewhat sorted by water, and the sharp angles preserved in the rocks would have been rounded by the force of the flood (Fick,1973). In addition, the scientific realm of the time generally viewed the Earth as a planet that had been cooling off since the beginning of its creation, and Agassiz's views directly opposed this idea. Thus, Agassiz put aside his work on fossil fish every summer from 1837 to 1845 to completely spend his time in the Swiss Alps, with visits to England, Scotland, and Germany to collect more evidence for the idea of an Ice Age existing in the Pleistocene epoch (Figure 3.12) (Lurie, 1966).

Figure 3.12. Agassizhorn, a mountain in the Bernese Alps of the Swiss Alps named and studied by Agassiz on an expedition in 1840.

Studying Glacier Flow

In 1840, Agassiz traveled to Unteraargletscher, a glacier sourcing the Aare river in the Bernese Alps, to investigate the flow of the glacier. Agassiz drilled shallow holes into the glacier no deeper than seven meters and set a transverse line of flow markers set into the shallower of the holes. Agassiz wanted to measure the down-glacier displacement the following year but unfortunately, the flow markers had entirely melted when Agassiz returned in 1841. However, Agassiz was persistent and drilled a new set of holes, three to five meters deep with repositioned flow markers (Clarke, 1987). Agassiz also did not return to Unteraargletscher alone; in Glasgow the year before, he met James D. Forbes and introduced the physicist to glaciology. Forbes agreed to accompany Agassiz to Unteraargletscher the next summer, but once there withheld any remarks on Agassiz's research, which was an unrewarding process for Agassiz. Even more disheartening, Forbes had been carefully observing Agassiz's research and published his findings after returning from the glacier (Lurie, 1966). Agassiz was deeply betrayed. The following year, Forbes employed Agassiz's methods on the glacier la Mer de Glace to great success, accomplishing in days what Agassiz had been attempting for a year (Clarke, 1987).

Études sur les glaciers

Even with the betrayal of Forbes, this was an exhilarating time in Agassiz's career; he began to gain acknowledgement from his work in glaciology, a field which he had only begun to study as an aside to his work in fossil fish. He basked in the public acclaim he received and further disseminated his ideas in his travels (Lurie, 1966). Furthermore, Agassiz worked efficiently and with purpose, publishing a 363-page summary of his findings from three years of research in 1840 titled *Études sur les glaciers*.

It highlighted four important concepts, all bolstered with his personal field research. First, there was explanation of how glacial movement led to the large boulders, erratic blocks, and other disjunct geological features in Switzerland. Two other concepts were that the Swiss Alps arose by an uplift underneath the glaciers and that the cause of the ice was a sudden drop in temperature globally, a part of the climatic cycle that Earth continuously undergoes. Finally, glaciers once covered large parts of Europe at one time in an Ice Age. Only the idea of an Ice Age was original to Agassiz, if only partially, but Agassiz's detailed data further strengthened the other ideas (Carozzi, 1966).

In addition, his book contained extremely detailed diagrams. For example, in Figure 3.13, Agassiz shows the Lauteraar glacier and Finsteraar glacier on either side of a moraine that includes accumulations of rounded rock fragments resting along the border of the glaciers, the study site that he visited with Forbes. Agassiz explains that the glaciers which "drag along with them all the loose objects they encounter, which are continuously ground against each other and against the rocky walls forming their bed" (Agassiz and Bettannier, 1840).

Figure 3.13. "Glacier inférieur de l'Aar, partie supérieure, avec la cabane de M. Hugi"; a hand-drawn sketch by Joseph Bettannier. The sketch appeared in Études sur les glaciers *by Agassiz.*

The timing of his publication was carefully chosen. Agassiz knew that Charpentier was preparing a large publication, and he deliberately released his book before Charpentier's publication date in 1841. To Charpentier's dismay, his book received little attention because it contained the same main ideas as Agassiz's, except that it was missing the theory of an Ice Age. Agassiz's book was also released in both French and German, resulting in a wider a reach and the general public associating him with not only the idea of the Ice Age but also glacial theory (Lurie, 1966). However, at least Charpentier was acknowledged within Agassiz's book; Schimper's name was never mentioned, which led to another relationship that Agassiz lost (Irmscher, 2013).

Moving to the Americas

Up to 1846, Agassiz continued his work in fossil fishes and glaciers and published work in both areas. However, money was running short for Agassiz and his wife had left him in 1845, so when he was offered an opportunity teach zoology and investigate the natural history and geology of North America, he quickly grabbed it (Lurie, 1966). His reputation skyrocketed in America and he became a beloved figure in American science thanks to his charm and compassion in natural science.

However, people were transitioning from a religious to an evolutionary viewpoint on the origin of life and changes in the Earth. This shift was catapulted by Darwin's *Origin of Life* being published in 1859. Soon, in the 1860s, Agassiz was one of the last well-known scientists to hold onto the idea of catastrophism and adamantly refute Darwin's theories. During this time, fellow naturalists began to lose their admiration for Agassiz, commenting that scientists should think critically and openly about new evidence that may oppose their standpoints (Roberts, 2011). In an attempt to preserve his fame, Agassiz conjectured that an Ice Age occurred in Brazil based on the similarity of land formations and geological features in the Amazon Valley of Brazil to what he had observed in North America and Europe (Lurie, 1966). This was shocking since established naturalists like Alfred Wallace had explored the Amazon Valley in detail and reported no signs of glaciation. Agassiz interpreted loose rocks and pebbles in unstratified clay deposits as debris from moraines and erratic boulders and polished rocks as further evidence of glacial action. However, he admitted to a lack of glacial evidence in his field work, but claimed that it was due to the hot climate of the area eliminating further geological evidence (Roberts, 2011).

Ultimately, Agassiz was confined in his belief of special creationism and his pride, which led to a lack of empiricism. It was clear that he was trying to convince the world that the Ice Age covered as much land as possible to dispute Darwin's theory that there is a genetic relationship between the organisms before and after the Ice Age. The Ice Age for Agassiz was the great catastrophe that wiped the Earth of previous organisms and sprung entirely new species as a result. Agassiz's protests against evolution quieted down after he published his work on Brazil due to its negative reception in the scientific realm, but he continued to look for more objective evidence that supported his beliefs until his death in 1873 (Lurie, 1966).

Overall, Agassiz was a very bright man who did not let anyone or anything stand in between him and the completion and dissemination of his research. His fixation on his science did not falter even through his unfortunate encounter with Schimper and the separation from his wife. Furthermore, he was a proud man who never doubted his skills and never thought to credit those who aided him. His early success and talent in addition to the catastrophism that was instilled in him by his beloved mentor shaped the stubbornness and pride that led to the perilous end to his academic career. Despite the many intricacies in Agassiz's life, there is no doubt that he made important modifications on the idea of an Ice Age covering the Earth and thrust glaciology into the spotlight through his work.

Modern Evidence of Ice Ages

Since Agassiz had first proposed a period in which the world was covered in glacial ice, scientists have concluded that the Earth has been alternating through glacial and interglacial periods since the Mesoarchean era, 3,200 million years ago (Bailey, Harff and Sakellariou, 2017). Great strides have been made in discovering further evidence of Ice Ages, and several possible causes of Ice Ages have been introduced, an area that Agassiz himself never delved into.

Chemical Evidence of Ice Ages

The three types of evidence supporting glacial ages are geological, chemical, and paleontological. Of the three, geological and paleontological evidence, which involve the observation of landscapes and features and the correlation of fossils over varying time periods and environments, respectively, have been studied for centuries, dating back to before Agassiz's glacial theory (Fick, 1973). However, the chemical evidence of Ice Ages, the analysis of isotope ratios, is a more recently developed technique (Alley, 2000).

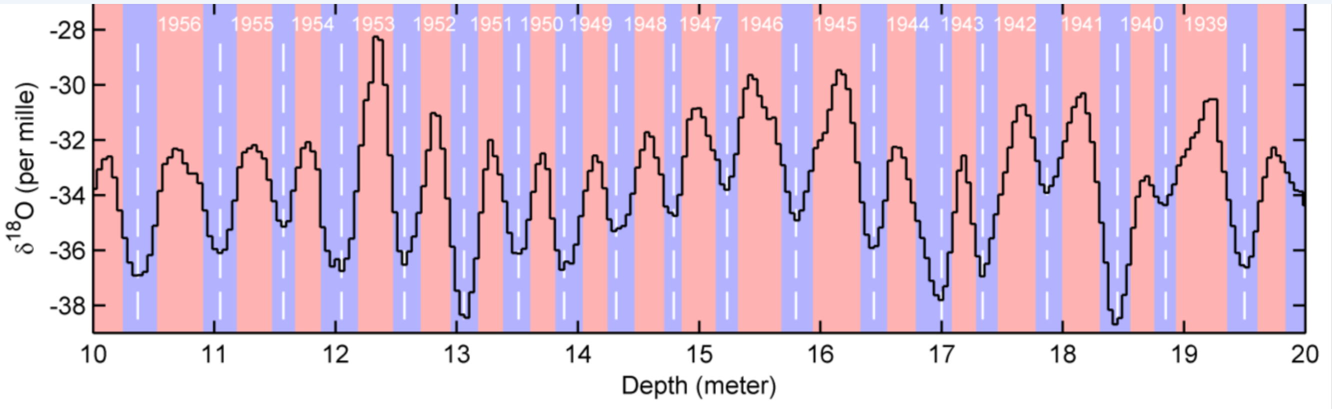


Figure 3.14. Isotope data from Central Greenland ice core Crete, displaying 10 meters of δ^{18}O layers over 19 annual cycles. The winter layers are shown with dashed white lines. Higher concentrations of ^{18}O indicate a cooler climate, typical of an Ice Age.

As water containing heavier isotopes requires a higher heat for evaporation, in cooler climates, the proportions of isotopes shift, with heavier molecules precipitating at higher rates. Therefore, cylindrical ice cores drilled from sheets or glaciers can be analyzed for their isotope ratios to create a proxy of the climate (Alley, 2000). Oxygen and hydrogen isotopes, ^{1}H and ^{16}O, respectively, comprise over 99% of water molecules, interspersed with the far less common heavier ^{2}H, or deuterium (D), and ^{18}O isotopes. Using mass spectrometers, glaciologists can determine the composition of the ice cores, and plotting the values of the heavier isotopes, represented as δD and δ^{18}O, along the length of an ice core determines the relative temperature of the environment at the time of ice formation (Figure 3.14) (Niels Bohr Institute, 2013).

Dust containing radioisotopes, such as uranium, has also been used to date ice cores and determine the timing of periods of glaciation (Aciego et al., 2011). Atmospheric gas samples, preserved as air bubbles frozen within the ice cores, can also be analyzed (Alley, 2000). Greenhouse gases, including carbon dioxide and methane gas, are associated with warmer climates, and so an increase in these gases within the air bubbles trapped in the ice can indicate the end of a glacial episode (British Antarctic Survey, 2014).

Milankovitch Cycles Contributing to Global Cooling

Defining an Ice Age as a long-term period of temperature reduction of Earth's surface and atmosphere, which results in the expansion of continental and polar ice sheets and alpine glaciers, glaciologists have researched numerous causes of the cooling that triggers Ice Ages (Rapp, 2012). One such trigger is associated with Milankovitch cycles, which describe the effect of the Earth's orbital movement on climate (Strelich, 2017). The Milankovitch cycles, named for the Serbian astronomer and mathematician Milutin Milankovitch, quantify the Earth's eccentricity, obliquity, and precession as it rotates around the sun, factors that alter the amount and timing of solar radiation that reaches the Earth's surface (McFadden, Weissman and Johnson, 2007). Eccentricity describes the shape of the Earth's orbit around the sun, with a more elliptical shape heightening the variation between seasons; obliquity is the axial tilt, describing the angle of the Earth's tilt towards the sun, shifting the amount of solar radiation a region receives, or in which season it is maximized; precession is the change in the orientation of the Earth's rotational axis which can alter the intensity of the radiation received (Lemieux-Dudon et al., 2010). These factors only influence the regions and seasons that receive the most solar radiation, impacting relative rather than global climate. Further research is required to fully understand the impact of the Milankovitch cycles on glaciation, as the changes in solar radiation generated by these orbital changes are not sufficient to shift the global climate, but affect specific regions (Strelich, 2017). While the Milankovitch cycles were discovered in the 1920's, they are still used in modern research, including the creation of orbital models to simulate Earth's rotation around the sun and the possible future cooling trends in climate. For instance, Imbrie's 1980 orbital model predicted a long-term cooling trend, expected to last another 23,000 years into the future (Imbrie and Imbrie, 1980).

Snowball Earth

Another factor associated with a global decrease in temperature is the position of the continents. Depending on their location, the continents can disrupt the flow of warm water from the equator to the poles. Without this consistent heat supply, ice sheets in polar regions can expand (Gwyther et al., 2017). The expansion of ice sheets acts as a positive feedback loop, as increased ice coverage also heightens albedo, or light reflectivity, of the planet, leading to further cooling and production of ice; this cycle is known as the ice albedo feedback (Naegeli, Huss and Hoelzle, 2019). Changes in atmospheric conditions can also be connected to the onset of glaciation, as an increased presence of greenhouse gases will increase the temperature of the Earth, while the opposite is also true (Willeit et al., 2015). The 'Snowball Earth' hypothesis, put forward by the American geobiologist Joseph L. Kirschvink in 1992, outlined that, at least once, a thick layer of ice covered Earth's oceans and separated the surface from the atmosphere (Figure 3.15).

A possible cause for the Snowball Earth state is that exhaustion of oxygen in the oceans resulted in extremely low temperatures, as well as the position of the continents preventing the flow of warm water from reaching the polar regions and ice sheets. The increased albedo created by the ice sheets would have perpetuated the cold climate (Cabej, 2013).

Uplift Weathering Hypothesis

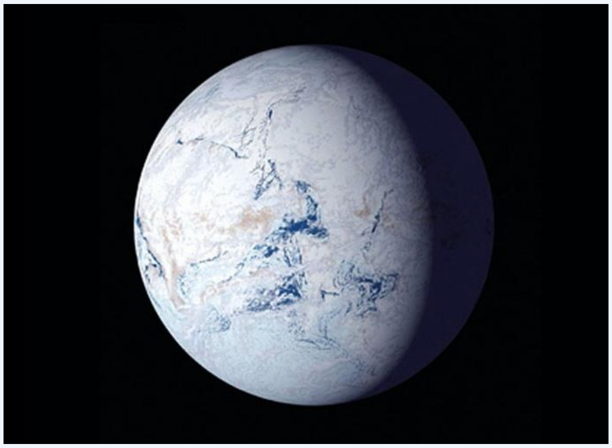


Figure 3.15. An interpretation of how the Earth would have appeared during its snowball state, sometime before 650 million years ago.

American paleoclimatologist Maureen Raymo's uplift-weathering hypothesis from 1988 attributes the decrease in temperature to tectonic uplift of the continents, such as through collisional events at convergent plate margins. The uplift exposes silicate materials within continental crust and, upon weathering the silicate converts carbon dioxide to carbonate products that sink into the oceans, removing carbon dioxide from the atmosphere. Increased uplift and weathering rates may have decreased the temperature enough to begin an Ice Age during the Quaternary (Ruddiman, 1997). German geographer Matthias Kuhle developed a theory related to the uplift-weathering hypothesis, stating that the uplift of Tibet led to the formation of Quaternary ice sheets. This increased the albedo, further cooling the region and glaciating Asia during the most recent Ice Age (Kuhle, 2018). With considerable evidence to support the development of past ice sheets in the region, including till, erratic boulders, and moraines, Kuhle attributed the extensive glacial cover to cooling induced by the ice-albedo feedback (Kuhle, 2005). However, neither Raymo's nor Kuhle's theories would have been proposed without the efforts of Louis Agassiz in the 19th century.

It is clear that field of glaciology and the idea of Ice Ages has advanced a long way since the time of Louis Agassiz. However, Agassiz laid the groundwork for research on Ice Ages with his extensive field work and wide dissemination of his theories that implanted the idea of an Ice Age into the geologists across the world. Without the Louis Agassiz's theory of Ice Ages, glaciology would not be the same today.

Marie Tharp's Discovery of the Mid-Ocean Ridge

The year is unforgettable. It is September, 1939, the beginning of a war that would result in the involvement of over 30 countries and end with a death toll of 50 million people (Weisser, 2018). At this time, battle lines have been drawn in Europe and parts of East Asia, but WWII has not yet reached the borders of North America. The early role of the United States included sending battle supplies such as ships, planes, weapons, and more to the Allied forces. It wasn't until 1942 that they officially joined the war (Weisser, 2018). By 1944, however, American forces were advancing into Japan while the Allies advanced into Germany and Asia (Weisser, 2018). The significance of the events that transpired during the last two years of the war cannot be done justice by a small paragraph of explanation, but the rest of this story is not about the war. Our story is about the events that transpired in the United States as a result of social changes and the intelligence of a single woman and her colleagues.

Figure 3.16. Marie Tharp as an undergraduate student in the mid 1940s

In the 1940s WWII became the catalyst for monumental social change. The enlistment of millions of male American soldiers left giant gaps in the labour force, and for the first time ever, women were being sought out and encouraged to work in male dominated fields. By 1944 more than 18 million American women were working, contrasted with only 10.1 million in 1941 (Miller, 1980). Women were being hired as nurses, mechanics, factory workers, and more, however over in Michigan a less obvious position had been left vacant by WWII (Miller, 1980). The petroleum industry was short on geologists, and so the University of Michigan distributed fliers promising a guaranteed job upon graduation from their master's program (Eppinga, 2009) (Figure 3.16). This flier fell into the hands of none other than our story's focus: Marie Tharp, a young women who had just completed her undergraduate studies in English and Music and was unsure of her next steps (Eppinga, 2009). As author Hali Felt writes in *Soundings* 2012, an extensive biography on Marie's life, Marie excitedly asked her professor about the flier who knew it was a rare opportunity. He encouraged her to pursue it, but not before suggesting she take a drafting course to increase her employability in the male dominated field of geology (2012). This would prove to be some of the best professional advice she ever received.

Two years later Marie received her master's degree following which she began a job with the Stanolind Oil Company in Tulsa, Oklahoma (Felt, 2012). As she worked, Marie acquired yet another undergraduate degree in mathematics from the University of Tulsa. Eventually, she left her job with the petroleum company and applied to Columbia University, one of the centers for geological research. Her diverse background resulted in the University sending her to professor William Maurice Ewing, a prominent American geophysicist. In her 2012 interview with Felt, Marie says the first question he asked was, "can you draft?". The answer, of course, was yes. She was hired that day and began creating diagrams, maps, and geologic profiles in Ewing's lab. About two weeks later Tharp was introduced to Bruce Heezen, a graduate student at Columbia with a keen interest in a daunting yet important task: mapping the entirety of the ocean floor (Felt, 2012). In Tharp's personal 1999 essay entitled *Connect the Dots: Mapping the Seafloor and Discovering the Mid-ocean Ridge*, she says working on this project was a "once-in-the-history-of-the-world opportunity for anyone, but especially for a woman in the 1940."

Mapping the Ocean Floor

At the time, WWII had led Ewing and his colleagues to develop a continuous echo sounder, a device capable of collecting constant Bathymetric data (Luskin et al., 1954). It was exclusively used by the navy to improve navigation, but once the war ended, it was released to oceanographers who wasted no time in putting it to use. By 1952, thousands of depth measurements had been collected of the North Atlantic Ocean (North, 2010).

The technology was highly effective, all a ship had to do was sail while the echo sounder did its

Figure 3.17. Marie Tharp's first transoceanic bathymetric map of the North Atlantic ocean depicting an indentation running down the center of the depth profile. Marie believed this to be a deep valley along the axis of the Atlantic Oceanic ridge (Tharp, 1999).

work. High frequency sound waves were sent out through the water, reflected off the seafloor, and then received by a microphone (Luskin et al., 1954). A pen was then set to continuously record the time required for the soundwaves to leave the ship and echo back, allowing depth measurements to be continuously recorded across spools of paper (Ewing and Ewing, 1961). Heezen wanted to take the accumulating data and use it to map the entire Atlantic, and with an undertaking this large, Tharp says she soon began working for him full time (2012).

Tharp sifted through and interpreted thousands of data points from different ships to sketch out highly detailed profiles of the sea floor (Kemp, 1998). Heezen himself spent most of his time at sea, amassing more and more bathymetric data for Tharp to analyze at home. Unfortunately, she never took part in the early data collection process as women were considered "bad luck" on field expeditions (Felt, 2012). The work was tedious yet highly complicated. Geologists didn't have a clear idea of the topography of the ocean floor, and so with no final picture in mind, Tharp interpreted thousands of quantitative data points and puzzled together a cohesive topographic profile (Felt, 2012).

This was no game of connect the dots; an accurate profile required an educated hypothesis of the seafloor topography based on known geologic processes, and the amalgamation of data from multiple sources required cross-checking and a strict assessment of quality (Kemp, 1998). By 1952, Tharp's careful work and the help of a team of graduate students led to the creation of six transoceanic bathymetric profiles of the North Atlantic (North, 2010). This was a feat in itself, and yet the pieces of seafloor emerging before her revealed something highly interesting: an indentation running down the center of the depth profiles (North, 2010) (Figure 3.17). Tharp was sure it represented a deep rift valley along the axis of an ocean ridge, however Tharp divulges to Felt that Heezen dismissed this as "girl talk" (Felt, 2012).

The issue was, if Tharp's theory was correct it would support a highly contentious theory known as continental drift. Alfred Wegener had first proposed the theory in 1912, stating that continents were able to move by plowing through the seafloor (Hallam, 1975). A deep oceanic valley could be the site of new seafloor creation, thus explaining how continental plates were able to spread. However, like Heezen, most geologists and geophysicists found the theory to be absurd and lacking in evidence, thus Tharp's idea was quickly dismissed (North, 2010). Tharp, however, was convinced and determined to prove it. This required her to demonstrate that the valley was a continuous and active site instead of simply a passive, disjointed strip along the seafloor. Thankfully, the evidence Tharp needed coincided perfectly with Heezen and Ewing's additional project.

Mapping Earthquake Epicentres

During this time, on November 18th, 1929, a 7.2 magnitude earthquake off the coast of Eastern Canada had just occurred, sending powerful seismic waves through the ground (Eppinga, 2009). The secondary effects of this event included an underwater landslide which then formed a tsunami and ultimately led to the snapping of 12 telegraph cables running through the bottom of the ocean (Hasegawa and Karamori, 1987). These cables were vital for fast and effective transatlantic communication, so when they snapped in succession, the cable company Bell Laboratories was at a loss. They knew the earthquake had to be the root cause of the snapping, but what secondary effect could possibly have damaged cables all the way at the bottom of the ocean? To answer this question, they turned to none other than Heezen and Ewing. Using the data of the exact time of each successive cable break, the two discovered and defined the culprit to be turbidity currents: rapidly moving underwater currents filled with sediment that are often triggered by earthquakes (Hasegawa and Karamori, 1987). In order to lay down new cables, Bell laboratories hired the two scientists to determine a transatlantic location that would be safe from future breaks. Heezen passed this task to his graduate student Howard Foster, asking him to plot the epicenters of earthquakes in the ocean (Eppinga, 2009). Though this data may initially seem unrelated to Tharp's work, she decided to take the plotted epicentres and overlay them with her own map of the ocean floor using a light table. As the two maps illuminated, Tharp's hypothesis came to life before her; a continuous line of thousands of epicenters ran through her plotted rift valley, proving it was an active margin where the seafloor was diverging, and new sea floor was being created (Eppinga, 2009).

Figure 3.18. Marie Tharp and Bruce Heezen analysing the South Atlantic bathymetric map data in the mid 1960s, with the ridge now plotted down the entire Atlantic Ocean.

This correlation led to Tharp's undeniable certainty in the rift valley, yet Heezen still considered the theory of continental drift to be impossible (Tharp, 1999). Heezen instead put his beliefs into the theory of radial expansion, a hypothesis that attributed the fragmentation of plates to the slow inflation of Earth. Due to his steadfast views, Tharp continued with her exploration alone, knowing that if the continental drift theory were true, these rift valleys and associated features would not only be found in the Northern Atlantic but around the entire world. With Heezen still interested in mapping the entire ocean floor, the pair worked together to extend Tharp's map to the Southern Atlantic (depicted above) followed by the Arabian Seas and East Africa, while Howard continued his work plotting epicentres (Eppinga, 2009) (Figure 3.18). Their initial map of the Atlantic slowly but steadily expanded to oceanic rift valleys running hundreds of miles long around the world, with epicenters consistently found along their centres. In a 1997 interview with Tanya Levin from the American Institute of Physics, Tharp states that despite her mounting evidence, the continental drift theory was so violently opposed that supporting it was enough to get one fired (Levin and Tharp, 1997).

Though the theory behind continental drift was poorly received, Heezen and Ewing still presented her findings of the extensive rift valley in 1956 to the American Geophysical Union, ironically with little credit given to Tharp (Levin and Tharp, 1997). She describes the range of reactions that followed from "amazement, to skepticism, to scorn" (Tharp, 1999). Regardless, her work ignited a shift in perspective on the ocean floor, and a heated debate began between Heezen and Ewing as to the origins of the rift valley. Tharp knew her opinion was unwelcome in the debate, however in her personal essay she says, "I was so busy making maps, I let them argue", directing her efforts towards collecting more evidence (Tharp, 1999). At this time, Heezen continued to present her findings to geologists around the world, creating a new area of research based on an increasingly important question: what was this rift valley?

The Rift Valley Debate

In 1956, the oceanic rift valley was gaining global traction, and though initially met with skepticism, more and more oceanographers were beginning their own investigations into the truth about its origins. Oceanographers such as Jacques Cousteau explored the proposed rift hands on by lodging cameras and flashlights on a sled and towing it through the ocean waters in the Mid Atlantic. This video evidence proved exactly what Tharp had suggested, showing black mountain formations in the depths of the ocean near the rift valley (Matsen, 2010).

During this time, the relationship between Heezen and Ewing was tense, with Ewing doubting that Earth's continents moved at all and Heezen insisting the expanding Earth hypothesis was correct. Their relationship took a turn for the worse when Ewing grew paranoid that his ideas were being stolen by Heezen, and thus, he made drastic cuts to Heezen's budget. Ewing went so far as to attempt to fire Heezen despite the fact he was tenured (Felt, 2012). Near the end of their work together, Ewing began internally reviewing each of Heezen's publications and pulling ranks to prevent Heezen from publishing his work (Levin and Tharp, 1997). Heezen and Tharp bonded over their disdain for Ewing's attitude and continued to investigate the rift valley through their own expeditions as well as any bathymetric data available, allowing them to continue developing accurate maps (Levin and Tharp,1997). Eventually, through continuous arguments between Tharp and Heezen, and the continuous inflow of data and evidence, Bruce Heezen had a monumental change in heart. He agreed that the rift valley was a result of land masses being pulled apart. Maurice Ewing was absolutely furious. Ewing banned Heezen from all future expeditions and denied him access to any data they collected. As a woman without tenure, Tharp was fired from Ewing's team in 1959. Thankfully, the vast connections Heezen had made with researchers and experts around the world allowed him to obtain alternate sources of data, and Tharp was able to continue her work from home, receiving compensation through research grants. Seeing their work of the Atlantic, the International Council of Scientific Unions hired the two to map the floor of the Indian Ocean for the International Indian Ocean Expedition (Tharp, 1999) (Figure 3.19).

At Last, Marie Tharp's Work is Recognized

At this time, the Cold War was at its peak, providing an immense amount of bathymetric data, with Soviet ships surveying the Indian ocean and Japanese ships providing information on the waters between South Africa and Antarctica. Claiming it as an international effort, Tharp along with Heezen published the finished map of the Indian Ocean in 1964 (Doel et al., 2006). The map caused quite a stir, catching the eye of National Geographic who wanted to develop a bathymetric map of their own that was both accurate and visually stunning. As a result, they sought the help of an artist by the name of Heinrich Berann (Felt, 2012). National Geographic then hired Tharp and Heezen as consultants on the piece, marking the beginning of their relationship with the artist, who not only worked with them to develop a beautiful map of the Indian Ocean seafloor, but continued to work with them to tackle the Antarctic Ocean floor in 1975 (Tharp, 1999). With mounds of data and a skilled artist, Tharp and Heezen knew they were ready to take on their greatest project yet: developing a panorama of the Earth's ocean floor. Submitting a proposal to the Office of Naval Research in 1973, the three of them began the task of mapping the ocean floors of a planet with 71% of its surface covered by water (Eppinga, 2009). This involved condensing and simplifying their collected data, updating previously collected data, and travelling around the world to fill in the missing pieces. Not only were they collecting new data, but the data that Ewing had previously withheld became available once he moved to the University of Texas (Levin and Tharp, 1997). Finally, they had all the puzzle pieces they needed. With a first draft complete, Heezen decided he wanted to observe the rift himself using the U.S Navy's newly developed nuclear submarine. It was here in 1977, on an expedition exploring Iceland's mid ocean ridge, where Heezen had a sudden heart attack and passed away (Tharp, 1999). A few months later, the map was published by the Office of Naval Research, with credit given solely to Heezen (Tharp, 1999) (Figure 3.20).

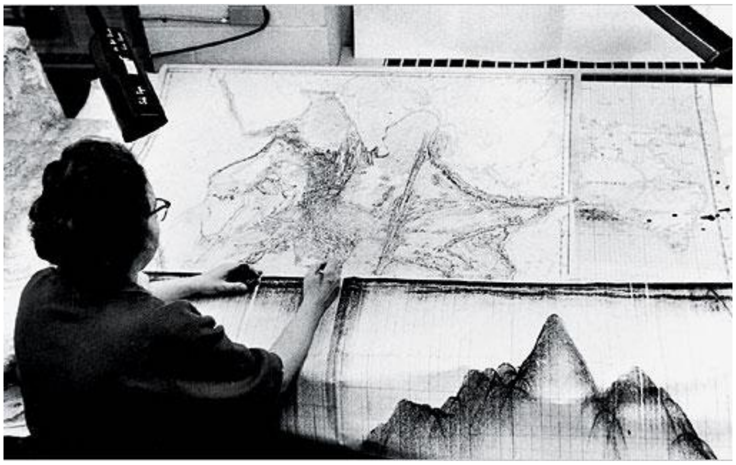


Figure 3.19. Marie Tharp plotting the topography of the Indian Ocean in Lamont's Oceanography Building in the mid 1960s.

Marie Tharp's contributions were not recognized until years later when she received double Honours from the Library of Congress in 1997, and the first Lamont-Doherty Heritage Award for paving the way in oceanography and cartography (Barton, 2002). In her personal essay, Tharp notes seeing her map hung up in the Library of Congress was extremely emotional. To her, the significance of the piece and its impact on our understanding of continental drift was evident from the start, but her entire career had been riddled with objections and obstacles. In her final thoughts in her 1999 essay on her journey, she concludes with:

"I worked in the background for most of my career as a scientist, but I have absolutely no resentments. I thought I was lucky to have a job that was so interesting. Establishing the rift valley and the mid-ocean ridge that went all the way around the world for 40,000 miles—that was something important. You could only do that once. You can't find anything bigger than that, at least on this planet."

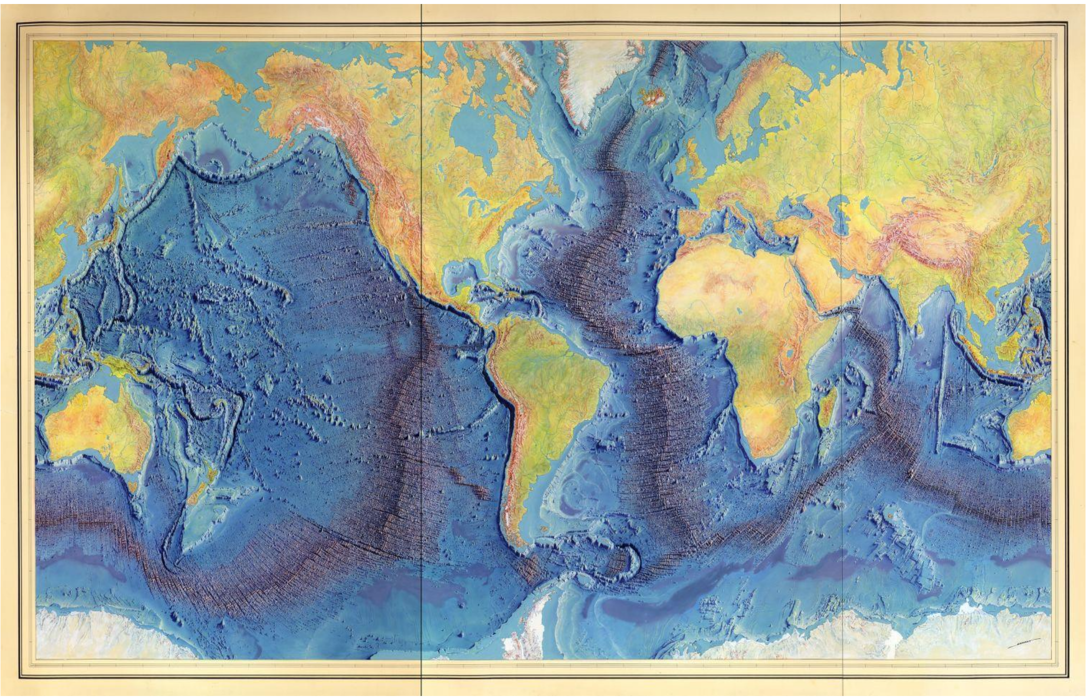


Figure 3.20. The panorama map of the Entire Ocean floor developed by Marie Tharp, Bruce Heezen and Heinrich Berann published by the Office of Naval Research in 1977.

The Mid Ocean Ridge and Plate Tectonics

Marie Tharp's findings of the the rift valley, now known as the Mid Ocean Ridge (MOR), were pivotal in shaping our understanding of both historical and current Earth processes. The MOR allowed the contentious theory of continental drift to become widely accepted and transformed into the modern day theory of plate tectonics. Plate tectonics now provide the basis for our understanding of geologic processes, the formation of landscapes, and the deposition of subsurface sediments and fossils. Following Tharp's discoveries and maps, scientists now have a more thorough understanding of how the MOR developed, the mechanisms behind sea floor spreading, and the resulting affects on Earth.

Plate Tectonic Theory

The Plate Tectonic Theory suggests that the lithosphere, which contains the crust and upper mantle, is comprised of seven major plates, ten minor plates and several microplates which are constantly moving (Coltice et al., 2017). These plates are driven by the flow of heat from the hot core to the mantle-crust boundary. This heat is supplied by two main sources: the radioactive decay of isotopes in the core, and primordial heat left from the formation of the Earth's core (Drchal et al., 2019). When transferred to the mantle, the described heat flow causes magma to reduce in density and rise to the mantle-crust boundary. Once it reaches the boundary, this hot magma pushes up through the ridge as well as moving horizontally along the base of the crust, pulling apart each side of the ridge. The hot, rising magma loses its heat, causing it to become denser and fall back down which creates continuous convection currents in the entirety of the mantle (Coltice et al., 2017) (Figure 3.21). Convection currents in the mantle are also attributed to the subduction of plates, a process called slab pull, as the inward cycling of the cooling magma causes the cold, dense, and older tectonic plates to subduct into the asthenosphere. The exact driving forces behind this mechanism are still being researched.

Evidence Supporting Active MORs and Plate Tectonic Theory

Tharp's findings not only serve as a benchmark to understanding current tectonic processes, they also provide a vital starting point to understanding the tectonic processes that led to the formation of the Earth. Following Tharp, Harry Hess's development of the Seafloor

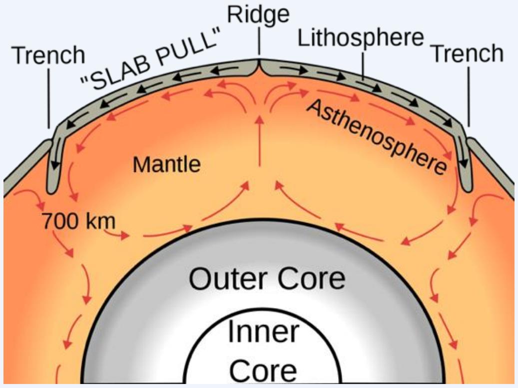


Figure 3.21. Convection currents in the mantle driving the movement of plates away from the ridge, pulling the plate inward of downward current (Coltice et al., 2017).

Spreading theory, paired with the Morley-Vine Matthews hypothesis to scientifically prove Hess's theory using paleomagnetism led to the wide acceptance of the plate tectonic theory.

(Kusky et al., 2013). Through analyzing the magnetic minerals in the rocks surrounding the MOR, Morley, Vine and Matthews discovered a symmetric pattern of normal and reversed magnetization on either side of the ridge, indicating the masses were once together and had then split apart (Kusky et al., 2013). This led to further research into using other forms of stratigraphic correlation to determine historical tectonic movement, including biostratigraphy - the use of fossils, and lithostratigraphy - matching strata from one region to another, producing a wide array of evidence (Ehlers et al. 2018, Simões et al. 2016). For example, the Mesosaurus was a genus of reptile living in the Early Permian era. The morphology of the species suggests it likely lived in coastal regions and would not have been able to cross the Atlantic Ocean, however its fossils have been discovered in both South Africa and eastern South America. This suggests the continents must have been connected during the Mesosaurus' time on Earth (Simões et al. 2016). In addition to this, a major glaciation during the late Carboniferous and Early Permian Era, occurring around 300 million years ago, left extensive glacial deposits and landforms across what is now South-East America, South Africa, India, Antarctica and South Australia (Ehlers et al. 2018). One of the identified landforms were striations and glacial tillites found across each of these areas. This indicates the modern continents were once a cohesive unit, and the striations were created by boulders being dragged across their joined surface by glaciers (Eyles, 1993). The striations also indicate the direction of glacier movement. When they are observed separately by continent, the striations appear to point in different directions and locations, but when the continental pieces are fit together, the striations work together to describe a glacier that originated at the pole and moved outwards (Eyles, 1993). This evidence along with other geomorphic features shows how the continents fit together in our past to create supercontinents (McKerrow et al.,2000).

What Else does the MOR Tell Us?

The MOR not only serves as a piece of evidence used to prove plate tectonics but also provides a wealth of information based on its surrounding topography and the environmental conditions within the ridge itself. By observing the topography of the mountain ranges on either side of the ridge, it can be observed that the topography is a product of varying rates of seafloor spreading throughout history (Small, 1994). During periods of rapid spreading, there is fast heat flow and magma transfer from the mantle to Earth's surface, giving the seafloor a relatively flat topography. Conversely, during periods of slow spreading, the magma rising up through the MOR has more time to cool and solidify before the underlying magma can push it outwards. This leads to layers of magma building upwards, creating a steeper and more sloped topography (Small, 1994). This is evident when comparing the more rugged topography developed by the slow spreading (<10 mm/yr) of the Eurasian Basin along the Indian Ocean Ridge, to the extremely fast spreading (150 mm/yr) of the Nazca and Pacific plates, which have produced relatively smooth sea floor terrain (Nikishin et al. 2018, Zhang et al., 2018).

Though there are still many geologic questions left unanswered regarding plate tectonic theory, the discovery of the Mid-Ocean Ridge has provided explanations for the most notable events in Earth's formation and development as well as the activity of current processes. It is safe to say that Marie Tharp's discovery will remain the basis for understanding Earth's processes for the foreseeable future, allowing scientists to continue investigating the activity of the seafloor and the dynamic plates which continue to shape our planet.

Chapter 4: The Origin and Evolution of Earth

Discussing the history of Earth, it is difficult to avoid the origin and evolution of Earth. In order for the current Earth to be present at the moment, the evolution of the Earth was mandatory. In addition, for us to exist on the Earth with other living beings, the origin of the Earth is important, especially regarding the start of life. Over many years in the past, numerous historical figures have proposed various theories that support the origin of Earth. In addition, for evolution to occur within the Earth after the creation of initial life, multiple historical events occurred in order for the Earth to evolve to the current stage. Evidence that supports the evolution of lives and even humans are still present on the Earth and became a useful source of our understanding of the past. Throughout this section, “The Origin and Evolution of Earth”, theories on origins of life, the historical occasion that contributed to the evolution of Earth, evidence of evolution with our current knowledge and understanding will be introduced.

The Oparin-Haldane Theory

Early Origin of Life Theories

Some of the first recorded theories about the origin of life came from Greek philosophers. The two main theories at the time were panspermia and spontaneous generation. The panspermia theory suggests that life is abundant in space and ended up on Earth (Hollinger, 2016). The means by which life came to Earth from space was debated. Anaxagoras was the first to suggest life on Earth came from space. He believed that rain interacted with the air and produced life (Hollinger, 2016). Benoît de Maillet had a very similar opinion regarding the origins of life on Earth. Maillet believed that semen existed in space and was attracted to planetary bodies (presumably by gravity or magnetism) and interacted with the oceans to create life. He further hypothesized that life existed on land because sea levels lowered a significant amount, encouraging life to crawl out of the ocean (Hollinger, 2016).

Figure 4.1. John Burdon Sanderson Haldane

Friedrich Wähler was convinced that life could have arrived on a meteor. He came to this conclusion by identifying carbon and organic compounds in two meteors he was researching (Hollinger, 2016). Hermann Richter expanded upon this theory using Darwinian evolution principles and the laws on conservation of energy. Richter believed that the universe must have come from somewhere and that life traveled from wherever the universe originated to Earth in a meteor where evolution then took place (Hollinger, 2016). Panspermia theory prevailed over spontaneous generation theory when Louis Pasteur proved that microorganisms exist nearly everywhere and could not suddenly appear without having been the product of other microbes reproducing. His famous experiment involved boiling a broth to sterilize it in a swan neck flask that prevented microbes from entering the broth. There was no microbial growth in the broth until it came into contact with external microbes that had been introduced to the system (Hollinger, 2016). Lord Kelvin advocated for the validity of panspermia theory sourced by meteors. The first to publish this theory under the name "panspermia" was Svante Arrhenius in 1906 (Hollinger, 2016).

J.B.S. Haldane

John Burdon Sanderson Haldane was born in England in 1892 (Pirie, 1966). From a young age he showed great intelligence. From the age of eight, Haldane began to do experiments with his father, John Scott Haldane, who was a well-known physiologist revered for his understanding of the respiratory system and gas exchange (Sekhar and Rao, 2014). Haldane gained admission and a scholarship to Eton College, a prestigious all male boarding school, where he was bullied for his arrogance. He had great successes in math and science while there, earning a scholarship to the University of Oxford where he studied mathematics and classics (Pirie, 1966).

Soon after Haldane's graduation in 1914, World War I began, and he joined the fight (Pirie, 1966). After the war, he openly admitted to enjoying killing people and expressed that it was more dangerous to rationalize such violence than to accept that it satisfied a primal urge (Haldane, 1932). He was wounded in battle in 1915, rejoined the war, then was wounded again. After recovering from his second injury, Haldane oversaw a bombing school in India (Pirie, 1966). After the war finished, he returned to academics.

Throughout his scientific career, Haldane became respected in the fields of physiology, genetics, biochemistry, enzymology, and evolution theory (Tirard, 2017). From 1923 to 1932, Haldane worked at the University of Cambridge, focusing on population genetics and enzyme kinetics (Wilmot, 2017). From 1927 through 1937, Haldane worked on his genetics research at the John Innes Horticultural Institute (JIHI). Haldane's work at the JIHI helped him in the development of his linkage theory (Wilmot, 2017). He then worked at University College London from 1932 through the 50s where he studied human genetics (Wilmot, 2017). He published many papers throughout his career. In 1929 he published an article entitled The Origin of Life.

Haldane's Theory on the Origin of Life

Haldane's theory of how life came to exist on Earth is abiogenesis. Abiogenesis is very similar to the spontaneous generation theory. However, instead of proposing that life just suddenly came to be, it explains how inorganic compounds can be converted to organic compounds. Haldane was driven to identify the true origin of life by Darwin's evolution theory. He thought it important to find out how life first came to be on Earth if we evolved from it and therefore descended from it. At this time people believed that life either arrived on Earth from a meteor or that it formed on its own on the Earth (Haldane, 1929). The latter theory was still quite controversial because of Pasteur's experiment. Many viewed Pasteur's experiments to be simplistic, though the conclusions drawn from them were absolute. His results were absolute by two definitions: 1) no one who replicated them found different results and 2) Pasteur drew conclusions from his experiments that reached beyond the results that were proved by his experiment (Haldane, 1929). Haldane believed, in spite of Pasteur's experiment, that spontaneous generation theory was the most plausible explanation for the origins of life on Earth. He argued that atoms are to a cell as cells are to humans (Haldane, 1929). This leads to the conclusion that the building blocks of life must be on a scale between that of an atom and that of a cell (Haldane, 1929). The phrase for which Haldane's theory on the origin of life is well known, and arguably the phrase with the most modern relevance, is 'primordial soup'. Primordial soup is used by Haldane to describe the ocean around the time that life began (Haldane, 1929). With no oxygen in the atmosphere and no significant ozone layer, the ultraviolet rays from the sun could more easily reach the surface of the Earth. These UV rays could interact with the water in the oceans as well as the carbon dioxide and ammonia in the atmosphere to create organic molecules like sugars and amino acids (Haldane, 1929). These organic molecules would continue to form, turning the ocean into Haldane's primordial soup of organic compounds (Haldane, 1929). When life did form in the ocean, according to this theory, it would have been some form of anaerobic lifeform with an abundant source of food around it in the water and no competition (Haldane, 1929). These were very simple particles that likely could not reproduce without other particles (Haldane, 1929). Haldane proposed that all life on Earth now has evolved from those first cells. He argued that if multiple cells came into existence in different locations or at different points in time that it would be unlikely that life would have its current limitation of using only L enantiomers. According to Haldane, plant life came to exist when the first cells were consuming nearly all of the food from the primordial soup and instead began to produce their own food using internal structures and the light from the sun. According to Haldane, after much time and evolution, those cells from the soup lead to life as we know it, including ourselves.

Birth of a Fascination

Aleksandr Oparin was born in Uglich, a town in west Russia, in 1894 (Birstein, 2004). Early on in his life, Oparin became fascinated with a question that he quickly realized humanity had been gripped with since we made our debut on this Earth - where did life come from? As said by Oparin himself in his landmark publication The Origin of Life, "[n]o religious or philosophical system, no outstanding thinker ever failed to give this question serious consideration" (Oparin, 2003). Early on in his life, prior to his entrance into Moscow State University, Oparin began to take an interest in the theories of philosophers on this matter, first becoming fascinated by the most interesting and fantastical theories to exist in history. These were theories on the spontaneous generation of life. As Oparin noted when commenting on another book on the origin of life, written by E. Lippman, it was evident that under favorable conditions, life could rise where previously it did not exist (Oparin, 2003). Although ancient theories seemed more like a fairy-tale to Oparin, this was the singular fact which he carried with him into his development of his own model for the initial emergence of life.

Figure 4.2. A photograph of Aleksandr Oparin taken in 1938, shortly after his founding of the USSR Institute of Biochemistry.

In order to fully understand Oparin's fascination, it is important to outline a few key theories on the spontaneous generation of life. Upon doing so, it is easy to see how an adolescent could take such an interest in the matter. One such early body of theories originated in 600 BC, with the philosophers of the Ionian school. The evidence which they touted as truth was that neither creation nor destruction of life is possible, and thus, living organisms must arise from the Sea and the Earth's slime, produced by the mechanism of heat, sun, and air (Oparin, 2003). The theories of the Greek from the Ionian school were not, however, implicative of the rise of life from that which is lifeless. According to the ancient Greeks, the entire universe was conceived to be living (Oparin, 2003).

This perception of an inherent presence of life stayed with Greek philosophers far past 600 BC, being a part of even Aristotle's theory on the origin of life circa 384-322 BC (Oparin, 2003).. According to Aristotle, life needed two components in order to arise - some passive principle "matter," and some active principle "entelechy." Entelechy is, essentially, soul. The Greeks of this period still believed that the soul was present in the primary elements, being a property of the Earth, and to a greater degree, a property of water, air, and fire. The Earth was believed to produce plants, the water aquatic animals, the air terrestrial animals, and fire celestial bodies such as the Moon (Oparin, 2003).

A number of other theories fascinated Oparin, such as trees which bore fruit filled with the meat of lamb, and the production of homunculi from human sperm with blood as nourishment, but between all of these, there was one commonality. As Oparin himself stated, "[s]ince the most remote times, we find among the various peoples all over the world the solid conviction, based frequently on observation, that the simplest animals, both of the lowest and highest order, can originate spontaneously" (Oparin, 2003). He would go on to dedicate his life to the pursuit of the truth behind this idea.

Figure 4.3. Trofim Lysenko, the agricultural scientist revered by Stalin who founded Lysenkoism.

Oparin's Theory on the Origin of Life

In 1917, Aleksandr Oparin graduated from Moscow State University (Birstein, 2004). It must be understood that at this time, many of the common folk in Europe still held beliefs that aligned with the spontaneous generation of life. Many were of the opinion that worms and other parasites arose spontaneously from manure or filth, a common viewpoint born of daily experience (Oparin, 2003). As such, when Oparin began to develop his theory on the origin of life in 1922, he felt it important to outline a series of tenets which the common folk could understand simply, in preparation for his larger theory. These were the following (Birstein, 2004):

1. There exists no distinction between the living and lifeless matter, with characteristics of life simply being a product of the evolution of matter.
2. The infant Earth had a strongly reducing atmosphere, containing methane, ammonia, hydrogen, and water vapor. These are the ingredients of life.
3. As simple molecules became more complex, their properties were dictated by the spatial arrangement and relationship between the atoms.
4. Competition, speed of growth, struggle for existence, and natural selection determined the form which life takes today.

Here, the state of national interests in Russia made its first large influence on Oparin. At the time, much interest was being taken in the universe beyond the Earth, and it had recently been discovered that there existed methane in the atmosphere of Jupiter and the other giant planets. It was this discovery which pushed Oparin to the belief that the infant Earth may have possessed a similar composition, and to his discovery of what he was convinced were the raw materials of early life (Birstein, 2004).

In 1924, Oparin put forward his theory on the development of life on Earth. In this theory, he postulated that carbon-based molecules developed through gradual chemical evolution in what would be parallelly termed by the previously discussed scientist, Haldane, as a primordial soup (Birstein, 2004). Oparin believed that systems of colloidal particles, dense enough to be coacervate droplets, were the first reproductively capable biological units. As such, Oparin stipulated that the first organisms formed in the oceans of early Earth under a strongly reducing atmosphere, and that they were cell-like in nature. Additionally, he stated that as the energy-rich organic compounds present on early Earth were consumed and depleted, photosynthetic organisms developed from the living systems already present (Oparin, 2003).

The Intrusion of Lysenkoism

In 1935, Oparin founded the USSR Institute of Biochemistry (Birstein, 2004). It was here that the politics of the Soviet Union began to entrench themselves in his work. This took shape in the 1940s-1950s, when Oparin found himself a supporter of Lysenkoism. Lysenkoism, the name given to the pseudoscientific body of thought founded by Trofim D. Lysenko, was a heavily Stalin endorsed alternate hypothesis to Mendelian genetics. The details of this theory are not relevant, other than that it has since been entirely rejected by the scientific community. What is relevant, however, is Oparin's endorsement of it (Jukes, 1997).

Lysenkoism represented, for many, the abandonment of a pursuit of truth in science. It was an alternative agricultural produce focused approach to genetics which was put out by a Russian scientist loved by Stalin. It was also, unfortunately, a method utilized by the Stalin regime to root out those who were not completely submissive to the state (Jukes, 1997). Oparin was motivated to this betrayal of what he believed in by the threat of losing his life's work, as he saw various other scientists defrauded and persecuted by the Russian state. Amongst these was Dmitrii Sabinin, a man known at the time as the foremost plant physiologist. Oparin refused to approve Sabinin's appointment to the Academy of Sciences Soils Institute, resulting in Sabinin committing suicide in 1951 (Jukes, 1997).

Oparin was never able to do any extensive experiments to investigate any of these ideas. In 1953, two years after Dmitrii Sabinin's death, Stanley Miller did what Oparin had dedicated his life to, performing the first experimental simulation of early Earth to investigate whether chemical self-organization could happen in this environment (Birstein, 2004). Perhaps it was Oparin's partially mandatory embroilment in in Soviet Union politics which kept him from realizing his dream. Of all the tragedies committed at the hands of the Stalin regime, one of the gravest is the obstruction of true pursuit of knowledge.

Miller-Urey Experiment

The Oparin-Haldane Theory was built upon by Stanley L. Miller and Harold C. Urey. Miller was an American scientist who is described as the father of prebiotic chemistry (Bada and Lazcano, 2012). He showed an aptitude for academics from a young age, particularly chemistry. Like his older brother, Miller pursued an undergraduate degree in chemistry from UC Berkley (Bada and Lazcano, 2012). He then attended University of Chicago because of its academic prestige and offer of financial assistance. While at the University of Chicago, Miller attended a seminar about the origin of life.

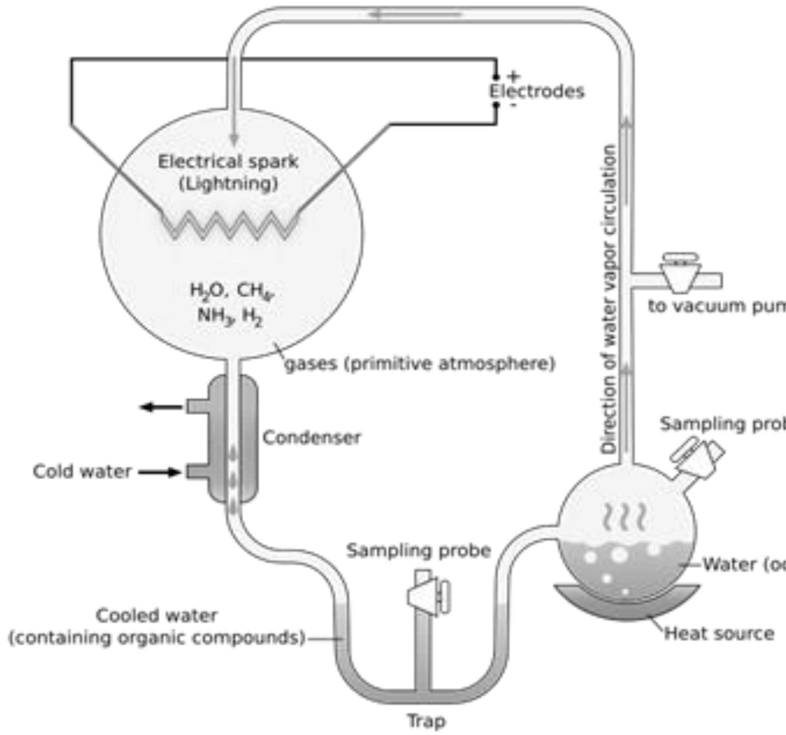


Figure 4.4. The set up of the Miller-Urey Experiment

In this seminar, Urey discussed the conditions of the early Earth and how few experiments used reducing conditions with no oxygen (Bada and Lazcano, 2012). This inspired Miller. While Miller was hesitant to take on experimental research and Urey was hesitant to supervise a graduate student in an experiment about which so little was known and there was no guarantee of significant results, it became official that Urey would supervise Miller's graduate study. In 1952 the two of them began an experiment that would carve their names in history (Bada and Lazcano, 2012).

The Miller-Urey experiment was incredibly significant to the development of theories on the origin of life. In this revolutionary experiment, organic compounds were created from inorganic compounds under primordial conditions. The experiment proved that abiogenesis was possible. Miller and Urey credit a great deal to Oparin. It was based on his understanding of the primitive Earth that this experiment took place (Miller and Urey, 1959). A great many scientists before Miller and Urey had attempted to create organic compounds from inorganic materials. However, these mostly took place where there was oxygen in the atmosphere, resulting in minimal success. Miller and Urey tried to replicate the early atmosphere by excluding oxygen from the experiment and found this to make the experiment successful (Miller and Urey, 1959). The Miller-Urey experiment involved a series of flasks, tubes, electrodes, and heat in attempt to replicate the conditions of the early earth. The flasks and tubes were a closed system so as to not allow in any oxygen that might contaminate the reducing artificial atmosphere. Within the system was water to act as the ocean as well as methane, ammonia, and hydrogen to be the primitive atmosphere (Miller and Urey, 1959). 250mL of water was contained within a 500mL flask. Under this flask, a Bunsen burner was used to evaporate the water. The water traveled up the tubing and into a 5L flask containing the atmospheric gasses. Electrodes on either side of the 5L flask provided constant electric discharges across the contents of the flask. The electric discharge represented lightning (Miller and Urey, 1959). While UV light would provide more energy than electric discharge and was believed to be common in the early Earth, it would have been more difficult to optimize in a laboratory setting (Miller and Urey, 1959). Also, UV light could be absorbed by atmospheric carbon and would not penetrate very deep into the oceans (Miller and Urey, 1959). The system was then cooled to allow the water vapour to condense and collect in a U-shaped tube. The contents of the collection tube underwent chromatography, revealing that the experiment had in fact produced a racemic mixture of multiple amino acids (Miller and Urey, 1959).

Miller and Urey applied the results of their experiment to the potential of life existing on other planets and suggested that neither oxygen nor ozone are necessary for life to form, but water likely is (Miller and Urey, 1959). While this experiment was not a perfect representation of what we currently believe to be the conditions of the primitive Earth, it remains significant to this day because it is proof that it is possible to create complex organic compounds from simple inorganic compounds that may have existed around the time life began on Earth.

The Origins of Life on Earth

Modern Perspective

The basis of Miller and Urey's experiments was, at its core, a hypothesis on the conditions of the infant Earth. Since their time, there has been a large amount of progression in the human understanding of early Earth conditions. On the origins of life, two main theories have emerged and come to prominence. The first is that life originated in submarine hydrothermal vents (Ross and Deamer, 2016). The second is that life originated in hot spring fields on land, heated geothermally (Martin et al., 2008). Both of these theories bear significant merit.

Hydrothermal Vents

The theory of life's origins at hydrothermal vents is relatively recent, with hydrothermal deep sea vents only having been discovered approximately 40 years ago. These 360ºC sulphide spewing vents have been a consistent chemical environment since the earliest stages of the Earth (Martin et al., 2008). This discovery immediately had a profound impact on hypotheses on the origins of life on Earth, as the vents are a highly chemically reactive environment which is suitable for the prebiotic reactions necessary to generate complex organic molecules. Additionally, the chemical conditions at these vents are able to maintain consistency for long periods of time (Martin et al., 2008).

The first of two types of hydrothermal vents which are candidates for the birthplace of life is the black smoker. Black smoker vents emit chemically modified sea-water, capable of reaching temperatures up to 405ºC and having a pH of around 2-3 (Martin et al., 2008). In this environment, there are also large amounts of dissolved transition metals such as iron and manganese and a high output of magmatic carbon dioxide (Martin et al., 2008). The temperatures at the vents also vary considerably with temperatures on the inner walls being as cold as 2ºC. Even today, there are large colonies of archaea bacteria which inhabit the environments surrounding these vents, fueled by the geochemical energy they release.

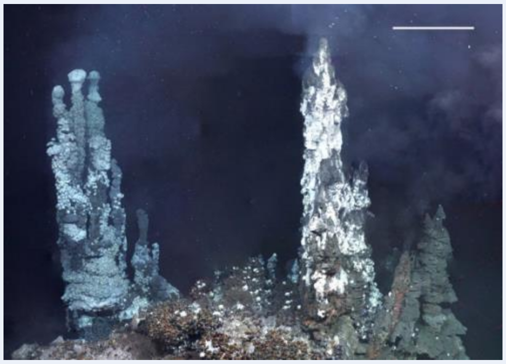


Figure 4.5. A deep sea hydrothermal vent on the East Scotia Ridge.

The second of two types of vents that may have allowed life to develop is termed the 'lost city hydrothermal field'. Lost city hydrothermal fields are large systems of off-axis vents which create a very different environment from black smokers. These vents are emitters of sea-water which has circulated through the crust but does not come in contact with the magma chamber (Martin et al., 2008). The temperatures they can reach are as high as approximately 200ºC, and the geochemical setting is a very alkaline one. The pH of water emitted from these vents is typically in the range of 9-11. There have been large communities of methanotroph bacteria found in these systems, a possible indication of the metabolism of early lifeforms on Earth (Martin et al., 2008).

Geothermal Pools

There is an abundance of chemical, geological, and computational evidence leaning towards the hypothesis that life originated in terrestrial hot spring fields. The most critical factor in this, and a current leading theory on how complex biological molecules first arose, is the ability for terrestrial hot springs to undergo wet-dry cycling (Martin et al., 2008). The springs would partially dry and recondense, sometimes multiple times a day, allowing prebiotic reactions to occur near the pool margins and in fractures. This would shield the reactions from UV radiation (Martin et al., 2008). This process aligns with the fact that most important prebiotic reactions identified require some form of dehydration in the form of condensation reactions. These reactions allow long-chain organic polymers such as polysaccharides, oligonucleotides and polypeptides to be created (Martin et al., 2008)

As hot spring fields are found on the surface of the Earth, they would also be able to concentrate meteoric material from impacts and interplanetary dust particles. These would contain many of the base building blocks for life, such as fatty acids, nucleobases, and amino acids (Martin et al., 2008). Additionally, the meteoric water and magmatic vapors present in the hot spring pools would have been high in phosphorus, ammonia and have a wide-ranging temperature and pH (Martin et al., 2008). This allows development of the broad range of chemical conditions necessary for the many different organic reactions to occur without any form of compartmentalisation. In a single terrestrial hydrothermal field, there can be a hundred or more separate geothermal pools all with a different chemical environment (Martin et al., 2008).

Terrestrial hydrothermal pools are a hotspot for chemical reactions. Through repeated drying and evaporation processes, they are essentially concentrating factories, allowing many cycles of complex chemical reactions to occur. Their water temperatures fall within the golden zone for supramolecular assembly, being typically 10-70ºC, high enough for molecules to become distorted and search their chemical environment, but not too cold for there to be a lack of activation energy (Martin et al., 2008). As such, terrestrial hydrothermal pools are a suitable location for the potential beginnings of life. This theory of life's origins has large astrobiological implications, and is a large factor in exploration strategies when looking at possible Earth analog planets (Martin et al., 2008). The change in perception of how life may have started on Earth has changed how we look for it in the stars.

Human Obsessions with the Origin of Life

Humankind has an unquenchable thirst for knowledge. We are born with an inquisitive mind and a will to question from a very young age. Our curiosity for the universe results from a sense and self-awareness and is only unmatched by our quest to answer these questions. One of the most fundamental questions that has fascinated humankind is who we are and how we came to be?

The Ancient Greeks

According to our current definition, the ancient Greeks can be considered the oldest 'scientists'. For them, philosophy and science was integrated and as such they can be aptly characterized as scientific philosophers. The first Greek tribes to civilize were the Ionians and the Dorians. Ionian descendants were the settlers and formers of the Greek city-state of Athens which remained an academic hub from 7th to 4th Century B.C. For the Greeks, origin of things was imperative to understanding and building the right way of life (Finley, 1975). With hindsight, we now know that most of their theories were incorrect. However, their passion and desire to understand the universe, and the quality of their inquiry were of great importance as they influenced discussions and research even into the modern era. They were one of the first free civilized peoples and as such transcended beyond superstitions. They could do so because of the lack of power vested within the state or religious institutions to influence free thought unlike much of the rest of the world at that time.

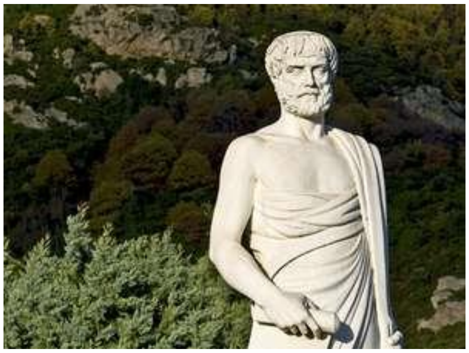


Figure 4.6. Aristotle's statue in Greece (Wikipedia Commons, 2013)

Thales the Milesian (639-544 B.C), an Ionian, was one of the first to separate theology and science. This distinction proved useful as it allowed the Greeks to look beyond the gods for explanations and instead observe and study. He learnt a great deal by traveling, and like most philosophers, was a wealthy man of high social status and as such gained many disciples (Finley, 1975).

Thales observed that water was the most abundant material on Earth and that all lifeforms required it and postulated that all lifeforms originated from water (Finley, 1975).

Anaximander (611-547 B.C.), a student of Thales, furthered this postulation by amending that spontaneous generation of the germ of a fetus occurred in the residue of the mud when the heat from the sun evaporated the water from the mud. He also theorized of an ethereal substance called "apherion" which was endless and unlimited. It existed either as hot or cold and mixing them in different proportions formed water, air, fire and earth and as such, life.

Empedocles of Argas (495-444 B.C.) postulated that the four elements water, air, fire, and earth were all contributors and that plants, animals and humans all formed from fire coming from deep within the Earth. (Finley, 1975)

During the 4th and 5th century both city-states of Sparta and Athens were flourishing. As their culture advanced, so did scientific thought and the School of Hellas in Athens was formed. It was the epicentre for all great Greek philosophers of that century, including Hippocrates (460-370 B.C.) (Hamilton, 1948).

Hippocrates' views on origin of life closely matched Empedocles', however as he was far more successful and also adopted Empedocles' view he is often accredited. Hippocrates postulated earth, air, blood and fire were synonymous with phlegm, blood, yellow bile and black bile. The doctrine of four humors and their balance was credited with the creation and maintenance of all lifeforms. This doctrine revolutionized the origin of life debate up until the Elizabethan era (Silverberg, 1964).

Aristotle (figure 4.6) and his pupil Plato both believed that all lifeforms were a result of different proportions of the four elements. Furthermore, like the other Greeks before them they believed life spontaneously arose (Silverberg, 1964).

Although these men were great scientific philosophers, they pursued these matters as an interest rather than to practically apply their knowledge. This was because these men were aristocrats, and to look for practical applications of their knowledge, especially those that would benefit the lower classes, would lower their own social status (Downey, 1962).

King Philip II ruled Macedonia in Aristotle's lifetime and summoned him to teach his son Alexander. Upon returning to Athens, Aristotle formed his school called the Lyecum. Thirteen years after its formation, military powers opposed to Macedonia conquered Greece and accused Aristotle of harboring Macedonian sympathies. He abandoned his school to Plato, fled and later died. With Aristotle's death followed the death of Greek scientific learning (Downey, 1962).

Disproving Spontaneous Generation

Although the Greeks all had very different ideas as to what elements may have composed life they all believed that life spontaneously arose. Even until the 1600's, almost 2000 years after Aristotle's death, spontaneous generation was widely accepted. It was thought flies appeared from rotting flesh, and mice arose from wheat. An imperative development in disproving these theories was a result of Francesco Redi's (1626-1697 A.D.) work (Klymkowsky and Cooper, 2016). Redi was an eminent Italian physicist and a nobleman. Redi was an anomaly of his time as he pursued his interests in science on the origin of life without persecution. Historians believe his education at the University of Pisa placed emphasis on polite literature that would not upset the Jesuits and the church. It's also possible he didn't incur the incur the wrath of the Catholic Church because just a few miles from Redi's school lived Galileo, who's work on the Universe and the existence of planets was far more blasphemous (Klymkowsky and Cooper, 2016).

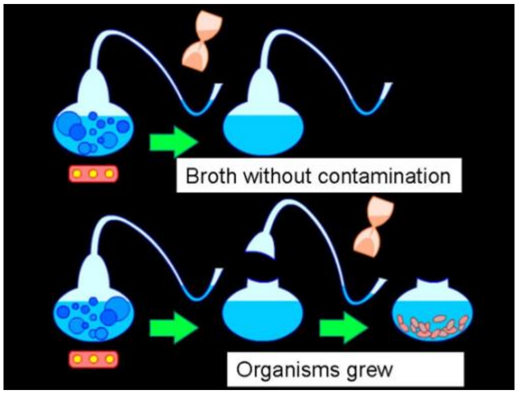


Figure 4.7. Louis Pasteur's Experiment involving the Swan neck shaped flask (Wikipedia Commons, 2012).

Redi hypothesized that spontaneous generation did not occur. His experiment involved two flasks both of which contained meat. One was covered with a cloth the other was exposed to the air and as such flies. He found only the flask exposed to the air gave rise to other maggots, proving life does not spontaneously appear but is instead continuous (Klymkowsky and Cooper, 2016).

A decade later, the invention of the light microscope exposed a whole new world of microorganisms. It seemed plausible that simpler organisms may form spontaneously (Klymkowsky and Cooper, 2016).

Lazzaro Spallazani (1729-1799) was an Italian catholic priest, biologist and physiologist who set out to prove that microbes were also not a result of spontaneous generation. Spallanzi was a vicarious reader and very methodical and skeptical by nature. He disproved spontaneous generation of microbes by boiling a broth and showing that it remained sterile for as long as it was isolated from contact with the air. His affiliation with the church was a huge advantage as it shielded him from the Italian Inquisition, which attempted to censor any work that was against the Christian doctrine. Moreover, the church actually provided financial support for his scientific endeavors (Sunderland, 2010).

His work was met with some criticism with the belief that the broth itself had nutrients that were destroyed after boiling, or that the air was the necessary ingredient. It became clear that boiling and isolation was obscuring the process by which the microbes came to be. Louis Pasteur (1822 – 1895), a French microbiologist, carried out a series of highly controlled and convincing experiments to support Spallanzi's work. He utilized a swan neck flask which allowed only air but no microorganisms to reach the broth. This addressed prior criticism that air was a requirement for spontaneous generation to occur. With the swan shaped flask containing a boiled broth he found that even when exposed to air, microbes did not grow. However, in a normal flask with a boiled broth exposed to air microbes grew easily (Klymkowsky and Cooper, 2016).

Louis Pasteur is still a polarizing figure among historians, as many see him as a noble-minded biologist with a creationist worldview, whereas others believe he was an atheist. This is likely due to the dichotomy of his work, which was evidently very anti-creationist, yet the speeches he gave frequently used the word 'creator'. Some even believe that he only supported the church to prevent interference or censorship of his work on the origins of life (Klymkowsky and

Cooper, 2016).

In any case, by the end of the 19th century, scientific consensus on the origin of life was that it had evolved from simpler forms, and neither microorganisms nor larger organisms were a result of spontaneous generation.

Figure 4.8. Alexsandr Oparin, author of The Origins of Life. Oparin was fundamental in the creation of the Oparin-Haldane theory (Wikipedia Commons, 1938).

Oparin-Haldane Theory

Although working separately, Alexsandr Ivanovich Oparin and J.B.S. Haldane developed and published their similar, incredibly influential theories at the same time in the 1920's (Schaefer, 2003). These theories initially met great rebuttal from the scientific community, however experiments by Stanley Miller and Harold Urey validated their hypothesis'.

Oparin (above) stated in 1924 that life developed by means of chemical evolution of carbon-based molecules in a primordial soup (Lazcano, 2016; Oparin, 1938). He believed that properties characteristic of life must have been formed from evolution of matter, that early Earth had an atmosphere containing the ingredients for the evolution of life (namely methane, ammonia, hydrogen, and water vapour), and that as molecules increased in complexity, a colloidal-chemical order was imposed on the chemical relationships according to the arrangement of the molecules thus creating membranes (Oparin, 1938). From there, he stated that natural selection directed evolution, and that the organisms are not limited by the Second Law of Thermodynamics because they are an open system. Initially writing his theories in a pamphlet in 1924, Oparin published his book, *The Origin of Life*, in 1936, and an English translation was released in 1938 (Oparin, 1938; Lazcano, 2016).

At the time, these postulates were considered radical, and were deeply intertwined with Marxist philosophies. Due to the Cold War, many prominent scientists working in the US dismissed the ideas immediately (Brangwynne and Hyman, 2012). A growing division between both Soviet and American ideas in science can be strongly linked to this time, and the origin of ideas in *The Origin of Life* are no different. After the Miller-Urey experiment in 1953, which functioned to credit his theory, Oparin began facing extensive Soviet criticism regarding his support of other scientists, and was forced to resign from his post at the USSR Academy of Science (Brangwynne and Hyman, 2012). Over two decades later, his work was ratified and he received the Lomonosov Gold Medal from the Soviet Science Academy for his work. Finally, by 1979, his work was officially being accepted (Campbell, 2012).

J.B.S. Haldane was a British biologist and geneticist and provided the second portion of the Oparin-Haldane theory (Clark, 2013). He frequently dabbled in many different aspects of research, as opposed to Oparin, who focused mainly on the origin of life. Haldane published a hypothesis in 1929, which contained a very similar process as described by Oparin's 1924 statement, although he reported that he had no prior knowledge of Oparin's work (Clark, 2013). Haldane's 1929 hypothesis included several postulates regarding the origin of life; that spontaneous generation is possible albeit in different terms than creationist theory, that organic molecules were synthesized in a primordial mixture containing water, carbon dioxide, and ammonia due to radiation from the sun, and cells were formed shortly after amino acids (Tirard, 2017; Haldane, 1968). As he worked on many areas of research, Haldane encountered resistance after publishing his hypothesis, as it was considered "wild speculation," and it is possible that without Oparin's work, his ideas may have become lost in history (Fry, 2000).

Although with incredibly similar postulates, there was no collaboration between the scientists. They only met after 40 years of working separately, while at a conference on the Origins of Prebiological Systems and their Molecular Matrices in Tallahassee (Clark, 2013).

Haldane addressed Oparin at this time, and stated to the audience that Oparin “has the priority over me” indicating that his ideas should be those remembered (Fry, 2000). Regardless of which scientist had priority, modern historians comment on the simultaneous, yet separate, publications as being a deciding factor which helped the combined theory gain traction (Tirard, 2017). Also due to this situation, the ideas put forth by the two scientists are collectively known as the Oparin-Haldane theory.

While each scientist struggled in acquiring acceptance of their theories, and the idea of organic material forming from inorganic material posed enough of a debate, another debate arose from the combined Oparin-Haldane theory. The two scientists both argued for cell (or protocell) formation prior to RNA formation, but there is argument for RNA formation first (Clark, 2013; Fry, 2000; Oparin, 1938; Haldane, 1968). At the time, it was believed that membranes formed first as the primordial soup had molecules with hydrophobic and hydrophilic areas that could self-assemble into liposomes (Oparin, 1938; Haldane 1968). However, to this day, this point is countered with the argument that bonds between molecules could form to create RNA almost as easily as to form membranes.

Including concepts and postulates put forth by each individual, the Oparin-Haldane theory was gradually accepted into the scientific community as a mechanism by which the basic building blocks of life may have formed under the conditions present on early Earth.

Miller-Urey Experiment

One of the greatest advances of the Oparin-Haldane theory was the experiment performed at the University of Chicago in 1953 by Stanley Miller and Harold Urey (Parker et al., 2014). Although this experiment was later determined to be flawed, the major principles remained intact, giving credence to the Oparin-Haldane theory, and the associated postulates.

Initially well-known for his work in the development of the atomic bomb, Harold Urey switched his research after the Cold War to isotopic ratios. He transferred to the University of Chicago, and helped establish the Institute for Nuclear Studies, where he soon began research regarding isotopic ratios in relation to evidence for Earth’s history (Science History Institute, 2016). In 1951, Urey published a paper discussing Earth’s early atmosphere holding the potential for life to emerge. At a seminar at the institute, he even mused about a potential experiment to determine the validity of this theory, which led him to Stanley Miller (Parker et al., 2014; Science History Institute, 2016).

Miller, a young chemistry graduate student at the time, approached Urey, and requested to design and run the experiment, with Urey supervising. Although Urey initially expressed concern about the viability of the study, Miller conducted the study in 1952, to great effect (Parker et al., 2014; Science History Institute, 2016; Johnson et al., 2008). Urey immediately recommended publication, albeit with Miller as the sole author. Declining to be the co-author, it is speculated that Urey was concerned Miller would receive little credit. Submitting to *Science*, a delay in a decision regarding acceptance led Urey to address the editorial board, request the return of the manuscript, and submit the document to the *Journal of American Chemical Society*. Reportedly annoyed by Urey’s actions, the *Science* editor informed Miller that the manuscript would be accepted, and it was later published by *Science* in 1953 (Parker et al., 2014).

Miller and Urey designed and conducted an experiment that tested the Oparin-Haldane theory, and showed that multiple organic compounds could spontaneously form under conditions that mimicked those of early Earth (Johnson et al., 2008; Parker et al., 2014). An apparatus of two glass flasks and a series of connecting tubes held a mixture of gases, including water vapour, methane, ammonia, and hydrogen (below). One flask had a heat source, whereas the other did not, to allow the gases to move between flasks and undergo state changes. The cooling flask had an electric current supplied via electrodes, to simulate energy in the form of lightning (Miller, 1953, 1955).

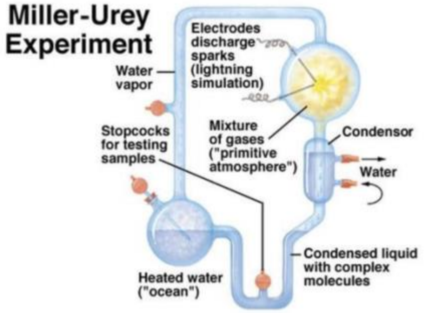


Figure 4.9. Diagram of the Miller-Urey apparatus. In the closed system, the gaseous mixture would circulate and undergo phase changes based on the temperature at the location within the apparatus (Wikipedia Commons).

The closed system was run for one week, and several organic amino acids were observed to have formed in the liquid pool, and collected to form coacervates (Miller, 1953). This was determined by the use of chromatography. In this pool, almost 15% of the carbon initially present had formed amino acids, and 13 of the 22 amino acids that form proteins in living cells were present (Miller, 1953).

Although no living systems were established from this experiment, and the molecules formed were only simple organic molecules, it provided strong support for the Oparin-Haldane theory. There was finally proof that conditions similar to those on early Earth could have allowed for the formation of organic molecules that are the basis of life, and do not require to be synthesized by life itself (Miyakawa et al., 2002).

While this experiment provided credence to the Oparin-Haldane theory, several inherent flaws have been frequently debated amongst the scientific community. Evidence has given reason to believe that the early atmosphere had less methane and ammonia than included in the experiment, however other evidence has supplied an argument for more hydrogen, which would lend to a greater likelihood of organic molecule formation (Parker et al., 2014). The other major flaw that is discussed is the amount of energy required in the Miller-Urey experiment. While the primordial atmosphere may have had frequent lightning storms in relation to the frequent volcanic activity, it is unlikely they occurred often enough to match the amount of electricity used in the Miller-Urey experiment (Johnson et al., 2008). This does not completely discredit the experiment however, as it merely indicates lower concentrations of organic molecules initially produced on early Earth.

The Miller-Urey experiment was the first of its kind, however the experiment is fairly simple and variations and modifications have been frequently repeated. Miller and his colleagues performed several of these repetitions, and eventually demonstrated that all alpha-amino acids and nonprotein amino acids can be formed, as well as various other molecules including hydrogen cyanide and formaldehyde (Stribling and Miller, 1987; Parker et al., 2014; Miller, 1955; Stribling and Miller, 1987). These numerous experiments have further solidified the evidence that supports the Oparin-Haldane theory. As well, improvements in techniques, especially chromatography, have allowed more amino acids to be confirmed upon completion of the experiment, over time (Parker et al., 2014).

Hydrothermal Vents

After thousands of years of thought, and experimentation the most plausible explanation as to the origin of life are hydrothermal vents.

Hydrothermal vents or seeps form at oceanic-continental subduction zones or on the sea floor, in areas undergoing or in close vicinity to sea-floor spreading. They can also form in close proximity to transform boundaries, due to the frictional heat generated in the slip regions of these areas (Campbell, 2006).

In these areas, the crevices and cracks that form on the sea floor as a result of the movement of the plates allow sea water to percolate down and be heated by the magma which is released from the vents through specific conduits. In some ways, hydrothermal vents are analogous to underwater volcanoes.

The largest of the hydrothermal vents are found along the mid-ocean ridge (MOR). The MOR is a 65000 km underwater mountain range formed as a result of convection currents rising in the mantle located below the thin oceanic crust (Campbell, 2006).

Hydrothermal vents are found in approximately 30 regions along the MOR system (above).

Originally, it was believed that only areas undergoing fast and intermediate sea-floor spreading resulted in venting, however it has been found that venting is not directly related to rate of sea floor spreading. Spreading rates ranging from <20 to >150 mm y^{-1} have been found to possess these vents. The vents are found on both bare basalt as well as sediment

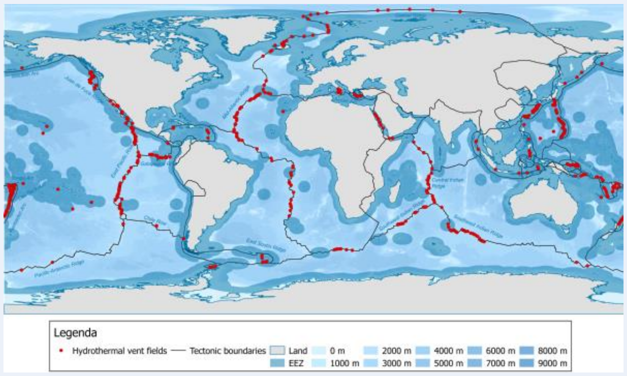


Figure 4.10. Hydrothermal vent locations on the sea floor. Notice the location of vents close to the location of mid-ocean ridges, and the spread across the globe (Wikipedia Commons, 2012).

covered ridges. However, understanding of the global distribution of vents may be biased, as most vents are found in areas in close proximity to developed nations that operate submersibles (Campbell, 2006).

Due to the extreme pressure at the depth of vents, the hot sea water released does not boil, but rises as it is buoyant. Furthermore, since the water temperature is very high (200-400° C), it can easily dissolve high amounts of methane, hydrogen sulfate, carbon dioxide, and nitrous oxides, which have all been identified as key components in the transition from inorganic to organic molecules referred to as a phase transition. Phase transition is a process whereby inorganic molecules come together and form the organic precursors to life (Campbell, 2006).

Although it has been long known that these compounds were likely present in sea water in the Archean time period when life arose, the mechanism for life effectively utilising these compounds was unclear. It had also been suggested that the temperatures of the vents may have been too high to support synthesis and preservation of any biological compounds. However, the high variance of temperature between the inner and outer margins of the vent indicated that early organic molecules likely formed along the edges of the hydrothermal vent (Campbell, 2006).

Although these vents possess hostile conditions to most organisms, they are high productivity areas for hyperthermophile chemoautotrophic bacteria. For instance, some bacteria, such as *Desulfotomaculum kuznetsovii* chemosynthesize sulfate-reducing organisms that do not need oxygen or carbon dioxide for metabolism (Visser et. al, 2013). Recently, benthic organisms (clams and mussels) have been found living in close proximity to these vents, and it is hypothesized they survive by forming a symbiotic relationship with the bacteria.

It is very likely that early bacteria would also have possessed highly sophisticated mechanisms for extracting, metabolizing, and utilizing the available compounds (Campbell, 2006).

Vented compounds from hydrothermal rock may have contributed to the phase transition from inorganic to organic molecules. In the early Archean era, most hydrothermal vents were composed of metal-rich Komatiites, which would outgas many of the compounds and important catalysts such as iron and zinc, required for chemosynthesis to occur at a sustainable rate for the bacteria (Campbell, 2006).

Another scenario for the origin of life at hydrothermal vents begins with carbon dioxide and nitrogen in vent waters at high temperatures. As these gases make their way to the shallower levels and lower temperatures away from vents, they are reduced to methane and ammonia. In the presence of certain metal catalysts, these can produce a plethora of organic compounds, including acetate and glycine. Further reactions between acetate and glycine found in deep sea hydrothermal vents could have produced the acetogenic precursors to chemosynthetic bacteria that diversified and gave rise to our complex biosphere today (Campbell, 2006).

As the sea floor spreading and subduction of the sea floor occurred, some of the chemosynthesizing bacteria moved into the photic zone where the first photosynthetic cyanobacterium formed (Campbell, 2006).

Due to the intransient nature of both hydrothermal vents there is no direct fossilized evidence of the earliest forms of life at hydrothermal vents. As such, we must instead rely on observational and experimental evidence. Experimental results and study of hydrothermal vents in the past 20 years have repeatedly shown that lipids, oligonucleotides, and oligopeptides can be synthesized under similar conditions to those found near hydrothermal vents. Furthermore, experimental results indicate that mononucleotides and amino acids, the prime markers of heritable life, can also polymerize along the hot-cold interface found in hydrothermal systems and can survive high temperatures. Finally, long chain hydrocarbons have been found in hydrothermal systems along the mid-Atlantic ridge. These hydrocarbons are the primary ingredient in the formation of membranes, and an integral part in separating the hostile outside conditions. The mechanism by which these long chain hydrocarbons form is still contested, however the prevailing theory is that they are a direct result of reactions between hydrogen released by serpentization of ultramafic rock and vent-produced carbon dioxide, with the extreme temperature and high hydrostatic pressure serving as catalysts (Campbell, 2006).

Although it seems counterintuitive that some of the harshest conditions on Earth served as the sites for the precursors of life, it is perhaps why life is so robust and resilient.

History of the Burgess Shale

The Burgess Shale had formed 530 million years ago, during the Cambrian period (Whittington, 1985). It is home to extremely well preserved Cambrian fossils, that appeared in a geologically abrupt event referred to as the Cambrian explosion (Erwin and Valentine, 2013). The Cambrian explosion was a radiation event that occurred when nearly all major living animal phyla appeared. It conveyed a rise in a diversity that has been traced via acritarchs, and an increase in trace fossils that recorded complex behaviour at this time (Erwin and Valentine, 2013). When it comes to the Cambrian explosion, there are three aspects that are critical to understanding the outburst of organisms: changes in the physical environment, the formation of new ecological relationships and the evolution of developmental systems.

In this chapter, the importance of fossils and the process by which they were discovered in the Burgess Shale will be discussed. The actions of two main individuals, Charles D. Walcott and Harry B. Whittington, will be highlighted and the overall significance of the Cambrian explosion will be discussed.

Fossils

Since geology is continuous, from the earliest Cambrian time to the present day, there exists a chronological sequence of life forms (Walcott, 1892). Zoologic characteristics were correlated across regions in order to group geologic time periods and rocks; the dating of fossils and the idea of a biozone was used to decipher geologic periods and events. Rocks present on Earth can be "zoned" through their zoologic content (Eldredge and Zimmer, 2014). It was originally understood that the most reliable time scale, deciphering chronologic events was based on the relative magnitude of zoologic change (Walcott, 1892). In other words, the geologic duration of a period is correlated to the magnitude and distinctness of its associated fauna (Walcott, 1892). Through this definition, proposed by Charles Walcott, the Cambrian explosion was of great significance in both ecological and evolutionary history (Erwin and Valentine, 2013).

Fossils are used to decipher earth history

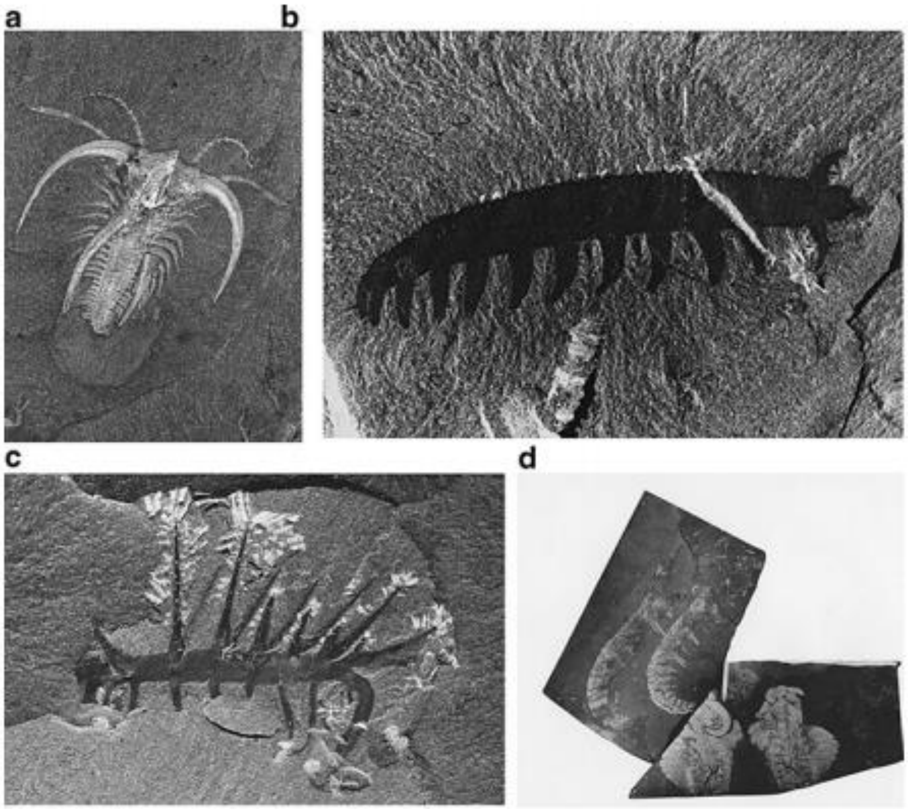


Figure 4.11. The images to the right show different types of fauna that were found in the Burgess Shale. a) A trilobite-like arthropod. b) A worm-like arthropod. c) A strange arthropod that has been hypothesized to use the spikes for protection. d) A predatory arthropod.

through biostratigraphical evidence (Rosen, 1988). This technique is able to indicate the relative ages of strata across different regions and help identify geological events that took place in the past. Most fossils are fragments or pieces of organisms that long ago, or in some cases, a trace of the activity of an organism such as a footprint or burrow (Whittington, 1985). It is rare that any soft component of an organism is conserved due to the usual chemical decomposition through bacteria and scavenging animals. However, the soft-tissue of Cambrian fossils in the Burgess Shale are often preserved (Whittington, 1985). As a result, the history of life is often understood from a fragmented record. Charles D. Walcott however, had made a discovery in the Rocky Mountains in British Columbia, Canada, while analyzing rocks that he referred to as the Burgess Shale (Whittington, 1985). These rocks consist of fully preserved fossils and were so significant that over thirty-five years following the discovery fossils by Walcott, discussion regarding the history of these creatures and their evolution continued.

The Discovery of Fossils in the Burgess Shale

In August of 1909, Charles D. Walcott had made his most tremendous discovery. He, alongside his family, was searching for fossils in the Burgess Pass while exploring the Canadian Rocky Mountains (Whittington, 1985). On their route southwards, Walcott's wife's horse had lost its balance and split a piece of rock loosely laying on the trail. The splitting of the slab of rock had exposed a shining silver layer on the dark rock; an amazingly preserved fossil. This particular fossil, known in the modern day as *Marella splendens*, was then referred to as a "lace crab". The fossil was complete, extraordinarily preserving soft-body parts of the organism. The following summer, Walcott and his sons had searched the slope above this trail and found layers of rock containing many fossils. He created a quarry which extended 3 metres into the ridge and split over 120 m$_3$ of shale looking for fossils (Whittington, 1985). To complete this process, picks, chisels, long iron bars and small charges of explosives were used. Walcott returned to the Burgess Shale in 1912, 1913 and for fifty days in 1917 (Whittington, 1985). He revealed over sixty thousand unique fossils from the Cambrian period, all of which are currently located in the National Museum of Natural History in Washington, DC (Whittington, 1985).

Following the discovery of the immense amount of preserved fossils in the Burgess Shale by Charles D. Walcott in the early 20th century, Harry B. Whittington and his colleagues discuss the earth's conditions and reasoning for the Cambrian explosion. In 1966, Aitken of the Geological Survey was appointed the leader of an expedition with the aim to decipher the environment in which the Burgess Shale was formed (Whittington, 1985). Harry B. Whittington was asked to join said expedition to the Burgess Shale due to his knowledge work on fossils. This expedition also included Fritz, who was an expert on Cambrian trilobites, MacDonell, Green, Lambert, Stesky, Johnson and Whittington's son. In the 1970s, Harry Whittington and his colleagues developed new reconstructions and models of the animals present in the Shale, and a more thorough and clear understanding of why and how they were so extensively preserved (Whittington, 1985).

As Walcott had made a large indent on the southern end of his quarry, Whittington and his colleagues started their research on the northern end. In the years of 1966 and 1967, they had extended the quarry 12 metres north and had split about 700 m$_3$ of shale (Whittington, 1985). When splitting the shale, they ensured to be careful, marking the level where the fossil came from and the date each fossil was collected. The team excavated the fossils in a similar manner to Walcott. However, the use of explosives was used more in moderation. Blasting was used on a smaller scale, with the purpose to open vertical cracks. This provided a new advantage as the use of heavier charges by Walcott caused the distribution of sediment layers, preventing the exact levels of fossils to be recorded (Whittington, 1985).

The majority of the fossils included shells composed of calcium carbonate, phosphatic material or chitin that were not broken down but rather were buried and preserved (Whittington, 1985). These shells were possibly buried in the sediment that accumulated on the shallow sea floor where they had existed or they were carried to this location in sands, silts or muds preceding their death (Whittington, 1985). The most common fossils present in the Cambrian rocks are trilobites, as well as other cap-shaped or flattened shells. The cap-shaped or flattened shells are mainly brachiopods whose shells were not connected together but instead held together by muscles and were formed of organic and phosphatic material (Whittington, 1985). They are present in early Cambrian rocks but are more common in post-Cambrian rocks. There were also needle-like spicules of sponges that were discovered within the Cambrian rocks (Whittington, 1985).

Preservation of Cambrian Fossils

As mentioned previously, the full body of an organism is not usually preserved as a fossil, but rather only a fragment of a piece of the animal. It was common for the skeletal portion of animals to be recorded in a fossil record but that the soft-bodied parts usually decay or are scavenged. In the Burgess Shale, however, complete fossils were present, including soft-bodied parts that lay parallel to the original surface of the deposition. In order to understand the process of preservation of these fossils, one must first understand the depositional environment and the burial process at the time. It is important to mention that the predictions conveyed regarding how and why Cambrian fossils were so well preserved came from comparing individual specimens of species.

At this time, a continent named Laurentia, mainly comprised of North America and Greenland, consisted of the sedimentary rocks that formed during the Cambrian. These rocks had provided clues indicative of the events that occurred during that time period (Whittington, 1985). There was no evidence of plants or animals on the land, nor in freshwater. Thus, it was assumed that Cambrian lands were barren and uninhabited (Whittington, 1985). It is believed that the Burgess shale was close to the submarine cliff (a continental shelf) at the edge of the Laurentian continent, the long section of the exposed Cambrian rock even suggesting a subaqueous depositional environment. Interesting enough, the rock consists of a sudden, nearly vertical, boundary separating shale and carbonate rocks. This suggests the presence of separate marine and depositional environments in the Cambrian period. Southwest of the boundary, the Cambrian rock consists of dark shale and thin layers of limestone. (Whittington, 1985). Thus, the southwest side formed in deep water located offshore where dark muds and thick limestones were the main deposits. To the northeast of the boundary, carbonate rocks and sandstone are present, both of which are deposited in almost horizontal sheets (Whittington, 1985). This indicates the northeastern component formed in shallow marine settings, covering carbonate banks such as reefs (Whittington, 1985). This formation of rock structures and their relationship in space and time can be used to analyze the original environment that encompassed the Burgess Shale.

David J. W. Piper investigated the quarry produced by Walcott, he observed

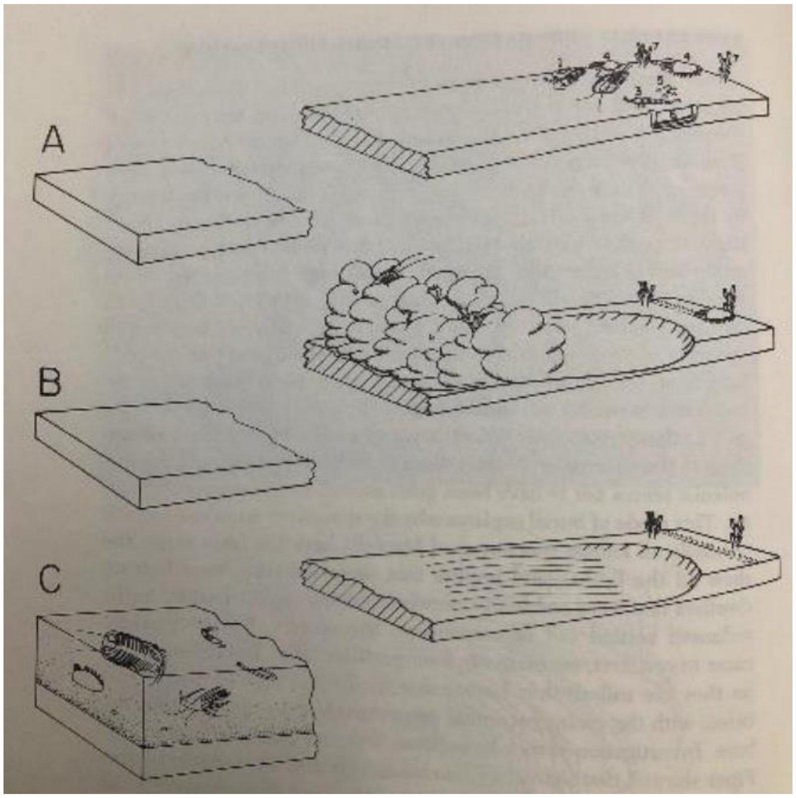


Figure 4.12. The diagram to the right shows the stages of fossil creation via a turbidity current. A) Organisms are present on the continental shelf. B) A turbidity current is created by the slumping of sediments transporting the organisms and sediments away from the shelf. C) The organisms and sediments travel down the slope and settle, overtime creating fossils.

characteristics of a normally graded bed; courser grains were deposited at the base and became finer as elevation increased (Whittington, 1985). A normally graded bed is often produced through turbidity currents, indicating organisms were buried through the submarine slumping of sediments. To further explain, along the continental shelf, muds and silts tend to slump down the slope. These slumps result from tremors or minor earthquakes, resulting in sediment along the continental shelf to lose contact with the bed, becoming suspending in a turbulent cloud. The sediments travel down the slope and eventually settles (Whittington, 1985). Organisms living along the slope would have been transported a couple of kilometres down the continental shelf in fine-grained sediments. These fine very-fine sediments such as mud would be able to fit between the small components of an organism while swirling energy in the turbulent cloud was not strong enough to disassemble the bodies of organisms. The organism would then become buried as the cloud settled (Whittington, 1985).

Majority of organisms living along the slope would settle parallel to the bedding, but due to the turbulent nature of the transport, some animals would settle at an angle. Many of the factors that influence the preservation of these organisms occurred within a few months or years after their burial (Whittington, 1985). One factor that took hundreds or thousands of years was the compaction of each layer of sediment. During compaction, the water present in the mud escapes and the sediments packed together. Therefore, animals did not settle on the surface of the mud once the turbulent cloud settles but rather was buried after additional mud was deposited on top (Whittington, 1985). Compaction is further indicated as the head, body and limbs of organisms flattened together into one layer. It is through a combination of these factors that the fossils from the Cambrian period were so well preserved (Whittington, 1985).

With all of that said, the question still remains as to why soft-bodied parts of the animals remained intact. Each layer of sediment is only a few centimetres thick and all layers appeared to be undisturbed by the tracks or burrowing habits of organisms and a very limited amount of decay in settled layers occurred proceeding the submarine slumps that were mentioned above. Rather than decaying, these organisms, such as trilobites were buried under thickening layers of mud. They were then transformed into a stony replica of the original organism through mineralogical alchemy, as suggested by Conway Morris (Whittington, 1985; Eldredge and Zimmer, 2014). Several of the internal organs of these animals remained intact.

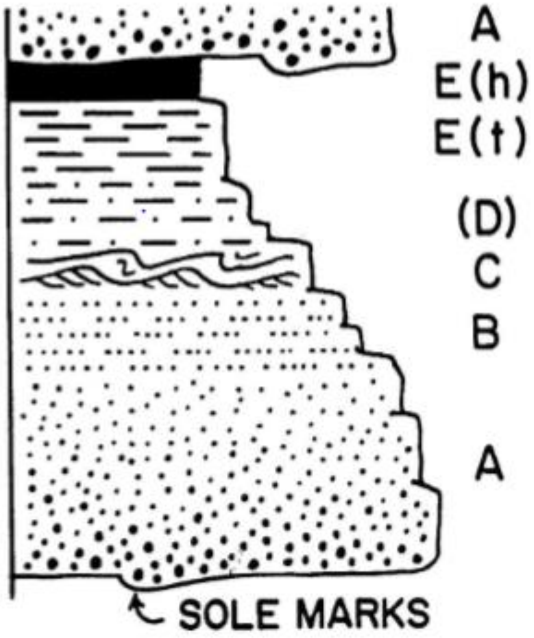


Figure 4.13. The diagram to the left shows the sediment log created in the presence of a turbidity current. A) Sedimentary rock. E(h))Hemipelagic mud. E(t)) Turbidite mud. D) Parallel laminae. C) Ripples and convolute bedding. B) Parallel laminae. Sole Marks) Preserved on the underside of a bed and is typically a cast of the underlying bed.

Modern Day Outlook on the Cambrian Explosion

Current Research

Through analyses of the molecular and morphological data of arthropods, it has been suggested that rates of evolution increased by a 4 to 5.5 fold in the early Cambrian (Yang et al., 2018). Over the years, there have been several theories to explain the mechanisms for the Cambrian Explosion, and the rapid evolution that took place. Theories have often surround environmental changes, changes in the genome of organisms, as well as ecological explanations (Yang et al., 2018). Recently however, research has focused on the elevated levels of atmospheric oxygen as a driving force for the Cambrian Explosion (Yang et al., 2018).

Between the years of 950 and 540 mya, the oxygen content in the atmosphere had rapidly increased (Yang et al., 2018). High levels of oxygen are required to support metabolically active animals, as well as the formation of collagen (Yang et al., 2018). In other words, the elevated levels of oxygen had removed an environmental barrier associated with the evolution of larger, metabolically active animals. It is understood that oxygen can lead to reactive oxygen species (ROS) (Yang et al., 2018). ROS can result in organisms experiencing oxidative stress, which in turn, can potentially lead to genomic damage and mutations, as well as support novel regulatory mechanisms for development. Increased ROS levels, caused by increased oxygen consumption, can produce single-stranded or double-stranded breaks, deoxyribose modifications, DNA crosslinks and thus overall DNA damage that can lead to mutations (Yang et al., 2018). It is suggested that the increased rates of evolution that are present in the Cambrian explosion can potentially be explained via mutations caused by ROS (Yang et al., 2018). Therefore, recent research has suggested that ROS were important factors in driving the Cambrian Explosion.

Debated Magnitude and Significance

In the modern day, there is a lot of controversy and debate regarding the significance of the Cambrian explosion. When the fossils of the Burgess Shale were originally discovered by Walcott, there was no evidence of any fossils predating the Cambrian period. Charles Darwin had even recognized this, stating that there was no record of fossil deposit belonging to periods preceding the Cambrian system (Darwin and Matthews, 1975; Prothero, 2017). It was not until the 1940s and 1950s that Stanley Tyler and Elso Barghoorn discovered cherts and flints that had preserved fossils predating the Cambrian period (Prothero, 2017). In particular, in 1946 fossils attributed to the Ediacaran fauna were first discovered in the Rawnsley Quartzite in the Ediacaran Hills of Australia by Reg Sprigg. These organisms existed from 600 Ma to the Cambrian era and were primarily soft-bodied organisms.

Through analyses of the fossil record, it is suggested that the organisms present in the Cambrian era supported the rapid origination of modern phyla that we see today (Mángano and Buatois, 2016). The Cambrian explosion is a very significant event in the development of life forms on Earth as it is broadly viewed as evolutions 'big bang', shaping the history of life. With that said, the Cambrian explosion does not mark the peak of animal diversity (Deline et al., 2018). Instead, organisms in the Cambrian era enabled the evolution of novel organisms. These novel organisms have been able to expand into a new morphospace (Deline et al., 2018). Modern day organisms have diversified and evolved since the Cambrian era, consisting of complex skeletons that are able to support life on terrestrial and aerial environments (Deline et al., 2018). In particular, vertebrates and arthropods have expanded into this novel morphospace (Deline et al., 2018). This is contrasted to those organisms in the Cambrian era that had simple skeletons and soft bodies, restricting them to water-based environments.

However, there is an opposing position which emphasizes how the fossil record is incomplete (Mángano and Buatois, 2016). It is suggested that there are strong Precambrian roots in metazoan evolutionary history. This perspective essentially suggests that the sudden outburst of animal phyla, recorded in fossils, at the start of the Cambrian period is just an "artifact" (Mángano and Buatois, 2016). According to Prothero (2017), the increase in diversity from the Cambrian 'explosion' is misleading as it only documents the apparent initial appearance of soft-bodied phyla. Therefore, it does not indicate the rapid origination of modern phyla but rather just suggests that there an increase in preservability of body fossils (Mángano and Buatois, 2016).

Furthermore, it is argued that the Cambrian explosion was not even an explosion at all. The early period of the Cambrian was characterized by fossils, only a few millimetres long, referred to as "small shelly fossils" (Prothero, 2017). For almost 25 million years, these small shelly fossils were present in large quantities but fossils of larger size were nowhere to be found (Prothero, 2017). Prothero (2017) argues this outburst of organisms is actually just that of normal evolutionary transformations. In addition, what was assumed to be rapid evolution of species and unusual evolutionary mechanisms may not be that at all. It is suggested that the evolutionary radiations in the Cambrian period were slow-fused and this was analyzed from a theoretical perspective (Prothero, 2017; Budd and Mann, 2018). Currently, the number of living species is so small compared to the total biodiversity seen in the past, with over 99% of species extinct

(Budd and Mann, 2018). Therefore, this paper recognizes that focusing on living taxa can give a biased perspective on the dynamics of evolutionary outbursts. In a model where speciation and extinction probabilities are constant throughout time, it is through luck which monophyletic group will undergo high speciation. It is the idea that clades are most vulnerable to extinction when they comprise of only a small number of species. If they are lucky enough for speciation to occur, they are more resilient to random total extinctions. If one focuses on surviving clades, history would indicate a high rate of speciation indicative for the rapid outburst of evolutionary radiation. However, the overall rate of speciation has not altered throughout time and living clades can create an illusory perspective for the early-outburst evolution. Speciation rates in young clades are hard to analyze as a result of the small sample size.

There are several debates regarding the significance of the Cambrian explosion. Some argue that the importance of the event should be re-evaluated as it may not have been the geologic instantaneous event that everyone considers it to be. Overall, one simply suggests being aware to not overestimate the magnitude of the Cambrian explosion.

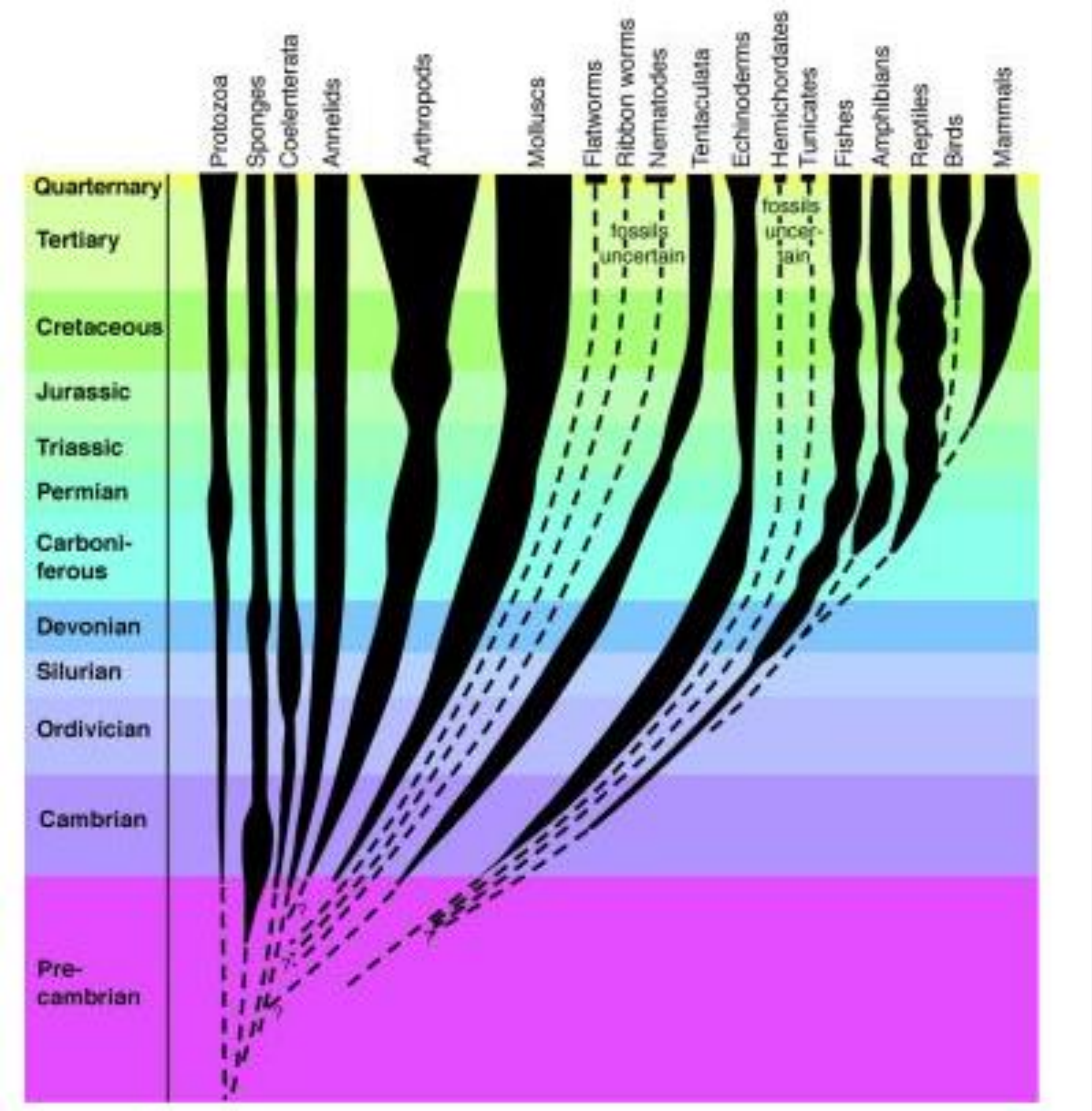


Figure 4.14. The image to the left shows the explosion of fauna found during the Cambrian

The Influence of Geology on Charles Darwin

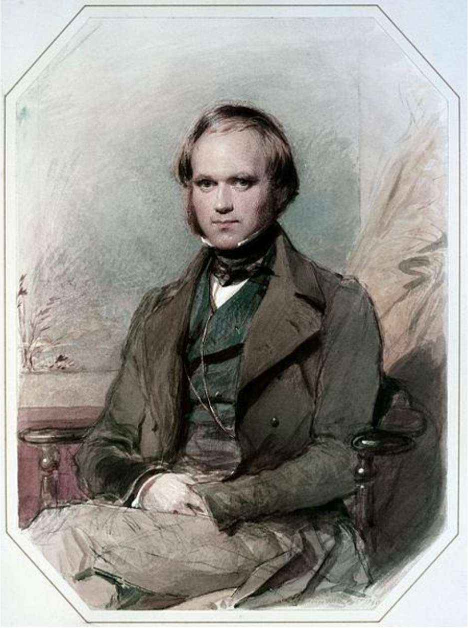


Figure 4.15. A portrait of Charles Darwin while in his late twenties

Charles Darwin is best known for his work proposing the Theory of Evolution by Natural Selection, leading him to be known as the Father of Evolution. He published his work explaining this theory in *On the Origin of Species* in 1859, which revolutionized the field of biology (Darwin, 1861). In brief, Darwin's theory of evolution by natural selection is that species change in small amounts over many generations as a result of natural pressures acting on small variations that may occur between individuals of a population (Jane B. Reese et al., 2011). Darwin is one of the best-known biologists of all time; what he is less known for his work as a geologist. In fact, this work greatly influenced his life and thought; geology was so crucial to Darwin that without it, *On the Origin of Species* would likely not have been written.

Darwin's Introduction to Geology

Darwin was not unique in the fact that he studied multiple scientific disciplines; many scientists at this time had many interdisciplinary interests and studies. Specifically, many of the scientists who influenced Darwin were both botanists, geologists, and zoologists (Secord and Pearn, 2016a). Through his circle of professors, mentors, colleagues and friends, Darwin was greatly influenced both by the field of geology and those who studied it.

While studying at the University of Cambridge, Darwin met John Stevens Henslow, a botanist and mineralogist who became a close friend and mentor of his (Secord and Pearn, 2016b). Henslow was a crucial part of Darwin's life; not only did he offer him the spot on the *Beagle*, but Henslow helped Darwin with identification and preservation of species found on the trip. Beyond this, Henslow and Darwin were frequent correspondences of each other's, constantly sending letters and asking one another for advice (Secord and Pearn, 2016b). Darwin was first introduced to Henslow through a series of public lectures while he was studying medicine at the University of Edinburgh (Darwin, 1838). At this time Darwin was greatly uninterested in school and had no passion for medicine; he left Edinburgh after two years and without completing his degree. He subsequently enrolled in a Bachelor of Arts program at the University of Cambridge, where Henslow worked and studied (the University of Edinburgh, 2019). This allowed Darwin to come to know Henslow more closely; he was a frequent attendee at dinners which Henslow held, and started to accompany him on daily walks. It was through these events that the men got to know each other more personally, and in the winter of 1830, Henslow suggested that Darwin take up the study of geology, forever changing his future career in science (Darwin, 1838).

Throughout that winter, Darwin worked on taking and examining rock samples and creating a coloured map of the area around Shrewsbery. Since he enjoyed this work, Henslow introduced Darwin to Adam Sedgewick, a professor of geology at Cambridge (Darwin, 1838). Coincidentally, Sedgewick had also given public lectures at Edinburgh, and while Darwin never attended any, he later said that "had I done so, I likely would have become a geologist earlier than I did." (Darwin, 1838). Of these same lectures, Darwin said that "while he enjoyed those of Henslow, he did not become a botanist" (Darwin, 1838). This comparison between one of Darwin's greatest mentors and Sedgewick shows the true impact and interest that the study of geology had on him.

In the summer of 1831, Darwin accompanied Henslow on a trip to northern Wales to map the area. It was on this trip that Darwin was introduced to the many field methods of geology and he learned how to determine the geology of a country, skills which would come back to be used on the *Beagle* voyage in his study of the Galapagos (Darwin, 1838). On this trip Darwin was also introduced to the idea of glacial phenomena; while this information was not used on his *Beagle* voyage, it helped provide him with a greater understanding of processes that shaped the earth's surface (Darwin, 1838).

In a letter written to Henslow a few months later, following Darwin's departure on the *Beagle*, he says:

"Tell Prof: Sedgwick he does not know how much I am indebted to him for the Welch Expedition.-- it has given me an interest in geology, which I would not give up for any consideration.-- I do not think I ever spent a more delightful three weeks, than in pounding the NW mountains." (Secord and Pearn, 2016b)

In the August following his trip to Wales, Darwin obtained his Bachelor's degree from Cambridge, and only months later he left on the *Beagle* (Darwin, 1838). One of the reasons why this trip was so seminal to his future work was that it was one of the only times that Darwin had to explore science outside of a classroom. As stated by Gavin de Beer, an evolutionary embryologist who served as the director of the Linnaean Society of London and as the Director of the British Museum, Darwin had very little "systematic instruction in biology, and [that he] learnt it the hard way" (de Beer, 1974). Although he had only completed a bachelor's degree by the time he left on the *Beagle* voyage (Darwin, 1838), the geological training with Sedgewick provided him with an experience and was foundational to his understanding of performing science.

The Voyage of the *Beagle*

In the fall of 1831, Henslow wrote to Darwin, once again offering him an opportunity that would change his future. This time, the letter contained an invitation to act as a naturalist on the ship the *HMS Beagle* (Secord and Pearn, 2016b). That winter, the 22-year-old scientist departed on his voyage on the *Beagle*, getting the chance to travel to the coasts of South America, Africa, and Australia. The next five years could arguably be considered the most influential of his career, as this is when he made the observations required to publish his infamous work (Reece et al., 2011). Originally, Darwin's father was reluctant to allow his son to partake in the voyage as he thought it would not be relevant to his career; however, after garnering support from his uncle and future father in law, was allowed to accompany the crew (Darwin, 2001). Each day while travelling, Darwin would record daily events and any interesting observations in his diary. He almost never made observations while on shore, instead electing to record any necessary information when returning to the ship (Darwin, 1838). When he felt he had to make note of what he was seeing inland, he wrote down his observations in a separate series of pocketbooks which contain a plethora of details pertaining to his discoveries (Darwin, 1838).

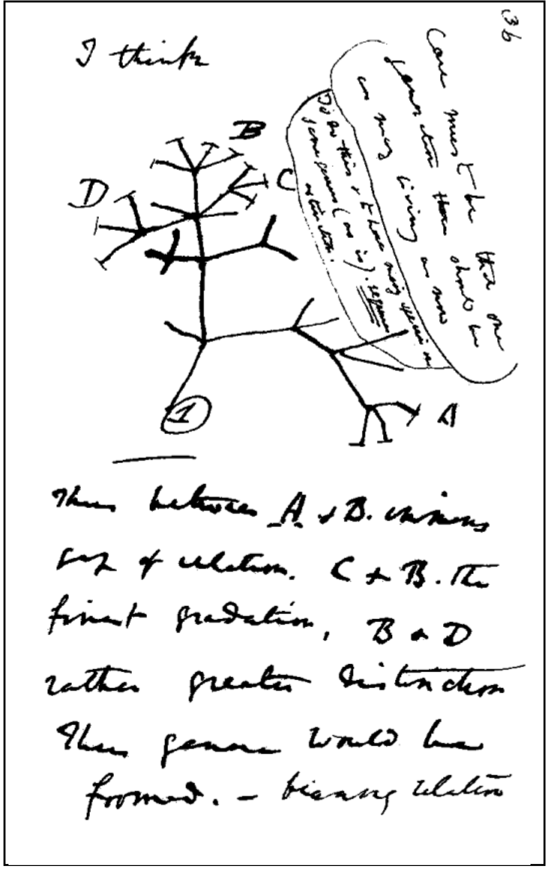


Figure 4.16. An 1837 drawing from Darwin's "First Notebook on Transmutation of Species" The interpretation of text from his notebook reads "I think the case must be that one generation should have as many living as now. To do this and to hae as many species in the same genus (as is) requires extinction. Thus between A+B the immense gap of relation. C+B the finest gradation. B+D rather greater distinction. Thus genera would be formed. Bearing relation…"

While on the ship, he made record of many plants and animals, focusing specifically on what made these organisms suitable for the environment which they were in. He was able to study both fossils and living organisms from jungles, plains, grasslands, and mountains of South America, which influenced many of his theories (Reece et al., 2011). He centered many of his observations upon adaptations that organisms had which make them more likely to survive in their climate. This study of adaptations eventually allowed him to develop his theory of evolution by natural selection, hypothesizing that individuals with these better traits would survive and reproduce at higher rates than those with less favourable characteristics (Reece et al., 2011).

In writing his autobiography, Darwin refers to "the Voyage [of the *Beagle*] as the first real education or training of [his] mind" (Darwin, 1838, p. 44). In these reflections of his trip, it is his geological observations that dominate over all of his other endeavours (Darwin, 1838). One such observation is that of an earthquake along the Chilean coast and the rock movements that followed. Following this observation, he hypothesized that fossils found high in the mountains were placed there by similar earthquake and rock movements (Reece et al., 2011).

While on the *Beagle*, Darwin had the opportunity to read The Principles of Geology, written by Charles Lyell, which proved to be of great influence to him (PBS Evolution Library Editors, 2001). The Principles of Geology is as foundational to geology as *On the Origin of Species* is to biology. Lyell argued against the biblical idea that landforms were created by sudden, catastrophic events; instead, he looked to the theory of uniformitarianism – the idea that one must look at the processes currently occurring in order to understand the past (British Library, 2019). More specifically, he proposed that processes acting on the earth's surface today are the same ones that have always been acting on it, and at the same intensity (British Library Archives, 2019). Given this knowledge, we can better understand how different landforms were formed and how they changed. All of Darwin's observations while on the voyage supported those made by Lyell, which fully convinced him of their accuracy (Darwin, 1838). Another concept that was introduced to Darwin in The Principles of Geology was the idea of vast periods of time, or the geologic timescale (Darwin, 1861). At this time, many people still believed the earth to be just a few thousand years old, as was biblically suggested, yet this length of time is not sufficient for the geologic or evolutionary change that Lyell and Darwin were suggesting.

The concepts suggested by Lyell in The Principles of Geology, as well as Darwin's own observations on variation, were the first inspirations to the theory of evolution by natural selection (Jane B. Reese et al., 2011; Secord and Pearn, 2016a). If the geologic landscape can change over time, why is this not the case with species? What is to say that the variation seen in animals is not also a result of the natural environment?

In addition to his studies while aboard the *Beagle*, it was during this time that Darwin truly became passionate about scientific work and discovery. He recalls his first thoughts of publishing a book while on the *Beagle*, which made him "thrill with delight" (Darwin, 1838). It was not a book on speciation, but a book on the geology of all of the islands visited that Darwin thought of writing (Darwin, 1838). In reflecting on this journey, he says:

"The investigation of the geology of all the places visited was far more important, as reasoning here comes into play. On first examining a new district nothing can appear more hopeless than the chaos of rocks; but by recording the stratification and nature of the rocks and fossils at many points, always reasoning and predicting what will be found elsewhere, light soon begins to dawn on the district, and the structure of the whole becomes more or less intelligible." (Darwin, 1838, p. 44)

In the decade following his return to England, Darwin did in fact publish many articles and books, the first three of which were based upon geology. It was not until much later in his life that Darwin started putting together his work for On the Origins of Species (Darwin, 1838).

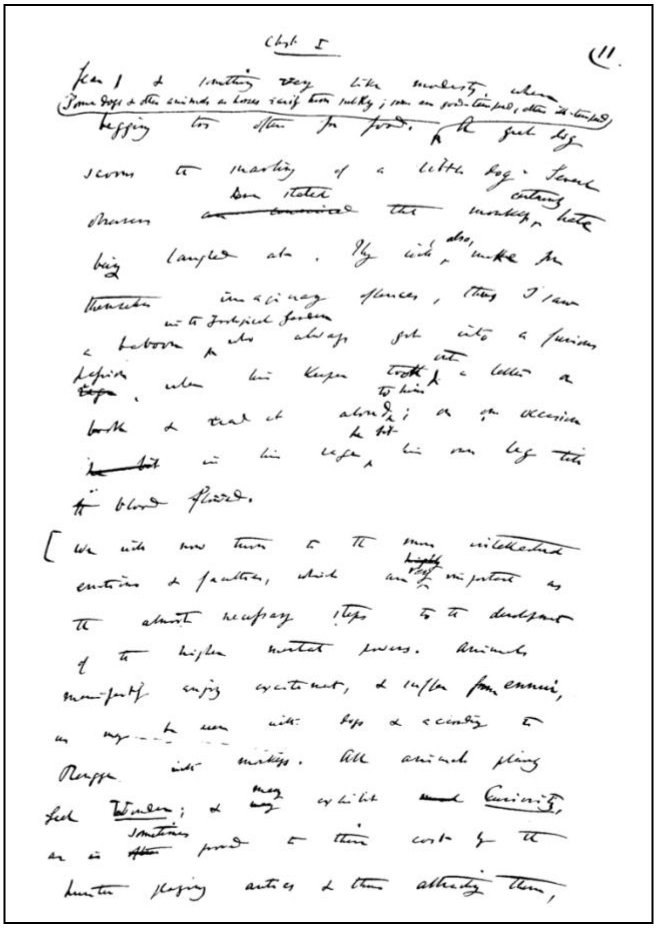


Figure 4.17. A copy of a letter sent from Charles Darwin to the geologist Charles Lyell. Their correspondence is indicative of the influence Lyell had on his peer, which aided in the creation of Darwin's evolutionary theories. The full text is not of this letter is not known.

Upon Returning to England

Once Darwin returned to England, he came to know Lyell more personally, once again being able to learn from him while developing his own ideas. Darwin recalls that when he talked to Lyell on the subject of geology "he never rested until he saw the whole case clearly, and often made me see it more clearly than I had done before. He would advance all possible objections to my suggestion, and even after these were exhausted would long remain dubious" (Darwin, 1838, p. 58). Lyell helped Darwin to think critically, not just about geology but about all of his work - a skill that Darwin put to use in writing Origin of Species. On top of this, it was Lyell who suggested to Darwin that he write up his ideas and publish them as *On the Origin of Species* (Secord and Pearn, 2016a; Darwin, 1838).

During this same period, Darwin came to know many of the other leading geologists of this time (Darwin, 1838). He had many frequent correspondences whom he would ask for assistance from as well as those among professional circles. It was through these, along with his own work in geology, that he served as the Hon. Secretary of the Geologic Society from 1836-1839 (Darwin, 1838).

On the Origin of Species

The extent to which geology influenced Darwin is clear while reading *On the Origin of Species*. Of the fourteen chapters, four are solely centered on geology and earth science; chapters nine through to thirteen focus on the geologic record, geological succession, and geographical distribution (Darwin, 1861). The detail and extent to which Darwin explains these processes makes it clear that he has a thorough understanding of the subject. Furthermore, the majority of his examples are fully supported by more modern developments in geology.

One of the largest critiques on Darwin's theory of evolution by natural selection is the lack of intermediate fossils present in the geologic record; Darwin was unique in writing *On the Origin of Species* in that he fully predicted the holes that may be poked in his theory and argued against them in his book (Gawne, 2015). Darwin acknowledges that there must be a massive number of intermediate species between the two known forms, and his response to the fact that many of these are not present as fossils is that the fossil record is in no way complete. He explains that "no organism wholly soft can be preserved" and that "shells and bones will decay and disappear when left on the bottom of the sea" (Darwin, 1861). He goes on to explain that sediment is not being deposited continuously at a fast-enough rate to preserve all potential fossils from bones (Darwin, 1861). These points have been continuously cited, as they are a very accurate and clear response to Darwin's critics.

Additionally, Darwin relates the fossil record to his explanation for his theory, saying "Extinction and the theory of natural selection are intimately connected together. The study of tertiary formations gives evidence that species and groups disappear gradually, not all of a sudden" (Darwin, 1861). Darwin understood the theory of geologic time, which in relation to forms of life, is incredibly vast (Secord and Pearn, 2016a). The time between which different strata formed provided ample time for many different intermediate species to have formed and evolved (Darwin, 1861). The study of geology, both in relation to the fossil record and the age of different strata, supported the idea of gradual change, which is another integral part of his theory.

In a letter written to Emma, Darwin's wife, he requested that if he were to die before *On the Origin of Species* could be published, that 400 pounds be set aside for this purpose. Additionally, he asked that its editor would be both a geologist and a naturalist (Herbert, 2005). This makes it clear of the true impact that geology had in the theory of evolution by natural selection; Darwin felt that the geological aspect of the book was equally as important to its clarity as the aspect of a naturalist.

Without Darwin's knowledge and training in the field of geology, it is likely that he never would have developed the Theory of Evolution by Natural Selection. It was the first scientific discipline that he became truly passionate about, and is crucial for understanding the naturalist processes that he explains. While Darwin is today known as the father of evolution, he should also be remembered for his extensive knowledge in a variety of interdisciplinary scientific fields.

Fossils and Molecular Clocks

Darwin's theory of evolution has been widely accepted in the scientific community for decades. Although his postulates and findings were published back in the 1850s, many unanswered questions about evolution still exist. One such mystery is discerning when two species diverged; this is essential in the reconstruction of the phylogenetic tree, which is vital to the understanding of evolution. In the nineteenth century, the answers to many of Darwin's questions were found in the study of geology, and the absolute age of divergence may be unearthed in a similar fashion. An exciting advancement in the field of evolutionary biology is the potential to reconcile absolute dating with the geologic record through the use of fossils in molecular clocks.

A molecular clock is a methodology or model that utilizes genetic information to show how the time frame of evolution differs for a variety of living species, frequently by comparing genetic differences between a species of an unknown age and a known one. Essentially, it is a way of measuring when divergence occurred across the tree of life (Lee and Ho, 2016). Genome sequencing has shown that the rate of evolution is not the same for all organisms; divergence time can vary between species, as well as between time periods for the same species (Lee and Ho, 2016). In the late 1900s, it was suggested that paleontological data should be ignored in the use of molecular clocks; however, modern techniques have determined that this should not occur (Donoghue and Benton, 2007). Although molecular clocks seem to be based mainly upon ecological and genetic information, advancements in this field would likely not be possible without the study of Earth science and the history of the world.

In order to use molecular clocks to calculate divergence time, they must be calibrated by determining the evolutionary rate of one organism, and then inferring divergence times of other organisms from these data. Genetic techniques can only provide a relative estimate for the rate of evolution, not a definitive time period in which divergence occurred (Lee and Ho, 2016). In order to calibrate the molecular clock such that it provides an absolute time frame, either the timeline of known geologic events, or more commonly, the fossil record can be utilized (Lee and Ho, 2016). An age estimate for a fossil that is either as old or older than the unknown organism, provides a time constraint for that organism; this can then be used as a calibration point to interpret the divergence time of other organisms (Donoghue and Benton, 2007; Lee and Ho, 2016). The method of using the timing of known geological events, such as rifting or island formation to estimate or further constrain the time scale at which divergence occurred can also be applied if the species was known to be affected by the event (Lee and Ho, 2016). Knowing the relative time at which a species appeared in the phylogenetic tree makes it possible to convert the relative age based on genetic data to an absolute age using the fossil calibration (Lee and Ho, 2016). The usefulness of this technique is accentuated by its ability to extrapolate data for soft-bodied organisms which have not left fossilized remains, or other organisms whose origins are unknown (Lee and Ho, 2016).

It has been commonly known since Darwin's time that the fossil record cannot perfectly record evolutionary history; the problem that now arises with this technique is its accuracy (Donoghue and Benton, 2007). The fossil record is not complete and although there is an extensive fossil record for some periods of Earth history, there are others with very little

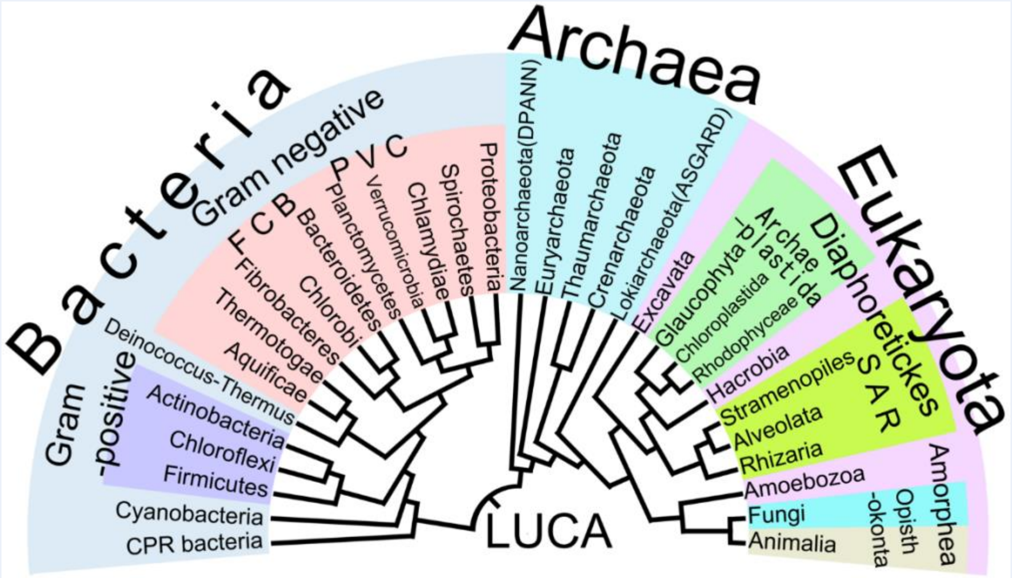


Figure 4.18. An artistic model of the currently understood phylogenetic tree of life. Molecular clock techniques can aid in reconstructing the tree and calculating age of divergence to add more detail to it

(Donoghue and Benton, 2007). Additionally, the quality of the fossil record changes over time; early Cretaceous fossils are much better preserved than late Cretaceous fossils, which can prove problematic while attempting to date their origins (Donoghue and Benton, 2007). Making inferences based on the phylogenetic tree can be dangerous if calibration points based on inaccurate fossil dates are erroneous, and can result in inaccuracies throughout the reconstruction of the phylogeny; it is therefore essential to garner as much data from the fossil record as possible (Lee and Ho, 2016). Given that organisms generally appear before fossil evidence, it is also likely that much of the fossil evidence researchers have uncovered establishes the divergence of that species later in time than it actually originated (Parham and Irmis, 2008).

Many scientists also argue that molecular and fossil evidence do not always agree with each other (Donoghue and Benton, 2007), which creates discrepancies when dating the tree of life; however, for most species they are in agreement (Donoghue and Benton, 2007). Despite advancements in genetic techniques, current molecular clocks will continue to rely on the temporal control established by the fossil record, as this is the best approximation of age that is available (Donoghue and Benton, 2007). Additional genomic data increases knowledge of map distances (ie. the physical distance between various genes) which are already understood (Lee and Ho, 2016). Increasing the amount and quality of genetic data does not address the previously discussed sources of error, so it is unlikely that any evolutionary estimates can be made without an understanding of paleontology (Donoghue and Benton, 2007; Lee and Ho, 2016). In fact, some researchers argue that increasing molecular data actually worsens knowledge of divergence times (Lee and Ho, 2016).

Recent analytical developments offer promising ways to reconcile the fossil and molecular evidence. In 2004, a team of molecular phylogenists from France created what they call a "relaxed" molecular clock, which allows for varying rates of genetic change between organisms (Maris, 2004). Using 129 nuclear proteins for thirty-six extant species of animals, plants, and fungi, they worked to create a tree of life that relates these organisms to the fossil record at six key points (Douzery et al., 2004). They then reconstructed a tree that fits within the upper and lower bounds of the date ranges provided by these six species; in determining the most accurate dates for the origins of these organisms using fossils, they ensure that any future divergence must also agree with these measurements (Douzery et al., 2004). After determining mutation rates using protein analysis between species, researchers ran simulations to correlate mutation rates to the new phylogenetic tree with the six constraining fossil points. They found that some of the dates precede the appearance of these fossils in the record; however, this may not be inaccurate as fossils often indicate a later divergence date as they are not immediately incorporated into the record (Douzery et al., 2004; Parham and Irmis, 2008). This new model of divergence hints towards major advancements in evolutionary biology.

Figure 4.19. A fossil found at Joggins Fossil Cliffs in Nova Scotia, Canada.

Although evolution is a foundational principle of modern science, using molecular clocks to refine our understanding of the process allows current science to make invaluable advancements. Molecular clock techniques could provide evidence for the origins of life (Lee and Ho, 2016), which has fascinated scientists for decades. Being able to determine divergence rates is also critical in the field of medicine as it allows for the study of mutations of antibiotic resistant bacteria that cause many of the infections and illnesses doctors face today (Lee and Ho, 2016). Darwin's discoveries in the 1800s provided the foundation for evolutionary principles that are now being used to uncover some of science's greatest mysteries; this undoubtedly shows that the key to the present actually lies within the past.

The Bone Wars

Setting the Stage

At the turn of the nineteenth century, the United States of America was still a young nation. She had just gained independence from Great Britain, and the Revolutionary War left the nation in a vulnerable state. The burdens of war had inflicted many socio-economic changes to the United States, and there is no denying that the nation went into a period of economic depression following the war (The Metropolitan Museum of Art, 2019).

Great Britain recovered quickly, and soon after, was on the verge of the start of their industrial revolution. Though American colonies had the advantage of land and resource availability against Britain, they lagged behind in the industrial revolution as the American labor force was scarce (The Metropolitan Museum of Art, 2019). Once the American precursors for industrialization—discovery of natural resources, boom in number of inventions created, immigration of migrant workers, completion of the Transcontinental railroad—were met, America's agriculture-based society entered its industrial revolution headstrong (The Metropolitan Museum of Art, 2019). The American industrial revolution was characterized by rapid production and consumption. There was a strong emphasis put on productivity and speed of work.

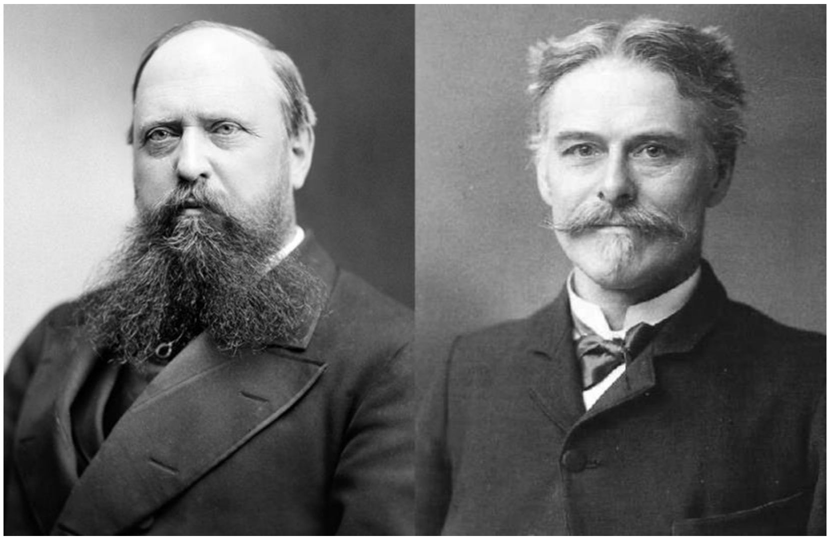


Figure 4.20. Portraits of Othniel Charles Marsh (left) and Edward Drinker Cope (right).

It was shortly after this time that Othniel Charles Marsh and Edward Drinker Cope *(Fig. 4.20)*, two competing paleontologists who would shift the perception of American geologic history and change history themselves, were born. Similar to the industrial revolution, there was a very strong emphasis placed on speed and quantity, sometimes over quality, of contributions in the two's careers and publications. The race between the two eventually lead to their mutual demise, in more ways than one, but there is no denying that their feud, referred to now as 'The Bone Wars' uncovered an immense amount of fossils, many of which are still studied today.

Early Life and Meeting

Marsh was born in 1831, and his mother passed away when he was three years old. His father was a farmer and shoe manufacturer, and their family lived quietly and modestly in Lockport, New York. Marsh's interest in paleontology began during his childhood with minerals and invertebrate fossils mainly from formations exposed by Erie Canal, which was close to his childhood home (Complete Dictionary of Scientific Biography, n.d.). Fortunately, his uncle George Peabody was a wealthy banker and philanthropist. Peabody aided Marsh's education at Yale (Complete Dictionary of Scientific Biography, n.d.), and then again with his graduate studies in several German universities. After Marsh's eventual passing away, much of his fossil collection would be displayed at the Peabody Museum at Yale.

A few years later, in 1840 Philadelphia, Pennsylvania, Cope was born. His family also came from a modest background. When he became of age, to avoid being drafted into the Civil War that was occurring across America, Cope's father sent him to Europe to study natural history (PBS, n.d.). Thus, in the spring of 1863, Cope travelled abroad to Berlin. That is where he met Marsh for the first time (PBS, n.d.). The relationship between the two started amicably, their common passion for fossils drawing them together. In fact, shortly their meeting, each had named one of their own fossils after the other; Cope naming an amphibian fossil Ptyonis marshii, and Marsh naming a serpent fossil Mosasaurus copeanus. The two remained friends in Germany during their respective studies, and then returned to America separately. They would once again be reunited soon after by their common interests.

Figure 4.21. Marsh (top center) and his crew. Later in his work, Marsh was known to leave all in-field work to his crews, rarely going on site himself.

Upon returning to America, Cope became a professor of natural science at Haverford University (Osborn, 1929). Cope continued looking into fossils in his spare time and in October of 1867, he went to work with Eocene and Miocene beds (Osborn, 1929). These beds lie between the Potomac and Patuxent rivers in Maryland and contain fossils that are 42 to 16 million years old (Storer, 2013). In the following March, Cope changed his focus to Burlington County in New Jersey (Osborn, 1929). He explored the marly sands in Burlington County with Marsh. Together, the two scientists found three new saurians of a known genera which Cope tentatively identified as the *Mosasaurus, Glavialus,* and *Brimosaurus* (Osborn, 1929).

Before collaborating with Cope, Marsh was holding a position as professor at Yale. From 1870 to 1873, Marsh led four expeditions through the western territories. The expeditions started from South Dakota and Nebraska to Wyoming, Utah, Colorado, Oregon, and Kansas. He studied the White River badlands, Green River basins, John Day fossil fields, as well as the Cretaceous chalk region during the three years (Complete Dictionary of Scientific Biography, n.d.). Both paleontologists were becoming more published and gaining recognition in the American geology community. No one foresaw the devastating feud between the two that would soon follow.

Start of Feud

All was looking well for the two, until Marsh's greed manifested and he went behind Cope's back to steal his fossils in 1868. As a gesture of friendship, Cope had shown Marsh a fossil quarry he was excavating in Haddonfield, New Jersey, and Marsh made an agreement behind Cope's back with the quarry owner to have any new fossils discovered sent directly to him at Yale instead (PBS, n.d.). Cope inevitably learned of this terrible truth and henceforth the life-long feud between the two commenced.

Feud

The feud between the two paleontologists started with Marsh making backhanded deals with the quarry owner, but definitely did not cease there. The race between the two to uncover and name more fossils than the other also extended to the workers in their crews (*Fig. 4.21).* It was well known that the crews would spy on each other, as well as use various methods to prevent the other from obtaining fossils. It has been noted that minor fossils were purposefully destroyed to prevent the other paleontologist from gaining them. In other situations, fossils were outright stolen. In some extreme cases, Cope and Marsh used dynamite to bomb and destroy fossils on each other's sites to hinder any chances of discovery by their foe. Even harder to believe, was that they also used dynamite on their own sites (Linda Hall Library, 2019). This was done to prevent the other from stealing fossils from their sites. Many valuable fossil samples were destroyed in these endeavours, and both paleontologists began to gain bad reputations as their backhanded methods were becoming increasingly publicized.

Since the basis of the feud between the two was to determine who could uncover and name more fossils, there were many instances in which the quality of the work was compromised to increase publication output. Both paleontologists made declarations of new species based on sparse materials, sometimes mixing up the bones from different animals and giving different names to the same fossils, or even naming fossils before sufficient amounts of the fossil was uncovered. For example, in 1870,

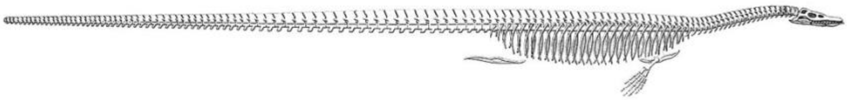


Figure 4.22. Cope's mis-labelled Elasmosaurus. The skull should be on the

Cope published a description of the Elasmosaurus (Linda Hall Library, 2019). He wrongfully placed the skull and the back-end of the plesiosaur (*Fig. 4.22).* After Marsh triumphantly pointed out his mistake, Cope shamefacedly tried to buy all copies of the publications back to prevent further humiliation (PBS, n.d.). Needless to say, this took a financial toll on Cope. Unfortunately, this was just the beginning of the string financial strains that each paleontologists brought on the other, eventually, leading to their mutual demises.

Marsh was not exempt to these incidents of rash naming either. In 1877, Marsh named the Apatosaurus, which he thought was a new species of Sauropods, when he only had fossils of some pieces of vertebrae and parts of the pelvis (Linda Hall Library, 2019). Then again in 1879, he named a Brontosaurus based on incomplete material (Linda Hall Library, 2019). On another instance, Marsh mistakenly placed the skull of a Camarasaurus on his skeleton of a Brontosaurus, and named it as a new species (Linda Hall Library, 2019). All these mistakes were shown to be wrong years later once the complete fossils were found and excavated and his mistakes exposed (Linda Hall Library, 2019).

Figure 4.23. New York Herald Issue. Heading reads, "Scientists Wage Bitter Warfare, Prof. Cope of the University of Pennsylvania Brings Serious Charges against Director Powell and Prof. Marsh of the Geological Survey". An image of Marsh can be seen on the middle left and one of Cope on the upper right side.

The Demise of Cope

The feud increased in intensity over the years and in 1877, Cope purchased the American Naturalist journal to guarantee his work would get published and recognized (PBS, n.d.). In response, Marsh used his connections in Washington and became chief paleontologist at the U.S. Geological Survey (PBS, n.d.). Using his newly gained power and access to federal funds and institutional support, Marsh began isolating Cope from the geological community. Now financially hindered, Cope ventured into a new silver mining venture in New Mexico out of desperation (PBS, n.d.). However, it was unsuccessful and he ended up losing what little he had left.

By 1890, Cope had become estranged from his wife and child, and all he had in his possession was his fossil collection (PBS, n.d.). The fossil collection contained Cope's life's work and was quite monetarily valuable. Cope struggled to find an institution willing to purchase his collection entirely, as he wished to keep his fossils together. Furthermore, at this point his reputation was quite damaged and many in the geology community did not wish to purchase his collection. Seeing that Cope was at his worst, Marsh deviously schemed to end the feud once and for all by attempting to confiscate Cope's collection. Marsh claimed that Cope's fossils were collected during federally funded expeditions and were thus government property. However, Cope was able to provide evidence that the fossils were indeed his as he had personally funded everything. Marsh had failed to bury Cope and his work.

The Demise of Marsh

Through the years, Cope had been collecting information or records of corrupt, underhanded dealings along with accusations of scientific indecency to use against Marsh should the situation arise (PBS, n.d.). In retaliation to Marsh's attempt to confiscate his fossil collection, Cope turned his evidence over to a journalist at The New York Herald, a publication known for being a keen curator of scandalous news. The headline of the published story was "Scientists Wage Bitter Warfare" (PBS, n.d.) (*fig. 4.23*). The publishing of this article set off a public cascade with Marsh and his colleagues at the Geological Survey being accused of corruption, ineptitude, and the exploitation of government funds. The government soon became involved and Congress, after reviewing the case, cut off funding for the survey and eventually completely dismantled the entire department of paleontology (PBS, n.d.). The Smithsonian also stipulated the handing over of a large component of Marsh's fossil collection as it was obtained using government funds. Ultimately, Marsh lost his position, income, and power over over Cope (PBS, n.d.). Furthermore, his own reputation was completely destroyed. In fact, it has been reported and Marsh died with $186 in his bank account (Complete Dictionary of Scientific Biography, n.d.).

Differences in Evolutionary Beliefs

Cope's interest shifted to evolutionary theory as he continued fossil collecting. In his letters to his father, Cope stated his scientific beliefs outright. However, his published works show that his views were less forthright. He supported both adaptive and divine influences on evolution, and his internal debate between science and religion was a significant theme throughout his life (Moeller, 2012). Cope navigated this tough debate by scaling the two influences; a divine deity played a larger role in changes in body structure, however adaptation also played a small-scale role as well.

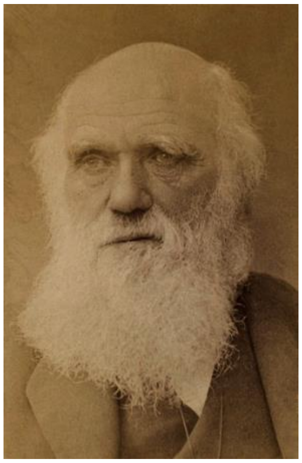


Figure 4.24. Charles Darwin, the father of the theory of evolution.

On the other hand, Marsh believed in Darwinism or Darwin's Theory of Evolution, whereby evolution is based on natural selection. Not only was Marsh a Darwinist, but his fossil findings of toothed birds would ultimately help provide North American evidence for Darwin's theories (*Fig. 4.24)* (Tuna, 2015). Marsh's work with fossilized birds was so significant even Cope recognized and praised him. In fact, Cope had sent Marsh a letter, in 1873 when their feud had already began. Cope wrote, "Your bird with teeth is simply delightful. Vae evolutionis opponentibus! De mortuis nil nisi boneum! [Woe to the opponents of evolution! Speak nothing but bones of the dead!]" (Tuna, 2015).

Looking Back

The friendship between Othniel Charles Marsh and Edward Drinker Cope transformed into a malicious competition of who could discover and name the more fossils. Their feud consequently resulted in both scientists' reputations being ruined, and additionally contributed many negatives and positives for the field of paleontology and geology as a whole. When assessing their feud in a negative light, both Marsh and Cope often made foolhardy declarations that were simply put, bad science. Some of their mistakes included basing descriptions of new species from insufficient materials and evidence, mixing up bones of different animals, as well as giving different names to the same animal (Linda Hall Library, 2019). Furthermore, the amount of showmanship between the two and the drama surrounding and publicized about their competition unfortunately tarnished public perception of paleontology and geology.

However, it is noteworthy that the publicization of their drama also increased the public's interest in paleontology. Previous to the 'Bone Wars', American paleontology and geology were both underdeveloped fields. Until Marsh and Cope began digging for fossils, few remains had been uncovered in North America and only a few dozen species had been identified (Tuna, 2015). Most notably of Marsh and Cope's contributions remain the fossils they unearthed. By the time of their deaths, Cope had developed Cope's rule, a postulate stating animal groups tend to evolve to have larger body masses through time (13) and published 1400 papers (PBS, n.d.). Meanwhile, Marsh described 80 dinosaur fossil species (Complete Dictionary of Scientific Biography, n.d.), established the existence of early primates in North America, and presented the first known toothed birds which proved useful in determining their ancestral relation to dinosaurs. In fact, Marsh sent Darwin many of his toothed bird fossils (*Fig. 4.25)*, and they were used by Darwin to support his theory of evolution. It is evident that both paleontologists made significant contributions to science and they should be remembered for such.

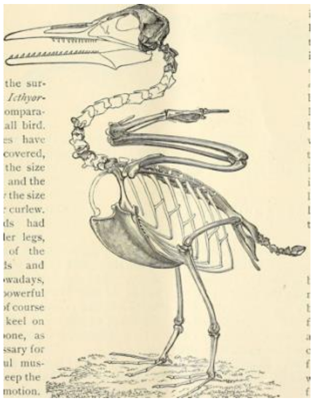


Figure 4.25. Ichthyornis victor fossil. This is the fossil of the first known toothed bird. Marsh sent his samples to Darwin, who used it to support his theory of evolution.

Dinosaur Fossils Today

Remembering Cope and Marsh

Today, the majority of Marsh's fossil collection is displayed at Yale's Peabody Museum, where there is also an archived letter in which Darwin personally writes his thanks to Marsh for the bird fossils which Marsh sent him to aid with supporting his theories (Yale Peabody Museum, 2014). In the letter, Darwin writes "Your work on these old birds, and on many fossil animals of North America, has afforded the best support to the theory of Evolution, which has appeared within the last twenty years" (Tuna, 2015). It is undeniable that Marsh's work contributed greatly to Darwinism, and he will continue to be recognized for those contributions. For Cope, a memorial was unveiled in 2002 close to Cope's previous residence to acknowledge his contributions to the field of paleontology (Levins, 2002). Michael O'Neill, a senior paleontologist at the U.S. Bureau of Land Management said, "in the hope it will remind the public of the connection between past and future, eastern cities and the Wild West, and how ideas nurtured in young minds can grow to materialize into things yet unseen" (Levins, 2002). The curator of the New Mexico Museum of Natural History says that the vertebrate fossils collected by Cope and his collectors are some of the most important vertebrate fossil collections the museum owns (Levins, 2002). His collection can be seen at notable museums through Washington, D.C., New York, and Philadelphia including the Smithsonian.

Figure 4.26. Quarry Site where Dinosauria International recovered the Allosaurus and Stegosaurus skeletons.

The Market for Dinosaur Fossils

Paleontology and dinosaur hunting remains popular today (Forbes, 2011), perhaps thanks to the amount of public interest Cope and Marsh raised just over a century ago. Even with advances in the field of paleontology, dinosaur hunting has maintained its competitive drive. The sometimes seven-figure prices of specimens have helped the extinct giants remain in the market (Forbes, 2011). Thomas Lindgren, the consulting director at the Bonhams auction house, says that there is a growing demand for dinosaur fossils collections. Whether it be for a natural history museum or as interior decor, the market exists. Individual claws and teeth can retail for $10,000 each, and fossilized dinosaur excrement can sell for more than $5,000 (Forbes, 2011) (*Fig. 4.26*). Most impressive, in 2009, Lindgren sold a Tyrannosaurus rex fossil to an anonymous collector for almost $5 million (Forbes, 2011). Dinosaur fossil collecting has perhaps transcended into the world of fine art. Collectors will pay up to hundreds of thousands of dollars to have them professionally mounted in custom made frames.

The Society of Vertebrate Paleontology and many museums oppose the private ownership of fossils, however it is indisputable that many private companies do frequently discover valuable information about the fossils. In 2007, Dinosauria International, a private company, returned to a quarry in Wyoming where Marsh and Cope had fought for fossils just over century ago (*Fig. 4.27).* They uncovered a complete Allosaurus skeleton along with the leg bone from a Stegosaurus. Further digging revealed the remainder of the stegosaur with bite marks along its neck plate. These fossilized bones showed the first concrete evidence that these two species coexisted and did not evolve in separate time periods.

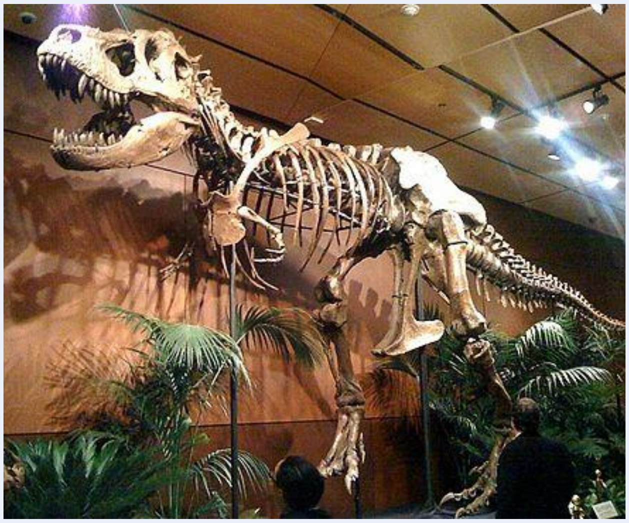


Figure 4.27. Reconstructed fossil of t-rex, sold for $5 million.

New Technology

New technologies are helping scientists uncover more information from dinosaur fossils including enabling them to reconstruct bone fragments as well as take a look at the internal component of fossils such as the skull (Worrall, 2018). The best example is probably computerized axial tomography, or CT/CAT scans. CAT scans can be used to look inside the skulls of dinosaurs such as the infamous *T. rex*. Digital models of its brain were created and revealed that *T. rex*'s actually had fairly large brains (Worrall, 2018). For example, models have shown that it had large, forward-facing eyes and large portions of its brain was dedicated to its sense of sight (Morrall, 2018). Modern day advances like this one provide support against past beliefs that dinosaurs were unintelligent, which we now believe to be incorrect.

Another use for the technology is that of digital visualisation techniques. CT scanning provides the ability for scientists to become closer to restoring fossil animals to their once life-like condition (University of Bristol, 2014). Bones can be virtually disassembled into individual elements before the cracks and fractures are filled in (University of Bristol, 2014). The elements are then reassembled and further studied. Another advantage is that while the internal and external features of a fossil can be analyzed, the digitization can allow for the easy sharing of information (University of Bristol, 2014). This prevents any risk to the fossil and also reduces need for travel.

Moving Forward

As technology continues to advance, so will our knowledge of dinosaurs and the environment in which they lived. Even with scanning technology, a lot can be discovered about the features of the dinosaurs that are lost when they become fossilized. With our already existing knowledge on past geologic environments, connections can be made between information derived from dinosaurs during scans and the conditions in which they lived thousands of years ago. These technologies can help paleontologists and geologists to gain a better understanding of the timeline in which dinosaurs evolved and lived. Understanding dinosaurs can also help broaden our understanding of what the conditions were like during the early years. Making connections and finding correlations between multiple fields of science such as geology and paleontology will only expand our knowledge of Earth history.

A Brief History of Human Knowledge of Neanderthals

For a great deal of human history, the idea of human-like species with whom we share a common ancestor was not only completely lacking in the public consciousness but would be thought – if introduced – to be an idea worthy of ridicule. This sort of concept simply would not fit into the already established ideas of creation of the world. The idea that humans at some point did not exist was simply beyond the times for a great majority of human history. This idea, however, needed to be challenged in the face of evidence to the contrary. As we came to discover the remains of animals that were not only human-like, but a range of fossils that seemingly became more and more human, some reconsideration needed to be done.

Initial Discovery

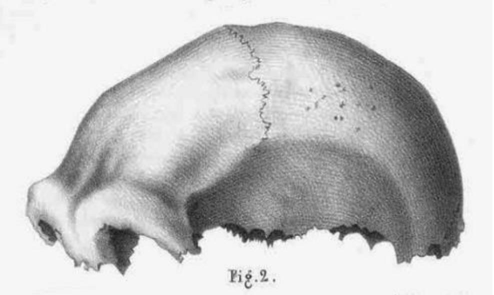


Figure 4.28. A drawing of the Neanderthal 1 skull drawn by Johann Carl Fuhlrott in 1859.

The first Neanderthal remains were found in 1829 – but it was not at that point, nor would it be for several decades, known what the remains actually were (William King, 1864). Further remains were found in 1848, and again, the true origin of the remains were yet to be known. The 1829 remains were found in Engis, Belgium, and the 1848 in Forbes Quarry, in Gibraltar (Eiseley, 1957). These two remains represent the earliest discoveries of human fossils in recorded history. The most well-known Neanderthal remains, however, are neither of those previously mentioned. In fact, the most famous remains were found in 1856 in the Neander Valley, Germany. (Tal, in German, is the word for valley and hence the Neanderthal name.) It was another eight years until these remains were considered to be the first named hominin fossil: Neanderthal 1 (See Figure 4.28) (William King, 1864). When they were first found, however, scientists of the time had never seen anything of the sort. What was discovered was only a skull, with an ovular shape and a low, receding forehead and distinctive browridges that clearly indicated this was anomalous, and not human. The bones were also thicker than would be expected of *Homo sapiens* remains (Kortlandt, 2002). It was thus termed by William King *Homo neanderthalensis*, immediately identifying it to be in the same genera as *H. sapiens,* while still a distinct species. Notice that this is classed as a separate species from *H. sapiens*, not as a subspecies. At this point in time, modern humans were known as *H. sapiens*, rather than the more current usage of *H. sapiens sapiens*. There was, and still is, an ongoing debate as to the classification of Neanderthals. There are those in favour of the subspecial classification using *H. sapiens sapiens* and *H. sapiens neanderthalensis* for humans and Neanderthals respectively – while those against omiting a '*sapiens*' in each name (Donovan, 2016). After the identification and naming of this 1856 fossil, further review of previous Belgian and Gibraltar findings concluded that the two previously unknown fossils were, in fact, of the same species as Neanderthal 1.

Further Excavations

Figure 4.29. A reconstruction of the Neanderthal burial at Chapelle-aux-Saints, France.

Over the next century, various other fossilised Neanderthal remains were found around Europe and south-western Asia by several groups – only some of whom were in search of such fossils. After the first was found, it was only a matter of time before the interest of anthropologists and palaeontologists alike was sparked to find more remains. Of particularly great interest is the eponymous La Chapelle-aux-Saints, found in 1908 at La Chapelle-aux-Saints. This was the first nearly complete Neanderthal skeleton that had been found (See Figure 4.29), and as such had great potential to inform the scientists of the time about how similar or dissimilar these hominids really are from humans – a question that was still quite open for discussion and interpretation (Rendu et al., 2014). This skeleton, colloquially known "The Old Man of La Chapelle", was found buried in the limestone bedrock of a cave near the chapel for which he is named. The skeleton was mostly complete, possessing the skull, ribs, most vertebrae, bones of the arms and legs, and a significant number of bones of the hands and feet. His skull shared many of the hallmarks of Neanderthal crania that had been observed in the previously excavated skeletons. It was estimated by the state of his bones that the Neanderthal had been quite aged (relative to the mean age of Neanderthals) at the time of his death (Dibble et al., 2015). There is an interesting social aspect to this specific discovery, that went on to shape the public perception of Neanderthals for a great deal of the time we've known of their existence.

The Controversy of La Chapelle-aux-Saints

The original reconstructor of La Chapelle was a scientist by the name of Marcellin Boule. A French palaeontologist, Boule was known in his lifetime best for his work and speculation on the origin of eoliths: chipped flint nodules that were once thought to be the earliest manmade tools. They are now widely thought to be geofacts (Boule, 1905). Boule's original reconstruction of the skeleton had a severely curved spine, as well as a slouching posture with the knees bent and the head and hips thrust forward (See Figure 4.30). In whole, it led one to thoughts of vacuity and – as simple as posture may seem – it reflected the idea of a Neanderthal as a terribly unevolved, very primitive ape-like creature (Trinkaus, 1985). Boule wrote that the low-vaulting of the skull was quite similar to that of gorillas, and went on to associate these features with low intelligence and primitivity (Dibble et al., 2015). His work was quite influential in his time, and for the next half-century, this was the concept that we had of Neanderthals in general – but later work shows that this may not have been correct. In the early 1950s, a group of scientists re-examined the skeleton, and their study supported the idea that this individual suffered from a degenerative bone disease: gross deforming osteoarthritis (Hammond, 1982). This gives context for the structure of the skeleton that Boule had put together, and which had spread an inaccurate perception of the Neanderthals. It was also suggested that the original reconstruction by Boule was not conducted in earnest. It is known that Boule rejected the idea of a close common ancestor between humans and Neanderthals. There are those in the scientific community who, after the re-examination, believed that Boule put together his reconstruction with his preconceptions of Neanderthals in mind in lieu of the objective facts of the skeleton (Hammond, 1982). To this same point, it has been noted that Boule constructed La Chapelle-aux-Saints with an opposable hallux, which would place Neanderthals in the same family as the great apes, despite the lack of bone deformity that would lead to that conclusion (Straus and Cave, 1957). The unfortunate history of this skeleton nicely highlights the role that bias can play in the scientific process, and why one need be critical of even those who should be able to be trusted in their field.

Figure 4.30. Boule's interpretation of Neanderthal morphology (left) beside modern human morphology (right).

Sociality

One of the central questions of studying extinct organisms is that of understanding behaviours when they are, by definition, unobservable. To be able to interpret and piece together how an organism or group of organisms behaves solely based on fossils and the environments in which we found them is a non-trivial problem, but the process used to do so is of great interest if we wish to gain a better idea of the history of our world. This is no less the case for Neanderthals. In order to understand this process, it can be beneficial to examine a specific example – and to that end we will discuss Shanidar 1. Shanidar 1 is a Neanderthal whose remains were found in 1957 in a cave after which he was named. The Shanidar Cave is found in Shanidar, Iraq – and there have now been ten individual Neanderthals found within it (Crubézy and Trinkaus, 1992). What is specifically interesting about Shanidar 1 is the state of his remains. Given an examination of his skeletal structure, it is evident that, at a young age, Shanidar 1 underwent a crushing blow to the skull (See Figure 4.31), which caused fractures in his skull, as well as damage to the left eye that may have left him blinded. As well, the right-side of his brain would have been damaged, which lead to the withering of his right arm and possible paralysis of his right leg (Crubézy and Trinkaus, 1992). He was also made hard-of-hearing, if not completely deaf (Trinkaus and Villotte, 2017). Whilst none of this may be all that surprising to see considering the lifestyle of Neanderthals, what is shocking is his age: Shanidar 1 died at about 40 years old, not due to any of these injuries. All of his various fractures show signs of healing over time. So why would a Neanderthal that was so grievously injured as a child, when they are of least use to their community, be able to live to such an old age?

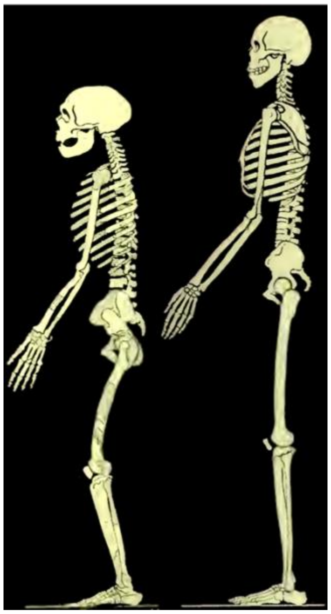


Figure 4.31. The skull of Shanidar 1 as photographed by James Gordon in 2012.

The answer here lies in the social structure of the Neanderthals. One of the remarkable aspects of this fossil is that, by examining simply the structure of the remains of Shanidar 1, palaeontologists studying him were able to provide themselves a better understanding of Neanderthal society. With his sense of hearing lost, and potential blindness, this is a terribly evolutionarily unfit individual who is unlikely to be able to live long given the carnivorous predators that were abundant at the time. Shanidar 1 must have had immense social support in order to reach old age. In the age of the hunter-gatherer life regime, the regular difficulties of life are only amplified by such severe injuries as Shanidar 1's. What this tells us, however, is that Neanderthals were clearly social creatures, and exhibited strong group dynamics such that they care for the members of their clan, even if those individuals may add significantly less to the society than another (Trinkaus, 2014).

Ritualism

Speaking further to the idea of ritualistic social behaviours, there is more we can infer about the lives of Neanderthals based on the environments in which their remains are found, rather than the remains themselves. One of the reasons why we find a good number of Neanderthal remains is because it appears that they purposefully buried their dead (Akazawa et al., 1995). They would either bury a single individual or several in the same burial site, and this burial greatly increases the chance of fossilisation over the body simply being left out in the open. For the same reasons as discussed before, it is impossible to know with certainty why and sometimes even if certain events and behaviours were as we think, but with enough evidence we can make good guesses. As such it is not known whether these burials were simply pragmatism on the part of Neanderthals in order to prevent attracting predators or if they were ritualistic – but that being said, there is good evidence to the latter (Pettitt, 2002). Neanderthal burial sites have been found to contain items from flowers and decorative rocks to pollen and honey. Caves in which Neanderthal remains are found will often skeletons from several individuals, and it is not uncommon to find complete or near-complete skeletons – the implication being that the completeness of the body indicates care taken towards its preservation (See Figure 4.32) (Leroi-Gourhan, 1975). Remains found in the previously mentioned Shanidar Cave specifically had a number of flowers encased with the remains. It was determined that the flowers are unlikely to have been there without the intervention of them being placed during the burial, although this is debated (Leroi-Gourhan, 1975). Although there is evidence, it has been and still is debated to be too weak to make definite conclusions (Pettitt, 2002). Nonetheless, the discussion is still a wonderful look at how dynamic relationships can be analysed from static remains – which seems immediately unintuitive, but is an important aspect of how we come to understand the past.

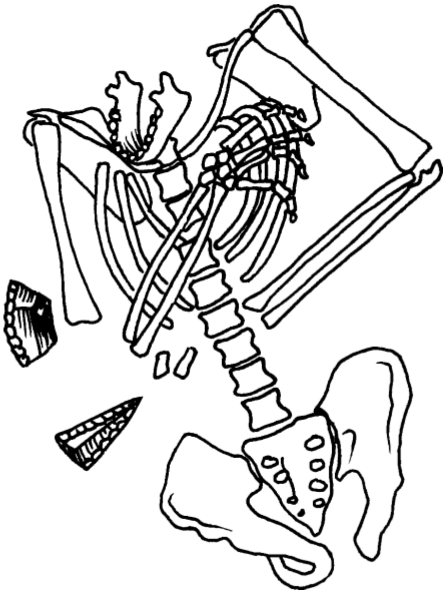


Figure 4.32. A drawing of a Neanderthal uncovered at a burial site in Kebara Cave, shown with decorative stones found near the body.

Changing View of Neanderthals

When Alberto Carlo Blanc narrowly squeezed into a cave at Mount Circeo, Italy in 1939, he could not anticipate the impact his discoveries were to have on the scientific community. Blanc uncovered what seemed to many people as simply another example of a Neanderthal skull (Figure 4.33). However, what intrigued Blanc and plagued his mind for the next 20 years, was the specific arrangement in which the skull was found. The skull was found to lay in the centre of a circle of stones. What could have possibly caused such an arrangement? (Trinkaus and Shipman, 1993)

As more Neanderthal remains were discovered and the notion that they displayed ritualistic behaviours became more accepted, the attitude towards these hominins changed. The perception that Boule propagated of these ancient being as ape-like, unevolved creatures morphed into one much human. In fact, a cartoon published by scientist Carleton Coon depicted a Neanderthal man wearing a hat and dressed in human clothing. This simple image, humanising Neanderthals, began to change the perception of these hominins in the minds of many people (Trinkaus and Shipman, 1993).

The rise of evidence suggesting Neanderthals displayed ritualistic behaviours alongside Coon's cartoon created the image of Neanderthals as incredibly human-like. As such, many scientists were prone to attributing complex social behaviours to Neanderthals with arguably too little evidence. As all these views began rising in popularity, Alberto Blanco slowly internalised many of these ideas and in 1969 eventually published a conclusion regarding the fossils found at Mount Circeo. After careful examination of the skull, he discovered a distinct blow to the cranium which he deemed similar to marks found on Neanderthal skulls elsewhere in the world. The circular placement of stones around the skull he claimed was done as a ritualistic burial. This conclusion was neither incredibly profound nor novel, however it was not the sole conclusion he formed. Rather, Blanco affirmed that his finding provided evidence that Neanderthals were, in fact, ritually cannibalistic in nature. This characterisation of Neanderthals as cannibals was then further interpreted as a primitive form of spirituality - and that Neandertals were similar to humans not only in their ritual behaviours regarding burial, but also in their spirituality and perhaps even beliefs (Trinkaus and Shipman, 1993).

Blanc's conclusions did not hold to the scrutiny of time or further examinations of the evidence, with White and Toth disproving both the stones as evidence of a ritualistic burial and the skull fracture as evidence of cannibalism in 1991 (White et al., 1991). The case is a perfect display of how the scientific community began changing its view of Neanderthals. Blanc's projection of present day behaviours onto the past and his own preconceived notions began to affect the quality and calibre of his scientific investigations and he was not alone in this mistake (White et al., 1991).

The Question of Lineage

The discovery of Neanderthal remains, along with other hominin fossils began the long and still-occurring research into the evolution of modern humans. The question of where each of these proto-humans fit into our evolutionary history and how Neanderthals and all other hominins fit into the timeline, is a central question that remains elusive. However, several developments have resulted in significant advancements in our knowledge.

Figure 4.33. The neanderthal skull found by Alberto Blanc in Italy, 1939. A notable skull fracture can be

Darwin's publication *On the Origin of Species by Means of Natural Selection* changed how scientists viewed evolution and the history of life on our planet. However, while Darwin set out his theory on how natural selection drives evolution, he did not define how variation within populations occur. The discovery of DNA by Watson, Crick, and Franklin was additionally an incredibly influential milestone in our understanding of biology. From that point onwards, there seemed to be two major disparate fields of biology. Those who studied genetics and tried to understand how genetic variations occur within populations, and those studying greater morphological changes in species over time. In a sense, there were those looking at the genotypic changes while others studying phenotypic changes (Trinkaus and Shipman, 1993).

In 1940, Theodosius Dobzhansky claimed that speciation occurs due to the aggregation of genetic mutations which occur randomly within individuals in a population. Thus was born the theory of modern evolutionary synthesis (Singh and Singh, 2017).

While Dobzhansky used his observations on extant flies to justify his claims regarding evolution, George Simpson used the fossil record to support this new evolutionary synthesis. In doing so he paved the way for scientists to utilise a growing number of tools from genetics to morphological considerations as they parsed through our evolution in their attempts to recreate our past (Laporte, 1994). As such, they began to classify ancient fossils and construct the lineages of modern man. Neanderthals were quickly placed within the genus *Homo*, and are even now considered to be subspecies of *Homo sapiens*, making ourselves *Homo sapiens sapiens*. In heavy contrast with Boule's initial depiction of Neanderthals as brutish and unevolved, we had now placed them not only within our own genera, but as the same species. Scientists had a come a long way from those initial discoveries, and had many more to make.

New Analyses of Neanderthals

The modern era came with new ideas and new tools to investigate these ideas. Revolutions in commercial technology also meant revolutions in scientific technology. Instruments were created which allowed for more precise measurements, examinations at new depths, and techniques which allowed for very specific results. Advancements in many different sectors of biology began to come together to paint an incredibly surprising picture.

The Rise of Molecular Biology

The discovery of mitochondrial DNA in the latter half of the 20th Century was generally viewed as an incredible finding. Nuclear DNA provided scientists with access to the genes which encode our very beings, however, genetic DNA is influenced by both mother and father. This duality of input towards ones nuclear genetic makeup results in difficulties tracing mutations through time and populations. Mitochondrial DNA, however, is directly inherited from the mother's ovum, and thus displays a much more exact progression in the study of mutations (Cann, Stoneking and Wilson, 1987).

In 1987, three scientists from the University of California, Berkeley, sampled a variety of individuals and examined their mitochondrial DNA to further understand our common ancestors. What Rebbeca Cann, Mark Stoneking, and Allan Wilson discovered in 1987 changed the way we understand human evolution and what we thought we knew about our past.

After sampling over a hundred individuals from all over the world of many different geographic populations, they saw that the mitochondrial DNA was incredibly similar among them all. In fact, they concluded that each of these individuals alive today had a common ancestor that lived 200,000 years ago in Africa (Cann, Stoneking and Wilson, 1987).

These findings spurred lively debates in the paleontological community as this estimate of the most recent common ancestor was well after Neanderthals and other hominins had spread to Europe and Eastern Asia. This paper implied that Neanderthals, whose fossils found in Eastern Europe dated to only 100,000 years ago, were not involved in the evolution of modern humans (Cann, Stoneking and Wilson, 1987).

Naturally, many paleontologists became vocal in their disagreement with this analysis. They claimed that assumptions made in the study were invalid (Thorne and Wolpoff, 1992). They remained certain that Neanderthals must have been related to ancient modern humans.

To settle the debate, in 1997, a group of researchers decided to use the same method of mitochondrial DNA analysis on Neanderthal genes. While DNA degrades over time and can be difficult to find intact, Neanderthal fossils were young enough to ensure that the potential was there. With the advent of molecular techniques such as PCR which allowed small segments of DNA to be amplified for more accurate analyses, the team had all the necessary tools. The specimen under examination was the Neander 1, the fossil that kicked off the Neanderthal revolution in the middle of the 19th Century (Krings et al., 1997).

The examination of the Neanderthal mitochondrial DNA showed very few genetic similarities to the mitochondrial DNA sequenced by Cann et al. (1987) 10 years prior. This settled the debate: Neanderthals were not direct precursors to modern humans. Rather, they must have diverged from a shared ancestor (Krings et al., 1997).

This began to complete the picture of human evolution. At some point before 100,000 years ago, an ancestor of both Neanderthals and modern humans existed. A group from this species began to explore and make their way out of Africa and into Europe, while some remained behind. Those that spread into Europe became Neanderthals while those remaining further evolved into ancient modern humans.

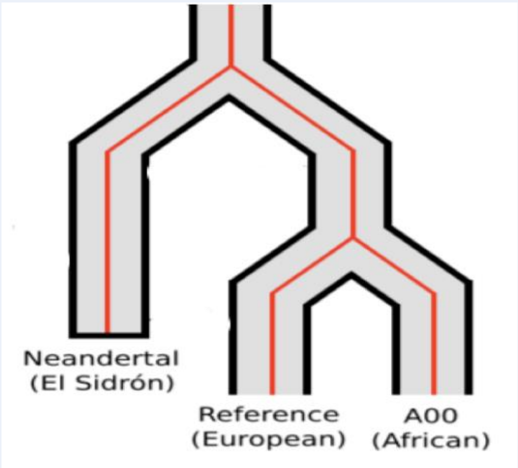


Figure 4.43. A proposed lineage hominin evolution displaying the separate evolution of Neanderthal from modern humans. The two lineages shown as modern humans refer not to different species, but rather to different samples used in a genetic study

If, however, these two species lived concurrently, why did *Homo sapiens sapiens* thrive? What caused the extinction of the Neanderthals? And during their existence, did Neanderthals interbreed with ancient modern humans?

Are We Neanderthals After All?

The question of whether Neanderthals and modern humans interbred was one which carried into the 21st Century. Renowned scientists argued on both sides of the debate, with those adamantly claiming that admixture occurred (Trinkaus et al., 2003), while others were thoroughly unconvinced (e.g., Currat and Excoffier, 2004).

In 2010, new data emerged once again as genetic sequences of Neanderthal genomes were identified. In a remarkable revelation, the Neanderthal genome was discovered to be strikingly similar to modern Eurasian people. In fact, those currently in Eurasia share approximately 1-4% of their genome with Neanderthals. This relationship, however, is not seen in those currently in Africa. This finding greatly suggests that there was indeed interbreeding between modern humans and Neanderthals (Green et al., 2010).

And So, It Ends

The demise of Neanderthals is an interesting question, and one with many possible answers. Once scientists discovered that Neanderthals and modern humans lived at the same time, a natural conclusion that prevailed among the scientific community was that modern humans, being culturally more advanced, outcompeted Neanderthals. Due to the cultural and intellectual superiority of the modern humans, the Neanderthals did not survive the competition (Gilpin, Feldman and Aoki, 2016).

While this view remains somewhat popular, the perceived disparity between Neanderthal and modern human culture is now thought to be overstated given new evidence. Discovery of Neanderthal cave paintings, and their use of symbols and advanced tools suggest that they were not so inferior as was once thought (Appenzeller, 2013).

In light of these new ideas, alternative explanations are required to describe the decline and eventual extinction of the Neanderthal species. Modern theories have begun to consider the interbreeding with modern humans as indicative of assimilation of Neanderthals into modern human society. Rather than competing, they interbred and the Neanderthal population was absorbed into that of modern humans (Villa and Roebroeks, 2014).

Other possible explanations for the extinction of Neanderthals have utilised evidence regarding the changing climate at the time of their dying out. Their extinction occurred over 48-36,000 years ago. During this time, the Earth underwent rapid fluctuations in climate. Using speleothems (structures formed by water in caves) in Romania and their relative carbon and oxygen isotope ratios, the paleoclimate during this time was determined. Scientists found that there were periods of extreme cold at this time which would have influenced populations as food resources became limited. As the climate changed, so did the population structure. Neanderthals, having very specific climactic adaptations are thought to have been less capable of surviving these rapid fluctuations, and as such, did not survive (Staubwasser et al., 2018).

From start to finish, the Neanderthals were an incredibly important species. The discovery of that first Neanderthal fossil launched decades of intrigue into our origins and how we became the species we are today. The story is one with many curves and twists, with much debate and much unknown. Neanderthals are a key to our past, offer insight into the present, and we have much to learn.

Chapter 5: The Evolution of Theories on Extinction

Throughout Earth's history, there have been multiple instances of extinction, naturally leading to a variety of theories on how they occurred, as proposed by various scientists. Extinction theories progressed from ideas and evidence regarding evolution, changes in water levels and glaciation, changes in temperature, and meteorites and volcanoes. Currently, modern techniques monitor trends of extinction due to global warming using permafrost. The most well-known and intriguing extinction event is that of the dinosaurs, for which theories have been debated for years before the current, leading theory was established. To this day, evidence from different parts of the world fuels the battle between scientists as to how the K-Pg extinction, the fifth of the five major mass extinctions, occurred. Before the idea of a K-Pg extinction, there was an evolution on the ideas of mass extinctions, as proposed by various scientists such as Cuvier, Lyell, and Darwin. Extinctions continue to occur on Earth during current times, and it is interesting to compare them with mass extinctions from the past.

Progression of Extinction Theories

The fossil record contains over a quarter of a million species, which are mostly extinct. Fossil species are grouped into approximately 35,000 genera and 4,000 families. However, about 75% of them are extinct (Ayala and Fitch, 1995). Fossils have been helpful with recording the species as they preserve them for a long period of time, especially those that do not exist in the present. Based on fossil analysis, approximately 25% of species became extinct every million years (Sepkoski, 1998).

The origin of fossils was a mystery in the 17th century. Fossils were seen as mythical creatures, dragons, giants or unicorns as they were different from the ones that existed at the moment. In the 18th century, scientists started to compare the fossils with modern species, which raised questions due to the different morphologies (Lyell, 1837).

Various researchers and scientists in the past proposed a variety of theories regarding the causes of extinction and interacted with other researchers to further understand extinction as a whole.

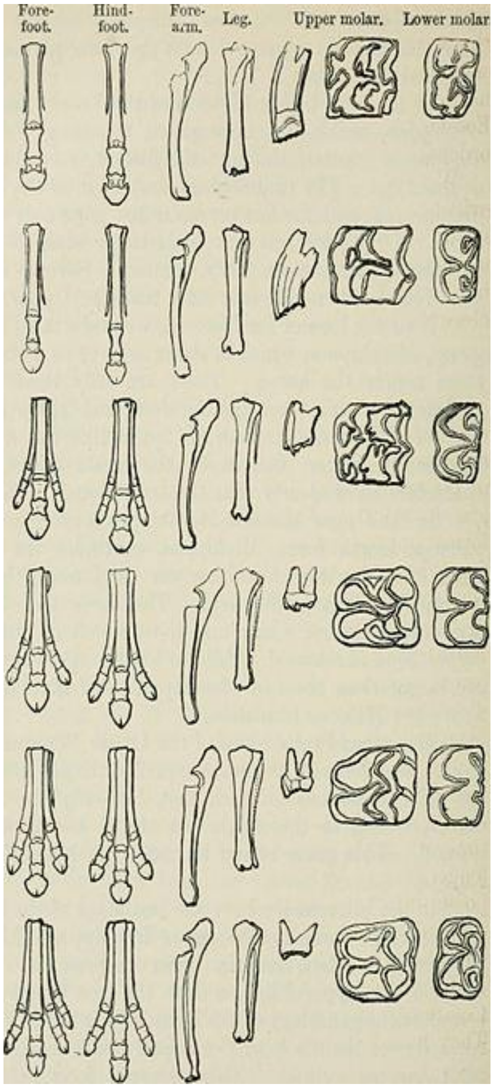


Figure 5.1. An application of Darwin's theory of natural selection, showing the evolution of some body parts and the extinction of others.

Evolution

Charles Darwin (1809 – 1882) was a biologist and naturalist who is well known for his theory of evolution, 'Origin of Species' (Beer, 2009). He acknowledged that life originated by natural causes while adapting to the surrounding through evolution. Instead of believing that life emerged from a unique event, he considered life emerging as the result of a long-term evolutionary process (Peretó and Català, 2012).

Charles Lyell (1797-1875), with his philosophy of 'uniformitarianism', influenced Darwin's idea. Lyell believed that extinction is a regular phenomenon that was caused due to slow environmental changes. He thought the organisms become extinct when they fail to adapt to such changes (Vidal and Dias, 2015).

Darwin's theory of natural selection through evolution contributed to a theory of extinction (Figure 5.1). He believed that local extinctions led to global ones (Beer, 2009). Darwin viewed extinction as an ordinary and necessary evolutionary process that occurred regularly through natural selection. He thought that extinction allowed the remaining species to adjust to changing environments (Beer, 2009).

Darwin proposed that the sudden disappearance of species, known as mass extinctions, did not actually occur. He was against the theory of those who thought extinctions were caused by great catastrophes (Ayala and Fitch, 1995). From his perspective, the fossils that he observed did not explicitly show evidence of any major event that would cause a large number of species to disappear (Ayala and Fitch, 1995).

Similar to Darwin, Jean-Baptiste Lamarck (1744-1893) did not agree that there was an exceptional event that caused mass extinction (Burkhardt, 1972). Instead, he believed that the gradual erosion and deposition by water that shaped the surface of the Earth led the species to evolve due to the change in environment (Burkhardt, 1972).

Changes in Water Levels and Glaciation

George Cuvier (1769-1832) established the idea of extinction about 60 years before Darwin by studying the difference between the lower jaws of a mammoth and an Indian elephant (Outram, 1976). Unlike Darwin, his study of fossil deposits in the Paris basin led him to think that a series of great revolutions or catastrophic mass extinctions had occurred (Vidal and Dias, 2015). However, Cuvier's theory was rejected, and discussion of mass extinctions was avoided for more than a century after Darwin published 'Origin of Species' in 1859 (Vidal and Dias, 2015).

William Buckland (1784-1856), an influential natural theologian, believed that mass extinction was caused by the Flood of Noah. This was especially due to the population that strongly believed in the biblical perspective of the development of species at that time (Chapman, 2008).

This hypothesis was popular until Louis Agassiz (1807-1873) (Figure 5.2), a colleague of George Cuvier, announced that the fossils Buckland referred to for his theory were actually deposited by glaciation (Geikie, 1886). Buckland himself abandoned his hypothesis of a flood in favour of Agassiz's theory on glaciation (Grayson, 1980). After Cuvier's death, Agassiz took over the professorship at the Lyceum of Neuchatel in Switzerland and his study of glaciers (Smith and Borns, 2000). Agassiz observed extinct and extant fish fossils on glacier deposits, which made him believe that glaciers were a major force that shaped geology worldwide. He recognized paleoindicators of glaciation on Earth, including the great valleys, large glacial erratic boulders, scratches of rocks and mounds of debris (Smith and Borns, 2000). Agassiz's theory represents a change in scientists' perspectives on Pleistocene extinction from a creationist to a catastrophist view (Grayson, 1980).

Although Agassiz was able to convince Buckland with his views, he was not able to change Lyell's point of view. disagreed with Agassiz's hypothesis of glaciation. Lyell saw that European mammals that became extinct during the Pleistocene had been discovered above and below glacial deposits. To him, this showed that glaciation was not universal nor intense enough to cause mass extinction. Thus, he refuted Agassiz's hypothesis (Grayson, 1980).

Changes in Temperature

At the beginning of the 20th century, scientists continued to develop theories for extinction, but this time with regards to temperature changes on the other side of the spectrum. A group of scientists believed that extinction was due to the development of arid weather, called the Desiccation Hypothesis. E. C. Stirling (1848-1919) thought that large marsupials and birds became extinct in South Australia due to a period of aridity, which followed a period of regular rainfall and water availability (Grayson, 1980). His hypothesis was supported by W. R. Browne (1884-1975) and J. Gentilli (1912-2002). Similarly, D. T. MacDougal (1865-1958) believed that the extinction of megafauna such as mammoths and mastodons in North America was also due to aridity (Grayson, 1980). In 1967, J. E. Guilday further developed the Desiccation Hypothesis by saying it was a global event which caused habitat fragmentation, and thus a lethal competition among larger mammals. Guilday suggested that smaller mammals survived the extinction as they were not as affected by habitat fragmentation, due to their body size (Grayson, 1980).

In 1978, Dewey M. McLean further sophisticated Guilday's idea by suggesting that land and marine fauna became extinct at the end of the Mesozoic era from an increase in global temperatures due to a rise in carbon dioxide levels (Gartner and McGuirk, 1979). In 1966, Syukuro Manabe (1931-present) and Richard Wetherald (1936-2011) created a model which showed that a doubling in quantities of carbon

Figure 5.2. Woolly mammoths and other various mammals roaming a late Pleistocene landscape. The melting of snow depicted indicates the possible occurrence of climate change, leading to the extinction of megafauna

dioxide in the atmosphere would increase the temperature at latitudes less than 60° by 3°C (Manabe and Wetherald, 1967). McLean suggested that oxygen isotopes from marine microfossils show climate cooling to the mid-Maastrichtian and subsequent warming into the late Mesozoic (McLean, 1978). During climate cooling, he thought there would have been an increase in carbon dioxide dissolved in water, which would have created acidic conditions. Afterwards, warming could release carbon dioxide from water reservoirs, due to its poor solubility in warm temperatures, creating a contribution to greenhouse effects (McLean, 1978).

However, oxygen isotope ratios gathered by Polsak showed a decrease in temperatures by 5°C in the late Maastrichtian (Cornell and Lemone, 1979). William Cornell (1947-1999) and David Lemone (1932-present) believe that the lowered temperatures would have caused extinction. Colder temperatures would also allow for the dissolution of carbonates in the water, as previously explained by McLean, which would also explain why McLean noticed large solution of carbonates at the end of the Mesozoic (Cornell and Lemone, 1979).

Unlike scientists such as Agassiz, Guilday, and McLean, Norman D. Newell (1909-2005) thought that climates in the past were not clearly differentiated and were mainly mild (Newell, 1962). Although he recognized that the Permian and Cretaceous periods were most likely to have experienced climate change, there was nothing definite regarding the characteristics and the causes of the change. He believed that changes in climate may have been due to fluctuations in solar radiation or the development of the atmosphere, but they would not have been enough to cause mass extinction (Newell, 1962). Similar to Darwin, the plant fossils he studied did not show changes in temperatures as a cause of mass extinction. Instead, he believed that local extinctions at high or low latitudes due to change in a few degrees of temperature was more likely to happen (Newell, 1962).

Meteorites and Volcanoes

Rather than looking for intrinsic causes of extinction, some scientists focused on extrinsic factors. Luis Alvarez (1911-1988) and Walter Alvarez, his son carefully looked at limestone layers both above and below the Cretaceous Paleogene boundary. They discovered a layer of dinosaur fossils but were not sure how they became extinct (Alvarez et al., 1980).

With the assistance of nuclear chemists at the Lawrence Berkeley Laboratory, Frank Asaro and Helen Michel, Luis and Walter Alverez published a seminal paper on an extraterrestrial cause for the extinction (Alvarez et al., 1980). Using neutron activation analysis, they found a large quantity of iridium in the clay boundary (Figure 5.3). Deep-sea limestones in Italy, Denmark and New Zealand showed an increase in iridium levels by 30, 60 and 20 times respectively, about 65 million years ago (Alvarez et al., 1980). Alverez believed that this the large concentration of iridium could not have been produced by volcanoes alone (Weisburd, 1987). These researchers believed that an asteroid or a comet, approximately 10 km in diameter, struck the Earth, travelling at about 30 to 60 km/s (Wohl, 2007). The impact of the asteroid was measured to be equivalent to one hundred million megaton bombs, where each bomb is

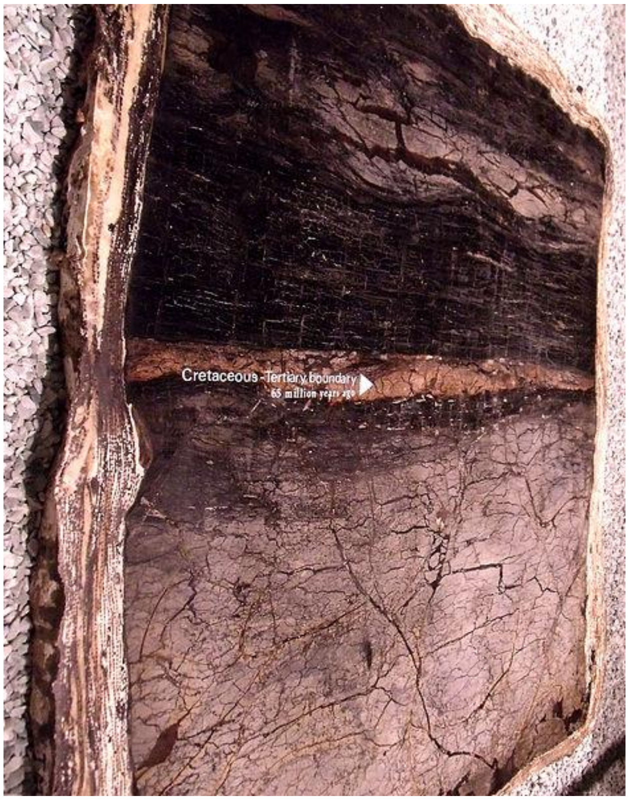


Figure 5.3. Iridium-rich 65.5 million-year-old clay layer highlighting the Cretaceous-Tertiary boundary. Iridium-rich layer is indicated by the white arrow in the photograph.

equivalent to 14,000 tons of dynamites. The kinetic energy applied by the asteroid was thought to be transferred to heat energy, which led to the extinction of dinosaurs (Wohl, 2007). The layer of clay and iridium was observed all around the world, which explains its global effects (Wohl, 2007).

Following the publication, soot, glassy spherules, shocked quartz crystals, microscopic diamonds and rare minerals were found at Chicxulub, Mexico (Figure 5.4), which is only possible under great temperature and pressure (Wohl, 2007). Alverez and their research team further proposed that the asteroid impact caused dust to be distributed around the world and stay in the stratosphere for numerous years. They believed that this event caused sunlight to be covered, thus suppressing photosynthesis, leading to a decrease in the number of plant species and dependent species (Wohl, 2007).

In 1979, Vincent E. Courtillot (1948 - present) revisited the idea of extinction caused by a meteorite impact, with his colleague Stanley Cisowski and determined that extinction due to volcanic eruptions were not impossible (Weisburd, 1987). Courtillot recognized that the Deccan Traps in India consists of a million cubic kilometres of basalt and lava flows. Through potassium-argon dating of freshwater ray teeth, he estimated that the Deccan Traps were 66 million years old. Alvarez argued that high concentrations of iridium cannot be found in volcanoes, but Olmez found high concentrations of iridium released by the Kilauea volcano (Weisburd, 1987). Olmez estimates that if the Deccan eruption were similar, the volcanoes may have spewed 300 000 tons of iridium, which is a bit less than that seen at the Cretaceous-Triassic (K-T) boundary. The theory is that Deccan eruption may have caused the release of sulphur and other materials which blocked the atmosphere, causing cooling, and creating acid rain (Weisburd, 1987).

On the other hand, Bruce Bohor agreed with Alvarez's hypothesis because the shocked-minerals at the sites of impact and K-T boundary are similarly stressed in various directions, whereas shocked-minerals from volcanoes only point in one direction (Weisburd, 1987).

Similar to Cuvier and Agassiz, Luis and Walter both believed that a catastrophic event caused the extinction of numerous species. Instead of extinction occurring due to evolution through a natural process, they supported the idea of mass extinctions.

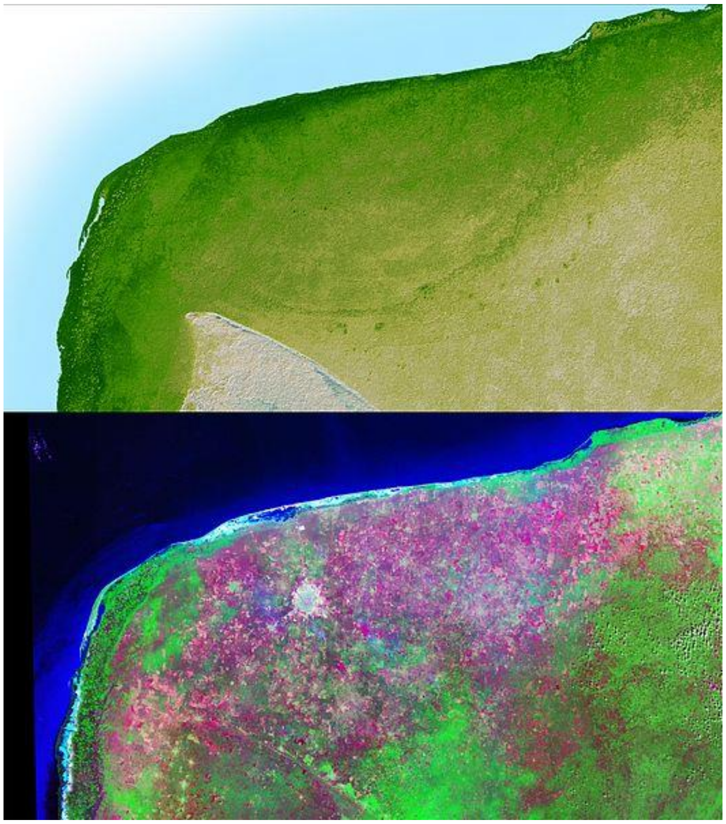


Figure 5.4. The top picture is a shaded relief image made from the Shuttle Radar Topography Mission (SRTM) data, showing the location of the Chicxulub impact crater in the northwest corner of the Yucatan Peninsula, Mexico. The bottom picture is the same area viewed by the Landsat satellite, showing different vegetation and land cover types.

Based on individual scientists, it is evident that they mainly divide into the group of researchers who believed in extinction due to evolution, versus the group of scientists who believed in catastrophic events that caused mass extinctions. This varies based on the time period that the researchers conducted their studies and the influences they had on each other during the same time period. The cause of extinctions remains an unsolved debate and will continue to be defined as hypotheses.

Monitoring Modern Extinctions

It is often said that history tends to repeat itself. This can be applied to the current extinction phase, which is predicted to be as impactful as the previous five mass extinctions within the last 600 million years, that caused more than 65% of marine animals to disappear (Stork, 2010). In 1998, 70% of biologists believed that 20% to 50% of the species alive at that time would become extinct by 2028 (Stork, 2010). The causes of extinction rates today are different from those in the past. Anthropogenic activities are directly causing habitat destruction and an increase in greenhouse gas emissions from burning fossils fuels (Harnik et al., 2012). This causes an increase in global temperatures at a faster rate than expected and ultimately leads to warmer oceans with high acidity and sea levels (Harnik et al., 2012) (Figure 5.5).

Current Trends of Extinction due to Global Warming

By analyzing information regarding past extinctions using historical records, such as sedimentary cores, it has been established that larger body size, ecological specialization, and small geographic ranges were the most prevalent characteristics of species which became extinct when there was a change in global temperatures (Harnik et al., 2012). Similar traits are expected to be indicators of species in greatest danger today. The warming and acidification that led to three global reef crises and three mass extinctions of the Late Devonian (374 Ma), End Permian (251 Ma), and Triassic-Jurassic (202 Ma), are also affecting current wildlife today, especially corals (Harnik et al., 2012). Additionally, a similar trend from the past has been detected today with local extinctions of megafauna. In 98% of regions in South-East Asia, the local extinction of animals such as the Asian elephant, tiger, and orangutans was determined (Corlett, 2007). This is similar to large and slow-breeding mammals that became extinct about 8,000 to 12,000 years ago (Stork et al., 2009).

Changes in temperature lead to various consequences that could possibly lead to extinction. This includes the change of climate of various habitats, such as the occurrence of rainfall in originally dry forests (Stork et al., 2009). Temperature changes could also lead to narrow geographical ranges in which species can survive, including narrower and higher elevational limits (McCain, 2009). Moreover, invasive species are able to increase their range of habitat and threaten native species (Bradshaw et al., 2008). Since changes in temperature today are possibly causing similar consequences and extinctions as changes in temperature in the past, it is important to compare and monitor the rates of past and current temperature change. This can help establish which species are at immediate risk and predict future occurrences. One such technique involves the monitoring of temperatures using permafrost.

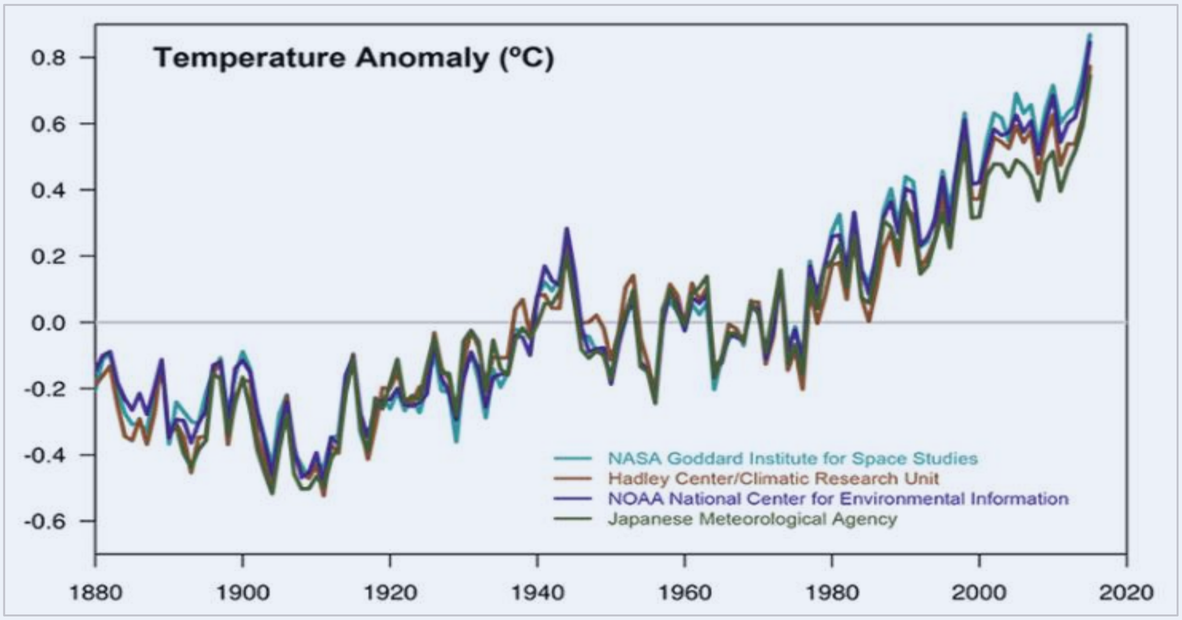


Figure 5.5. Temperature data from four different international scientific institutions. All records show that there has been an increase in temperature in the past few decades and that the last decade has been the warmest on record so far.

Tracking Global Temperature Changes Using Permafrost

Permafrost can be used to track changes in global temperatures over a long-time period. Permafrost consists of rocks and sediments that have been kept at freezing temperatures below 0˚C for at least two years (Romanovsky et al., 2002). Permafrost can exist around the melting point of ice or be as cold as -10˚C, and it can vary in depth from a few meters to 1400 meters deep (Romanovsky et al., 2002). This variation from cold and thick permafrost to warmer and thinner layers can be seen when comparing the Arctic to the Subarctic. In the northern hemisphere, permafrost underlies 12.8% to 17.8% of the exposed land (Zhang et al., 2000).

Permafrost can either be continuous or discontinuous. In the former, the entire area is covered with permafrost, except under large and deep bodies of water (Romanovsky et al., 2002). The latter consists of areas in which 10% to 90% of the area is composed of permafrost (Zhang et al., 2000). The thawing of permafrost can cause subsidence, in which the ground sinks inward, causing environmental and economic disturbances.

Inter-annual temperature variations can be monitored, as well as the variation in temperature from previous decades to centuries, at depths from 10 to 200 meters below the ground surface (Romanovsky et al., 2002). Variations in temperature over a short time period are not recorded as clearly due to the variations in the amount of snow, vegetation, and soil properties of the active layer of permafrost, which is where seasonal thawing and freezing occurs (Romanovsky et al., 2002).

The measurement of the temperature of permafrost below ground can be used to estimate the temperature above the ground during a specific time period. Lachenbruch and Marshall worked with the U.S. Geological Survey and were one of the first in North America to investigate permafrost temperature profiles with relation to climate change (Lachenbruch and Marshall, 1986). From 1901 to 2015, there has been an increase in the thawing index and a decrease in the freezing index in the Arctic (Shi et al., 2019). This was determined using daily and monthly data sets from 17 meteorological stations (Shi et al., 2019).

If the increase in global temperatures was not obvious before, there is currently degradation of the permafrost all around the world, including Alaska, Canada, Russia, and China (McCarthy, 2001). Ultimately, there will be an increase in sea level (Zhang et al., 2000).

Modelling of permafrost temperatures can be used to predict future changes in global temperatures. In 2002, Romanovsky et al. created a model which uses variations in air temperature and thickness of snow cover. The model is calibrated for a specific location using measured permafrost and active layer temperatures, as well as meteorological data (Romanovsky et al., 2002). Then, for any given time period, meteorological data from a nearby station can be used to predict future permafrost temperatures. A high degree of accuracy was noticed when calculated data from the model was compared with weekly recorded permafrost temperatures. At depths of a few to 18 meters, differences in temperature were less than 0.3˚C; however, depths up to two meters had a temperature difference of up to 1˚C (Romanovsky et al., 2002). The change in accuracy of the model with respect to depth is similar to how temperatures were recorded from decades ago, and thus deeper depths are more reliable than those from recent years.

The Geological Survey of Canada established more than 20 boreholes of approximately 20 meters deep since the mid-1980s in northern Canada to monitor the temperatures of permafrost (Smith et al., 2005). These boreholes can be found in the Mackenzie Valley and Delta, Yukon Territory, Nunavut, and the Cordillera. Data collected from Central and Northern Mackenzie basin, and Alert, Nunavut from the late 1900s to 2000 showed a variety of permafrost trends. These showed an increase of 0.03˚C/year, 0.1˚C/year, and 0.15˚C/year, respectively (Smith et al., 2005). It is interesting to note that from the late 1980s to mid-1990s, a 10-meter borehole established by the University Laval in northern Quebec showed a cooling of 0.1˚C/year (Allard, Wang and Pilon, 1995). The 1990s may have been an important turning point as this was when global warming and ozone depletion final became major environmental issues in society (Miller, 1990).

By tracking global temperature changes using permafrost, the current world is able to better understand and predict how changes in temperature may be a cause of extinction. With the technology and research methods that scientists have obtained until now, it is important to monitor the anthropogenic impact on the climate and thus species on earth, to prevent any future extinctions.

Scientific Hypotheses in Collision: Dinosaur Extinction

Murder mysteries have fascinated readers across the globe for centuries. But a murder mystery involving dinosaurs? Just as exciting as the magic of a good fictitious murder novel is this real-life mystery. In this story, the perpetrator is a giant space rock hurtling towards the Earth, eradicating all non-avian dinosaurs, and leaving the world upturned for a new beginning. The transition from the Cretaceous to the Tertiary on the geological time scale marks this immense global change as one to be forever remembered (see Figure 5.6). Moreover, the scientists involved in the development of this story were not always quite interested in the topic; putting it off through jokes and inviting others to do the same was ubiquitous. In addition, the disregard for serious contemplation and study on the subject was followed with encouragement by authorities of the time. The history became heated when the most fantastic idea of all, that of an extraterrestrial body, stepped into the arena. Welcomed by some, and not by others, it made its way to the top after years of scrutinization. The very struggle of scientific advancement is captured in this murder mystery, where the focus is not on the murder itself, but the detectives involved.

Figure 5.6. An artist's rendition of the K-T mass extinction event taking place.

Dilettante scholarship

Before the emergence and consolidation of the Alvarez hypothesis (Alvarez et al., 1980), a dilettante phase of scholarship predominated research on the cause of the dinosaur extinction. Major relaxation of scientific standards by some scientists invited others from all fields to partake in the study of dinosaur extinction. The speculative joke papers published further drove the study of dinosaur extinction as an unimportant topic. Overall, publications in the pre-1980s period demonstrate the lack of seriousness by scientists of the 20th century about determining the causes of the dinosaur extinction.

Many scientists simply enjoyed speculating about dinosaur extinction. For instance, Baldwin (1964) postulated the dinosaur extinction arising from the spread of angiosperms; the spreading of angiosperms and consequent decrease in availability of gymnosperms and more importantly, ferns, would reduce the presence of fern oil in dinosaur diets, leading to death by terminal constipation. To take constipation—a problem that occurs with humans due to the rather reversible and self-incurred phenomenon known as dehydration—and transfigure it into a terminal illness is anything but logical. Without much knowledge of the paleontological evidence, speculation was elaborate, and publication was unhindered. By the mid-1960s, self-reflecting scientists like Jepsen (1964) began reviewing the record of hypotheses formulated; Jepsen listed 40 separate hypotheses in a 20-pager published in the *American Scientist*.

Nevertheless, few scientists even contributed joke papers after testable ideas emerged in the 1980s; Dott (1983) framed dinosaur demise in the context of terminal hay fever: "In the spirit of fun…, I offer herewith my own homely asthmatic hypothesis for dinosaur extinction." Joining the "fun" with his intentionally archaic language, Dott offered his "asthmatic hypothesis" as another hypothesis to add to the list of many formulated. In addition, Dott's exaggeration of uniformitarian principles is evident in his inspiration for the hypothesis: "this hypothesis occurred to me early one spring several years ago when my eyes began to itch and my nose to tingle." Looking to present events to piece together the past shows his mocking use of uniformitarianism, resulting in his fantastical contribution of extinction by "asthma." Not only that, but many of the joke papers mentioned were published in reputed journals; in particular, Dott's paper (1983) was published in *Geology*. Regardless of established peer review practices by this time, the acceptance of such a paper showed the journal's encouragement of ideas that only served to read a satirical perspective on the subject. The continued publication of joke papers made it difficult to shake off the lack of importance surrounding the study of dinosaur extinction, undeniably delaying progress in the field.

Before the short, but rapid period of progress following the emergence of the Alvarez hypothesis, there was a much long-drawn period of development on the causes of dinosaur extinction characterized by a lack of seriousness. The very relaxation of scientific standards themselves were responsible for the continued participation of scientists in this approach to studying causes of the dinosaur extinction.

Publishing authorities' unquestioning acceptance of papers demonstrated their ignorance of basic biological principles. One such paper put forward by Flanders (1962) asked the question "Did the caterpillar exterminate the giant reptile?" Flanders' play on population regulation by controlling herbivory from the plant level is another example of exaggerated uniformitarianism. The observable phenomenon of population regulation by plants is why the Earth is "green"; however, taking this phenomenon and extrapolating it to the age of the dinosaurs should not be too far fetched. Though, it is the addition of the caterpillar in the interactions between the dinosaurs and plants that is flawed. Even if there were enough caterpillars to outcompete herbivorous dinosaurs, ignoring the plethora of omnivorous and carnivorous species that went extinct at the K-Pg boundary shows a lack of biological robustness in the paper. Furthermore, being published in the first issue of the first volume of the *Journal of Research on the Lepidoptera*, one would expect the journal to want to make a good impression on the scientific community. Yet, the publication of such an article as Flanders' says otherwise. The overall relaxation of scientific standards—in accepting Flanders' article, and publishing it in the first issue put out—was an open invitation to the scientific community for more uninformed research.

Not only did scientists accept this invitation in the form of journal articles, but also in the form of entire, outlandish books. Cuppy (1964), a humorist and literary critic wrote in his book that "racial senility" was behind the extinction of the dinosaurs, claiming that "the Age of Reptiles ended because it had gone on long enough." Seeing that scientists themselves were endlessly adding to the list of hypotheses on the cause of dinosaur extinction, it was not out of the ordinary for Cuppy to put forth his own two cents. By extrapolating the effects of old age, normally observable at the individual level, to the taxonomic grouping of "race" (that of the dinosaurs), Cuppy demonstrated that his work was at the pinnacle of the idea of relaxation of scientific standards. Moreover, if a humorist was to write about the causes of dinosaur extinction, it is evident that the subject had reached a level of freedom whereby it must be viewed by the collective as one not important enough to take seriously. This pattern of dilettante publication—relaxation of scientific standards and involvement of non-scientific contributors—effectively framed the study of the cause of dinosaur extinction as unimportant.

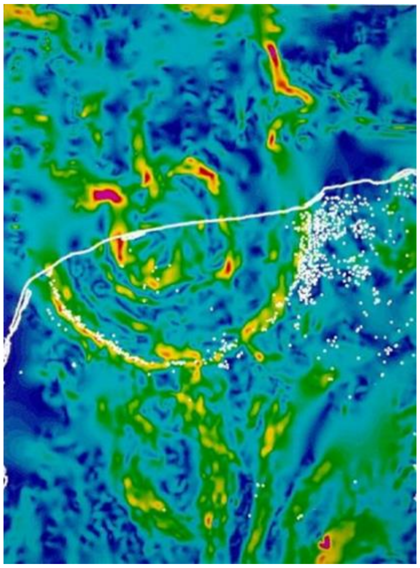


Figure 5.7. A view of the impact crater—first suggested by de Laubenfels—showing the circular impression in the gravitational field post-impact at Chicxulub, Mexico.

Benton (1990), a paleontologist interested in the history of his area of study, hinted that that the lack of seriousness before the 1980s was not as ubiquitous as it may seem. As early as in 1956, scientists like de Laubenfels let go of gradualist dogma and considered catastrophist, impact (see Figure 5.7) hypotheses for the cause of dinosaur extinction. Although uniformitarianism has and continues to successfully allow reconstruction of paleoenvironments, it favours gradualism in that most processes observable in the present could be characterized fully, with every step of every mechanism able to be modelled. Although catastrophic processes could also fit uniformitarian criteria (de Laubenfels' inspiration for the impact came from the near approach of the Hermes asteroid, an event of the present allowing reflection on the past), the suddenness and infrequency of such events would not allow as extensive characterization as available to gradualism. Nonetheless, de Laubenfels' venture away from gradualism and towards catastrophism made important progress in that it was one of the few papers of the pre-1980s period that considered extra-terrestrial possibilities. Despite the achievement the emergence of this hypothesis signified, failing to influence other scientists to adopt similar thinking was marked by a gap in the literature until 1980. Although not all papers in the pre-1980s period were papers that lacked robust

Figure 5.8. Luis (left) and Walter (right) Alvarez, the father-son duo that suggestd an extraterrestrial cause for the cause of the dinosaur extinctionst. The two stand flanking an outcrop of the iridium-filled K-T boundary in Gubbio, Italy.

evidence or simply speculative joke papers, the majority of papers fell into these categories.

The dilettante phase of scholarship was the dominant approach of research on the causes of dinosaur extinction in the pre-1980s period of the 20th century. The utter tarnishing of scientific standards encouraged both scientists and nonscientists to build the mountain of half-built hypotheses. Furthermore, with scientists who were simply interested in writing joke papers on the subject, it is imperative how difficult it would be to think of dinosaur extinction as an important topic of study. The struggle manifest in the research timeline of 20th century is evident in the delay between de Laubenfels' 1956 paper and Alvarez et al.'s 1980 paper. Therefore, the lack of seriousness by most scientists allowed for the 24-year gap, a gap filled but by speculation.

The heated debate begins

The impact theory first proposed by Alvarez et al. in 1980 was heavily opposed by other ideas, and this conflict was seen by some as an upheaval in science by 1983 (Glen, 1998).

One possible source of conflict was because Luis Alvarez (above) was a physicist. He was the first author on the 1980 publication, while Walter Alvarez, a Professor of Geology, was second author. Thus, Luis was suggesting a theory to oppose ideas in a field in which he was not an expert; he was an outsider. This was received by the earth science community in an offending way as described by, the physicist, Robert Jastrow: "Professor Alvarez was pulling rank on the palaeontologists. Physicists sometimes do that; they feel they have a monopoly on clear thinking. There is a power in their use of math and the precision of their measurements that transcends the power of the softer sciences" (Williams, 2011). Furthermore, James D. Williams, Lecturer in Science Education at University of Sussex, said the Alvarez team paper arguably did not deserve the prominence it received by being published in the Journal *Science*. This meant that not only was Luis Alvarez gaining a lot of recognition but being published in a notable journal generally has great financial benefit as a professional researcher. It can be hypothesized that this publication made some geologists jealous; this could contribute to unfair opposition of his theory.

Besides the idea of Luis Alvarez being an outsider to field of earth science, scientists were mostly strongly biased against the impact hypothesis due to the uniformitarian assumption of historical geology present beforehand (Oard, 1997). The uniformitarian assumption of the present being the key to the past was strongly challenged by the impact theory (Oard, 1997). To summarize, considering the asteroid hypothesis required a drastic change in thinking, a paradigm-shift, and that is another reason why it was strongly opposed. This is an example of how a person's preconceived ideas can lead to difficulty in accepting new ideas. Stephen Jay Gould, paleontologist and historian of science, expanded on this idea: “institutions, universities in particular, are very conservative places. Their function is not - despite lip service - to generate radically new ideas. There's just too much operating in tenure systems and granting systems” (Oard, 1997).

To expand on the idea of conservative thinking, Zipp and Fenwick analyzed the political orientation and educational values of professors across the US and concluded that the ratio of conservative to liberal faculty 2:1 in 1969, 1.2:1 in 1984, and 2.6:1 in 2005 (Zipp and Fenwick, 2006). Provided that this was an accurate representation for American geologists, this supports the notion by Stephen Gould that universities were conservative at the time. To reiterate, this conservative thinking may have manifested in greater resistance to the paradigm-shifting ideas presented by Alvarez.

A statement by Dr. J. Keith Rigby Jr., a paleontologist, illustrates the idea of financial or personal factors contributing to bias that would affect one's ability to accept the impact hypothesis: “he controversy over the impact theory of extinctions has so polarized the scientific community that the acceptance or rejection of grant proposals and papers may depend on the personal views of the reviewers assigned to pass on them. Scientific careers are at stake” (Browne, 1985). In addition, the statement also presents the idea that the peer review process may have been unfair in favour of Alvarez; this consequently supports the idea from James D. Williams that the Alvarez hypothesis received more prominence than it deserved. The concern that the Alvarez hypothesis was more unfairly favoured in publishing was rebutted by, editor of *Science*, Dr. Daniel E. Koshland Jr.: “We bend over backward to be fair in our selection of the reviewers who decide whether a paper will be published or not. Contributors should realize that because we receive so many fine papers, we're forced to reject four out of five submissions, and these include a lot of very good papers that are subsequently published elsewhere. We only have room for what we deem to be the best” (Browne, 1985). It is hard to judge whether there was favourable treatment in the peer review process for Alvarez due to limited documentation or evidence, but it is important to note that both possibilities exist. On the contrary, if the alternate hypotheses are supported with strong evidence, then the opposition to the impact hypothesis could be seen as fair. The most recent notable theory for the extinction of the dinosaurs that came in immediate opposition to the impact theory was of volcanism with ideas put forth by Dewey Mclean (1978). McLean argued that Deccan volcanism was the most likely cause for the dinosaur extinction. The main piece of evidence for the impact hypothesis was the iridium layer at the K-T boundary. This distinctly higher concentration of iridium (see Figure 5.9) coincides with the concentrations of iridium found in asteroids (Carroll, 2004; Alvarez et al., 1980). However, volcanism theories accounted for this because volcanic eruptions release iridium. Still, the Deccan volcanism theory did not have a direct link to the mass extinction established until the 21st century (Keller et al., 2011). Though, an impact location was not yet determined for the impact hypothesis, so it seems that both arguments were not well supported until further research had been done.

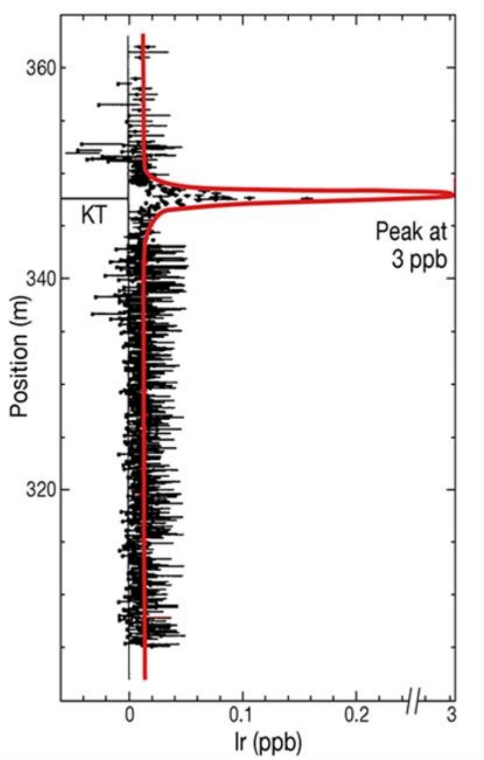


Figure 5.9. A plot of iridium levels at the Gubbio formation. Note the spike at the K-T position.

Another contrasting idea is that the opposition to the Alvarez hypothesis was partially self-inflicted. One allegation claims that Luis Alvarez made libellous public utterances about his opponents (Browne, 1988). Secondly, Leigh Van Valen, an evolutionary biologist, claims that Luis Alvarez made insulting remarks about paleontologists (Valen, 1984). Thirdly, However, the following statement from Luis Alvarez is not necessarily insulting "a physicist can react instantaneously when you give him some evidence that destroys a theory that he previously had believed. But that is not true in all branches of science, as I am finding out" (Alvarez, 1983). It is presumed that this was meant to be insulting towards earth scientists. Conversely, from the perspective that earth science can be complicated, it is fair to say that earth scientists would not react instantaneously. With no explicit insults, it seems that the bias may have affected the interpretation by earth scientists of comments made by Luis Alvarez.

The obvious issue here is that not all statements made by Alvarez were documented and available now. Fortunately, statements Luis Alvarez's autobiography reveal more, "I don't like to say bad things about paleontologists, but they're really not very good scientists. They're more like stamp collectors" (Browne, 1988). This can be seen as undermining the profession of these earth scientists and supporting the idea that some of the opposition was self inflicted. Furthermore, Gerta Keller, a professor of geoscience and Deccan volcanologist, argued that Luis Alvarez personally anyone who disagreed with the impact hypothesis (Keller, 2017). To expand, Alvarez allegedly interfered with the academic promotion of McLean, which Alvarez denied but stated, "If the president of the college had asked me what I thought about Dewey McLean, I'd say he's a weak sister. I thought he'd been knocked out of the ball game and had just disappeared, because nobody invites him to conferences anymore" (Keller, 2017). With this supposed hostile behaviour from Luis Alvarez, one can argue that it was fair for him and his theory to face notable opposition.

To conclude, these ideas contribute to the notion of many types of biases against the impact hypothesis, but Luis Alvarez's action may have also promoted opposition to his theory.

In closing, there are many factors that must be considered when evaluating whether the resistance to accepting the Alvarez hypothesis was fair. While Luis Alvarez was an outsider to the field of earth science, his actions seemed to work against him. Regardless of whether the opposition was fair, this rivalry caused great advancement in research on the topic. Our current understanding of the topic may not be this thorough if that rivalry did not happen.

K-Pg Extinction by Impact

Background

The Cretaceous-Paleogene (K-Pg) extinction event was the fifth of five major mass extinctions that have occurred on Earth. At approximately 66 Ma, about ¾ of all species on Earth are thought to have become extinct (Renne et al., 2013); these included species belonging to non-avian dinosaurs, marine and terrestrial vertebrates and invertebrates, microbiota, and plants. The event appears to have left its mark on all continents simultaneously; in particular, non-avian dinosaurs are known to have prospered during the Mesozoic on all seven continents, but none have sustained presence during the Cenozoic (Weishampel and Barrett, 2004). To solve one of the greatest murder mysteries of all time, many scientists have put forth their views about dinosaur extinction; today, the Alvarez hypothesis (Alvarez et al., 1980) has emerged as the leading idea.

Alvarez hypothesis

From the faction of extrinsic catastrophists, Alvarez et al. (1980) have suggested an asteroid impact was behind the extinction event. Marked by a thin layer of the metal iridium, the K-Pg boundary presents itself as a sedimentological anomaly; the extremely high concentration of iridium in comparison to the concentrations typically found on Earth suggest an extraterrestrial source. Furthermore, despite its extreme rarity in the rock record, the presence of iridium sites at many outcrop sites across the globe—at least 36 (Alvarez, 1983)—has been one of the strongest supporting factors weighing the debate in favour of an impact; the iridium layer has been studied in Gubbio, Italy and Stevns Klint, Denmark (Alvarez et al., 1980) and even thousands of kilometres away in Drumheller, Alberta, Canada (below) (Sweet and Braman, 1992).

Chicxulub crater

The hypothesis was further validated when the location of a possible impact crater was found buried underneath the town of Chicxulub on the Yucatán Peninsula in Mexico (Hildebrand et al., 1991). Geophysical and stratigraphic evidence shows that the structure found was characteristic of an impact crater. Gravity-field data reveal a 180 km diameter circular anomaly similar in shape to previously found impact craters; magnetic-field data show a 210 km diameter anomaly with concentric structures present, nearly coincident with the gravity anomaly. Stratigraphic data, provided by petroleum exploration drill holes, consist of sedimentary facies and fauna that indicate a deep-water environment such as fossiliferous limestones and marls, with minor shale, bentonite, and chert, indicative of paleoenvironments associated with the Late Cretaceous. In addition, the presence of shocked quartz, recording deformation in the crystalline structure due to intense pressure, and tektites, gravel-sized bodies of glass formed as molten debris from extraterrestrial impacts, suggest the existence of an impact crater at the Chicxulub site. Recent reviews of the evidence confirm the validity of the evidence in suggesting an asteroid impact (Renne et al., 2013; Stanley and Lucjaz, 2015).

Figure 5.10. The K-T boundary at the Badlands near Drumheller, Alberta, Canada is one of many sites in the world with an extremely high concentration of iridium in the K-T clay boundary.

Effect of impact

The asteroid that impacted Earth at the K-Pg boundary is thought to have released 420 zettajoules of energy, equivalent to one billion atomic bombs (Schulte et al., 2010). A massive tsunami is thought to have been triggered by the impact of the asteroid (Range et al., 2018). Ejecta from the impact would produce a vast dust cloud that could block sunlight to cause an event called the impact winter, a drastic decrease in global temperature due to asteroid impact (Robertson et al., 2013). Combustible hydrocarbons and sulphur in the ground would have been vaporized by the impact and cause sulfuric acid aerosols to be ejected into the stratosphere (Pope, D'Hondt and Marshall, 1998; Ohno et al., 2014). The evidence of these processes is found in the extinction record for plants and phytoplankton (Cockell, Koeberl and Gilmour, 2006). The impact would have released large amounts of gases, including H_2O, CO_2, and SO_2, and caused global warming (Pope et al., 1997; Kawaragi et al., 2009).

Alternate hypotheses

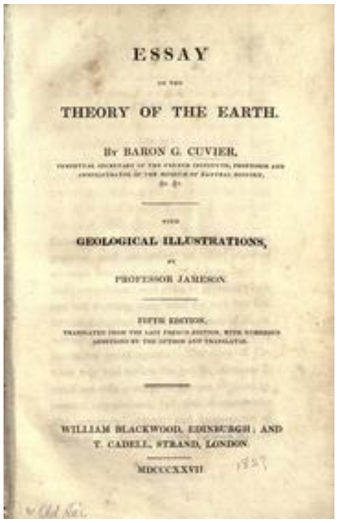
In the 20th century, the idea of Deccan volcanism being the main cause for the K-Pg extinction was problematic. This is because the link between the timing of the main Deccan eruptions, that occured over less than 0.8 million years, to the mass extinction event was not clearly established (Keller, 2017). In 2008 and 2009, studies suggested that severe environmental and climatic consequences leading to extinction occurred from the massive release of CO_2, SO_2, and Cl from Deccan volcanism (Self et al., 2008a; b; Chenet et al., 2008, 2009). A direct link between Deccan volcanism and the K-Pg mass extinction was established by results from analyses of basalts from four Rajahmaundry quarries (Keller, Sahni and Bajpai, 2009). Moreover, a 2013 review of the events at the K-Pg boundary suggest that while volcanism may be contemporaneous with the boundary itself, it was also active prior to this time and existing geochronological data are insufficiently precise to resolve the synchronicity of these events (Renne et al., 2013). This means that the role of Deccan volcanism in the K-Pg mass extinction remains unresolved.

Conclusion

In summary, the great controversy regarding the cause of the dinosaur extinction at the K-Pg boundary began in the 1980s with the publication of the Alvarez impact hypothesis. This triggered a period of intense rivalry between impact theorists and volcanologists, which had the positive outcome of advancing research on the K-Pg extinction. The debate is still ongoing and cannot be entirely resolved due to uncertainties regarding the timing of the potential impacte event and the period of intense volcanism.

Mass Extinctions: Beliefs Through the Ages

When comparing the life which exists on earth today to life when it originated, it is incredible the amount of evolution which has taken place. From a basic single celled organism to the wide variety of current organisms, the evolution of life is and has been an extremely complex process. But this process has not come without any setbacks, one of which being mass extinctions. A mass extinction refers to a rapid decrease in biodiversity on Earth and is typically classified as at least a 20% decrease in marine genera. There are believed to have been 5 mass extinctions to date, the End Ordovician (444 Ma), Late Devonian (375 Ma), End Permian (251 Ma), End Triassic (200 Ma), and End Cretaceous (66 Ma) (Raup, 1987). It is also believed that we are currently in the 6th mass extinction, with an extinction rate greater than the earth has ever experienced before (Alroy, 2015)



ESSAY

THEORY OF THE EARTH.

BY BARON G. CUVIER,

GEOLOGICAL ILLUSTRATIONS,

PROFESSOR JAMESON.

FIFTH EDITION.

WILLIAM BLACKWOOD, EDINBURGH; AND
T. CADELL, STRAND, LONDON.

MDCCCXXVII.

Figure 5.11. Image of the front page of the fifth edition of Georges Cuvier's Theory of the Earth, which was published in 1813.

Species have been going extinct for almost as long as life has existed, however this fact was not always believed. As early as 500 BC, evidence of previously existing species has been recorded. Philosophers and early scientists such as Xenophanes and Strabo wrote about fossils of marine organisms. At this time, most scientific fields had not even been established and this led to misguided hypotheses, but since these people were held to such high authority, their beliefs were treated as true. One of the most popular beliefs about how these marine fossils existed was that land used to be underwater (Roller, 2017). Without the proper knowledge of fossilization, previously existing life, and many geologic techniques we have today, there was no reason to disagree at the time. Also, at this time they were unaware of whether or not the organisms in these fossils still existed today, as much of the earth was undiscovered. A crucial step in formulating theories about extinction, and subsequently mass extinctions, was to first confirm that there once existed species which no longer exist today.

First Proposal of the Mass Extinction Theory

While evidence of fossils was present early on in human history, it wasn't until the early 18th century that the barrier created by religion was contested, and theories began to form, stating that species can cease to exist. The belief was that all living creatures were made in God's image and the world which He created was so perfect that He would not allow species to undergo extinction (Pigliucci, 2005). Fossils of previous living organisms had been described as early as 500 BC, but it was still against popular belief that extinction could occur. In the 17th century, fossils were thought of as remains of mythical creatures such as dragons, giants, or unicorns (Bressan, 2015). If we fast forward to the early 18th century, ideas about extinction were proposed by the "father of paleontology", Georges Cuvier, and with the available fossil evidence it was hard to dispute extinction has taken and is currently taking place. However, the method by which species cease to exist was not as clear. In Cuvier's Essay on the Theory of the Earth (1813) he proposed that now-extinct species had been wiped out by catastrophic events, which included extraterrestrial impacts, increased volcanism, and rapidly changing sea levels (Cuvier, 1813). This idea of catastrophic events wiping out species from the earth entirely was not accepted at first, with many scientists of historical importance disagreeing with Cuvier.

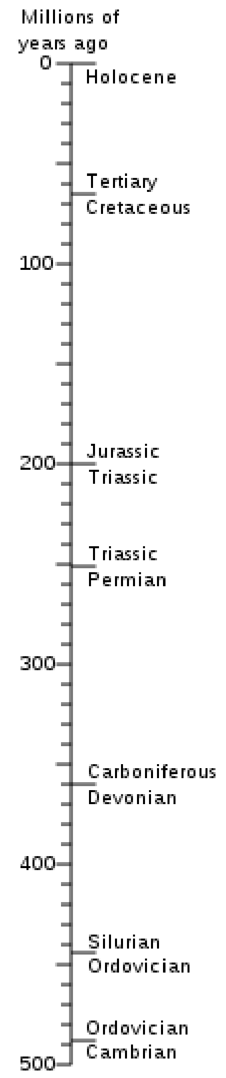


Figure 5.12. Timeline showing each of the five mass extinctions.

Lyell and Darwin's Thoughts

Famous geologist Charles Lyell was in disagreement with Cuvier's theory about mass extinctions. He was known for the development and popularization of uniformitarianism, which is the belief that the scientific processes which shaped the earth are the same ones which operate today. In the same book which presented uniformitarianism, Principles of Geology (1830-1833), he also challenged Cuvier's claims about catastrophic events causing extinctions, as he believed that extinction, much like the events which shape the earth, was a slow and gradual process (Lyell, 1830). Much like Charles Lyell, Darwin was also opposed to Cuvier's theory. He accepted and agreed with Cuvier on the principle of species reaching extinction and new species evolving, but he was also a firm believer that extinction was a gradual process, and catastrophic events were not the cause of the extinction of species.

The next chapter in the understanding of Cuvier's theory of mass extinctions caused by catastrophic events was to identify what these events were, and when they occurred. This task proved to be very difficult as most of the evidence from mass extinctions was either removed from the sea floor due to recycling of oceanic plates, or buried deep beneath many layers of rock. The most recent mass extinction, the Late Cretaceous, occurred about 66 million years ago and disputes regarding its cause have allowed for many advancements in our knowledge and approach towards solving the mysteries that are these catastrophic, specie wiping events.

K-Pg Extinction

The last confirmed mass extinction occurred 66-64 Ma in the late Cretaceous period (Bramlette, 1965). It is known as the K-Pg extinction, as it occurred on the time border of the Cretaceous (Kreide in German) and Paleogene geologic periods (Krug, Jablonski and Valentine, 2009). Arguably the most well-known global extinction, the K-Pg extinction brought an end to the dinosaurs and the ammonites, along with winged and large marine reptiles (Alvarez et al., 1980). Overall, this event claimed 76% of all species (Pope, D'Hondt and Marshall, 1998). It is believed to have terminated rapidly following a period of diversity declination (Sakamoto, Benton and Venditti, 2016). There are multiple theories as to the cause of the K-Pg extinction, including sea level change, volcanism, and extraterrestrial impacts (Alvarez et al., 1980). These theories have evolved throughout time.

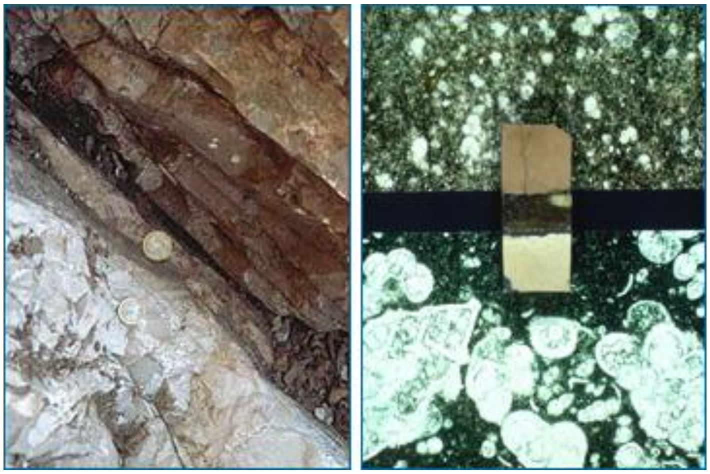


Figure 5.13. Left: Naked eye image of Cretaceous (bottom) and Paleogene (top) rock. Right: Magnification of Cretaceous (bottom) – Paleogene (top) boundary.

The rocks at the K-Pg border clearly illustrate the event that occurred. Limestone from 66-64 Ma was formed in part by fossilized carbonate shells of benthic foraminifera, otherwise known as forams (Carroll, 2016). These forams have been used by paleontologists to assign dates to rock strata (Powell and MacGregor, 2011). Cretaceous rocks illustrate a large amount of forams and fossil diversity (Alvarez et al., 1980), as shown below. The darker, less diverse Paleogene rocks smell of sulfur, contain a significantly lower concentration of forams and fossils, and display a massive fern spike up to 30 cm above the border (Alvarez et al., 1980). A fern spike is a significant increase in the ratio of fern spores relative to angiosperm pollen. Ferns are opportunistic plants that have been shown to grow, adapt, and reproduce rapidly following burning or land devastation (Wiewiora, 2003). Higher order plants take time to recapture the land prepared by ferns, causing the fern spike to be temporary (Wiewiora, 2003). This spike is seen not only at the K-Pg boundary, but also at other extinction events such as the late Permian extinction (Wiewiora, 2003).

Some evidence is essentially scientifically irrefutable. The K-Pg border displays rapid climate change and a layer of iridium at unnaturally high concentrations (Alvarez et al., 1980). The layer of iridium was discovered in 1979 by Luis and Walter Alvarez, forming the basis of the Alvarez Hypothesis, which will be discussed later. Oxygen isotopes at the K-Pg boundary suggest rapid fluctuations in ocean temperature before and through the boundary (Cowen, 1994). Carbon isotopes at the K-Pg boundary indicate rapid fluctuations in ocean productivity and circulation leading up to the mass extinction, followed by a large decrease in temperature as well as a complete gap of ocean productivity and circulation for tens of thousands of years after the extinction event (Cowen, 1994). It is evident and irrefutable that this rapid climate change had severe and long-lasting impacts on species and ecosystems globally. The central cause of this extinction has been disputed by two main groups; the intrinsic gradualists and the extrinsic catastrophists.

Over 90% of all species that have inhabited this Earth are currently extinct (Simpson, 1985). A family or genus will remain extant providing species within it develop or prosper faster than others die out (Sakamoto, Benton and Venditti, 2016). About 90 million years ago, the dinosaurs began a gradual decline, with species going extinct faster than new ones could evolve (Sakamoto, Benton and Venditti, 2016). It appears that dinosaurs may have gone extinct without the impact of a single catastrophic event. Intrinsic gradualists believe that this is the case, that the decline of the dinosaurs is due to gradual internal factors, namely volcanism and plate tectonics (Cowen, 1994).

The Indian Deccan Traps is a large igneous province formed by a rising mantle plume from the Réunion hotspot east of Madagascar (Monastersky, 1987). It was formed as India was drifting northward 63-67 Ma. The light melted material created a province of mafic rock with a surface area as large as 1,500,000 km^2, before erosional processes reduced the traps to the 500,000 km^2 area they cover today (Thompson, 2008). These traps grew 100,000 km^3 each year, and the lava flows affected a myriad of species locally and globally (Thompson, 2008). The Deccan Traps created lava and ash falls that destroyed ecosystems (Weisburd, 1987), but more significant is the effect that the traps had on global carbon and sulphur cycles (Jones et al., 2016). It is believed that these traps released thousands of gigatons of sulfur dioxide and carbon dioxide into the atmosphere, leading to global warming, gas poisoning, and ocean acidification (Jones et al., 2016). Clouds of ash and dust blocked sunlight, creating a volcanic winter, and subsequently, anoxic terrestrial and marine conditions unfavourable for most organisms (Weisburd, 1987). Plants and animals began to die out. Magma from the Deccan Traps contains a high concentration of iridium, possibly explaining the unusually concentrated iridium layer separating K-Pg rocks (Shukla et al., 2001).

Figure 5.14. Satellite image of Indian Deccan Traps

These traps were active before a potential asteroid impact, and became more active nearing the K-Pg boundary, thus providing a hypothesis as to a cause of the K-Pg mass extinction (Schoene et al., 2015). Intrinsic gradualists also discuss how the movement of tectonic plates at the end of the Cretaceous period not only promoted volcanism, but led to sea regression, causing a less mild climate over a long period of time (Smith, 1995). This was one of many theories in the mid to late 20th century. Other theories include a magnetic reversal, a nearby supernova, freshwater flooding of the ocean surface from a postulated Arctic lake, or a combination of various factors (Alvarez et al., 1980). No theory predominated and no consensus was made. The beginning of the Alvarez Hypothesis in 1979 set the foundation for the present consensus causality of the K-Pg extinction.

The K-Pg boundary has long been seen as an abrupt end, described by a distinct clay layer up to 30 cm in thickness (Alvarez et al., 1980). It was suggested previously that low concentrations of platinum group elements in sedimentary rock are due to ablation as meteorites entered the atmosphere (Goldschmidt, 1954). In 1979, Luis and Walter

Alvarez, along with their colleagues, discovered K-Pg layers in Italy, Denmark, and New Zealand, with respective iridium concentrations 30, 160, and 20 times greater than the background level (Alvarez et al., 1980), as illustrated below. Tests indicate that the iridium originated from an extraterrestrial source, but was not of supernova origin due to a lack of plutonium-244 in the clay layer (Alvarez et al., 1980). Using various methods, Alvarez et. al calculated the diameter of a potential asteroid to be 10 ± 4 km in diameter. It was calculated that an asteroid this size, with a standard meteoric speed of 25 km/s, would create an impact crater around 200 km in diameter (Perkins, 2003). Thus, arose a flaw in their hypothesis. To their knowledge, no such crater had been found.

Ironically, the crater was discovered the year earlier by Glen Penfield, a PEMEX geophysicist (Shonting and Ezrailson, 2017). In 1951, the Mexican oil company PEMEX, had drilled exploratory boreholes into the Campeche Bank, a continental shelf north of the Yucatán Peninsula (Shonting and Ezrailson, 2017). One borehole unexpectedly found breccia, fused rocks, and shocked quartz 1300 m below sea level (Bohor, Modreski and Foord, 1987). This was described as an unknown volcanic dome and the data lay unused. Almost 3 decades later, Penfield observed magnetic and gravitational anomalies in the area, under the town of Chicxulub (Shonting and Ezrailson, 2017). Using two separate gravity data maps of the Yucatán Peninsula, made over 10 years earlier, Penfield discovered a massive circular crater exceeding 180 km in diameter (Shonting and Ezrailson, 2017). In 1991, the pieces were put together, and the consensus theory was that the K-Pg mass extinction event was due to the impact of a 10 km diameter asteroid at the Gulf of Mexico, creating the Chicxulub crater (Carroll, 2016).

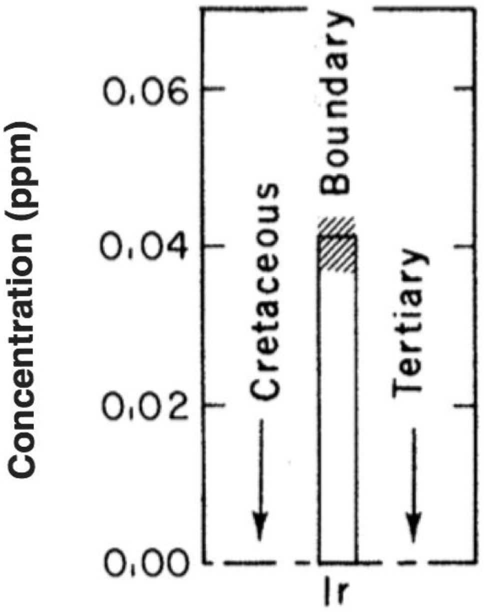


Figure 5.15. Graph illustrating iridium concentrations in sedimentary rock before, after, and at the Cretaceous-Tertiary (or Cretaceous-Paleogene) boundary.

Prior to impact, the upper 3 km of rock at the Yucatán site contained large amounts of water, carbonate, and sulfate (Pope, D'Hondt and Marshall, 1998). The impact launched 200 gigatons each of H20, S20, and other gasses into the atmosphere, where they mixed into the opposite hemisphere and covered the entire globe within a year (Pope, D'Hondt and Marshall, 1998). This cloud also included 60 times the mass of the asteroid in the form of dust and ejecta (Shonting and Ezrailson, 2017). Models indicate that the dust and ejecta would have blocked out the sunlight and created an impact winter for at least a year, while the gasses and aerosols would have stayed in the atmosphere for up to 12 years, blocking around 50% of the sunlight for the first 10, and devastating species and climate conditions globally (Pope, D'Hondt and Marshall, 1998). It is believed today that the decline of the dinosaurs began 90 Ma, shown by decreased genetic diversity (Sakamoto, Benton and Venditti, 2016), and that the asteroid provided the tipping point (Higgins, 2016). It is believed that the asteroid amplified the impacts of the Deccan Traps, and that both of these factors created an impact winter that ravaged global climate conditions, as well as species such as the dinosaurs (Smith, 1995).

Are We Part of the Sixth Mass Extinction?

The Alvarez Hypothesis marks the first consensus agreement on the cause of any mass extinction. Fortunately for Alvares and other scientists, this mass extinction only happened 66 Ma, meaning there theoretically should be the most evidence available today. Since many of the most of the mass extinctions occured over 200 million years ago, most of the evidence has been either recycled along with the sea floor or is buried deep beneath many layers of rock. This makes pinpointing the exact causes of past extinction events extremely difficult. Scientists today however, are using what we know about the most recent mass extinction to form theories about the older known mass extinctions. A good example of this is the current theories on the Late Permian mass extinction, also known as the great dying.

Current Theories About The Great Dying

The Late Permian Mass Extinction or "The Great Dying" occurred about 252 Ma and was the largest mass extinction in earth's history. It is believed that up to 96 percent of all marine species and 70 percent of all terrestrial vertebrate species were wiped out (Sahney and Benton, 2008). In recent years, theories about the cause of this extinction have been based off of those for the cause of the Late Cretaceous one. One of the most popular theories being an impact event, much like the one found at the K-Pg boundary. Geologists began looking for evidence of an impact crater at the Permian-Triassic boundary in both Antarctica and Australia. There does appear to be some evidence of an impact in both locations, as shocked quartz, iridium anomalies, and helium and argon isotope ratios from fullerenes resembling extraterrestrial rocks have all been discovered (Retallack et al., 1998). However, in comparison to evidence of the Cretaceous impact, it is underwhelming and does not provide any definitive proof of an impact crater existing.

Another popular theory for what caused the great dying was sulphur poisoning from heavy volcanic activity. Much like the Deccan traps produced at the K-Pg boundary, the Siberian Traps located in Russia is a large igneous province created by one of the largest known volcanic events in the last 500 million years. About 200 Ma mass amounts of basaltic lava erupted from a mantle plume in the Siberian craton and the result is an area of basaltic rock which is about seven million square kilometers (Ogden and Sleep, 2012). With this much volcanic activity going on at the same time as the Late Permian extinction, many geologists believe that these eruptions played a large role in the great dying (Burgess, Muirhead and Bowring, 2017). With many different outcomes possibly coming from the volcanic activity such as global warming, this theory stands as a plausible cause for the mass extinction and the search for more evidence is ongoing.

As we are learning more about each extinction, new ways of looking at these extinctions have evolved. Another theory was that elevated carbon dioxide levels as a result of increased volcanic activity was the cause for the great dying. To test this theory, most geologists would have looked at rocks present in the Permian Triassic boundary for geochemical evidence of higher CO2 levels. Instead of taking this traditional approach, Knoll looked at what species went extinct and what survived to see if the species that survived would have been able to better tolerate elevated CO2 levels (Knoll et al., 1996). Using comparative physiology, they classified species present just prior to the event and classified them based on vulnerability to elevated carbon dioxide levels and they found that those in the vulnerable category saw a higher rate of extinction than those who would be more tolerant (Knoll et al., 1996). With these findings, they were then able to establish a theory on a combination of causes including volcanism and elevated carbon dioxide levels in the atmosphere which led to the development of their theory on the cause of the Permian mass extinction.

The 6th Mass Extinction

While there is ongoing research into the 5 previous mass extinctions, scientists believe that we are currently in the 6th mass extinction. This mass extinction is known as the Holocene extinction, and the affected animals vary greatly among each other (Pimm et al., 1995). Just 11,000 years ago, giant mammals ruled the planet. From massive wooly mammoths to sabre toothed tigers, these colossal beings dominated the world. However now, just 11,00 years later, they are all gone. Now the cause for this is a topic of heavy debate. There are multiple sides to the debate, with humans overkilling them as one, global warming as another, and loss of habitats as another popular one. With evidence to support each of these sides, there is no clear consensus as of yet, and it is likely that it was not just one of these factors, but a combination of multiple factors that led to the demise of the megafauna (van der Kaars et al., 2017).

These extinctions, however, were just the beginning. It is estimated that the current extinction rate are 1000 times that of the background extinction, which is the largest rate ever experienced on Earth (Pimm et al., 2014),

Since the 1970's, at least 3.1% of all frog species have disappeared, which is an alarmingly fast rate (Alroy, 2015). With the largest mass extinction in the Late-Permian lasting about 15 million years, we are currently on track for the worst mass extinction ever to occur.

Figure 5.16. Image of the extinct Woolly Mammoth, part of the Megafauna which went extinct 10,000 years ago.

There is one distinguishing feature about the current mass extinction, and it is that it was not caused by a catastrophic event like those in the past. Instead, it is believed that for the first time, a mass extinction is being caused by a species; humans. Scientists have been compiling modern data about the current extinction rate and comparing it to paleontological records, and they have confirmed that extinction rates are higher than ever (Barnosky et al., 2011). With the rapid loss of extremely biodiverse habitats such as coral reefs and rainforests, these rates seem like they could get even worse (Pimm et al., 1995). There have been numerous studies done to determine if we really are in the midst of a mass extinction and if so, what is the magnitude. One study was completed by a group in Los Angeles, California where they looked at the arrival of humans onto a previously uninhabited island and what they saw was that the arrival of humans onto these island always resulted in a mass extinction in the islands biota (Barnosky et al., 2011). Even though this as a model has some shortcomings in terms of similarities with our current world, it still provides valuable insight on the damage humans can do to wildlife.

Conclusion

We hope this book brought to light the truly interdisciplinary nature of both science and history. Science is not only a story of numbers and theories, but of the people behind them. A single scientific breakthrough relies on the countless small steps taken previously and the inquisitorial nature of scientists involved. We hope that you too were inspired to ask questions and continue to view science as a story. A new theory is not an endpoint, but a springboard for new questions and new discoveries.

Reference List

Aciego, S., Bourdon, B., Schwander, J., Baur, H. and Forieri, A., 2011. Toward a radiometric ice clock: uranium ages of the Dome C ice core. *Quaternary Science Reviews*, 30(19–20), pp.2389–2397.

Adams, L., 2013. *Geology lecture 10 | Pyroclastic Debris*. [online] Available at: <https://www.slideshare.net/laurenadams718/geology-lecture-10-16952980> [Accessed 25 Jan. 2019].

Adkins, A. and Pollard, J., n.d. *Greek mythology | Gods, Stories, & History | Britannica.com*. [online] Encyclopaedia Britannica. Available at: <https://www.britannica.com/topic/Greek-mythology> [Accessed 8 Feb. 2019].

Agassiz, L. and Bettannier, J., 1840. *Études sur les glaciers;* [online] Neuchâtel, Jent et Gassmann. Available at: <http://archive.org/details/etudessurlesgla00agasgoog> [Accessed 13 Feb. 2019].

Agricola, G., 1955. *De Natura Fossilium: (Textbook of Mineralogy)*. Translated by J.A. Bandy and M.C. Bandy.

Akazawa, T., Muhesen, S., Dodo, Y., Kondo, O., Mizoguchi, Y., Abe, Y., Nishiaki, Y., Ohta, S., Oguchi, T., and Haydal, J., 1995. Neanderthal infant burial from the Dederiyeh Cave in Syria. *Paléorient*, 21(2), pp.77–86.

Allard, M., Wang, B. and Pilon, J.A., 1995. Recent Cooling along the Southern Shore of Hudson Strait, Quebec, Canada, Documented from Permafrost Temperature Measurements. *Arctic and Alpine Research*, 27(2), p.157.

Alley, R.B., 2000. Ice-core evidence of abrupt climate changes. *Proceedings of the National Academy of Sciences of the United States of America*, 97(4), pp.1331–1334.

Alroy, J., 2015. Current extinction rates of reptiles and amphibians. *Proceedings of the National Academy of Sciences of the United States of America*, 112(42), pp.13003–13008.

Alvarez, L.W., 1983. Experimental evidence that an asteroid impact led to the extinction of many species 65 million years agoa. *Proceedings of the National Academy of Sciences of the United States of America*, 80(2), pp.627–642.

Alvarez, L.W., Alvarez, W., Asaro, F. and Michel, H.V., 1980. Extraterrestrial Cause for the Cretaceous-Tertiary Extinction. *Science*, 208(4448), pp.1095–1108.

American Museum of Natural History, n.d. Inge Lehmann: Discoverer of the Earth's Inner Core. *Earth Inside and Out Curriculum Collection*, [online] Available at: <https://www.amnh.org/learn-teach/curriculum-collections/earth-inside-and-out/inge- lehmann-discoverer-of-the-earth-s-inner-core> [Accessed 1 Feb 2019].

Ammon, C.J., 2019. *Seismic Waves and Earth's Interior.* [online] SLU EAS-A193 Class Notes. Available at: <http://eqseis.geosc.psu.edu/cammon/HTML/Classes/IntroQuakes/Notes/waves_and_interior.html> [Accessed 10 Feb. 2019]

Anderson, D. L., 2002. The Inner Core of the Earth. *Proceedings of the National Academy of Sciences of the United States of America, Vol. 99, No. 22*, [online] Available at: <https://www.pnas.org/content/99/22/13966#ref-1> [Accessed 5 Feb 2019].

Andrei, M., 2016. *What are the layers of the Earth?* [online] ZME Science. Available at: <https://www.zmescience.com/other/science-abc/layers-earth-structure/> [Accessed 4 Feb 2019].

Anon 2019. *Projections*. [online] Intergovernmental Committee on Surveying and Mapping. Available at: <https://www.icsm.gov.au/education/fundamentals-mapping/projections> [Accessed 14 Feb. 2019].

Appenzeller, T., 2013. Neanderthal culture: Old masters. *Nature News*, 497(7449), p.302.

Arrhenius, G. and Bonatti, E., 1965. Neptunism and vulcanism in the ocean. *Progress in Oceanography*, 3, pp.7–22.

Auerbach, M.P., 2018. *Geographic information systems (GIS)*. [online] Salem Press Encyclopedia of Science. Available at: <http://eds.a.ebscohost.com.libaccess.lib.mcmaster.ca/eds/detail/detail?vid=0&sid=be2192f8-2e48-4244-b3b8-e248a83733b6%40sessionmgr4007&bdata=JnNpdGU9ZWRzLWxpdmUmc2NvcGU9c2l0ZQ%3d%3d#AN=88806495&db=ers> [Accessed 14 Feb. 2019].

Australian Government. Available through: McMaster University Library website <https://library.mcmaster.ca/> [Accessed 14 Feb 2019].

Available at: https://news.nationalgeographic.com/2018/06/why-now-is-the-best-time-ever-for-dinosaur-discoveries/ [Accessed 15 Feb. 2019].

Ayala, F.J. and Fitch, W.M., 1995. *The Role of Extinction in Evolution: Genetics and Paleontology 50 Years After Simpson*. Washington, D.C.: National Academies Press (US).

Bada, J. and Lazcano, A., 2012. Stanley L. Miller. National Academy of Sciences.

Badro, J., Côté, A. S., and Brodholt, J. P., 2014. A seismologically consistent compositional model of Earth's core. *Proceedings of the National Academy of Sciences of the United States of America,* 111(21), pp. 7542-7545.

Bailey, G. N., Harff J., Sakellariou, D., 2017.*Under the Sea: Archeology and Palaeolandscapes of the Continental Shelf.* [ebook] Cham: Springer Netherlands. Available through: McMaster University Library website <https://library.mcmaster.ca/> [Accessed 12 Feb 2019].

Baldwin, E., 1964. *An Introduction to Comparative Biochemistry*. 4th ed. Cambridge: Cambridge University Press.

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B. and Ferrer, E.A., 2011. Has the Earth's sixth mass extinction already arrived? *Nature*, 471(7336), pp.51–57.

Barton, C., 2002. Marie Tharp, oceanographic cartographer, and her contributions to the revolution in the Earth sciences. *Geological Society, London, Special Publications*, [online] 192(1), pp.215–228. Available at: <http://doi.org/10.1144/gsl.sp.2002.192.01.11> [Accessed 1 Feb. 2019].

Bartrip, P.W., 2003. History of asbestos related disease. *Postgraduate Medical Journal*, 80, pp.72–76.

Bates, C., 2010. *The Cambridge companion to the epic*. United Kingdom, Europe: Cambridge University Press.

Becker, T.W. and Faccenna, C., 2009. A Review of the Role of Subduction Dynamics for Regional and Global Plate Motions. In: S. Lallemand and F. Funiciello, eds., *Subduction Zone Geodynamics*, Frontiers in Earth Sciences. Springer Berlin Heidelberg, pp.3–34.

Beer, G., 2009. Darwin and the Uses of Extinction. *Victorian Studies*, 51(2), pp.321–331.

Belmont, M., 2016. *Typhon in Greek mythology - The Father of Monsters*. [online] Available at: <http://www.gods-and-monsters.com/typhon-in-greek-mythology.html> [Accessed 8 Feb. 2019].

Benton, M.J., 1990. Scientific methodologies in collision: the history of the study of the extinction of the dinosaurs. *Evolutionary Biology*, 24, pp.371–400.

Beringer, J., 1963. *The Lying Stones of Dr. Beringer, Lithographiae Wirceburgensis*. Translated by M.E. Jahn. and Translated by D.J. Wolff. Berkeley: University of California Press.

Bernard, E.N. and Robinson, A.R., 2009. *Tsunamis*. Harvard University Press.

Betz, F., 2011. Managing Science. Springer Science & Business Media, (9).

Biography Editors, 2014. *J.B.S. Haldane*. [online] Biography. Available at: <https://www.biography.com/people/jbs-haldane-37847> [Accessed 15 Feb. 2019].

Birrell, A., 1997. The Four Flood Myth Traditions of Classical China. *T'oung Pao*, 83(4/5), pp.213–259.

Birstein, V.J., 2004. *The perversion of knowledge: the true story of Soviet science.* Cambridge, Mass: Westview.

Bispham, E., Harrison, T. and Sparkes, B.A., 2010. *The Edinburgh Companion to Ancient Greece and Rome*. Edinburgh: Edinburgh University Press.

Bloise, A., Punturo, R., Ricchiuti, C. and Apollaro, C., 2017. Mineralogy and Geochemistry of Asbestos Observed in Soils Developed within San Severino Lucano Village (Southern Italy). *Geophysical Research Abstracts*, [online] 19. Available at: <http://adsabs.harvard.edu/abs/2017EGUGA..19.4547B>.

Bodkin, H., 2018. *Massive volcano described in an apocalyptic poem ushered in Christianity for Iceland's Vikings*. [online] The Telegraph. Available at: <https://www.telegraph.co.uk/science/2018/03/19/massive-volcano-described-apocalyptic-poem-ushered-christianity/> [Accessed 8 Feb. 2019].

Bohor, B.F., Modreski, P.J. and Foord, E.E., 1987. Shocked Quartz in the Cretaceous-Tertiary Boundary Clays: Evidence for a Global Distribution. *Science*, 236(4802), pp.705–709.

Bolt, B. A., 1997. Inge Lehmann. *University of California, Berkeley: Biographical Memoirs of Fellows of the Royal Society*, [online] Available at: <http://cwp.library.ucla.edu/articles/bolt.html> [Accessed 25 Jan 2019].

Boule, M., 1905. L'origine des Éolithes. Anthropologie Offprint. [online] Masson. Available at: <https://books.google.ca/books?id=W3uDmgEACAAJ>.

Bradshaw, C.J.A., Giam, X., Tan, H.T.W., Brook, B.W. and Sodhi, N.S., 2008. Threat or invasive status in legumes is related to opposite extremes of the same ecological and life-history attributes: Twin fates of legume species. *Journal of Ecology*, 96(5), pp.869–883.

Bramlette, M.N., 1965. Mass Extinctions of Mesozoic Biota. *Science*, 150(3701), p.1240.

Brangwynne, C. and Hyman, A., 2012. In Retrospect: The Origin of Life. *Macmillan Publishers Limited*, 491, p.525.

Braun, T., 2004. Hecataeus' Knowledge of the Western Mediterranean. *Greek Identity in the Western Mediterranea*.

Bressan, D., 2015. *How Scientists Discovered The Extinction Of Species*. Forbes.

British Antarctic Survey, 2014. *Ice Cores and Climate Change.* [online] Available at: <https://www.bas.ac.uk/data/our-data/publication/ice-cores-and-climate-change/> [Accessed 10 Feb 2019].

British Library Archives, 2019. *Principles of Geology*. [online] The British Library. Available at: <https://www.bl.uk/collection-items/charles-lyells-principles-of-geology> [Accessed 6 Feb. 2019].

Brockhaus, F.A. and Schimper, K.F., 1838. *Blätter für literarische Unterhaltung.*

Browne, M.W., 1985. Dinosaur Experts Resist Meteor Extinction Idea. *The New York Times*. 29 Oct. p.1c.

Browne, M.W., 1988. The Debate Over Dinosaur Extinctions Takes an Unusually Rancorous Turn - The New York Times. *The New York Times*. 19 Jan. p.1c.

Bryant, E., 2014. Introduction. In: E. Bryant, ed., *Tsunami: The Underrated Hazard*. Cham: Springer International Publishing, pp.3–18.

Budd, G.E. and Mann, R.P., 2018. History is written by the victors: The effect of the push of the past on the fossil record. *Evolution*, 72(11), pp.2276–2291.

Bulfinch, T., 1913. *Bulfinch's Mythology: The Age of Fable, Stories of Gods and Heroes*. [online] *Bartleby*, Available at: <https://www.bartleby.com/181/365.html>.

Bullard, F.M., 1962. *Volcanoes in history, in theory, in eruption.* Austin, Texas: University of Texas Press.

Bunbury, E.H., 1883. *A History of Ancient Geography Among the Greeks and Romans*. 2nd ed. New York: Dover Publications.

Burgess, S.D., Muirhead, J.D. and Bowring, S.A., 2017. Initial pulse of Siberian Traps sills as the trigger of the end-Permian mass extinction. *Nature Communications*, [online] 8. Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5537227/> [Accessed 16 Feb. 2019].

Burgess, S.D., Muirhead, J.D. and Bowring, S.A., 2017. Initial pulse of Siberian Traps sills as the trigger of the end-Permian mass extinction. *Nature Communications*, [online] 8. Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5537227/> [Accessed 16 Feb. 2019].

Burkhardt, R.W., 1972. The Inspiration of Lamarck's Belief in Evolution. *Journal of the History of Biology*, 5(2), pp.413–438.

Burnet, T., 1719. *The Sacred theory of the earth : containing an account of the original of the earth and of all the general changes which it hath already undergone, or is to undergo, till the consumation of all things*. London : Printed for John Hooke.

Cabej, R. N., 2013. *An Epigenetic Narrative of Development and Evolution of Animals.* 1st ed. Elsevier.

Caley, E.R. and Richards, J.F.C., 1956. *Theophrastus On Stones*. [online] *Farlang*. Columbus, OH: The Ohio State Univ. Available at: <http://farlang.com/books/theophrastus-on-stones-translation-into-english>.

Campbell, K.A., 2006. Hydrocarbon seep and hydrothermal vent paleoenvironments and paleontology: Past developments and future research directions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 232(2), pp.362–407.

Campbell, R., 2012. *A Biographical Dictionary of Russian and Soviet Economists*. Routledge.

Cann, R.L., Stoneking, M. and Wilson, A.C., 1987. Mitochondrial DNA and human evolution. *Nature*, 325(6099), p.31.

Carlowicz, M., 2018. Inge Lehmann. *American Geophysical Union*, [online] Available at: <https://honors.agu.org/inge-lehmann-1888–1993/> [Accessed 7 Feb 2019].

Carozzi, A.V., 1966. Agassiz's Amazing Geological Speculation: The Ice-Age. *Studies in Romanticism*, 5(2), pp.57–83.

Carpenter, K., n.d. The Dinosaurs of Marsh and Cope. p.31.

Carroll, S.B., 2004. *Into The Jungle: Great Adventures In The Search For Evolution.* New York: Pearson Education. pp.113-131

Carroll, S.B., 2016. *The Day the Mesozoic Died*. Nautilus.

Caryl, S., 2014. *Magma | Encyclopedic Entry.* [online] National Geographic Society. Available at: <https://www.nationalgeographic.org/encyclopedia/magma/> [Accessed 9 Feb. 2019].

Cassidy, M., Manga, M., Cashman, K. and Bachmann, O., 2018. *Controls on explosive-effusive volcanic eruption styles*. [online] Nature Communications, 9(1), p.2839.

Chapman, A., 2008. William Buckland and the foundation of English geology. *Hobbs the Printers Ltd.*, [online] 29(2). Available at: <https://ougs.org/files/ouc/archive/journal/OUGSJ_29_(2)_screen_res.pdf#page=5>.

Chenet, A.-L., Courtillot, V., Fluteau, F., Gérard, M., Quidelleur, X., Khadri, S.F.R., Subbarao, K.V. and Thordarson, T., 2009. Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: 2. Constraints from analysis of eight new sections and synthesis for a 3500-m-thick composite section. *Journal of Geophysical Research*, 114(B6), pp.1-38.

Chenet, A.-L., Fluteau, F., Courtillot, V., Gérard, M. and Subbarao, K.V., 2008. Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: Results from a 1200-m-thick section in the Mahabaleshwar escarpment. *Journal of Geophysical Research*, 113(B4), pp.1-27.

Clark, R., 2013. *The Life and Work of J.B.S. Haldane*. 1st ed. Bloomsbury Reader.

Clarke, G.K.C., 1987. A short history of scientific investigations on glaciers. *Journal of Glaciology*, 33(S1), pp.4–24.

Cockell, C., Koeberl, C. and Gilmour, I. eds., 2006. *Biological processes associated with impact events*. Impact studies. Berlin ; New York: Springer.

Coleman, D.S., Mills, R.D. and Zimmerer, M.J., 2016. The Pace of Plutonism. *Elements*, 12(2), pp.97–102.

Coltice, N., Gérault, M. and Ulvrová, M., 2017. A mantle convection perspective on global tectonics. *Earth-Science Reviews*, [online] 165, pp.120–150. Available at: <http://doi.org/10.1016/j.earscirev.2016.11.006> [Accessed 7 Feb. 2019].

Complete Dictionary of Scientific Biography, n.d. Marsh, Othniel Charles. [online] Available at: <https://www.encyclopedia.com/people/history/historians-miscellaneous-biographies/othniel-charles-marsh> [Accessed 11 Feb. 2019].

Connors, C., 2015. In the Land of the Giants: Greek and Roman Discourses on Vesuvius and the Phlegraean Fields. *Illinois Classical Studies*, [online] 40(1), p.121-137. https://doi.org/10.5406/illiclasstud.40.1.0121.

Corlett, R.T., 2007. The Impact of Hunting on the Mammalian Fauna of Tropical Asian Forests. *Biotropica*, 39(3), pp.292–303.

Cornell, W.C. and Lemone, D.V., 1979. A Terminal Mesozoic Greenhouse. *Science*, 206(4425), pp.1428–1429.

Cowen, R., 1994. *The History of Life*. 2nd ed. Boston, Massachusetts.

Crubézy, E. and Trinkaus, E., 1992. Shanidar 1: a case of hyperostotic disease (DISH) in the middle Paleolithic. *American journal of physical anthropology*, 89(4), pp.411–420.

Cuppy, Will, 1964. *How to Become Extinct*. New York: Dover.

Currat, M. and Excoffier, L., 2004. Modern Humans Did Not Admix with Neanderthals during Their Range Expansion into Europe. *PLOS Biology*, 2(12), p.e421.

Cuvier, G., 1813. *Essay on the Theory of the Earth*. 1st ed.

Danish Cultural Heritage, n.d. Cultural and Historical Guide. *History of Copenhagen - In Brief*, [online] Available at: <http://www.copenhagenet.dk/cph-history.htm> [Accessed 7 Feb 2019].

Darwin, C., 1838. *An Autobiographical Fragment*. London: Oxford University Press.

Darwin, C., 1861. *On the Origin of Species*. [online] New York: D. Appleton and Company. Available at: <http://darwin-online.org.uk/converted/pdf/1861_OriginNY_F382.pdf> [Accessed 14 Feb. 2019].

Davison, C., 1936. Richard Dixon Oldham. 1858-1936. *Obituary Notices of Fellows of the Royal Society*, 2(5), pp. 111-113.

Davy, H., 1828. *On the Phaenomena of Volcanoes*. Philosophical Transactions of the Royal Society of London, 118, pp.241–250.

de Beer, G., 1974. *An Autobiographical Fragment - Introduction*. Chatham: Oxford University Press.

de Laubenfels, M.W., 1956. Dinosaur Extinction: One More Hypothesis. *Journal of Paleontology*, 30(1), pp.207–212.

Dean, D.R., 1983. *John Playfair and his books*. Annals of Science, 40(2), pp.179–187.

Dean, D.R., 2017. Mount Vesuvius. In: *Salem Press Encyclopedia of Science*. [online] Salem Press, pp.1–5. Available at: <http://search.ebscohost.com.libaccess.lib.mcmaster.ca/login.aspx?direct=true&db=ers&AN=88802587&site=eds-live&scope=site > [Accessed 2 Feb. 2019].

Debus, A.A., 2006. Re-Framing the Science in Jules Verne's 'Journey to the Center of the Earth'. *Science Fiction Studies*, 33(3), pp.405–420.

Decker, R. and Decker, B., 2006. volcano. In: *Encyclopedia Britannica*. [online] Encyclopedia Britannica, Inc. Available at: <https://www.britannica.com/science/volcano> [Accessed 12 Feb. 2019].

Deline, B., Greenwood, J.M., Clark, J.W., Puttick, M.N., Peterson, K.J. and Donoghue, P.C.J., 2018.

Dibble, H.L., Aldeias, V., Goldberg, P., McPherron, S.P., Sandgathe, D. and Steele, T.E., 2015. A critical look at evidence from La Chapelle-aux-Saints supporting an intentional Neandertal burial. *Journal of Archaeological Science*, 53, pp.649–657.

Dobran, F. ed., 2006. *Vesuvius: Education, Security and Prosperity*. Netherlands: Elsevier.

Dodson, R. and Hammar, S., 2005. Asbestos: Risk Assessment, Epidemiology, and Health Effects. CRC Press.

Doel, R.E., Levin, T.J. and Marker, M.K., 2006. Extending modern cartography to the ocean depths: military patronage, Cold War priorities, and the Heezen–Tharp mapping project, 1952–1959. *Journal of Historical Geography*, [online] 32(3), pp.605–626. Available at: <http:/doi.org/10.1016/j.jhg.2005.10.011> [Accessed 11 Feb. 2019].

Donnelly, I., 1882. *Atlantis: The Antediluvian World*. New York: Harper & Brothers.

Donoghue, P.C.J. and Benton, M.J., 2007. Rocks and clocks: calibrating the Tree of Life using fossils and molecules. *Trends in Ecology & Evolution*, 22(8), pp.424–431.

Donovan, S.K., 2016. Neanderthal Man: In Search of Lost Genomes by Svante Pääbo. Basic Books, New York, 2014. No. of pages: ix+275. ISBN 978-0-465-02083-6 (hardback). *Geological Journal*, 51(6), pp.968–969.

Dordrecht: Springer Netherlands. Available through: <https://www.springer.com/gp/book/9789401795999> [Accessed 12 February 2019].

Douzery, E.J.P., Snell, E.A., Bapteste, E., Delsuc, F. and Philippe, H., 2004. The timing of eukaryotic evolution: does a relaxed molecular clock reconcile proteins and fossils? *Proceedings of the National Academy of Sciences of the United States of America,* 101(43), pp.15386–15391.

Downey, G., 1962. *Aristotle: dean of early science*. New York: Franklin Watts.

Drabkin, I.E., Drake, S., Galileo, G., 1960. On Motion and Mechanics. The University of Wisconsin Press.

Drake, S., Galileo, G., 1973. Two New Sciences. The University of Wisconsin Press.

Drchal, V., Kudrnovský, J., Wagenknecht, D. and Turek, I., 2019. Alloy disorder and fluctuating magnetic moments in the Earth's core. Journal of Magnetism and Magnetic Materials, [online] 475, pp.767–771. Available at: <http://doi.org/10.1016/j.jmmm.2018.11.112> [Accessed 11 Feb. 2019].

Ducheyne, S., 2011 Measuring Gravity "more exactly" or the Significance of Experimental Research on the Density of the Earth and Big G, 1798-1898: *Changing Pursuits and Long-term Methodological Continuity*. [online] Available at: <https://www.academia.edu/14021124/Measuring_Gravity_more_exactly_or_the_Significance_of_Experimental_Research_on_the_Density_of_the_Earth_and_Big_G_1798-1898_Changing_Pursuits_and_Long-term_Methodological_Continuity> [Accessed 12 Feb. 2019].

Dundes, A. ed., 1988. *The Flood myth*. Berkeley: University of California Press.

Dziak, M., 2018. Scientific method. In: Salem Press Encyclopedia of Science. [online] Salem Press. [Accessed 11 Feb. 2019].

Editors of Encyclopaedia Britannica, 2001. *Geochronology*. In: Encyclopedia Britannica. [online] Encyclopaedia Britannica, Inc. Available at: <https://www.britannica.com/science/geochronology> [Accessed 8 Feb. 2019].

Editors of Encyclopaedia Britannica, 2018. *James Hutton*. In: Encyclopaedia Britannica. [online] Encyclopaedia Britannica, Inc. Available at: <https://www.britannica.com/biography/James-Hutton> [Accessed 8 Feb. 2019].

Editors of Encyclopaedia Britannica, 2019. *Vulcan | Definition & Mythology*. [online] Encyclopedia Britannica. Available at: <https://www.britannica.com/topic/Vulcan> [Accessed 8 Feb. 2019].

Egerton, F.N., 1970. Humboldt, Darwin, and population. *Journal of the History of Biology*, 3(2), pp.325–360.

Ehlers, J., Gibbard, P. and Hughes, P., 2018. Quaternary Glaciations and Chronology. *Past Glacial Environments*, [online] pp.77–101. Available at: <http://doi.org/10.1016/b978-0-08-100524-8.00003-8> [Accessed 7 Feb. 2019].

Ehrenburg, R., 2016. Making of the Modern Map. *Library of Congress Magazine*, 5(5), Oct., pp.15–18.

Eiseley, L., 1957. Neanderthal Man and the Dawn of Human Paleontology. *The Quarterly Review of Biology*, 32(4), pp.323–329.

Eldredge, N. and Zimmer, C., 2014. *Extinction and Evolution: What Fossils Reveal about the History of Life.*

Elliot, S.W., 1896. *The Story of Atlantis*. London: Theosophical Publishing House Ltd.

Elliot, S.W., 1904. *The Lost Lemuria*. London: The Theosophical Publishing House Ltd.

Encyclopaedia Iranica, 2019. *Hecataeus of Miletus*. [online] Encyclopaedia Iranica. Available at: <http://www.iranicaonline.org/articles/hecataeus-of-miletus> [Accessed 15 Feb. 2019].

Encyclopedia Britannica, 2019. *Pliny the Younger*. [online] Encyclopedia Britannica. Available at: <https://www.britannica.com/biography/Pliny-the-Younger> [Accessed 6 Feb. 2019].

Erwin, D.H. and Valentine, J.W., 2013. *The Cambrian Explosion: The Construction of Animal Biodiversity*.

Evolution of metazoan morphological disparity. *Proceedings of the National Academy of Sciences*, 115(38), pp.E8909–E8918.

Eyles, N., 1993. Earths glacial record and its tectonic setting. *Earth-Science Reviews*, [online] 35(1-2), pp.1–248. Available at: <http://doi.org/10.1016/0012-8252(93)90002-o> [Accessed 10 Feb. 2019].

Federico, C., Aiuppab, A., Favaraa, R., and Valenzab, M., 2004. Geochemical monitoring of groundwaters (1998–2001) at Vesuvius volcano (Italy). *Journal of Volcanology and Geothermal Research*. 133(1–4), pp.81–104.

Fick, F. S., 1973. *Louis Agassiz's Contributions to Glaciology.* Simon Fraser University.

Fiig, C., Siim, B., 2007. Democratization of Denmark - the Inclusion of Women in Political Citizenship. *Department of History, International and Social Studies, Aalborg University*, No. 66, [online] Available at: <http://vbn.aau.dk/en/publications/democratisation-of-denmark--the-inclusion-of-women-in-political-citizenship(ca3507d0-e389-11dc-8eac-000ea68e967b).html> [Accessed 8 Feb 2019].

Finley, M.I., 1975. The ancient Greeks: an introduction to their life and thought. New York: Viking.

Finnegan, D.A., 2004. The Work of Ice: Glacial Theory and Scientific Culture in Early Victorian Edinburgh. *The British Journal for the History of Science*, 37(1), pp.29–52.

Flanders, S.E., 1962. Did the caterpillar exterminate the giant reptile? *Journal of Research on the Lepidoptera*, 1(1), pp.85–88.

Fossen, H., 2010. *Structural geology*. Cambridge ; New York: Cambridge University Press.

Frazer, J., 2019. *Apollodorus, The Library Book 2*. [online] Theoi Texts Library. Available at <https://www.theoi.com/Text/Apollodorus2.html> [Accessed 14 Feb. 2019].

Fry, I., 2000. *The Emergence of Life on Earth: A Historical and Scientific Overview.* Piscataway, New Jersey: Rutgers University Press.

Garfinkel, L., 1984. Asbestos: Historical Perspective. *CA: A Cancer Journal for Clinicians*, [online] 34(1), pp.44–47. Available at: <https://doi.org/10.3322/canjclin.34.1.44>.

Gartner, S. and McGuirk, J.P., 1979. Terminal Cretaceous Extinction Scenario for a Catastrophe. *Science*, 206(4424), pp.1272–1276.

Gawne, R., 2015. Fossil Evidence in the Origin of Species. *BioScience,* 65(11), pp.1077–1083.

Geiger, H., Barker, A.K. and Troll, V.R., 2016. *Locating the depth of magma supply for volcanic eruptions, insights from Mt. Cameroon.* [online] Scientific Reports, 6(1), pp.1–10.

Geikie, A., 1886. Louis Agassiz. *Nature*, 33, pp.289–291.

Geikie, A., 1910. *Notes on Seneca's 'Quaestiones Naturales'.* Physical Science in the Time of Nero. London: Macmillan.

Gill, C., 1980. Plato: *The Atlantis Story*. Bristol: Bristol Classical Press.

Gilpin, W., Feldman, M.W. and Aoki, K., 2016. An ecocultural model predicts Neanderthal extinction through competition with modern humans. *Proceedings of the National Academy of Sciences*, 113(8), pp.2134–2139.

Gingerich, O., 1982. The Galileo Affair. Scientific American, 247(2), pp.132–143.

Gingerich, O., 2011. Galileo, the Impact of the Telescope, and the Birth of Modern Astronomy. Proceedings of the American Philosophical Society, 155(2), pp.134–141.

Giudicepietro, F., Orazi, M., Scarpato, G., Peluso, R., D'Auria, L., Ricciolino, P., Bascio, D.L., Esposito, A.M., Borriello, G., Capello, M., Caputo, A., Buonocunto, C., Cesare, W.D., Vilardo, G. and Martini, M., 2010. Seismological Monitoring of Mount Vesuvius (Italy): More than a Century of Observations. *Seismological Research Letters*, 81(4), pp.625–634.

Glen, W., 1998. A Manifold Current Upheaval in Science. *Earth Sciences History*, 17(2), pp.190–209.

Goldschmidt, V.M., 1954. *Geochemistry.* New York: Oxford University Press.

González, F.I., Milburn, H.B., Bernard, E.N. and Newman, J., 1998. *Deep-ocean Assessment and Reporting of Tsunamis (DART) Brief Overview and Status Report.* [online] National Oceanic and Atmospheric Administration.

González-Cataldo, F., Davis, S. and Gutiérrez, G., 2016. *Melting curve of SiO2 at multimegabar pressures: implications for gas giants and super-Earths.* Scientific Reports, 6, p.26537.

Goodchild, M.F., 2007. Citizens as sensors: the world of volunteered geography. *GeoJournal*, 69(4), pp.211–221.

Gould, S.J., 1987. *Time's Arrow, Time's Cycle*. Harvard University Press.

Grayson, D.K., 1980. Vicissitudes and Overkill: The Development of Explanations of Pleistocene Extinctions. *Advances in Archaeological Method and Theory*, 3, pp.357–403.

Green, R.E., Krause, J., Briggs, A.W., Maricic, T., Stenzel, U., and 49 others, 2010. A Draft Sequence of the Neandertal Genome. *Science*, 328(5979), pp.710–722.

Greenberg, M., 1999. A study of lung cancer mortality in asbestos workers: Doll, 1955. *American Journal of Industrial Medicine*, 36(3), pp.331–347.

Greenberg, M., 2017. Experimental asbestos studies in the UK: 1912-1950. *American Journal of Industrial Medicine*, 60(11), pp.956–962.

Greene, J., MFA, 2017. Flat earth. In: Salem Press Encyclopedia. [online] Salem Press. [Accessed 14 Feb. 2019].

Greenwood Village, USA: Ben Roberts.

Griffin, D., 2012. *What Curiosity in the Structure: The Hollow Earth in Science.* Bucknell University Department of Geography, Lewisburg, Pennsylvania, USA.

Guyot, A., 1878. *A Memoir of Louis Agassiz*. National Academy.

Gwyther, D., Cook, S., Fenzi, G. B., Fraser, A., Graham, F., Kusahara, K., Treverrow, A., Jong, L., Roberts, J., Rintoul, S., Worby, A., van Ommen, T., 2017. *Position Analysis: the Antarctic Ice Sheet & Sea Level.* [ebook]

Haldane, J. B. S., 1932. *The Inequality of Man*. [online] Harmondsworth Middlesex England: Penguin Books Limited. Available at: <http://jbshaldane.org/books/1932-Inequality-of-Man/haldane-1932-inequality-of-man-ocr.pdf>.

Haldane, J.B.S., 1929. *The Origin of Life*. The Rationalist Annual, 148, pp.3–10.

Haldane, J.B.S., 1968. *Science and Life: Essays of a Rationalist*. 1st ed. Great Britain: Pemberton.

Hali Felt, 2012. Soundings: the story of the remarkable woman who mapped the ocean floor. 1st ed. New York: Henry Holt and Company.

Hallam, A., 1975. Alfred Wegener and the Hypothesis of Continental Drift. *Scientific American*, [online] 232(2), pp.88–97. Available at: <https://www.jstor.org/stable/24949733> [Accessed 4 Feb. 2019].

Hamilton, E., 1948. *The Greek way to Western civilization*. New York, NY: New American Library.

Hamilton, J., 2012. *Volcano: Nature and Culture*. London: Reaktion Books Ltd.

Hamilton, W., 1786. XVIII. Some particulars of the present state of Mount Vesuvius; with the account of a journey into the province of Abruzzo, and a voyage to the island of Ponza. In a letter from Sir William Hamilton, K.B. F. R. S. and A.S. to Sir Joseph Banks, Bart. P. R. S. *Philosophical Transactions of the Royal Society of London*, 76, pp.365–381.

Hammond, M., 1982. The Expulsion of the Neanderthals from Human Ancestry: Marcellin Boule and the Social Context of Scientific Research. *Social Studies of Science*, 12(1), pp.1–36.

Hansen, B., 1970. The Early History of Glacial Theory in British Geology. *Journal of Glaciology*, 9(55), pp.135-41.

Harley, J. and Woodward, D. eds., 1987. *The History of Cartography, Volume 1: Cartography in Prehistoric, Ancient, and Medieval Europe and the Mediterranean*. Chicago: University of Chicago Press.

Harnik, P.G., Lotze, H.K., Anderson, S.C., Finkel, Z.V., Finnegan, S., Lindberg, D.R., Liow, L.H., Lockwood, R., McClain, C.R., McGuire, J.L., O'Dea, A., Pandolfi, J.M., Simpson, C. and Tittensor, D.P., 2012. Extinctions in ancient and modern seas. *Trends in Ecology & Evolution*, 27(11), pp.608–617.

Hasegawa, H.S. and Kanamori, H., 1994. Source Mechanism of the Magnitude 7.2 Grand Banks Earthquake of November 1929: Double Couple or Submarine Landslide? *Bulletin of the Seismological Society of America*, [online] 77(6), pp.1984–2004. Available at: <http://doi.org/10.4095/194327> [Accessed 10 Feb. 2019].

Heidel, W.A., 1935. *Hecataeus and the Egyptian priests in Herodotus, Book II*. Memoirs of the American Academy of Arts and Sciences. Boston: American Academy of Arts and Sciences.

Herbert, S., 2005. Charles Darwin, Geologist. *Cornell University Press*.

Herodotus, 1920. *The Histories*. [online] Translated by A.D. Godley. Cambridge: Harvard University Press. Available at: <http://www.perseus.tufts.edu/hopper/text?doc=Perseus%3atext%3a1999.01.0126>.

Higgins, E., 2016. *Scientists Conjecture the True Cause of Dinosaur Extinction*. The Wellesley News.

Higgins, E., 2016. Scientists Conjecture the True Cause of Dinosaur Extinction. *The Wellesley News*.

Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo Z., A., Jacobsen, S.B. and Boynton, W.V., 1991a. Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico. *Geology*, 19(9), p.867.

Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo Z., A., Jacobsen, S.B. and Boynton, W.V., 1991b. Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico. *Geology*, 19(9), p.867.

Hine, H.M., 2015. Aetna, Latin didactic poem by unknown poet, 1st half of 1st cent. CE. *Oxford Research Encyclopedia of Classics*. Oxford University Press.

Hjortenberg, E., 2009. Inge Lehmann's work materials and seismological epistolary archive. *Annals of Geophysics, Vol. 52, No. 6*, [online] Available at: <https://www.annalsofgeophysics.eu/index.php/annals/article/view/4625/4693> [Accessed 2 Feb 2019].

Hollinger, M., 2016. *Life from Elsewhere – Early History of the Maverick Theory of Panspermia*. Sudhoffs Archiv, 100(2), pp.188–205.

Holm, N.G., Oze, C., Mousis, O., Waite, J.H. and Guilbert-Lepoutre, A., 2015. Serpentinization and the Formation of H2 and CH4 on Celestial Bodies (Planets, Moons, Comets). *Astrobiology*, [online] 15(7), pp.587–600. Available at: <https://doi.org/10.1089/ast.2014.1188>.

Homer, 1914. *The Homeric Hymns*. Translated by H.G. Evelyn-White. Cambridge: Harvard University Press.

Hull, E., 1892. *Volcanoes: Past and Present*. New York, NY: Charles Scribner's Sons.

Humboldt, A.V., 1845. *Cosmos: A Sketch of a Physical Description of the Universe*. London.

Imbrie, J. and Imbrie, J.Z., 1980. Modeling the Climatic Response to Orbital Variations. *Science*, 207(4434), pp.943–953.

Institute of Medicine (US) Committee on Asbestos: Selected Health Effects. Asbestos: Selected Cancers, 2006. Washington (DC): National Academies Press (US). *Background Information on Asbestos*. [online] 3. Available at: <https://www.ncbi.nlm.nih.gov/books/NBK20335/> [Accessed 11 Feb. 2019].

International Journal for Geographic Information and Geovisualization, 41(3), pp.187–199.

Irmscher, C., 2013. *Louis Agassiz: Creator of American Science*. Houghton Mifflin Harcourt.

Jane B. Reese, Urry, L.A., Cain, M.L., Wasserman, S.A., Minorsky, P.V. and Jackson, R.B., 2011. *Campbell Biology.* 9th ed. Pearson.

Jane Eppinga, 2009. *They made their mark: an illustrated history of the Society of Woman Geographers*. 1st ed. United States of America: The Lyons Press.

Jashemski, W. F., 2019. *Pompeii.* [online] Encyclopedia Britannica. Available at: <https://www.britannica.com/place/Pompeii> [Accessed 5 Feb. 2019].

Jenkins, B., 2016. Neptunism and Transformism: Robert Jameson and other Evolutionary Theorists in Early Nineteenth-Century Scotland. *Journal of the History of Biology*, 49(3), pp.527–557.

Jepsen, G.L., 1964. Riddles of the Terrible Lizards. *American Scientist*, 52(2), pp.227–246.

Johnson, A.P., Cleaves, H.J., Dworkin, J.P., Glavin, D.P., Lazcano, A. and Bada, J.L., 2008. The Miller Volcanic Spark Discharge Experiment. *Science*, 322(5900), pp.404–404.

Johnson, S., 1755. *A Dictionary of the English Language*. London: W. Strahan.

Jones, M.T., Jerram, D.A., Svensen, H.H. and Grove, C., 2016. The effects of large igneous provinces on the global carbon and sulphur cycles. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 441, pp.4–21.

Jones, M.T., Jerram, D.A., Svensen, H.H. and Grove, C., 2016. The effects of large igneous provinces on the global carbon and sulphur cycles. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 441, pp.4–21.

Jordan, T., 1979. *Structural geology of the Earth's interior.* Proceedings of the National Academy of Sciences of the United States of America, 76(9), pp.4192–4200.

Joseph, D.A. and Joseph, D.A., 2011. *Tsunamis: Detection, Monitoring, and Early-Warning Technologies*. [online] San Diego, United States: Elsevier Science & Technology. [Accessed 3 Feb. 2019].

Jukes, T.H., 1997. Oparin and Lysenko. *Journal of Molecular Evolution*, 45(4), pp.339–340.

Kang, D., Myung, M.-S., Kim, Y.-K. and Kim, J.-E., 2013. Systematic Review of the Effects of Asbestos Exposure on the Risk of Cancer between Children and Adults. *Annals of Occupational and Environmental Medicine*, 25, p.10.

Katz, B., 2018. *A Violent Volcanic Eruption Immortalized in Medieval Poem May Have Spurred Iceland's Adoption of Christianity | Smart News | Smithsonian*. [online] Smithsonian.com. Available at: <https://www.smithsonianmag.com/smart-news/violent-volcanic-eruption-may-have-spurred-icelands-adoption-christianity-180968566/> [Accessed 8 Feb. 2019].

Kavanagh, J.L., Engwell, S.L. and Martin, S.A., 2018. A review of laboratory and numerical modelling in volcanology. *Solid Earth*, 9(2), pp.531–571.

Kawaguchi, K., Araki, E., Baba, T., Nakamura, T. and Kaneda, Y., 2013. Tsunami monitoring using submarine cabled seafloor observatory. *2013 Ocean Electronics* (SYMPOL). pp.1–5.

Kawaragi, K., Sekine, Y., Kadono, T., Sugita, S., Ohno, S., Ishibashi, K., Kurosawa, K., Matsui, T. and Ikeda, S., 2009. Direct measurements of chemical composition of shock-induced gases from calcite: an intense global warming after the Chicxulub impact due to the indirect greenhouse effect of carbon monoxide. *Earth and Planetary Science Letters*, 282(1–4), pp.56–64.

Keats, J. (2011). *Fossil Hunting*. [online] Forbes.com. Available at: https://www.forbes.com/forbes-life-magazine/2011/0509/at-auction-collecting-edward-cope-othniel-marsh-fossil-hunting.html [Accessed 15 Feb. 2019].

Keller, G., 2017. *Introduction: Volcanism and Impact Hypotheses Collide*. [online] Volcanism, Impacts and Mass Extinctions. Available at: <http://massextinction.princeton.edu/deccan-volcanism/volcanism-and-impact-hypotheses-collide> [Accessed 15 Feb. 2019].

Keller, G., Bhowmick, P.K., Upadhyay, H., Dave, A., Reddy, A.N., Jaiprakash, B.C. and Adatte, T., 2011. Deccan volcanism linked to the Cretaceous-Tertiary boundary mass extinction: New evidence from ONGC wells in the Krishna-Godavari Basin. *Journal of the Geological Society of India*, 78(5), pp.399–428.

Keller, G., Sahni, A. and Bajpai, S., 2009. Deccan volcanism, the KT mass extinction and dinosaurs. *Journal of Biosciences*, 34(5), pp.709–728.

Kellner, C., 2019. *Alexander von Humboldt*. In: Encyclopedia Britannica. [online] Encyclopaedia Britannica, Inc. Available at: <https://www.britannica.com/biography/Alexander-von-Humboldt> [Accessed 8 Feb. 2019].

Kemp, M., 1998. Heezen's highlands. *Nature*, [online] 395, p.23. Available at: <http://www.nature.com/articles/25622> [Accessed 4 Feb. 2019].

Knight, P.G., 2011. Glaciology. In: V.P. Singh, P. Singh and U.K. Haritashya, eds., *Encyclopedia of Snow, Ice and Glaciers*. [online] Dordrecht: Springer Netherlands, pp.440–443. Available at: <https://doi.org/10.1007/978-90-481-2642-2_215> [Accessed 27 Jan. 2019].

Knoll, Bambach, Canfield, and Grotzinger, 1996. Comparative Earth History and Late Permian Mass Extinction. *Science (*New York, N.Y.), 273(5274), pp.452–457.

Kortlandt, A., 2002. Neanderthal anatomy and the use of spears. 11(5), pp.183–184.

Krings, M., Stone, A., Schmitz, R.W., Krainitzki, H., Stoneking, M. and Pääbo, S., 1997. Neandertal DNA Sequences and the Origin of Modern Humans. *Cell*, 90(1), pp.19–30.

Krug, A.Z., Jablonski, D. and Valentine, J.W., 2009. Signature of the End-Cretaceous Mass Extinction in the Modern Biota. *Science*, 323(5915), pp.767–771.

Kuhle, M., 2005. Glacial geomorphology and ice ages in Tibet and the surrounding mountains. *Island Arc*, 14(4), pp.346–367.

Kuhle, M., 2018. *The Glaciation of High Asia: From the Last Ice Age to the Present.* [ebook] Cham: Springer Netherlands. Available through: McMaster University Library website <https://library.mcmaster.ca/> [Accessed 13 Feb 2019].

Kusiorowski, R., Zaremba, T., Piotrowski, J. and Adamek, J., 2012. Thermal Decomposition of Different Types of Asbestos. *Journal of Thermal Analysis and Calorimetry*, [online] 109(2), pp.693–704. Available at: <https://doi.org/10.1007/s10973-012-2222-9>.

Lachenbruch, A.H. and Marshall, B.V., 1986. Changing Climate: Geothermal Evidence from Permafrost in the Alaskan Arctic. *Science*, 234(4777), pp.689–696.

Lærke, M. and Andrault, R., 2018. *Steno and the Philosophers*. BRILL.

Larsen, C., 2018. Danish secondary schools 1880–1950: national legislative framework and local implementation. *Nordic Journal of Studies in Educational Policy,* 4(1), pp. 13-23.

Latter, J.H., 1981. Tsunamis of volcanic origin: Summary of causes, with particular reference to Krakatoa, 1883. *Bulletin Volcanologique,* 44(3), pp.467–490.

Laufer, B., 1915. Asbestos and Salamander, an Essay in Chinese and Hellenistic Folk-Lore. *T'oung Pao*, [online] 16(3), pp.299–373. Available at: <www.jstor.org/stable/4526458>.

Lazcano, A., 2016. Alexandr I. Oparin and the Origin of Life: A Historical Reassessment of the Heterotrophic Theory. *Journal of Molecular Evolution*, 83(5), pp.214–222.

Leafloor, L., 2015. *Deadly Volcanoes: The Eruptions that Reshaped the World and Became Legends – Part I.* Ancient Origins.

Lee, M.S.Y. and Ho, S.Y.W., 2016. Molecular clocks. *Current biology: CB*, 26(10), pp.R399-402.

Lee, R.J., Strohmeier, B., Bunker, K.I. and Van Orden, D.R., 2008. Naturally Occurring Asbestos - A Recurring Public Policy Challenge. *Journal of Hazardous Materials*, [online] 153(1-2), pp.1–21. Available at: <https://doi.org/10.1016/j.jhazmat.2007.11.079>.

Lehmann, I., 1987. Seismology in the days of old. *American Geophysical Union*, 68(3), pp.33-35.

Lemieux-Dudon, B., Blayo, E., Petit, J.-R., Waelbroeck, C., Svensson, A., Ritz, C., Barnola, J.-M., Narcisi, B.M. and Parrenin, F., 2010. Consistent dating for Antarctic and Greenland ice cores. *Quaternary Science Reviews*, 29(1–2), pp.8–20.

Lendering, J., 2019. *Hecataeus of Miletus*. [online] https://www.livius.org/articles/person/hecataeus-

Leroi-Gourhan, A., 1975. The Flowers Found with Shanidar IV, a Neanderthal Burial in Iraq. *Science*, 190, pp.562–564.

Levin, T. and Tharp, M., 1997. *Oral Histories - Marie Tharp*. [interview] American Institute of Physics. 28 Jun. Available at: <https://www.aip.org/history-programs/niels-bohr-library/oral-histories/22896-4> [Accessed 10 Feb. 2019].

Levins, H. (2002). *Memoralizing Edward Drinker Cope*. [online] Historiccamdencounty.com. Available at: http://historiccamdencounty.com/ccnews44.shtml [Accessed 15 Feb. 2019].

Lill, A., 2015. *Myths of Pompeii: Reality and Legacy.* Tartu, Estonia: University of Tartu, pp.139–180. Available at: <https://www.ancient-origins.net/history/deadly-volcanoes-eruptions-reshaped-world-and-became-legends-part-i-003489> [Accessed 2 Feb. 2019].

Linda Hall Library, 2019. *Othniel Charles Marsh (1832-1899).* [online] UCMP Berkely. Available at: <https://ucmp.berkeley.edu/history/marsh.html> [Accessed 11 Feb. 2019].

Lisle, R.J., 2006. Google Earth: a new geological resource. *Geology Today*, 22(1), pp.29–32.

Longo, B.M. and Longo, A.A., 2013. *Volcanic ash in the air we breathe*. [online] Multidisciplinary Respiratory Medicine, 8(1), p.52.

Lukermann, F., 1961. The Concept of Location in Classical Geography. *Annals of the Association of American Geographers*, 51(2), pp.194–210.

Lunine, J.I., 2006. *Physical conditions on the early Earth.* Philosophical Transactions of the Royal Society B: Biological Sciences, 361(1474), pp.1721–1731.

Lurie, E., 1966. *Louis Agassiz: A life in science*. 2nd ed. The University of Chicago Press.

Luskin, B., Heezen, B.C., Ewing, M. and Landisman, M., 1954. Precision measurement of ocean depth. *Deep Sea Research*, [online] 1(3), pp.131-IN7. Available at: <http://journals.scholarsportal.info/detailsundefined> [Accessed 4 Feb. 2019].

Luus, K., 2007. Asbestos: Mining Exposure, Health Effects and Policy Implications. *McGill Journal of Medicine*, [online] 10(2), pp.121–126. Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2323486/>.

Lyell, C., 1830. *Principles of Geology*. 9th ed. London.

Lynch, P.A. and Roberts, J., 2010. *African Mythology, A to Z*. Infobase Publishing.

Macdougall, D., 2013. *Frozen Earth: The Once and Future Story of Ice Ages*. University of California Press.

Machamer, P., 2017. Galileo Galilei. In: E.N. Zalta, ed., The Stanford Encyclopedia of Philosophy, Summer 2017. [online] Metaphysics Research Lab, Stanford University. Available at: <https://plato.stanford.edu/archives/sum2017/entries/galileo/> [Accessed 7 Feb. 2019].

Mallatt, J.M., 1982. Dr Beringer's fossils: A study in the evolution of scientific world view. *Annals of Science*, 39(4), pp.371–380.

Malling, D.H., 1992. *Coordinate Systems and Map Projections*. 2nd ed. Great Britain: B.P.C.C. Wheatons, Ltd.

Manabe, S. and Wetherald, R.T., 1967. Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity. *Journal of the Atmospheric Sciences*, 24(3), pp.241–259.

Mángano, M. and Buatois, L., 2016. *The Trace-Fossil Record of Major Evolutionary Events*. [e-book]

Marshak, S., 2013. *Essentials of Geology*. New York, NY: W. W. Norton & Company.

Martin, W., Baross, J., Kelley, D. and Russell, M.J., 2008. Hydrothermal vents and the origin of life. *Nature Reviews Microbiology*, 6(11), pp.805–814.

Master, S., 2009. Plutonism versus Neptunism at the southern tip of Africa: the debate on the origin of granites at the Cape, 1776–1844. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 100(1–2), pp.1–13.

Mastrolorenzo, G., Petrone, P., Pappalardo, L. and Guarino, F., 2010. *Lethal Thermal Impact at Periphery of Pyroclastic Surges: Evidences at Pompeii.* [online] Plos One. [Accessed 19 Jan. 2019].

Matsen, B., 2010. Jacques Cousteau: the sea king. New York: Vintage Books.

McCabe, P.J., 1985. *Depositional Environments of Coal and Coal-Bearing Strata.* In: R.A Rahmani,

McCain, C.M., 2009. Vertebrate range sizes indicate that mountains may be 'higher' in the tropics. *Ecology Letters*, 12(6), pp.550–560.

McCarthy, J.J., 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

McFadden, L., Weissman, P. R., Johnson, T. V., 2007. *Encyclopedia of the Solar System*. 2nd ed. [ebook] Elsevier Inc. Available through: ScienceDirect website <https://www.sciencedirect.com/> [Accessed 14 Feb 2019].

Mckerrow, W.S., Niocaill, C.M. and Dewey, J.F., 2000. The Caledonian Orogeny redefined. *Journal of the Geological Society*, [online] 157(6), pp.1149–1154. Available at: <http://doi.org/10.1144/jgs.157.6.1149> [Accessed 10 Feb. 2019].

McLean, D.M., 1978. A Terminal Mesozoic 'Greenhouse': Lessons from the Past. *Science*, 201(4354), pp.401–406.

Miller, B.J., 1990. Global Environmental Change: Extension Frontier for the 1990s. *Extension Journal, Inc*, [online] 28(4). Available at: <https://joe.org/joe/1990winter/f1.php> [Accessed 15 Feb. 2019].

Miller, C., 2016. *Eruptible magma*. [online] Proceedings of the National Academy of Sciences of the United States of America, 113 (49) pp. 13941-13943.

Miller, C.C., 2006. A Beast in the Field: The Google Maps Mashup as GIS/2. *Cartographica: The*

Miller, M., 1980. Working Women and World War II. *The New England Quarterly*, [online] 53(1), pp.42–61. Available at: <https://www.jstor.org/stable/365288> [Accessed 4 Feb. 2019].

Miller, S., 1953. A Production of Amino Acids under Possible Primitive Earth Conditions. *Science*, 117(3046), pp.528–529.

Miller, S.L. and Urey, H.C., 1959. Organic Compound Synthesis on the Primitive Earth. *Science*, 130(3370), p.245.

Miller, S.L., 1955. Production of Some Organic Compounds under Possible Primitive Earth Conditions. *Journal of the American Chemical Society*, 77(9), pp.2351–2361.

Minnesota Legislative Reference Library, n.d. *Minnesota Legislature.* [online] Available at: <https://www.leg.state.mn.us/legdb/fulldetail?ID=12571> [Accessed 12 February 2019].

Miyakawa, S., Yamanashi, H., Kobayashi, K., Cleaves, H.J. and Miller, S.L., 2002. Prebiotic synthesis from CO atmospheres: Implications for the origins of life. *Proceedings of the National Academy of Sciences*, 99(23), pp.14628–14631.

Moeller, K., 2012. *Edward Drinker Cope (1840-1897).* [online] The Embryo Project Encyclopedia. Available at: <https://embryo.asu.edu/pages/edward-drinker-cope-1840-1897> [Accessed 11 Feb. 2019].

Monastersky, R., 1987. Delving deep into the Indian past. *Science News*, 132(4).

Murck, B., Skinner, B.J. and Porter, S.C., 1996. *Environmental Geology*. New York, NY: Wiley.

Mure, W., 1857. *A Critical History of Language and Literature of Ancient Greece*. London: Longman, Brown, and Green.

Naegeli, K., Huss, M. and Hoelzle, M., 2019. Change detection of bare-ice albedo in the Swiss Alps. *Cryosphere*, 13(1), pp.397–412.

NASA, 2019. SGP Applications. [online] Available at: <https://space-geodesy.nasa.gov/science_and_applications/science_and_applications.html> [Accessed 15 Feb. 2019].

National Cancer Institute, 2017. *Absestos Exposure and Cancer Risk*. [online] National Cancer Institute. Available at: <https://www.cancer.gov/about-cancer/causes-prevention/risk/substances/asbestos/asbestos-fact-sheet>

National Geographic, 2015. *Battle for the "Bone Wars" Beasts*. [online] National Geographic. Available at: <https://www.nationalgeographic.com/science/phenomena/2015/04/15/battle-for-the-bone-wars-beasts/> [Accessed 11 Feb. 2019].

National Park Service, 2018. *The Bering Land Bridge Theory - Bering Land Bridge National Preserve* (U.S. National Park Service) [online]. Available at: <https://www.nps.gov/bela/learn/historyculture/the-bering-land-bridge-theory.htm> [Accessed February 3 2019].

Negro, C.D., Cappello, A., Neri, M., Bilotta, G., Hérault, A. and Ganci, G., 2013a. *Lava flow hazards at Mount Etna: constraints imposed by eruptive history and numerical simulations.* [online] Scientific Reports, 3(1), pp.1–8.

Negro, C.D., Currenti, G., Solaro, G., Greco, F., Pepe, A., Napoli, R., Pepe, S., Casu, F. and Sansosti, E., 2013b. *Capturing the fingerprint of Etna volcano activity in gravity and satellite radar data.* [nline] Scientific Reports, 3(1), pp.1–8.

Neville, J.W., 1977. Herodotus on the Trojan War. *Greece & Rome*, 24(1), pp.3–12.
New York: Firefly Books.

Newell, N.D., 1962. Paleontological Gaps and Geochronology. *Journal of Paleontology*, 36(3), pp.592–610.

Niels Bohr Institute, 2013. *Ice Core Dating Using Stable Isotope Data.* [online] Available at: <http://www.iceandclimate.nbi.ku.dk/research/strat_dating/annual_layer_count/ice_core_dating/> [Accessed 13 Feb 2019].

Nikishin, A., Gaina, C., Petrov, E., Malyshev, N. and Freiman, S., 2018. Eurasia Basin and Gakkel Ridge, Arctic Ocean: Crustal asymmetry, ultra-slow spreading and continental rifting revealed by new seismic data. *Tectonophysics,* [online] 746, pp.64–82. Available at: <http://doi.org/10.1016/j.tecto.2017.09.006> [Accessed 10 Feb. 2019].

North, G.W., 2010. Marie Tharp: The lady who showed us the ocean floors. *Physics and Chemistry of the Earth*, [online] 35(15–18), pp.881–886. Available at: <http://journals.scholarsportal.info/detailsundefined> [Accessed 4 Feb. 2019].

Oard, M.J., 1997. The extinction of the dinosaurs. *CEN Tech. J,* 11(2), pp.137-150.

Ogden, D.E. and Sleep, N.H., 2012. Explosive eruption of coal and basalt and the end-Permian mass extinction. *Proceedings of the National Academy of Sciences of the United States of America*, 109(1), pp.59–62.

Ogden, D.E. and Sleep, N.H., 2012. Explosive eruption of coal and basalt and the end-Permian mass extinction. *Proceedings of the National Academy of Sciences of the United States of America*, 109(1), pp.59–62.

Ohno, S., Kadono, T., Kurosawa, K., Hamura, T., Sakaiya, T., Shigemori, K., Hironaka, Y., Sano, T., Watari, T., Otani, K., Matsui, T. and Sugita, S., 2014. Production of sulphate-rich vapour during the Chicxulub impact and implications for ocean acidification. *Nature Geoscience*, 7(4), pp.279–282.

Oparin, A.I., 1938. *The Origin of Life*. Second Edition ed. Mineola, New York: Dover.

Oparin, A.I., 2003. *The Origin of Life*. Courier Corporation.

Osborn, H., 1929. *Biographical Memoir of Edward Drinker Cope 1840-1897.* [online] Available at: <http://www.nasonline.org/publications/biographical-memoirs/memoir-pdfs/cope-edward.pdf>.

Outram, D., 1976. Scientific Biography and the Case of Georges Cuvier: With a Critical Bibliography. *History of Science*, 14(2), pp.101–137.

P.S. Giller, eds., *Analytical Biogeography: An Integrated Approach to the Study of Animal and Plant Distributions*. Dordrecht: Springer Netherlands, pp.437–481.

Parham, J.F. and Irmis, R.B., 2008. Caveats on the use of fossil calibrations for molecular dating: a comment on Near et al. *The American Naturalist*, 171(1), pp.132–136; author reply 137-140.

Parker, E.T., Cleaves, J.H., Burton, A.S., Glavin, D.P., Dworkin, J.P., Zhou, M., Bada, J.L. and Fernández, F.M., 2014. Conducting Miller-Urey Experiments. *Journal of Visualized Experiments : JoVE*, [online] (83). Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4089479/> [Accessed 15 Feb. 2019].

PBS Evolution Library Editors, 2001. Charles Lyell: Principles of Geology. [online] *Evolution Library*. Available at: <https://www.pbs.org/wgbh/evolution/library/02/4/l_024_01.html> [Accessed 6 Feb. 2019].

PBS, 1998. *A Science Odyssey: People and Discoveries: Hess proposes sea-floor spreading.* [online] Available at: <https://www.pbs.org/wgbh/aso/databank/entries/do62se.html> [Accessed February 12 2019].

PBS, 2019. *O.C. Marsh and E.D. Cope: A Rivalry*. [online] American Experience. Available at: <https://www.pbs.org/wgbh/americanexperience/features/dinosaur-rivalry/> [Accessed 11 Feb. 2019].

Pearson, L., 1939. *Early Ionian Historians*. Oxford: Clarendon Press.

Percival, D.B., Denbo, D.W., Gica, E., Huang, P.Y., Mofjeld, H.O., Spillane, M.C. and Titov, V.V., 2018. Evaluating the Effectiveness of DART® Buoy Networks Based on Forecast Accuracy. *Pure and Applied Geophysics*, 175(4), pp.1445–1471.

Peretó, J. and Català, J., 2012. Darwinism and the Origin of Life. *Evolution: Education and Outreach*, 5(3), pp.337–341.

Perkins, S., 2003. Killer Crater. *Science News*, [online] 163(11). Available at: <http://doi.wiley.com/10.2307/4014147> [Accessed 15 Feb. 2019].

Perkins, S., 2003. Killer Crater. *Science News*, [online] 163(11). Available at: <http://doi.wiley.com/10.2307/4014147> [Accessed 15 Feb. 2019].

Pettitt, P., 2002. The Neanderthal dead: exploring mortuary variability in Middle Palaeolithic Eurasia. *Before Farming*, 2002(1), pp.1–26.

Phys.org. (2014). *Modern technology restores ancient dinosaur fossil*. [online] Available at: https://phys.org/news/2014-11-modern-technology-ancient-dinosaur-fossil.html [Accessed 15 Feb. 2019].

Pigliucci, M., 2005. Science and fundamentalism. *EMBO reports*, 6(12), pp.1106–1109.

Pimm, S.L., Jenkins, C.N., Abell, R., Brooks, T.M., Gittleman, J.L., Joppa, L.N., Raven, P.H., Roberts, C.M. and Sexton, J.O., 2014. The biodiversity of species and their rates of extinction, distribution, and protection. *Science* (New York, N.Y.), 344(6187), p.1246752.

Pimm, S.L., Russell, G.J., Gittleman, J.L. and Brooks, T.M., 1995. The future of biodiversity. *Science (*New York, N.Y.), 269(5222), pp.347–350.

Pira, E., Donato, F., Maida, L. and Discalzi, G., 2018. Exposure to Asbestos: Past, Present and Future. *Journal of Thoracic Disease*, [online] 10(Suppl 2), pp.S237–S245. Available at: <https://doi.org/10.21037/jtd.2017.10.126>.

Pirie, N.W., 1966. John Burdon Sanderson Haldane. 1892-1964. *Biographical Memoirs of Fellows of the Royal Society*, 12, pp.219–249.

Playfair, J., 1802. *Illustrations of the Huttonian Theory of the Earth*. Edinburgh: Neill & Co.

Pliny the Younger, 1936. *The Letters of Pliny the Younger*. New York: G. E. Stechert.

Plummer et al., 2007. *Physical Geology and the Environment.* United States: McGraw-Hill Ryerson.

Poole, W., 2008. Sir Robert Southwell's Dialogue on Thomas Burnet's Theory of the Earth: 'C & S discourse of M^{r} Burnetts Theory of the Earth' (1684): Contexts and an Edition. *The Seventeenth Century*, 23(1), pp.72–104.

Pope, K.O., Baines, K.H., Ocampo, A.C. and Ivanov, B.A., 1997. Energy, volatile production, and climatic effects of the Chicxulub Cretaceous/Tertiary impact. *Journal of Geophysical Research: Planets*, 102(E9), pp.21645–21664.

Pope, K.O., D'Hondt, S.L. and Marshall, C.R., 1998. Meteorite impact and the mass extinction of species at the Cretaceous/Tertiary Boundary. *Proceedings of the National Academy of Sciences of the United States of America,* 95(19), pp.11028–11029.

Pope, K.O., D'Hondt, S.L. and Marshall, C.R., 1998. Meteorite impact and the mass extinction of species at the Cretaceous/Tertiary Boundary. *Proceedings of the National Academy of Sciences of the United States of America*, 95(19), pp.11028–11029.

Porter, R., 1978. Gentlemen and Geology: The Emergence of a Scientific Career, 1660-1920. *The Historical Journal*, 21(4), pp.809–836.

Pothecary, S., 2007. *When was Geography Written?* [online] Strabo the Geographer. Available at: <http://www.strabo.ca/when.html>.

Powell, M.G. and MacGregor, J., 2011. A geographic test of species selection using planktonic foraminifera during the Cretaceous/Paleogene mass extinction. *Paleobiology*, 37(3), pp.426–437.

Powell, M.G. and MacGregor, J., 2011. A geographic test of species selection using planktonic foraminifera during the Cretaceous/Paleogene mass extinction. *Paleobiology*, 37(3), pp.426–437.

Preiner, M., Xavier, J., Sousa, F., Zimorski, V., Neubeck, A., Lang, S., Greenwell, H., Kleinermanns, K., Tüysüz, H., Mccollom, T., Holm, N. and Martin, W., 2018. Serpentinization: Connecting Geochemistry, Ancient Metabolism and Industrial Hydrogenation. *Life*, [online] 8(4), p.41. Available at: <https://doi.org/10.3390/life8040041>.

Prothero, D.R., 2017. *Evolution: What the Fossils Say and Why it Matters*. Second ed. New York

Pyle, D.M., 2017. Visions of Volcanoes. *19: Interdisciplinary Studies in the Long Nineteenth Century*. [online] Available at: <http://19.bbk.ac.uk/articles/10.16995/ntn.790/> [Accessed 8 Feb. 2019].

R. H. Dott, Jr., 1983. Itching eyes and dinosaur demise. *Geology*, 11(2), p.126.

R. M. Flores eds. 1985. *Sedimentology of Coal and Coal-Bearing Sequences.* London: Blackwell Scientific Publications. Pp. 11-42.

Rafferty, J. P., 2015. Inge Lehmann: Danish Seismologist. *Encyclopedia Britannica*, [online] Available at: <https://www.britannica.com/biography/Inge-Lehmann> [Accessed 30 Jan 2019].

Range, M.M., Arbic, B.K., Johnson, B.C., Moore, T.C., Adcroft, A., Ansong, J.K., Ritsema, J. and Scotese, C., 2018. The Chicxulub Impact Produced a Powerful Global Tsunami. In: *PP53B-07: The Chicxulub Impact Produced a Powerful Global Tsunami.* [online] American Geophysical Union - Fall Meeting 2018. Washington, D.C. Available at: <https://agu.confex.com/agu/fm18/meetingapp.cgi/Paper/445502> [Accessed 16 Feb. 2019].

Rapp, D., 2012. *Ice Ages and Interglacials: Measurements, Interpretation, and Models.* [ebook] Cham: Springer Netherlands. Available through: McMaster University Library website <https://library.mcmaster.ca/> [Accessed 13 Feb 2019].

Rappaport, R., 1997. *When Geologists were Historians*, 1665-1750. Cornell University Press.

Raup, D.M., 1986. Biological Extinction in Earth History. *Science*, 231(4745), pp.1528–1533.

Raup, D.M., 1987. Mass extinction: a commentary. *Palaeontology,* 30(1), pp.1–13.

Raup, D.M., 1999. *The Nemesis affair: a story of the death of dinosaurs and the ways of science*. Rev. and expanded ed ed. New York: Norton.

Rendu, W., Beauval, C., Crevecoeur, I., Bayle, P., Balzeau, A., Bismuth, T., Bourguignon, L., Delfour, G., Faivre, J.-P., Lacrampe-Cuyaubère, F., Tavormina, C., Todisco, D., Turq, A. and Maureille, B., 2014. Evidence supporting an intentional Neandertal burial at La Chapelle-aux-Saints. *Proceedings of the National Academy of Sciences*, 111(1), pp.81–86.

Renne, P.R., Deino, A.L., Hilgen, F.J., Kuiper, K.F., Mark, D.F., Mitchell, W.S., Morgan, L.E., Mundil, R. and Smit, J., 2013. Time Scales of Critical Events Around the Cretaceous-Paleogene Boundary. *Science*, 339(6120), pp.684–687.

Retallack, G.J., Seyedolali, A., Krull, E.S., Holser, W.T., Ambers, C.P. and Kyte, F.T., 1998. Search for evidence of impact at the Permian-Triassic boundary in Antarctica and Australia. *Geology*, 26(11), pp.979–982.

Roberts, J.H., 2011. *Louis Agassiz on Scientific Method, Polygenism, and Transmutation: A Reassessment*. Almagest, 2(1), pp.76–99.

Robertson, D.S., Lewis, W.M., Sheehan, P.M. and Toon, O.B., 2013. K-Pg extinction: Reevaluation of the heat-fire hypothesis: K-Pg Extinction: Heat-Fire Hypothesis. *Journal of Geophysical Research: Biogeosciences*, 118(1), pp.329–336.

Roger, J. and Gunnell, Y., 2012. Vulnerability of the Dover Strait to coseismic tsunami hazards: insights from numerical modelling. *Geophysical Journal International*, 188(2), pp.680–686.

Roller, D.W., 2017. *The Geography of Strabo: An English Translation with Introduction and Notes*. Cambridge, Massachussets: Cambridge University Press.

Romanovsky, V., Burgess, M., Smith, S., Yoshikawa, K. and Brown, J., 2002. Permafrost temperature records: Indicators of climate change. *Eos, Transactions American Geophysical Union*, 83(50), p.589.

Rosen, B.R., 1988. From fossils to earth history: applied historical biogeography. In: A.A. Myers and

Ross, D. and Deamer, D., 2016. Dry/Wet Cycling and the Thermodynamics and Kinetics of Prebiotic Polymer Synthesis. *Life*, 6(3), p.28.

Ross, M. and Nolan, R.P., 2003. History of Asbestos Discovery and Use and Asbestos-related Disease in Context with the Occurrence of Asbestos within Ophiolite Complexes. Special Paper 373: *Ophiolite Concept and the Evolution of Geological Thought*, [online] pp.447–470. Available at: <https://doi.org/10.1130/0-8137-2373-6.447>.

Rossetter, T., 2018. *Realism on the rocks: Novel success and James Hutton's theory of the earth*. Studies in History and Philosophy of Science Part A, 67, pp.1–13.

Rousseau, C., 2013. How Inge Lehmann Discovered the Inner Core of the Earth. *The College Mathematics Journal, Vol. 44, No. 5,* [online] Available at: <https://www.jstor.org/stable/10.4169/college.math.j.44.5.399?#metadata_info_tab_contents> [Accessed 5 Feb 2019].

Ruddiman, F. W., 1997. *Tectonic Uplift and Climate Change.* [ebook] New York: Plenum Press. Available through: McMaster University Library website <https://library.mcmaster.ca/> [Accessed 13 Feb 2019].

Ryan, W.B.F., Major, C.O., Lericolais, G. and Goldstein, S.L., 2003. Catastrophic Flooding of the Black Sea. *Annual Review of Earth and Planetary Sciences*, 31(1), pp.525–554.

Sahney, S. and Benton, M.J., 2008. Recovery from the most profound mass extinction of all time. *Proceedings. Biological Sciences,* 275(1636), pp.759–765.

Sahney, S. and Benton, M.J., 2008. Recovery from the most profound mass extinction of all time. *Proceedings. Biological Sciences*, 275(1636), pp.759–765.

Saigeetha, A.F., Banyal, R.K., 2005. Alfred Wegener—From continental drift to plate tectonics. *Resonance,* [e-journal] 10(6), pp.43–59. https://doi.org/10.1007/BF02895794.

Sakamoto, M., Benton, M.J. and Venditti, C., 2016. Dinosaurs in decline tens of millions of years before their final extinction. *Proceedings of the National Academy of Sciences*, 113(18), pp.5036–5040.

Scarpa, R. and Gasparini, P., 1996. *A Review of Volcano Geophysics and Volcano-Monitoring Methods.* Monitoring and Mitigation of Volcano Hazards. [online] Springer, Berlin, Heidelberg. Available at: <https://link.springer.com/chapter/10.1007%2F978-3-642-80087-0_1> [Accessed 6 Feb. 2019].

Schaefer, H.F., 2003. *Science and Christianity: Conflict Or Coherence?*. 2nd ed. Watkinsville, Georgia: The Apollos Trust.

Schneuwly-Bollschweiler, M., Stoffel, M. and Rudolf-Miklau, F. eds., 2013. *Dating torrential processes on fans and cones: methods and their application for hazard and risk assessment*. Advances in global change research. Dordrecht ; New York: Springer Science+Business Media.

Schoene, B., Samperton, K.M., Eddy, M.P., Keller, G., Adatte, T., Bowring, S.A., Khadri, S.F.R. and Gertsch, B., 2015. U-Pb geochronology of the Deccan Traps and relation to the end-Cretaceous mass extinction. *Science, 347*(6218), pp.182–184.

Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claeys, P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales-Nishimura, J.M., Grieve, R.A.F., Gulick, S.P.S., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., MacLeod, K.G., Matsui, T., Melosh, J., Montanari, A., Morgan, J.V., Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo-Vieyra, M., Reimold, W.U., Robin, E., Salge, T., Speijer, R.P., Sweet, A.R., Urrutia-Fucugauchi, J., Vajda, V., Whalen, M.T. and Willumsen, P.S., 2010. The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary. *Science*, 327(5970), pp.1214–1218.

Science History Institute, 2016. *Harold C. Urey: Science, Religion, and Cold War Chemistry.* [online] Science History Institute. Available at: <https://www.sciencehistory.org/distillations/magazine/harold-c-urey-science-religion-and-cold-war-chemistry> [Accessed 15 Feb. 2019].

ScienceDirect, 2019. *Volcanism.* [online] Science Direct. Available at: <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/volcanism> [Accessed 2 Fed. 2019].

Sclater, P.L., 1864. The Mammals of Madagascar. *The Quarterly Journal of Science,* [online] 1(1) Available through: Biodiversity Heritage Library website <https://www.biodiversitylibrary.org/item/52516#page/6/mode/1up> [Accessed February 5 2019].

Secord, J.A. and Pearn, A., 2016b. John Stevens Henslow. [online] *Darwin Correspondence Project.* Available at: <https://www.darwinproject.ac.uk/john-stevens-henslow> [Accessed 6 Feb. 2019].

Sekhar, K. and Rao, S.C., 2014. *John Scott Haldane: The father of oxygen therapy*. Indian Journal of Anaesthesia, 58(3), pp.350–352.

Selby, K., n.d. Banning Asbestos in the US: History, Facts & the Murray Bill. *Mesothelioma Center - Vital Services for Cancer Patients & Families.* Available at: <https://www.asbestos.com/mesothelioma-lawyer/legislation/ban/>.

Self, S., Blake, S., Sharma, K., Widdowson, M. and Sephton, S., 2008a. Sulfur and Chlorine in Late Cretaceous Deccan Magmas and Eruptive Gas Release. *Science*, 319(5870), pp.1654–1657.

Self, S., Jay, A.E., Widdowson, M. and Keszthelyi, L.P., 2008b. Correlation of the Deccan and Rajahmundry Trap lavas: Are these the longest and largest lava flows on Earth? *Journal of Volcanology and Geothermal Research*, 172(1), pp.3–19.

Sepkoski, J.J., 1998. Rates of Speciation in the Fossil Record. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 353(1366), pp.315–326.

Shi, Y., Niu, F., Lin, Z. and Luo, J., 2019. Freezing/thawing index variations over the circum-Arctic from 1901 to 2015 and the permafrost extent. *Science of The Total Environment*, 660, pp.1294–1305.

Shnirelman, V., 2014. Hyperborea: The Arctic Myth of Contemporary Russian Radical Nationalists. *Journal of Ethnology and Folkloristics* [e-journal] 8(2), pp.121–138. Available through: Journal of Ethnology and Folkloristics website <https://www.jef.ee/index.php/journal/article/view/158/pdf_119> [Accessed 3 February 2019].

Shonting, D. and Ezrailson, C., 2017. *The Tale of Chicxulub*. In: Chicxulub: The Impact and Tsunami. [online] Cham: Springer International Publishing, pp.21–42. Available at: <http://link.springer.com/10.1007/978-3-319-39487-9_2> [Accessed 15 Feb. 2019].

Shukla, P.N., Bhandari, N., Das, A., Shukla, A.D. and Ray, J.S., 2001. *High iridium concentration of alkaline rocks of Deccan and implications to K/T boundary.* 110(2), pp.103–110.

Sigurdsson, H., 1999. *Melting the Earth*. 1st ed. New York: Oxford University Press.

Sigurdsson, H., Cashdollar, S. and Sparks, S.R.J., 1982. The Eruption of Vesuvius in A. D. 79: Reconstruction from Historical and Volcanological Evidence. *American Journal of Archaeology*, 86(1), pp.39–51.

Silverberg, R., 1964. *The great doctors*. New York: Scholastic Books Services.

Simões, M., Matos, S., Warren, L., Assine, M., Riccomini, C. and Bondioli, J., 2016. Untold muddy tales: Paleoenvironmental dynamics of a "barren" mudrock succession from a shallow Permian epeiric sea. *Journal of South American Earth Sciences*, [online] 71, pp.223–234. Available at: <http://doi.org/10.1016/j.jsames.2016.08.002> [Accessed 11 Feb. 2019].

Simpson, G., 1985. Extinction. *Proceedings of the American Philosophical Society*, 129(4), pp.407–416.

Singh, V. and Singh, K., 2017. Modern Synthesis.

Sleep, M.C., 1969. The geological work of Sir William Hamilton. Proceedings of the Geologists Association, 80(3), pp.353–363.

Slomka, J.M., Eyles, C.H., Mulligan, R.P.M., Mckay III, E.D. and Berg, R.C., 2015. Internal architecture of a till sheet, Tiskilwa Formation, north-central Illinois, USA: Application of architectural element analysis. Sedimentology, 62(5), pp.1328–1359.

Small, C., 1994. A global analysis of mid-ocean ridge axial topography. *Geophysical Journal International*, [online] 116(1), pp.64–84. Available at: <http://doi.org/10.1111/j.1365-246x.1994.tb02128.x> [Accessed 10 Feb. 2019].

Smith, D., 1995. *What Killed The Dinosaurs?*

Smith, D.C. and Borns, H.W., 2000. Louis Agassiz, the Great Deluge, and Early Maine Geology. *Northeastern Naturalist*, 7(2), pp.157–177.

Smith, J., 2013. *Humboldt's New World*. [online] The Nature Conservancy. Available at: <content/tnc/nature/master/en/explore/magazine/magazine-articles/humboldts-new-world-1.html> [Accessed 8 Feb. 2019].

Smith, S.L., Burgess, M.M., Riseborough, D. and Mark Nixon, F., 2005. Recent trends from Canadian permafrost thermal monitoring network sites. *Permafrost and Periglacial Processes*, 16(1), pp.19–30.

Song, X., 2015. The Core Within Earth's Inner Core. *Encyclopedia Britannica*, [online] Available at: <https://www.britannica.com/topic/Core-Within-Earths-Inner-Core-The-2046720> [Accessed 5 Feb 2019].

Stanley, S.M. and Luczaj, J.A., 2015. *Earth system history: Steven M. Stanley, University of Hawaii, John A. Luczaj, University of Wisconsin - Green Bay*. Fourth edition ed. New York, NY: W.H. Freeman and Company, a Macmillan Higher Education company.

Staubwasser, M., Drăguşin, V., Onac, B.P., Assonov, S., Ersek, V., Hoffmann, D.L. and Veres, D., 2018. Impact of climate change on the transition of Neanderthals to modern humans in Europe. *Proceedings of the National Academy of Sciences*, 115(37), pp.9116–9121.

Steno, N., 1671. *The Prodromus to a dissertation concerning solids naturally contained within solids.* Translated by H. Oldenburg.

Steno, N., 1916. *The Prodromus of Nicolaus Steno's dissertation concerning a solid body enclosed by process of nature within a solid; an English version with an introduction and explanatory notes.* [online] Translated by J.G. Winter. London,: Macmillan and company, limited,. Available at: <https://www.biodiversitylibrary.org/bibliography/54340>.

Storer, J., 2013. *Cypress Hills Eocene to Miocene Fossils*. [online] The Canadian Encyclopedia. Available at: <https://www.thecanadianencyclopedia.ca/en/article/cypress-hills-eocene-to-miocene-fossils> [Accessed 11 Feb. 2019].

Stork, N.E., 2010. Re-assessing current extinction rates. *Biodiversity and Conservation*, 19(2), pp.357–371.

Stork, N.E., Coddington, J.A., Colwell, R.K., Chazdon, R.L., Dick, C.W., Peres, C.A., Sloan, S. and Willis, K., 2009. Vulnerability and Resilience of Tropical Forest Species to Land-Use Change. *Conservation Biology*, 23(6), pp.1438–1447.

Strabo, 1928. *Geography, Volume V*. Translated by H. Jones. Harvard University Press.

Straus, W.L. and Cave, A.J.E., 1957. Pathology and the Posture of Neanderthal Man. *The Quarterly Review of Biology*, 32(4), pp.348–363.

Strelich, L., 2017. How Variations in Earth's Orbit Triggered Ice Ages. *Geophysical Research Letters*. [online] Available at: <https://eos.org/research-spotlights/how-variations-in-earths-orbit-triggered-the-ice-ages> [Accessed 8 Feb 2019].

Stribling, R. and Miller, S.L., 1987. Energy yields for hydrogen cyanide and formaldehyde syntheses: The hcn and amino acid concentrations in the primitive ocean. *Origins of life and evolution of the biosphere*, 17(3), pp.261–273.

Stromberg, J., 2015. How Inge Lehmann used Earthquakes to Discover the Earth's Inner Core. *Vox*, [online] Available at: <https://www.vox.com/2015/5/13/8595157/inge-lehmann> [Accessed 2 Feb 2019].

Suran, M., 2010. *The separation of church and science*. *EMBO Reports*, 11(8), pp.586–589.

Sweet, A.R. and Braman, D.R., 1992. The K-T boundary and contiguous strata in western Canada: interactions between paleoenvironments and palynological assemblages. *Cretaceous Research*, 13(1), pp.31–79.

Taube, K., 1993. *Aztec and Maya Myths*. University of Texas Press.

Tharp, M., 1999. Connect the Dots: Mapping the Seafloor and Discovering the Mid-ocean Ridge. In: Lamont-Doherty Earth Observatory of Columbia: Twelve Perspectives on the First Fifty Years 1949-1999 . [online] *Palisades.* Available at: <http://www.whoi.edu/page.do?pid=7500&cid=23306&c=2> [Accessed 12 Feb. 2019].

The Bible: New Revised Standard Version. National Council of the Churches of Christ.

The Island of Madagascar, n.d. *Lemurs: Ghosts of the Forest* [online]. Available at: < https://www.lemurs.us/madagascar.html>

The Metropolitan Museum of Art, 2019. Industrialization and Conflict in America: 1840–1875. [online] Available at: https://www.metmuseum.org/toah/hd/indu/hd_indu.htm> [Accessed February 15 2019].

The National Gallery, 2019. *Glossary.* [online] The National Gallery. Available at: <https://www.nationalgallery.org.uk/paintings/glossary/fresco> [Accessed 9 Feb. 2019].

the University of Edinburgh, 2019. Charles Darwin. [online] *The University of Edinburgh*. Available at: <https://www.ed.ac.uk/biology/about/notable-alumni/charles-darwin> [Accessed 14 Feb. 2019].

Thompson, A., 2008. *Dinosaur Killer May Have Been Volcanism, Not Asteroid*. Live Science.

Thomson, J.O., 1948. *History of Ancient Geography*. Cambridge: Cambridge University Press.

Thorne, A.G. and Wolpoff, M.H., 1992. The Multiregional Evolution of Humans. *Scientific American*, 266(4), pp.76–83.

Thüsen, J.V.D., 1999. *Painting and the rise of volcanology: Sir William Hamilton's Campi Phlegraei*. Endeavour, 23(3), pp.106–109.

Tirard, S., 2017. J.B.S. Haldane and the origin of life. *Journal of Genetics*, 96(5), pp.735–739.

Trinkaus, E. and Shipman, P., 1993. The Neandertals: changing the image of mankind. *ACLS Humanities E-Book*. [online]

Trinkaus, E. and Villotte, S., 2017. External auditory exostoses and hearing loss in the Shanidar 1 Neandertal. *PLOS ONE*, 12(10), p.e0186684.

Trinkaus, E., 1985. Pathology and the posture of the La Chapelle-aux-Saints Neandertal. *American Journal of Physical Anthropology*, 67(1), pp.19–41.

Trinkaus, E., 2014. *The Shanidar Neandertals*. Academic Press.

Trinkaus, E., Moldovan, O., Milota, Ş., Bîlgăr, A., Sarcina, L., Athreya, S., Bailey, S.E., Rodrigo, R., Mircea, G., Higham, T., Ramsey, C.B. and Plicht, J. van der, 2003. An early modern human from the Peştera cu Oase, Romania. *Proceedings of the National Academy of Sciences*, 100(20), pp.11231–11236.

Tuna, C. (2005). *In fossils, Marsh's legacy lives on*. [online] Yaledailynews.com. Available at: https://yaledailynews.com/blog/2005/01/26/in-fossils-marshs-legacy-lives-on/ [Accessed 13 Feb. 2019].

University of Bristol Earth Sciences. (n.d.). *Cope's Rule.* [online] Available at: http://palaeo.gly.bris.ac.uk/benton/reprints/2002Copesrule.html [Accessed 15 Feb. 2019].

University of Hawaii, 2010. *Mānoa: Mystery Unraveled: How Asbestos Causes Cancer | University of Hawaii News*. [online] Available at: <http://manoa.hawaii.edu/news/article.php?aId=3700>.

University of Liverpool, 2015. Earth's inner core was formed 1-1.5 billion years ago. *ScienceDaily*, [online] Available at: <www.sciencedaily.com/releases/2015/10/151007135656.htm> [Accessed 5 Feb 2019].

USGS. (2019). *Who We Are.* [online] Available at: https://www.usgs.gov/about/about-us/who-we-are [Accessed 14 Feb. 2019].

Valen, L.M.V., 1984. Catastrophes, expectations, and the evidence - Geological Implications of Impacts of Large Asteroids and Comets on the Earth.L. T. Silver and P. H. Schultz (eds.). Geological Society of America, Special Paper 190. 1982. xix + 528 pp. $40.00 (paper). *Paleobiology*, 10(1), pp.121–137.

van der Kaars, S., Miller, G.H., Turney, C.S.M., Cook, E.J., Nürnberg, D., Schönfeld, J., Kershaw, A.P. and Lehman, S.J., 2017. Humans rather than climate the primary cause of Pleistocene megafaunal extinction in Australia. *Nature Communications*, [online] 8. Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5263868/> [Accessed 16 Feb. 2019].

Vidal, F. and Dias, N., 2015. *Endangerment, Biodiversity and Culture*. Routledge Environmental Humanities Series. Routledge.

Villa, P. and Roebroeks, W., 2014. Neandertal Demise: An Archaeological Analysis of the Modern Human Superiority Complex. *PLOS ONE*, 9(4), p.e96424.

Virta, R., 2006. *Worldwide Asbestos Supply and Consumption Trends From 1900 Through 2003.* Science for a Changing World.

Visser, M., Worm, P., Muyzer, G., Pereira, I.A.C., Schaap, P.J., Plugge, C.M., Kuever, J., Parshina, S.N., Nazina, T.N., Ivanova, A.E., Bernier-Latmani, R., Goodwin, L.A., Kyrpides, N.C., Woyke, T., Chain, P., Davenport, K.W., Spring, S., Klenk, H.-P. and Stams, A.J.M., 2013. Genome analysis of Desulfotomaculum kuznetsovii strain 17T reveals a physiological similarity with Pelotomaculum thermopropionicum strain SIT. *Standards in Genomic Sciences*, 8(1), pp.69–87.

Walcott, C.D., 1892. *Correlation papers ; Cambrian*. Govt. Print. Off.

Wall, F., 2004. Letters from volcanoes. *Geology Today*, 20(5), pp.181–184.

Walter, M.J. and Reidar, G.T., 2004. Early Earth differentiation. Earth and Planetary Science Letters, 225(3–4), pp.253–269. Greene, J., MFA, 2017. Flat earth. In: Salem Press Encyclopedia. [online] Salem Press. [Accessed 14 Feb. 2019].

Wang, T. and Song, X., 2018. Support for equatorial anisotropy of Earth's inner-inner core from seismic interferometry at low latitudes. *Physics of the Earth and Planetary Interiors,* 276, pp. 247-257.

Waterfield, R., 2008. *Critias.* London: Oxford World's Classics.

Waters, B., 2018. Galileo. In: Salem Press Biographical Encyclopedia. [online] Salem Press. [Accessed 7 Feb. 2019].

Watts, R., 2013. Universities, medical education and women: Birmingham in the late nineteenth and early twentieth centuries. *History of Education,* 42(3), pp. 306-319.

Wegener, A., 1924. *On the Origins of Continents and Oceans*. Translated from the 3rd German Edition by J. G. A. Skerl, 1924. Great Britain: Butler & Tanner Ltd.

Weil, A., 1997. *Plate Tectonics: History of an Idea.* [online] Available at: <http://www.ucmp.berkeley.edu/geology/techist.html> [Accessed February 12 2019]

Weisburd, S., 1987. Volcanoes and Extinctions: Round 2. *Science News*, 131(16), pp.248–250.

Weishampel, D.B. and Barrett, P.M., 2004. Dinosaur distribution. In: *The Dinosauria*, 2nd ed. Berkeley, California: University of California, pp.517–606.

Weisser, H., 2018. World War II. In: Salem Press Encyclopedia. Salem Press.

West, S., 1991. Herodotus' Portrait of Hecataeus. *The Journal of Hellenic Studies*, 111, pp.144–160.

Westfall, R.S., 1979. Never At Rest: A Biography of Isaac Newton. Cambridge University Press.

Whiston, W., 1696. *A new theory of the earth, from its original to the consummation of all things wherein the creation of the world in six days, the universal deluge, and the general conflagration, as laid down in the Holy Scriptures, are shewn to be perfectly agreeable to reason and philosophy : with a large introductory discourse concerning the genuine nature, stile, and extent of the Mosaick history of the creation*.

White, T.D., Toth, N., Chase, P.G., Clark, G.A., Conrad, N.J., Cook, J., d'Errico, F., Donahue, R.E., Gargett, R.H., Giacobini, G., Pike-Tay, A. and Turner, A., 1991. The Question of Ritual Cannibalism at Grotta Guattari [and Comments and Replies]. *Current Anthropology*, 32(2), pp.118–138.

Whittington, H.B., 1985. *The Burgess Shale*. Yale University.

Wiewiora, K., 2003. *Fern spikes and global events - Impact related?*

William King, 1864. The Reputed Fossil Man of the Neanderthal. *The Quarterly Journal of Science*, 1, pp.88–97

Williams, J.D., 2011. *How science works: teaching and learning in the science classroom*. London ; New York, NY: Continuum.

Wilmot, S., 2017. J. B. S. Haldane: the John Innes years. *Journal of Genetics*, 96(5), pp.815–826.

Windle, B., 2013. *Twelve catholic men of science*. Place of publication not identified: Hardpress Ltd.

Wohl, C.G., 2007. Scientist as Detective: Luis Alvarez and the Pyramid Burial Chambers, the JFK Assassination, and the End of the Dinosaurs. *American Journal of Physics*, 75(11), pp.968–977.

Woodward, J., 2014. *The Ice Age: A Very Short Introduction*. OUP Oxford.

Worrall, S. (2018). *Why Today is the Golden Age for Dinosaur Discoveries*. [online] National Geographic News.

Yale Peabody Museum, 2014. *A Yale Tale: Darwin's Letter to O.C. Marsh*. [online] Fossil Fragments: Yale Peabody Museum. Available at: <http://peabody.yale.edu/exhibits/fossil-fragments/history/darwins-letter-oc-marsh> [Accessed 11 Feb. 2019].

Yang, D., Guo, X., Xie, T. and Luo, X., 2018. Reactive oxygen species may play an essential role in

Yanko-Hombach, V., Gilbert, A.S. and Dolukhanov, P., 2007. Controversy over the great flood hypotheses in the Black Sea in light of geological, paleontological, and archaeological evidence. *Quaternary International*, 167–168, pp.91–113.

Yarris, L., 2010. *Alvarez Theory on Dinosaur Die-Out Upheld: Experts Find Asteroid Guilty of Killing the Dinosaurs*. [online] News Center. Available at: <https://newscenter.lbl.gov/2010/03/09/alvarez-theory-on-dinosaur/> [Accessed 29 Jan. 2019].

Yu, L. and Gong, P., 2012. Google Earth as a virtual globe tool for Earth science applications at the global scale: progress and perspectives. *International Journal of Remote Sensing*, 33(12), pp.3966–3986.

Zhang, T., Gordon, R.G. and Wang, C., 2018. Oblique seafloor spreading across intermediate and superfast spreading centers. *Earth and Planetary Science Letters*, [online] 495, pp.146–156. Available at: <http://doi.org/10.1016/j.epsl.2018.05.001> [Accessed 11 Feb. 2019].

Zhang, T., Heginbottom, J.A., Barry, R.G. and Brown, J., 2000. Further statistics on the distribution of permafrost and ground ice in the Northern Hemisphere. *Polar Geography*, 24(2), pp.126–131.

Zhiping, L., Yunying Q., and Shubo, Q., 2014. Geodesy: An Introduction to Geodetic Datum and Geodetic systems. Springer Link.

Zilinga de Boer, J. and Sanders, D.T., 2002. Volcanoes in Human History. In: *Volcanoes in Human History*. Princeton and Oxford.

Zipp, J.F. and Fenwick, R., 2006. Is the Academy a Liberal Hegemony? The Political Orientations and Educational Values of Professors. *The Public Opinion Quarterly*, 70(3), pp.304–326.

Zuskin, E., Mustajbegovic, J., Jelinic, J., Cvetkovic, J. and Milosevic, M., 2007. *Effects of Volcanic Eruptions on Environment and Health* : Archives of Industrial Hygiene and Toxicology | Abstract (English). 58(4), pp.479–486.

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