# History of the Earth

## VOLUME XI

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# Foreword

Eduard Reinhardt

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# Foreword

There is no better monument to explorers sacrificing their lives to obtain field-collected data than the recently discovered H.M.S. Erebus and H.M.S. Terror; these vessels, and their discovery, elicited appreciation and awe for the toll early exploration exacted on the crew and scientists. Early exploration of the North and South poles required high levels of preparation and there were dire consequences for failure; the margin of error between the success and failure of the expedition was very narrow indeed. Today, we don't need to endure such challenges. The recent NASA Mars Perseverance Rover program allows us to explore the most remote parts of our solar system from our hand-held phone. We can explore without leaving the comfort of our office; we have satellite imagery, sensors, and remotely operated autonomous vehicles which collect large amounts of real-time data around the clock. This data is collected with relative ease versus those early years of exploration with likes of Sir Ernest Shackleton, Captain Sir John Franklin or Captain James Cook. Shackleton, Franklin and Cook obtained field-collected data that was hard earned in terms of cost, time and human life. While early expeditions are often romanticised as being daring feats of discovery, repeated by modem adventurers and thrill-seekers, it is likely Shackleton, Franklin or Cook would have gladly taken a helicopter to collect their data. The point of the expedition was not to test their fortitude or their respective country's technological prowess; the main goal was to collect new scientific data and explore and document the unknown. With recent technological advances, we can now effectively accomplish these goals without ever having to set foot on the landscape.

However, nothing is more beneficial than being physically present in the field: "being there" is important, observing and recording phenomena first-hand allows us to discover connections with the vast quantity of data further allowing us to test ideas and concepts never before possible. As an earth scientist who studies aquatic caves, I still need to SCUBA dive in these environments to collect my data. Autonomous or remote-controlled vehicles still don't have the capabilities to collect the data I require, and they likely won't for the foreseeable future. Although extensive data coverage is certainly one of our goals, and we use every tool to help accomplish that goal, I make some of my most important discoveries when I'm hovering in the water observing features and relationships. That pause, where I observe and think, often provides me a completely different perspective on my data and is an important learning tool for me as a scientist. To be present in the field and observe while testing ideas and hypotheses is where I'm the most scientifically creative and I obtain the most insight into the natural phenomena I am studying.

So "being there" is valuable; we don't need to go to such extremes like the early explorers anymore, but it's human nature to explore and discover, and exploration and discovery are integral to the earth sciences. So, if the earth sciences are your passion, go outside, observe, research, create, because that connection with your physical surrounding is the heart of exploration and discovery.

*- Dr. Ed Reinhardt*

*McMaster School of Earth, Environment & Society*

*March 2021*

# Introduction

Our Earth is a dynamic place shaped by countless processes. Geology is the study of such processes as well as the Earth's physical structure, substance, and history. As with all areas of science, geology remains an important area of progress. Numerous individuals and groups have contributed to the development of this discipline, sometimes leading to landmark discoveries. At times, the progress is incremental, while at others, it is abrupt. Regardless, the Earth sciences remain an exciting area of study.

All scientific discoveries can be contextualized by the societal conditions of the time. Social, political, economic, and cultural factors play unique roles in deciding *who* contributes *what* at a given point in time. The intersection of science and society, and their influence on each other, is revealed when studying the history of science. This book will cover some of the history of the Earth and the development of the Earth sciences with a focus on key contributors and societal contexts through the three sections: important figures, Earth and climate, and Earth surface and beyond.

Undoubtedly, much of the scientific progression towards understanding the Earth's origin, its processes, and life are attributed to the tremendous efforts of diligent individuals in several societies across history. It is from the work of early Earth scientists that we now have a better comprehension of the Earth's inner processes. Moreover, the identification of fossilized organisms, such as dinosaurs, has greatly influenced our perception of life. The development of theories on life's origin has provided us with increased knowledge of our own existence, along with greatly expanding our search for life beyond the planet we call home. While some individuals featured in this book may not be popularly known, their contributions are no less important than those that received immense recognition. Often, it is the discovery we remember, not the name of the person who devoted their life's efforts to make that discovery. As such, the first chapter of this book is a tribute to all those names that dominate the historical records, but also those that have long been forgotten in the tangles of time.

Throughout history, Earth's climate has been an extremely fascinating area of research for scientists. From the meticulous efforts of past geologists, we now have evidence for past climate conditions, in addition to the underlying events and processes that influenced them. With a greater understanding of the past, we can better predict the future. In discussion of climate history and the anthropogenic factors contributing to climate change, the second chapter of this book provides a glimpse into Earth's climate history in the light of historical and modern perspectives.

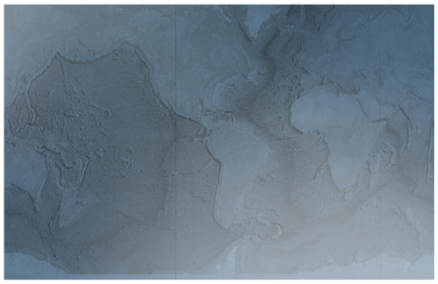
As we are all aware, humans are curious beings. All that we have discovered and learned about the Earth is, in some form, a manifestation of the intrinsic curiosity that lies in all of our hearts. It is no surprise that while some early scientists wondered about the composition of the deep waters of our planet, others pondered about what existed beyond our planet. Early advances in oceanography and space exploration have hugely impacted our outlook on both the geological evolution of the planet and the existence of life. The Earth's moon has been crucial in expanding our knowledge of the solar system, and eventually, the universe. As a dedication to all individuals in the past, present and future, that strive towards unveiling the secrets of the universe, the third chapter of this book features various aspects of Earth and space exploration.

Now, let us begin our journey through the diverse history of the Earth.

*-Tushar Sood & Lisa Bhatia*

# Chapter One

## IMPORTANT FIGURES



> It was during my enchanted days of travel that the idea came to me, which, through the years, has come into my thoughts again and always happily-the idea that geology is the music of the earth.
>
> -Hans Cloos

# Alexander Oparin & the Primordial Soup Theory

*What is life?* In 600BC, Aristotle defined life as a body of organic matter which takes on a dynamic relationship with the soul (Bedau & Cleland., 2010). However, to be able to understand the definition of life, a new explanation was required to interpret the meaning and purpose behind the word "soul" (Bedau & Cleland., 2010). Putting soul into context was a difficult concept to explain and even more so to understand. In the 17th - 18th century, philosophers Spinoza, Descartes, La Mettrie and Jean-Baptiste-René Robinet approached the notion of defining life by combining deism with a materialistic view of matter (Bedau & Cleland., 2010). The overbearing query on the definition of life has been researched for centuries amongst some of the greatest philosophers and scientists of all time. With regards to obtaining knowledge for the definition of life, it seems throughout the decades that the more information found, the less is truly known.

Perhaps the paradigm in which Soviet biochemist Alexander Ivanovich Oparin looked at the question provides a deeper understanding for the complex nature of the life, "*One can only understand the essence of things when one knows their origin and development. Life - the word is so easy to understand, yet so enigmatic for any thoughtful person.*"

Bedau and Cleland reprinted chapter one of Alexander Oparin's original book *The Nature of Life* where he illustrated his views behind the definition of life. The question pertaining to the origin of life was split into two viewpoints; the idealistic and the materialistic (Bedau & Cleland., 2010). The supporters for the idealistic origin of life, believed that matter was lifeless until it was given a purpose. Therefore, the spiritual concept of a soul was given to all things that assembled life, defined as everything that obtained a purpose (Bedau & Cleland., 2010). Animate objects obtained a soul and along with it life, whereas death was noted as the final departure as the soul left the body on Earth (Bedau & Cleland, 2010). It was even believed that a stylus, providing means of communication and literature, was alive and therefore in its simplicity possessed a soul.

The materialistic concept of life was grounded in scientific aspects, allowing it to be experimentally determined. The mechanical materialists defined life in terms of physical and chemical properties. They saw no qualitative difference between the organic and the inorganic, as they believed that categorization would result in substantial proof against either (Bedau & Cleland, 2010). Alexander Oparin's viewpoints were considered amongst the dialectical materialist, a group of scientists who understood the question from a biological view (Bedau & Cleland, 2010). Within this view, all life was given a unique form of motion and was therefore qualitatively separate from the inanimate. However, no matter the view; idealistic or materialistic, centuries of debates pertaining to the origins of life took place, never grasping the ultimate definition of life, or how it came to be.

## 1880 – 1900: Science in the Russian Empire

The most striking feature of the history of Russian science is the intertwined relationship of power and politics. The political climate in Russia during the late 19th century and the mid 20th century played a vital role in shaping the researchers of the day and the scientific community as a whole (Hachten, 2002). As well known, the pursuit of knowledge and research is not without financial burden and while a small minority of scientists were able to overcome this, many had to find patrons who were willing to fund their ventures. At the time, insight and knowledge also translated to power, meaning that the patrons who were financially able to support these causes became the powerhouses of the time – namely the church, royalty, industry, and state bureaucracy (Krementsov, 2006).

Alexander Ivanovich Oparin – born on March 2, 1884 in Uglich, Russia – would witness the transformation of Russian science throughout his lifetime. Oparin was born at the end of the 19th century, during a time in which Russian science was indistinguishable from its European counterparts (Krementsov, 2006). This could be seen in its institutional basis, which shared the same structure to that of Germany (Krementsov, 2006). Moreover, many of its scientific societies were patronized by the royal family and nobility, reflecting the monarchical ruling in Europe during this period. This European influence was the result of Russian scientists completing several years abroad in

Europe after university (Krementsov, 2006). As Russian scientists returned home, they brought with them the practices they witnessed abroad (Hachten, 2002). However, their form of criticism did not follow this trend as they avoided all ideological, political, and social language (Krementsov, 2006). This reflected the scientists' desire to protect their discipline from ideological authorities and their consequential interference (Krementsov, 2006).

At the age of nine, Oparin and his family moved to Moscow where he attended secondary school and later went on to major in plant physiology at the Moscow State University, photographed in Figure 1.1 (Fox, 2020). While there, he was introduced to Darwinian thinking as Russian plant physiologist K.A. Timiryazev, who had personally known Charles Darwin, became one of Oparin's mentors (Fox, 2020). The Darwinian approach would highly impact Oparin's young career in science and many of his writings – including that of his Primordial Soup hypothesis.

Simultaneously, the major institutional base of Russian science was a coalition of state universities and specialized educational institutions (Krementsov, 2006). There were approximately 4000 scholars working in 289 institutions – a small proportion when considering the population of Russia due to the minimal institutional support the scientific community received from the Russian government (Krementsov, 2006). For this, the government received a plethora of criticisms from Russian scientists, but continued to ignore their concerns, resulting in the majority of the institutions at the time to be under private patronage (Krementsov, 2006). Certain institutions during this time, including the Academy of Science, were patronized by the royal family and nobility in Russia.

## 1900 – 1920: The Russian Revolution and Rise of Russian Science

Government support for the sciences drastically changed after the February 1917 revolution, which dethroned Tsar Nicholas II. The liberal provisional government that resulted from this revolution had promises to increase support for education and scientific research (Krementsov, 2006). The Academy of Science capitalized on the liberties of the revolution, acting quick to elect a president who promised to work towards the establishment of "well-equipped research facilities and laboratories, along with museums, libraries, and teaching auditoriums" (Krementsov, 2006). These endeavors were interrupted in October of 1917, when the Russian Social-Democratic Labor Party (otherwise known as the Bolsheviks) carried out a coup d'état in the city of Petrograd (Todes and Krementsov, 2010). The change in regime was met with great suspicion and distrust from the scientific community, prompting protests and strikes against the Bolsheviks dictatorship. The Bolsheviks, preoccupied with consolidating their power, paid little attention, forcing protests to subside by the spring of 1918 (Krementsov, 2006).

*Figure 1.1. A photograph of the main building of Moscow State University, taken in 2012.*

In March 1918, the Bolsheviks signed a peace treaty with Germany to end Russia's participation in World War I (Krementsov, 2006). But that would not free them from conflict, as a civil war erupted only weeks later. This would impact the scientific community as the geographical and political division it caused hindered the ability of scientists to continue their work and create new institutions (Krementsov, 2006). Their troubles would only be mitigated when the Bolsheviks adopted an economic policy of "war communism" in June of 1918 (Krementsov, 2006). This resulted in the nationalization of all private enterprises and made the state the sole patron of science (Krementsov, 2006).

Given that the Bolsheviks political priority was to win the war and restore the national economy, they had an instrumental and utilitarian attitude towards the scientific discipline (Marsak, 1964). Russian revolutionist and political theorist Vladimir Lenin drafted documents that illustrated the central role of science in the Bolsheviks regime (Krementsov, 2006). In doing so, Lenin formed the basis of collaboration between the regime and the scientific community. Now, Oparin, living in a liberal and high-bourgeois cultural environment was encouraged, if not slightly biased, into a materialistic view after the Bolsheviks revolution. This was translated into his work, in which he expressed a strongly materialistic view, influenced by the forces of both scientific and political power, as there was a very thin line deciphering these bodies at the time.

In a short period of time, the majority of Russian scientists, including Oparin, joined the Bolsheviks in an effort to revive and expand Russian science. The state patronage would result in the rapid growth of the science system; as all Russian scientific institutions survived the revolution and an additional 33 research institutions were created in 1918 to 1919 (Krementsov, 2006). The government also took steps to establish and preserve Russia's scientific potential, providing scientists with a number of privileges such as enlarged food rations and immunity from property confiscation (Krementsov, 2006). The harassment and mistreatment of the bourgeoisie during the civil war caused many scientists to relish in the presented privileges.

## 1920 – 1929: The Establishment of Marxist Science

The new period for Russian science began after 1922, when the Bolsheviks regime succeeded in consolidating their power. During what is known as the period of "peaceful construction", the partnership between Russian scientists and the Bolsheviks state was cemented (Krementsov, 2006). Though the Bolsheviks held control over all assets, they required the expertise of the scientific community to fulfill their technocratic vision for society. Therefore, their science policy at the time worked to co-opt the pre-existing bourgeois scientific community and invite Russian scientists to collaborate with the regime (Krementsov, 2006). The co-opting consisted of large amounts of funding and gave rise to state agencies that acted as patrons to scientific endeavors. The state's influence on scientific work at this time was minimal, with the direction, content, and duration of research mostly in the hands of the scientists themselves (Krementsov, 2006).

During this time, the Bolsheviks worked to create their own "communist" science and proletarian scientific population. Starting in early 1918, the system of higher education was reformed despite protests. There was strict control over syllabi, curricula, professoriate, and the student body (Krementsov, 2006). In addition to altering existing educational institutions, "communist" educational institutions, research institutions, and scientific societies were established (Krementsov, 2006). An example would be the Communist Academy, which unlike the Academy of Science, was governed by a self-appointed body of high-ranking founders (Todes and Krementsov, 2010). The academy also strictly controlled its subordinate institutions, exerting "party discipline" over its members and workers. By the mid-1920s, the Bolsheviks began to work on the language of the scientific community, promoting a Marxist lexicon; Marxism was a set of political and economic theories that formed the ideological basis of the Bolshevik regime. Initially, the incorporation of this discourse was a cover for most scientists as Marxism acted as a way of distinguishing their research interests and institutionalizing their approaches (Todes and Krementsov, 2010). This was important as scientists needed to display their loyalty to the Bolsheviks state in order to receive funding. This language quickly became mandatory when Stalin consolidated his power over the Bolsheviks party. In 1929, the "Great Break" changed all aspects of Russian life (Todes and Krementsov, 2010). The Bolsheviks replaced their co-optation policies with those of command and control, signaling the beginning of a new relationship between Russian scientists and their patrons (Krementsov, 2006). Alexander Oparin, like the other scientists of his time, would be influenced by state politics due to his strong backing of their views.

One of the main implications of the Bolsheviks remodeling was the incorporation of dialectical materialism as a fundamental policy in scientific approaches; dialectical materialism was the underlying philosophy of Marxism (Todes and Krementsov, 2010). This caused many scientists to incorporate this rhetoric into their work. Oparin, being one of these influenced figures, believed many of these views. Therefore, he had to omit his own ideas as the process in which he proposed was not highly supported by the most influential figure of the time, Joseph Stalin. It is, however, most likely that his beliefs and rationale backing his biochemical view was influenced by the scientific and political powers of the time.

## 1920s – 1940s: The Development of the Primordial Soup Theory

When Alexander Oparin first introduced the Primordial Soup Theory at the 1922 meeting of the Russian Botanical Society, many scientists and political leaders disregarded his work as it did not comply with the popular belief at the time. Stalin backed the well-known biologist

Trofim Denisovich Lysenko, who proposed the idea known as Lysenkosim - a highly regarded anti-Mendelian theory that proposed all cells of organisms were inheritable (Kolchinsky et al., 2017). Given that Oparin's theory contradicted Lysenkosim, the initial response to his theory was almost universally negative. However, Oparin was not demotivated and continued to improve on his theory. In 1924, Oparin formally introduced his hypothesis in a booklet. Once fully developed, Oparin published the *Vozniknovenie zhizni na zemle* (*The origin of life on the Earth*) in 1936 identifying the Primordial Soup Theory. A second edition was published in 1941, however it was very similar to the original book. It was not until 1964 that the third edition was released regarding further scientific development for the theory of the origin of life. The books were all translated from Russian by Ann Synge shortly after being published.

Eluted during his first book, however drawn more completely in his third, was the proposal that millions of years prior Earth's atmosphere was composed of an array of free radicals formed through ultraviolet radiation, radioactive radiation, and electric discharge (Oparin, 1957). The oxidation of lower hydrocarbons occurred due to the presence of free radicals, giving rise to random chemical reactions (Oparin, 1957). Before this, the atmosphere consisted of inanimate particles colliding with one another in what he deemed a Primordial Soup (Oparin, 1957). Oparin termed the first dynamic reminisce of a system as the coacervate drop - a non-living entity thought to partake in the first simple biological processes on Earth - proposed to have been synthesized in the waters of the early hydrosphere (Oparin, 1957). The probability of reactions in this environment was high as the abundance of free radicals, in combination with the high temperature, created conditions which enabled the formation of coacervate drops (Oparin, 1957).

At the time Alexander was conducting his research, he understood that chemical principles governing open systems were imperative to the study of the origins of life. Cells could only exist with a flow of fresh particles of matter moving with energy from the external medium as well as the internal structure. It was experimentally determined that a series of reactions - including oxidation, reduction, hydrolysis, phosphorolysis, aldol condensation and transfer of methyl groups - were essential for metabolic processes occurring within living organisms (Oparin, 1957). However, Oparin distinguished that the reactions themselves did not define life, but rather the harmonious flow in which they occurred (Oparin, 1957).

He observed this to be much like principles governing an open system. There were similarities between the processes causing a decrease in system entropy resulting in an increase in the surrounding medium's entropy (Oparin, 1957). Within open systems there is an infinite number of equilibrium states as the system continually rearranges kinetic and diffusion principles to adjust its stationary state. The parallel between the interaction with the environment and organismal cells led to the understanding that the simplest abiogenic networks must have behaved as open systems (Oparin, 1957). Due to the probabilistic nature of chemical reactions, it was noted that there must have been a predominant reaction at the beginning of the first coacervate drop synthesis (Oparin, 1957). Kinetics favoring the timing and formation of certain products created new starting materials for unfamiliar reactions. This led to successive transformation of biological reactions simulating a network of cohesive events. Thermodynamic and kinetic properties began a chain of reactions in which the proceeding synthesis depended on the prior, resulting in a system that interacted with the external medium (Oparin, 1957). Oparin explained that the slow evolution of organisms presented by Charles Darwin occurred in the primordial molecules as well. Over thousands of years, a series of biological reactions joined to create cycles such as the tricarboxylic acid cycle of Krebs (Oparin, 1957). Oparin suggested that the ultimate life force was the dynamic and essential relationship between the environment and biological synthesis of reactions (Oparin, 1957). He defined this by proposing that if the interaction between the medium were to cease, the reaction itself would not continue, thus resulting in a failed open system relationship. As the cycle progressed, stability took on a more dynamic nature with reactions relying on previous products to sustain the developing chain (Oparin, 1957). Oparin defined the transformation of the open system as the first evidence of self-renewal and dynamic interaction between life systems and the environment.

The laws of physics and chemistry have invariably existed for all of time. By this knowledge, it was proposed by Oparin that the origins of life must coincide with these laws. The Primordial Soup Theory established that the polymers of life were randomly constructed through the synthesis of monomers due to an unorganized 'soup' of peptides and mononucleotides (Oparin, 1957). The original solution of these random components, having no function or purpose, assimilated together to form systems. Over thousands of years, this evolved into the simplest forms of living embodiments. Their interaction within the medium and natural selection, proposed strict evolutionary mechanisms ultimately leading to the establishment of chemical reactions indicative of self-sustaining life forms known as metabolism (Oparin, 1957). Oparin's work suggested that the synthesis of organic compounds and precellular evolution led to the formation of primordial anaerobic heterotrophs - the genesis of life on Earth (Oparin, 1957).

### The Influence of Politics on the Primordial Soup Theory

The alterations from the first published novel to the second and third additions can be attributed to the scientific progress, as well as the political environment of the time. The inspiration for Oparin's theory expanded beyond that of biochemistry and colloidal chemistry as it was also influenced by his personal philosophy and ideology (Fry, 2006). Oparin's 1924 second edition booklet exhibited influence by traditional materialism, as he denounced neo-vitalism and panspermia theories (Fry, 2006). Moreover, he attempted to demonstrate the similarities between biological and physicochemical systems; not surprising, as this approach was compatible with the Russian social and political climate in the 1920s.

When Oparin published his book in 1936, it was evident that he was influenced by the tenets of dialectical materialism (Fry, 2006). Specifically, those from the *Dialectics of Nature*, a book published in 1925 by Friedrich Engels, a co-founder of Marxism. In his theory, Oparin applied "basic dialectical postulates" by arguing that matter underwent changes when it evolved from one level of organization to the next, with each level characterized by new specific laws (Fry, 2006). His stance on the properties that he considered to be unique to life was the biggest difference between his 1936 book and his 1924 pamphlet, with an emphasis on complex organization and the purposeful nature of biological processes in the former (Fry, 2006). This change is not surprising when taking into account the socio-political environment of Russia during the time of publication. Stalin's "Great Break" of 1929 created strict control of the ideologies and motivations behind many thoughts. Given that dialectical materialism was heavily enforced after 1929 and the prominence of Oparin's status in the Russian political and scientific scene, the shift in Oparin's inspiration behind his theory can be interpreted as a direct response to the environment he was in. Although it is impossible to know whether or not his Marxist jargon was political opportunism or a truthful incorporation of his ideological views, it nonetheless reflects the effects of politics on science.

# The Search for Extraterrestrial Life

Defining life remains arduous, if not more so, in the world of science today. It seems the more that is learned about the origins of life, the less is understood. The search for life on other planets is thus misleading when considering the abundance of unknown aspects on Earth. Despite all of this, the search for extraterrestrial life has expanded in recent years with hopes to acknowledge any comparable existence on a cosmic scale. This venture, according to Longo and Damer (2020), is guided by three questions:

1. When was a planetary most habitable, and how long did these conditions last?
2. Where might life have appeared and thrived on this world as it gained and then lost some aspects of habitability?
3. What biosignatures should missions search for in each of the above environments?

Oparin's Primordial Soup Theory has played a critical role in answering the first two questions. Though the identity of where abiogenesis took place is still under debate, the two most popular contenders are submarine hydrothermal vents and terrestrial hydrothermal fields (Longo and Damer, 2020). The former is, in essence, a nod to Oparin's theory. With these two locations, scientists have been able to impose constraints on the environments that may have supported extraterrestrial life.

For the past three billion years, Mars has not sustained permanent bodies of liquid water (Longo and Damer, 2020). Though that limits the possibility of current life, it does not conclude that life has never existed there.

Deuterium-hydrogen ratios in carbonaceous chondrites suggest that water was delivered to both Earth and Mars early in their respective histories (Longo and Damer, 2020). Moreover, widespread deposits of hydrated minerals have been found in at least ten aqueous environments on Mars. These minerals formed during the Noachian period, suggest that Mars could have been habitable as early as 4.6 billion years ago (Longo and Damer, 2020). However, surface habitability was reduced during the Hesperian period due to the stripping of the atmosphere and the acidification of water, leading to life not easily seen here today

The origin of life on Mars could have occurred during the Noachian period, as it is thought that all conditions required for the origin of life in a marine and terrestrial hydrothermal system were met during this time (Longo and Damer, 2020). Candidate Noachian hot springs have been discovered in multiple locations on Mars, but the best-studied system is in the "Columbia Hills" in Gusev Crater (Longo and Damer, 2020). One such hill is shown in Figure 1.2. Discovered by the Mars Exploration Rover (MER) Spirit in 2007, analysis of this system has suggested the presence of bio-mediated micro stromatolites (Longo and Damer, 2020). These silica deposits are considered to be a target for future exploration due to their high biosignature preservation potential.

In an attempt to search for present life forms, the atmospheric and environmental conditions of Earth are used as an analog to distinguish where other life forms in the galaxy may exist. In recent studies, aspects including techno signatures, biosignatures, transit spectroscopy and the habitable zone of planets have been assessed (Brennan, 2020a). Techno signatures and biosignatures are the measurable property of past or present technology or biological forms. Using these signals, engineers are attempting to determine if there are other life forms that may be more 'advanced' than even the Earthly *Homo sapiens*. Transit spectroscopy is the measurement of stellar light able to penetrate the atmosphere, used to determine the chemical composition of exoplanets (Brennan, 2020a). By focusing the search on relevant habitable zones - which is the distance of a star needed for liquid water to be present on the surface of a planet - the exceedingly numerous list of planets could be filtered and minimized (Gonzalez, 2005; Brennan, 2020a).

Since the only known life is that which exists on Earth, it is thought that planets which have similar conditions may be more likely to contain life. This remains difficult to uncover due to the number of exoplanets remaining after filtering out those with unsuitable habitable zones. As a result, the search has been narrowed to focus on planets orbited by G-type stars or K-dwarf stars with an increased luminosity like that of the sun (Brennan, 2020b).

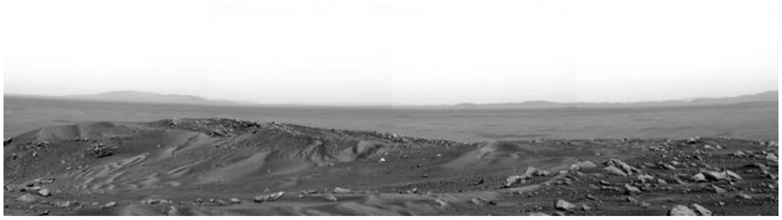


*Figure 1.2. A panorama taken by NASA's Spirit rover upon reaching summit of Husband Hill located in Columbia Hills in Gusev Crater, Mars.*

With this narrowed scope of exoplanets in mind, massive corporations such as the National Aeronautics and Space Administration (NASA) can further determine where to focus their energy. As such, the James Webb Space Telescope is scheduled to launch in 2021, with hope to set out on a 10-year mission to analyze exoplanets within the Milky Way Galaxy (Gardner et al., 2006). Equipped with IR imaging technology, the telescope will obtain information of the origin and evolution of space systems through complex investigation of the chemical atmosphere, while searching for signs of oxygen, carbon dioxide, methane, photosynthesis, pollutant products as well as other life-suggesting molecules (Gardner et al., 2006). Through past exploration and research, it has been found that interstellar space contains a mixture of molecules including amino acids, or the building blocks of life (Gardner et al., 2006). Perhaps the Primordial Soup Theory in which Alexander Oparin suggested decades ago remains the primary principle when determining potential extraterrestrial lifeforms.

# The Lady Who Illuminated the Sea Floor

In the 1920s, perceptions of the world were substantially different than they have become in current day. The 1920s were deemed the post-war era, where societies prospered in a time of wealth and growth. Scientifically, discoveries emerged in a multitude of fields while bewildering theories such as evolution and spatial relativity were controversially debated (Wazeck, 2014). In Earth science, this was no different. Scientific debacles exploded worldwide from "fixists" claiming the stationary nature of continents, expanding Earth theorists presuming that the Earth could enlarge and shrink, and a novel group of scientists fighting for the continental drift theory to gain prominence on the world stage (Spanagel, 2015).

Amidst all this, in Ypsilanti, Michigan, the year 1920 marked when a girl was born (Felt, 2017). She was to grow up in a time of many geological discoveries and ever-increasing scientific efforts to demystify the continents and the sea floor. Raised in this environment, little did she know the impact she would bring as a pioneer in her field. She would be a revolutionary cartographer and an inspiration to women in science. She would be vital leading up to Harry Hammond Hess' coining of seafloor spreading and ultimately, important to the development of the plate tectonic theory (Spanagel, 2015). This girl, by the name of Marie Tharp, would illuminate the mysteries of oceanography with world-renowned maps of the ocean floor.

## Early Life and Influences

Marie Tharp was an explorative child. Born to a soil surveyor and a schoolteacher who were both old enough to recognize that children need not be coddled, Tharp was set for a childhood of curiosity and discovery (Tharp, 1999; Felt, 2017). Some days she would be found making mud pies in her father's truck, while on others she would be found running to her mother with snake skeletons from field excursions (Tharp, 1994). She even fondly posed for her father next to a tree tumour, which was her then-newest scientific discovery from their walks (Tharp, 1994; Felt, 2017). In her school years, she'd be excitedly learning in her Current Science class, fascinated by the advancements but left feeling dejected from the already-substantial progress that had seemed to be made (Felt, 2017; Higgs, 2020). Although her father would bring her along as he relocated to survey soils and create maps, Tharp still did not regard science as her career trajectory, nor teaching, nor healthcare (Tharp, 1999; Felt, 2017; Higgs, 2020). Her father always advised her to find something she was capable of and enjoyed (Tharp, 1999). Though she did not know her specific path, these childhood experiences undoubtedly played a role in Tharp's education by providing scientific exposure and a sense of curiosity early on in her life in both academic and familial contexts.

Moving into postsecondary education, Tharp enrolled in an arts program at Ohio University in 1939, taking courses in a variety of disciplines such as in the social sciences, languages, and arts (Tharp, 1999; Felt, 2017). Sitting in her geology class though, contemplating tales of rocks and the Earth, Tharp became entranced and passionate about the field (Felt, 2017; Higgs, 2020). Dr. Clarence Dow, a professor of geology, encouraged this interest and became a close mentor to Tharp along her journey (Felt, 2017; Higgs, 2020). This seemingly "mundane" choice of taking geology classes, in hindsight, was pivotal in commencing her career in geosciences.

## Early Career

In Tharp's university years, her relationship with Dow was not only one of mentorship, but of great importance in jump-starting her career. Dow saw potential in this young woman and tried to help her succeed in a male-dominated and traditional-minded field (Felt, 2017). As per his recommendation, Tharp sat in drafting class as one of the three women in a class of 73, proud to be learning a lot about this subject. This was because, by learning to utilize maps and cross-sections, this not only opened Tharp's mind to a three-dimensional world but also the doors to better employment in a field of men (Felt, 2017; Higgs, 2020). In the 1920s, though women had begun to increasingly enter into PhD programs, conservatism led to a drop in engagement that began in the 1930s and continued through the 1960s (Schiebinger, 1993). Women in science were concentrated in fields that were regarded with less prestige and lower pay than their male-concentrated counterparts (Schiebinger, 1993). This difficult social climate for women made it important for Tharp to try to increase her chances in the field—her perseverance and the mentorship from Dow proved vital in her early career.

As Tharp continued to study geology, a golden opportunity soon presented itself before her. Tharp, visiting Dow in her final year of university, had her attention caught by a flyer on his bulletin board (Tharp, 1999; Felt, 2017). Scrawled across the posted sheet were promises of a job and a masters in geology (Tharp, 1999; Felt, 2017). This program was offering women guaranteed petroleum employment amidst the shortage of men during World War II (Tharp, 1999). The "Petroleum Girls" was an exciting step for Tharp's life (Felt, 2017). Despite the war's detrimental effects on the economy and worldwide devastation, it brought additional opportunities to women when men were working on war efforts. Under the advice of Dow, she pursued the degree, enrolling into a master's degree in geology at the University of Michigan in 1942 (Doel, Levin and Marker, 2006; Felt, 2017).

During her time in Michigan, Tharp worked as a drafter under George Cohee for the United States Geological Survey (USGS), which at the time began investigating the Michigan Base as a source for oil (Tharp, 1994). Cohee was a respected stratigrapher and geologist, and it was with him where she learned ink drafting. Tharp found joy in this job. However, with her education remaining her top priority, after some debate and long conversations with her father, she decided to stop working to focus on her studies (Tharp, 1994). Although her time as a drafter for USGS came to an end, its impact arguably lasted for the rest of her life. This opportunity, unbeknownst to Tharp, would later become one of the main factors in jumpstarting her life-long career in cartography.

## Post-Graduation and Employment

Upon graduation, she found work with Stanolind Oil and Gas Company in Tulsa, Oklahoma, having obtained a master's degree in petroleum geology in 1944 (Tharp, 1994). However, women at the time could not go into the field with men. So, Tharp was stuck working at the office, transferring data from well logs. Amidst the boring and tediousness of this work, one drafting task was given to her which required her to map the deepest hole in every US state, and this single project gave her more experience that greatly helped her future days of mapmaking (Tharp, 1994; 1999). In addition, being a keen seeker of intellectual stimulation, Tharp enrolled herself at the University of Tulsa in Oklahoma for a bachelor's degree in mathematics (Tharp, 1999). She did this while working her job in the hopes of quenching her boredom (Doel, Levin and Marker, 2006).

When Tharp realized that this job was not enough to satiate her desire for challenge, she decided to move to New York in 1948 to look for something else—perhaps a research assistant job with more interesting and engaging tasks (Tharp, 1999; Higgs, 2020). Initially, she had sought a position with the American Geographical Society, set on putting her writing skills to use to assist with their petroleum deposit publication (Frankel, 2012b). Despite her expertise, she was turned away and told that they did not need any file clerks, which exemplified the unbalanced climate for women in science at the time and how it held her back (Tharp, 1994; Frankel, 2012b). She next decided that Columbia University seemed particularly well known, since she remembered that many of her college textbooks were written by their professors, and so into Columbia she went in her quest for employment (Tharp, 1994). As she sat in Room 202 in Schermerhorn Hall, the secretary facing her remarked that a gentleman named Ewing might be interested in seeing her, given her math degree, but that she would need to wait three weeks for him to return from the sea (Tharp, 1994; 1999). Marie Tharp did nothing else for three weeks. She sat at home and waited to go back. When she went back to Columbia, she was ushered into Ewing's office (Tharp, 1999).

Perhaps it was Marie's educational background and part-time drafting job that piqued the interest of this leading geo-physicist at the time, William Maurice Ewing, less formally known as "Doc Ewing" to his working staff (Frankel, 2012a). As the founder and director of the Lamont Geological Observatory, a major centre for Earth science research, Ewing was highly respected within the scientific community (Levin and Doel, 2000). Ewing was amazed and bewildered at Tharp's unconventional educational background and her experience as a drafter with USGS, so he hired her (Tharp, 1999). At the time, Ewing was exploring the Michigan basin for its potential as an oil source, and he placed her to work for one of his students.

This job was not a dream come true though, as her work was more tedious than she had hoped for. It consisted of punching numbers into Monroe calculators, something that the only two other girls working in the lab were also tasked with (Tharp, 1994). This once again highlighted the discrepancy of positions available to men and women in scientific history; Tharp was presented with little opportunity and little power to voice her opinions or attend meetings, while also being assigned to lesser work despite her master's degree (Doel, Levin and Marker, 2006; Frankel, 2012b). However, as time went on, Tharp began working with another graduate student in the lab, Bruce Heezen, and her drafting skills slowly began to be recognized, so much so that many other researchers and students in the lab started asking her to draft for them (Tharp, 1994). Frustrated by the demands of drafting work, Tharp initially quit her job until Ewing realized it was not sensible to let Tharp work so thinly between all the requests (Frankel, 2012b). He instead assigned her solely to the more stimulating work of Heezen (Tharp, 1994; Frankel, 2012b). Bruce Heezen and Marie Tharp would go on to have a long working relationship of 25 years beginning officially in 1952, in which they would together take on one of the most revolutionary endeavours of their time: visualizing the ocean floor (Felt, 2017).

## The Ocean Floor in the 1950s

The ocean floor at the time was a mystery to everyone. No one had seen it and could only speculate on what it looked like, which at best was described as various discrete landforms and regions, at worst, a big pile of mud washed out from the various mountains on Earth (Tharp, 1994; Doel, Levin and Marker, 2006). Past efforts had been made; the 1900s marked the start of recognition for oceanography, 1905 was the beginning of the Carte Generale Bathymétrique des Océans (GEBCO), 1921 marked the establishment of the International Hydrographic Bureau, and the German government also made efforts to explore the seafloor (Doel, Levin and Marker, 2006). Oceanographic technology at the time was also developing as the US government and defense agencies heavily funded oceanic research endeavours in the face of World War II and the start of the Cold War (North, 2010). Seafloor mapping became a priority for submarine warfare and long-distance underwater communications, presenting itself as a nationalistic cause (Doel, Levin and Marker, 2006). Refined depth recorders and instruments for collecting data in the ocean were developed and utilized by the US Navy, whose data collected were released to the oceanographic research community (North, 2010). Heezen and Tharp utilized much of this data in their arduous seven-year journey of mapping the seafloor and these various circumstances set up the stage for Tharp's later success in her career (Doel, Levin and Marker, 2006).

Heezen, at the beginning of this endeavour, was on another research project with Ewing. In the 1950s, Bell Laboratories was preparing to lay the first transatlantic telephone cable and Heezen and Ewing were hired to link earthquakes and underwater cable ruptures to see if there were any correlations between the location of the ruptures and earthquakes (North, 2010). Heezen and Ewing were often out on the ocean collecting data, and since women could not sail the ocean, Tharp naturally became the drafter; she became the ultimate mapper of the ocean floor (North, 2010). It was crucial for Bell Laboratories to have accurate maps, not only for their transatlantic cables, but also for the secret underwater eavesdropping arrays that they were installing for the US government during the war (Doel, Levin and Marker, 2006). At the time, Ewing had obtained a new research ship *Vema* that would allow him and his team to travel to broader expanses of the ocean and aggressively collect oceanic data from different and deeper regions around the world (Tharp, 1999). Using echograms to record depth, this data was collected and was extremely advantageous for Tharp in drafting new maps of the Atlantic Ocean and beyond (Heezen, Tharp and Ewing, 1959).

## The Illumination of the Sea Floor

Tharp and Heezen worked together to lay the basic framework for the very first physiographic map of the ocean. However, it was Tharp who developed much of the details of the map and made many correlations from the scarce data that was available to researchers at the time. Tharp employed the strategies of other geologists and cartographers before her, such as Armin Kohl Lobeck in order to gain insights for her work (Doel, Levin and Marker, 2006). With only two-dimensional data of the ship track lines and depth measurements, Tharp worked tirelessly at her desk to transform these data sets into a detailed, three-dimensional, underwater world that was at the time, unknown to the rest of the world and those before her (Doel, Levin and Marker, 2006; Higgs, 2020). Through piecing together this data, she worked with geological scales, peaks, troughs, cross-sections, and more (Heezen, Tharp and Ewing, 1959).

Heezen and Tharp then used other available data from seismology, magnetism and bottom-photography to produce the most extensive and thorough map of any ocean floor until that time: the Heezen-Tharp North Atlantic Map of 1957 (Doel, Levin and Marker, 2006). Although the geological intuitions of both scientists were necessary in its production, many of Tharp's ideas prevailed over Heezen's and her interpretations were what contributed to the development of the seafloor spreading theory by Hess in 1962. This ultimately grew into the plate tectonic theory we know today (Doel, Levin and Marker, 2006).

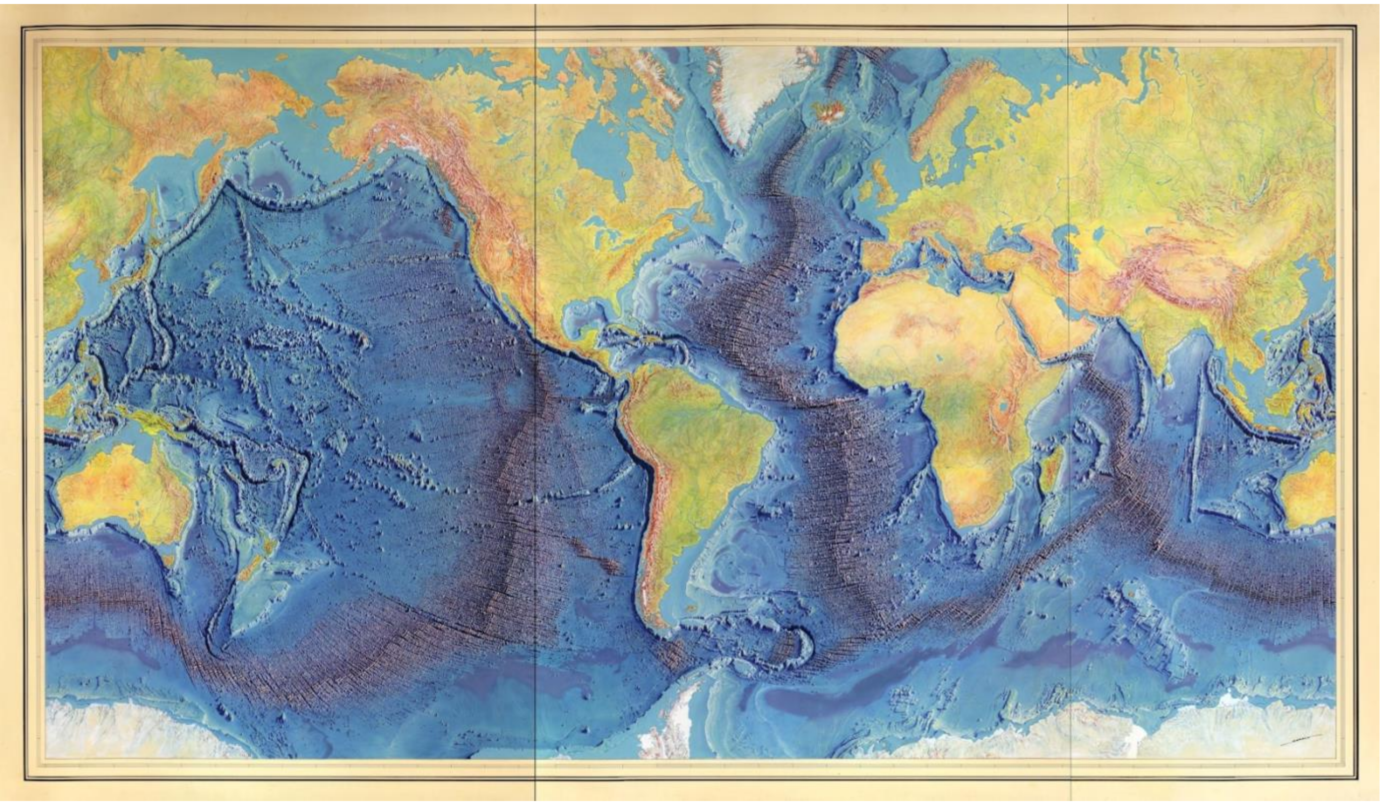


*Figure 1.3. 'World Ocean Floor Panorama', a map drafted by Marie Tharp and Bruce Heezen and painted by Austrian artist Heinrich Berann, published in 1977. This is the first physiographic map that showcased the world's ocean floors from a bird's eye view. The Mid-Ocean Ridge (dark purple) can be seen throughout all of the oceans on Earth.*

The extrapolation of one particular feature on the maps by Tharp laid the foundations for what was to become the seafloor spreading theory. From her detailed sketches, she noticed the existence of a Rift Valley in the Mid-Atlantic Ridge. In Tharp's mind, she clearly saw how well the shallow-focus earthquakes lined with the central axis of the ridge, although data was sparse. Heezen, on the other hand, disagreed adamantly and pronounced it "girl talk" (Tharp, 1999). She drew and redrew the feature and surrounding landscape, but she could not unsee what she had first seen. Her education was in anti-drift theory, but it was undeniable that she thought it looked as if the two continents on either side of the ridge were coming apart on the seafloor (Tharp, 1999; North, 2010; Higgs, 2020). Tharp knew that this perhaps could be evidence supporting the continental drift theory (Tharp, 1996). Her partner Heezen however, still could not believe that their data supported this theory and tried to argue that the data actually provided evidence for the Earth expansion theory, a more popular concept at the time. His opposition and the rejection of this data by others in the Lamont Geological Observatory could likely be due to their boss, Maurice Ewing, being an anti-drifter (Frankel, 2012a). Most scientists also opposed the idea of continental drift at the time and the dominant model regarding tectonics was the Earth contraction theory (Tharp, 1996; Sudiro, 2014). Finally, Heezen believed Tharp two years after she initially proposed the idea and together, they published their first map in 1957 (Doel, Levin and Marker, 2006; Frankel, 2012a). This map was still met with resistance from the scientific community and would have been published earlier if not for the denial of its validity from her male colleagues (Doel, Levin and Marker, 2006; Higgs, 2020).

Despite this resistance, Tharp and Heezen continued to update their map and set out to map other large water bodies around the world:

the South Atlantic Ocean, the Indian Ocean, and the Mediterranean Sea. They achieved their goal of mapping all the oceans in the world by the late 1960's (Doel, Levin and Marker, 2006). Their 'World Ocean Panorama' map released in the 1970s (as shown in Figure 1.3) went on to become one of the most widely recognized maps of the twentieth century as it highlighted an increased understanding of the final unexplored expanse on Earth: the ocean (Doel, Levin and Marker, 2006). It was also these maps that laid the foundation for Harry Hammond Hess's seafloor spreading theory. Tharp and Hess had presented their findings at Princeton, in which Hess was present as a geophysicist and the head of their Department of Geology (North, 2010). The maps provided initial evidence that seafloor spreading was a possibility, which later paleomagnetic data further supported (Doel, 1996; Tharp, 1996).

By the late 1960s, plate tectonic theory and seafloor spreading increased in evidence and later became one of the most prominent and widely accepted theories of Earth sciences; this progression would not have been possible without the supporting evidence that Tharp and Heezen's maps had provided. They were mandatory in changing perceptions of the Earth, promoting research to confirm their findings, and shifting the focus to the highly regarded theories that came after. Cartography and maps not only document the seafloor; Tharp's mapping results were a documentation of her journey to arrive at that point in her life. It was a snapshot to illuminate the ocean floor, but behind that, it was a snapshot that captured the political, social, and scientific contexts of her time. Despite the lower regard for women in science, the initial disbelief of her findings, and the ever-changing war and political climate, her skills and experiences prevailed. Her contributions to Earth science both outlined a path to understanding the seafloor and a path to plate tectonic discovery.

Tharp's impact on oceanography and geology is recognized in recent times as well. In 1996, 1997, 1999, and 2001, she received four awards celebrating her achievements as an outstanding female geographer, cartographer, oceanographer, and pioneer in science (Evans, 2002). From a modern perspective, it is clear that Marie Tharp had a profound impact in creating one of the most foundational works in seafloor mapping, inspiring a new generation of oceanographic studies, and propelling the discovery of one of the most important theories of the Earth Sciences.

# Oceanography and Plate Tectonics After Marie Tharp's Map

Marie Tharp's maps laid the blueprint for visualizing the structures found beneath the oceans. They also provided a viewpoint for further understanding the continents above the waters. This led to the plate tectonic theory, which drastically changed the modern view of the Earth and aboveground geological structures. This theory is often considered the unifying theory of Earth sciences today as it explains the formation and existence of the major features on Earth, such as volcanoes, shorelines and mountain ranges (US National Park Service, 2020).

## Current Sea Floor Views

Tharp's legacy continues with further discovery and research into the seafloor. With large amounts of additional data discovered nowadays with new technology, Tharp's initial stylized interpretations still are largely correct (Ferrini et al., 2020). Some of the major evidence that arose after Tharp's maps to support this modern-day model of the Earth's plates include the paleomagnetic evidence that demonstrated the repeated reversals of Earth's magnetic field as documented on the ocean floor, and the localization of earthquakes undersea that demonstrated the non-random pattern in which earthquakes and volcanic activity are located along plate boundaries and hot spots (Vine and Matthews, 1963; U.S. Geological Survey, 1999).

What also arose from Tharp's works was an increased interest in seafloor study and synthesis projects (Ferrini et al., 2020). In particular, technology of seafloor visualization and the corresponding software has progressed immensely from that time. There was a project to digitize the echo-sounding profiles from voyages which meant relevant technologies were to be developed to complete this project; soon, multibeam sonars were being used in the 1980s which also increased the data available (Ferrini et al., 2020). In the 1990s and 2000s even more projects emerged, including the Ridge Multibeam Synthesis (RMBS) Project and the Global Multi-Resolution Topography (GMRT) project, which took on even more ambitious goals in terms of data acquired and their scales, as they attempted to construct bathymetric grids and maps of the global ocean, respectively (Ferrini et al., 2020). Currently, employed bathymetric technologies include GIS mapping, various types of sonar, and submersibles to examine the bottom of the ocean, to name a few (National Oceanic and Atmospheric Administration, 2020). The GEBCO Seabed 2030 Project is a new project which aims to compile an open-source seafloor database that will help scientists worldwide for climate, wildlife, planning, marine, and other scientific purposes (Bastos, 2020). There would not be such a large investment and progression of seafloor exploration without the seminal mapping publication of Marie Tharp and Bruce Heezen (Ferrini et al., 2020).

## Current Plate Tectonic Views

Following Marie Tharp's discovery of the valleys along the mid-ocean ridges, evidence gathered disproving the expanding earth theory and steered discourse, and eventually trust, into the view that it is possible for the lateral movement of continents to exist. The modern plate tectonic theory that blossomed out of this, states that Earth's lithosphere, composed of the solid crust and the upper mantle, is divided into different parts that move horizontally in relation to each other above the semi-plastic asthenosphere (Stern, 2007), which can be seen in Figure 1.4. There are different types of plates, namely oceanic and continental plates and they interact at their boundaries in three different ways (Brenner et al., 2020). Convergent plate margins occur where two plates collide with one another. Where a continental plate meets another continental plate, there is obduction of the plates and formation of mountainous belts. In the case of continental and oceanic plate boundaries, the latter subducts underneath the former and becomes recycled back into the Earth's mantle (US National Park Service, 2020). There are also divergent plate boundaries between two oceanic plates, where the plates pull apart and new lithosphere is created at Mid-Ocean Ridges (US National Park Service, 2020). Transform boundaries exist where two plates slide past each other horizontally (Wilson, 1965). These ideas form the basis of how we view the world and its many processes today. It was a monumental occasion when Tharp and Heezen released their seafloor maps as it was one of the pivotal details that helped to signal that plate tectonic and continental drift theory could be true.

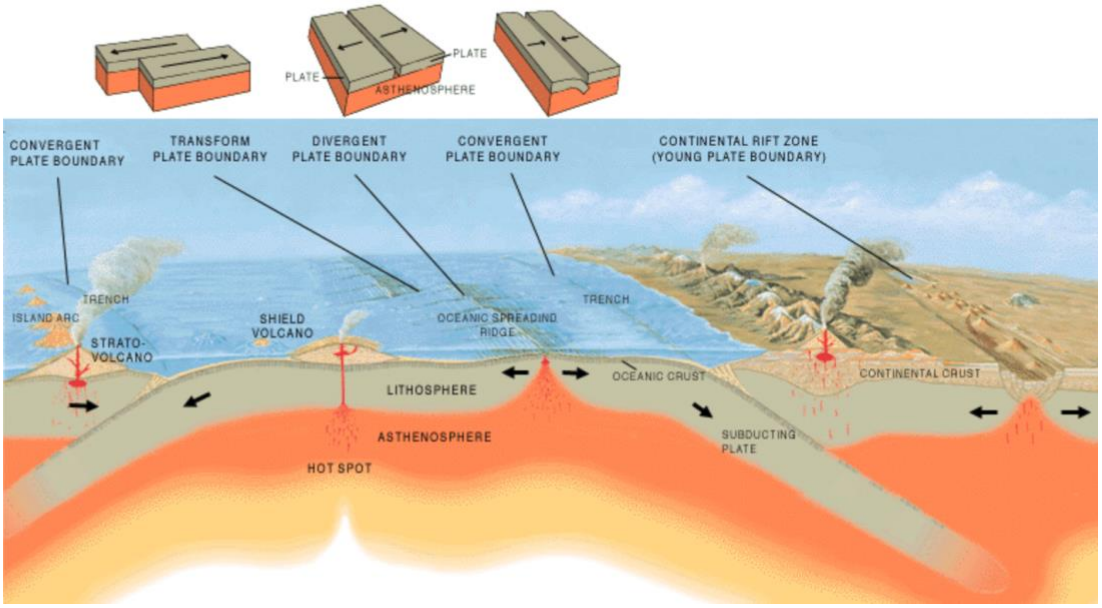


*Figure 1.4. An illustration of the model of plate tectonic theory and its associated features. The rigid lithosphere and crust lies overtop the softer asthenosphere. Convergent, divergent and transform plate boundaries can be seen on the top left of the image with the geological structures present at these margins depicted throughout the image.*

# Fossil Hunter Mary Anning

For centuries, fossils have captured the fascinated attention of many. Among other examples, some of the oldest recounts of fossils included the ancient Chinese possibly interpreting fossils as dragon bones (Zhiming, 1992). What is now known as paleontology, the study of fossils to understand Earth's history has helped progress many ideas, most notably extinction and evolution (Reisz and Sues, 2015). While paleontology today has evolved to utilize more scrutinous, collaborative, and interdisciplinary techniques, as with many science disciplines, our current understanding is thanks to the strong foundations built by many scientists dating back to around the 1700s.

Throughout history, many well-known paleontologists have made discoveries leading to important theories that have expanded our knowledge of the world. However, history often forgets those that are not rich, educated men. Excluded from the London Geological Society and repeatedly left uncredited, Mary Anning is one such example (Davis, 2012). Remembered as the "Princess of Paleontology" and "Geological Lioness", she made crucial discoveries and maintained impressive work throughout her life which have remained relevant to modern day. Despite her mistreatment by scientists and the Geological Society, she persevered and continued to pursue meaningful work, as an important figure for women in the field (Davis, 2012).

## An Early Start

Upon learning about Anning's life, it is hard to ignore the impact young Mary's environment likely had on her taking up paleontology as a career. She was born and raised in the coastal town of Lyme Regis in Dorset, England in 1799 and born into a poor family at a time where making ends meet was difficult for the working-class (Emling, 2011). The recent French Revolutionary and Napoleonic wars further suppressed the poor as food insecurities were common (Olson Jr., 2012).

It was common practice for families, Anning's family being one, to opt to selling fossils in order to supplement income (Emling, 2011). As the wars also limited travel opportunities to mainland Europe for the middle and upper class, a higher influx of these rich tourists in towns such as Lyme Regis served as customers (Cadbury, 2001). Common names given to the fossils such as "snake stones" for ammonites is indicative of a degree of popularity of the fossil selling and collecting business. Some fossils were also thought to have spiritual and healing properties, ideas which are akin to the Chinese dragon bones mentioned earlier. Ideas like these reflect an essence of folklore that must have been prevalent in 1800 Europe.

At a young age Mary started accompanying her father when fossil hunting along the coasts of Lyme Regis (Emling, 2011) along the geological formation now known as Blue Lias (Radley, 2008). During the winter, landslides along the unstable cliffs were common occurrences and attracted fossil hunters as they would often reveal new fossils (Mcgowan, 2002). However, it also made expeditions a treacherous task. The risk involved with collecting fossils along these cliffs manifested when Mary's father fell off a cliff, and later passed away (Mcgowan, 2002). Anning was only 11 years old when her father died, however that did not stop her as she continue to collect and sell fossils to support her family. In fact, only a few months later she made her first major discovery with her brother, Joseph (Emling, 2011).

## Ichthyosaur Fossils

One of the first discovery of the ichthyosaur skull and skeleton is credited to Mary and her brother (Emling, 2011). Specifically, her brother found an ichthyosaur skull and shortly after Mary found the skeleton. The fossil was sold to William Bullock, a respected collector and naturalist who then displayed it in London (Emling, 2011). On display, the fossil caused quite the stir as its unfamiliar form questioned human's knowledge surrounding the history of life on Earth (Torrens, 1995). Today the fossil is still in display in London in the Natural History Museum (Figure 1.5). Its huge length of 5.2 meters was truly shocking at the time and locals thought of it as monstrous (Eylott, 2020).

As Anning was still a young girl at the time, she likely did not do a large amount of, if any, scientific analysis of the fossils herself. The first published accounts of the ichthyosaur fossil

*Figure 1.5. Fossil specimen of Ichthyosaurus communis discovered by Mary and Joseph Anning fixed on cement and framed*

were the descriptions and discussions by Sir Everard Home, a British surgeon, in a paper called: *Some Account of the Fossil Remains of an Animal More Nearly Allied to Fishes than any Other Classes of Animals* (Emling, 2011). His analysis relied heavily on comparing observations with the physical attributes of currently extant species (Home, 1814). Different characteristics of the fossils were said to resemble crocodiles, fish, and platypuses. While some did call it monstrous, there was also a tendency among the public eye to explain the fossil in terms of an existing animal, which was perhaps shared in this paper. The motivation for this would be to deny the existence of animals that were foreign to human knowledge.

Despite Home being of high academic status, when reading the paper today there is a clear lack of coherence and overall confusion in the arguments. While the paper's academic rigour does not age well, it still valuable for its look into the standard of academic publishing at the time. What is particularly interesting was that in this paper as well as five subsequent papers, Homes failed to credit the Anning's for collecting the fossils (Emling, 2011). What is worse is Mary's tedious preparation of the fossils was miscredited to the museum. He writes, "The fossil remains of animals are too frequently brought under our observation in a very mutilated state; or are so intimately connected with the substances in which they are deposited. In the present instance, the pains that have been taken, and the skill which has been exerted in removing the surrounding stone, under the superintendence of Mr. Bullock, in whose Museum of Natural History the specimen is preserved..." (Home, 1814).

His complaint of the cleanliness of other fossils he received, is telling of the time and patience Mary put into preparing the fossils despite her young age. The reason that the fossil gained traction after it was displayed in London can be partly attributed to the larger number of educational facilities as well as overall population there, as opposed to a small town like Lyme Regis. It can be suggested that Anning's location in a small town, and hence reliance on collectors to display her work played a role in her lack of recognition. However, as it become prevalent later, other factors prove to be larger inhibitors.

For now, let us bask in the amazement from the fact that just as a young girl, Anning's discovery helped catalyze discussion of the history of life on Earth. But what exactly was the ideology surrounding life on Earth that were being questioned and why was it prevailing? To answer this, one must consider the force of religion in 19th century Europe.

## Religious Forces

In 1800s Europe, religion was an important feature that affected many areas of life. Anning's family were dissenters of the Church of England which at the time limited her opportunities, notably exclusion from university (Emling, 2011). This combined with her working-class status are likely major factors to why her formal education was limited to Sunday school.

Whether or not she knew it at a young age, Anning's work in paleontology was contributing to an opposing force against the biblical ideology of creationism, broadly that the universe and all life was created by god. The discussion surrounding creationism, while ancient (Sedley, 2007) was still prevalent in the 19th century. Still, it was around this time that many pieces of evidence for evolution were emerging. For example, French anatomist George Cuvier, who is now often referred to as the founding father of paleontology, provided fossil evidence for evolution in 1796, a time when it was widely believed that no species have become extinct (Cuvier, 1825). He did so by identifying fossils of extinct mammoths as being of different from the living elephants at the time. During Anning's time, preliminary support for evolution was still relatively new, and her fossils played an important role.

One of Mary's possessions which was gifted by her brother was the 1801 volume of *Theological Magazine and Review* which included works from her pastor (Goodhue, 2001). While it is not known if she read the book, it is still reflective of the type of information that Mary and other children her age were likely surrounding with. Unsurprisingly one of the pastor's works in the magazine asserted the popular belief that god created world. Another insisted dissenters that they study the emerging science of geology, the study of Earth's physical structure and processes. Ironically, geology, hand in hand with paleontology, were key disciplines in providing substantial evidence for advancing the theory of evolution. These two entries in the book exemplify religion and an emerging scientific era as two prominent yet amusingly contradictory forces in society at the time.

## Developing Mastery

Mary did not allow her lack of education or society's religious views on natural history to stop her from improving her personal work, knowledge, and fluency of the field. Reading advanced scientific papers to learn theories, and previous findings, she often would transcribe them, including detailed illustrations for her personal library. She was extremely dedicated to expanding knowledge, clearly evident by when she was teaching herself French in order to read works by Cuvier (Davis, 2012).

This way, Mary learned techniques in order to efficiently analyze and communicate her personal findings. A common method she inherited was to fix fossils on to a cement frame, (see Figure 1.5), and then making detailed drawings (Davis, 2012). One of Mary's works shown in Figure 1.6 is her sketch of a plesiosaur specimen accompanied with a letter about its discovery.

She sometimes went as far as to use dissection to improve her understanding of anatomy (Davis, 2012). She was able to compare and identify the genus of organisms to make connections between species, while observing their bodies. One such example is Mary's dissection of a Ray, in which she states in a letter to J.S. Miller from the Bristol Museum that, "...I do not think it the same genus, the Vertebrae alone would constitute it a different genus being so unlike any fish vertebrae" (Davis, 2012). It was during such instances where we can truly see the emergence of a powerhouse of a paleontologist. No longer was Mary simply a fossil hunter, she was a researcher on the front ends of paleontology.

Anning commonly impressed those she met, regardless of their scientific status. Her skills harnessed a perfect combination of finding and then developing her fossil specimens, as told by George Roberts, a historian and schoolmaster in Mary's town, it is clear that Anning had a keen eye and skill for fossils (Taylor and Torrens, 2014). Noted by Ludwig Leichhardt, a botanist and ecologist (Fensham, 2013) as "strong, energetic...tanned and masculine in expression", further commenting on her commitment to the field as "every morning, and after every stormy sea, she goes walking and clambering about on the slopes of the Lias to see whether fossils have been brought to light by falls of rock or wave action" (Torrens, 1995).

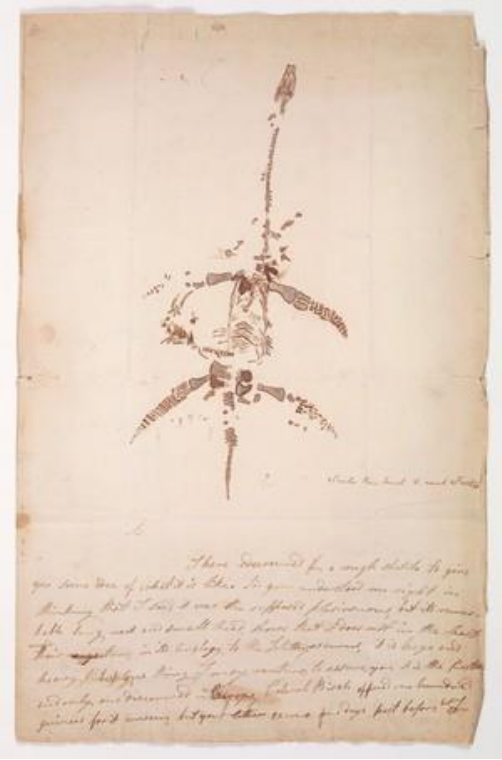


*Figure 1.6. Letter and drawing from Mary Anning announcing the* Plesiosaurus *fossil she discovered in 1823*

Those that spoke with her were often thoroughly impressed by her level of expertise despite her upbringing and social status. One such example was Lady Harriet Silvester, a widow of a former recorder based in London who stated "...should be so blessed, for by reading and application she has arrived at that degree of knowledge as to be in habit of writing and talking with professors and other clever men on the subject, and they all acknowledge that she understands more of the science than anyone else in this kingdom" (Torrens, 1995).

## Collaborations and the Geological Society

The Geological Society of London was founded in 1807 by members of an established science debate club (Jackson, 2008). As mentioned, Mary Anning or any woman for that matter, was not allowed to join the society or sit in meetings as a guest. This sexist policy stayed this way for the entirety of Mary's life as it was only lifted over a century later in 1919. The only people to publish scientific descriptions of fossil specimen were male (Mcgowan, 2002). When the fossils were those dug and prepared by Anning, her name was more often than not left out. Mary was likely one of many who were left uncredited during this period, as fossils were often found by the working class when out on the job such as during construction work (Torrens, 1995). This is suggestive of a superiority complex of the upper class as researchers had no problem crediting the wealthy, male 'collectors' who simply purchased the fossils.

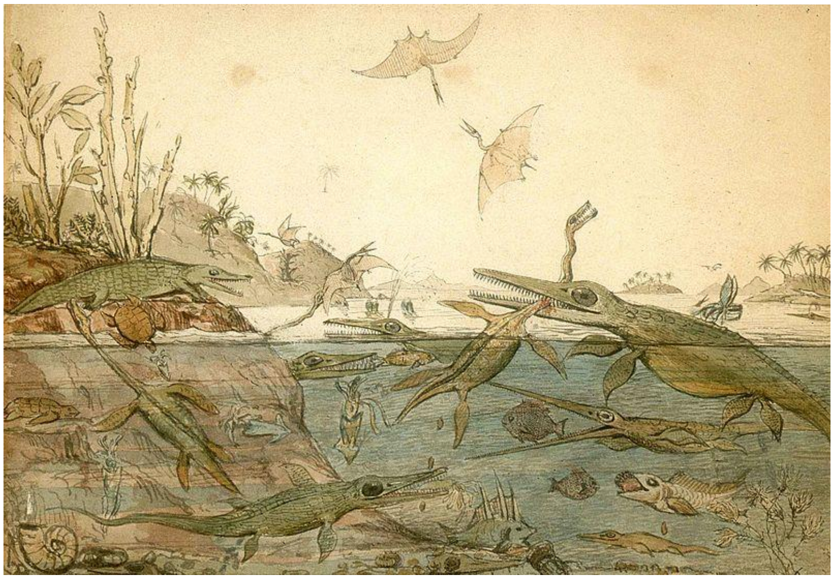
Receiving this constant dismissal by the scientific community, Mary did what she could in order to stay involved in paleontology. While her work in her family business started as a strive for survival, it became increasingly clear with her age that it was also her passion. Despite the exclusion for the geological society and lack of adequate credit, her ability to be very collaborative allowed her to stay involved in her passion. The simplest example of this would be that she would often be seen going fossil hunting with a variety of others in the paleontology network such as Henry De la Beche, a renowned geologist and paleontologist, and William Buckland, a geology professor (Emling, 2011). In spite of the resentment Mary must have felt for such rich, white men, her ability to collaborate with them shows her good character as she focusses on working towards the common goal of uncovering the Earth's mysteries. It can also be telling of her understanding of the importance of networking. In fact, Mary took on an apprentice Charlotte Murchinson, upon request of Charlotte's husband, another Paleontologist at the time (Emling, 2011). She aided in making observations, illustrations, sketches, and even helped introduce Mary to some of her husband's colleagues.

Anning' s expertise in the field was highlighted though an interaction with collector Thomas Hawkins as he was putting together ichthyosaur fossils (Mcgowan, 2002). She had commented that Hawkins had a tendency to "make things as he imagines they ought to be", in reference to how Hawkins inserted fake fossils to falsely complete skeletons. While the fraud was later uncovered, Hawkins was still initially able to sell the ichthyosaur skeletons to the government, revealing the lack of quality control in the review process. Anning's criticism also highlights the contrast in integrity between herself and Hawkins despite not being part of the geological society herself where presumably proper standards of work is taught.

Fraud like this was not uncommon and one instance even involved Anning's work. When English geologist William Conybeare presented Anning's plesiosaur skeleton, it was falsely accused of being illegitimate by Cuvier due to its unusual vertebrates (Emling, 2011). Although not formally credited for the discovery, the situation still could have caused a detrimental effect to Anning's reputation and other professional opportunities. This was yet another example of Anning's work being handled and discussed solely by men that were not involved with the discovery or preparation. When compared to Hawkin's case, a sexist undertone is revealed. If only Anning was able to join the geological society and present her work herself, the confusion could have been avoided.

On a more positive note, one of Anning's most notable collaborations was with Henry De la Beche in 1830. Beche created a water colour painting depicting a scene of prehistoric life based on fossils that Mary had found (Rudwick, 1995). This painting named *Duria Antiquior* (Figure 1.7) was notably the first circulated paleoart, which are artistic representation of what prehistoric life could have looked like based on evidence. In the piece's focal point in the middle right, you can see the depiction of an ichthyosaur biting a plesiosaur's neck. Paleoart remains as an important and exciting medium for communication data and interpretations of paleontological findings.

*Figure 1.7.*
Duria Antiquior, *watercolour painting by the geologist Henry De la Beche based on fossils found by Mary Anning*



## Legacy

Despite the barriers put in her way, Mary made many key contributions to palaeontology. Her determination and quality of work is evident not only by her work but also many positive testimonials. While often left uncredited, her quality work spoke volumes and slowly became a centrepiece in the local geological community. Charles Dickens wrote "The carpenter's daughter has won a name for herself, and has deserved to win it" (Dickens, 1865). It was only after she died of breast cancer at the age of 47 when the Geological Society contributed to create a stained-glass window in her memory (Mcgowan, 2002).

A portrait of Mary by an unknown artist, as seen in Figure 1.8, now hangs proudly at the Natural History Museum in London (Eylott, 2020). As time goes on, Anning's deserved recognition continues to be brought to the spotlight. Her story not only serves to inspire, but also demonstrates how far we have come in improving the scientific community and providing scientific opportuniti es for all.

*Figure 1.8. Portrait of Mary Anning with her dog Tray*

# If Mary Were Here Today

What if Mary was here today in the 21st century? What observations would she have made surrounding her recognition? What would she observe is going on surrounding the diversity appreciation of paleontologist working today? And what would she learn about how fossil finds form Lyme Regis continued to expand our knowledge of prehistoric Earth?

## Modern Recognition

Turned away from becoming a member of London's Geological Society and labelled an amateur, (Torrens, 1995). Mary never properly received adequate acknowledgement for her achievements at the time. It was through the work of historians who carefully tracked letters, which revealed Anning expertise notably as an astute debater in the field (Emling, 2011). Despite this, Anning played an important role for opening the door for other women to pursue careers in science as she persevered and continued in a field that never fully appreciated her during her lifetime.

With our knowledge of the barriers she fought, Mary has now become an important and much respected figure in science. Residing in the Natural History Museum located in London are many of Mary's distinguished findings, including the ichthyosaur, plesiosaur, and pterosaur (Eylott, 2020). The exhibit attracts many of visitors, intrigued by Anning's findings of early creatures.

Throughout the years, many modern depictions of Anning and her story have been made in media including books and film. Most recently, in 2020, a biopic film called *Ammonite* released based on Anning's life (Gutcaterman, 2020). The film can be critiqued for a speculatory romance between Mary and Charlotte Murchinson, who she once took as an apprentice, as it seems Mary's story was simply used as a canvas for performative lesbianism. Despite this, like much of the fictional media based on Anning, the film still manages to communicate Anning as a strong self-sufficient pioneer in paleontology. Other recent acts of recognition include the naming the plesiosaur genus *Anningasaura* after Anning in 2012, (Vincent and Benson, 2012) as well as the species *Ichthyosaurus anningae* in 2015 (Lomax and Massare, 2015). Unlike other leading paleontologists, no scientist had named a species after Anning during her lifetime.

## Battling Sexism

Some presume that Mary was an advocate and feminist in her time. She states in an unpublished essay in her journal: "And what is a woman? Was she not made of the same flesh and blood as lordly Man? Yes, and was destined doubtless, to become his friend, his helpmate on his pilgrim-age but surely not his slave" (Goodhue, 2001). Despite the importance of women in paleontological discoveries, it wasn't until 1904 that women were admitted into the Geological Society of London (Davis, 2012). And today, while there is relatively more diversity, the field remains predominantly male, and women are often mistreated and overlooked.

Although it may seem like a thing of the past, women are still often harassed, interrupted, ignored, and told they are distracted by male counterparts, creating potential for division between colleagues, in a field that thrives off collaboration. Due to this, initiatives and associations have been launched to try to highlight diversity, community, and awareness for women in paleontology. One such initiative was 2014's The Bearded Lady Project (Marsh and Currano, 2020). What started as a joke, in which women paleontologist posed with fake beards, became a documentary film and photography project based on two goals, one in which to celebrate the hard work and dedication of women in the field, and the second to highlight prejudices they face.

## Back to Where it Began

Today Lyme Regis, "The Pearl of Dorset" England, has become a notable tourist spot as it boasts its cliffs and scenery as well as the very essence of Mary Anning's life (Lyme Regis Town Council, 2020). Fossil hunters have continued to visit the site for hundreds of years, spending time at the lower Jurassic Blue Lias formation of the Church Cliffs seen in Figure 1.9, the same layer at which Mary found her ichthyosaur and plesiosaur. The bay consists of cliffs composed of medium to thinly bedded shales, limestones, and sandstones with an abundance of fossils, including ammonoids, belemnites, bivalves, gastropods, and nautiloids. Other less common fossils include brittle stars, coprolites, crinoids, ichthyosaurs, plesiosaurs, and sea urchins (Davis, 2009).

With modern geological understanding of stratigraphy and a more interdisciplinary approach, we have more accurate knowledge about the site than ever. This includes more information about the depositional environments giving insight into how prehistoric England looked. For example, minor bedforms of the Blue Lias formation, specifically within the Early Jurassic Shale Member which are composed primarily of mudstone, has been attributed to of weak seafloor erosion (Radley, 2008). As well, many trace fossils of ammonites and arthropods are well preserved. Together, this information can suggest the activity of distal storm flows that occurred below the storm wave base around this site in prehistoric times.

*Figure 1.9. Sea cliff of the Blue Lias Formation at Lyme Regis made up of an alternation of Lower Jurassic dark claystone and limestones*

As the area is still commonly visited by both tourists and paleontologists, fossils of varying rarities continue to be found. One particularly interesting find within the area occurred in 2016, when fossil hunter Chris Moore who had been filming with Sir David Attenborough found a new species of ichthyosaur. The fossil was determined to be approximately 200 million years old and had shockingly been preserved well enough to contain preserved skin (Mulcahey, 2018). This find helped develop what scientists believe regarding the appearance of these ancient predators, and is also evidence of how modern paleontology is continuing to broaden our knowledge to this day.

# John Tuzo Wilson: Canadian 'Rock'-star

One of the most intriguing scientific anecdotes that can be shared is the fact that the development of quantum mechanics took place several decades before modern plate tectonic theory. This seems odd considering the perceived complexity of each of the fields, but like any scientific endeavour the development of plate tectonic theory was a long and rigorous process that required new data to shape shifting hypotheses.

During the 20th century the majority of geoscientists around the world held one of two main views regarding the Earth: the contraction theory or the expansion theory (Wilson, 1963). These theories are best described as "fixist" in nature, where proponents of the theory believed that the continents of the Earth were fixed in place (Sudiro, 2014). To explain the geologic similarities between the coasts of continents, the expansionist theory argued that the Earth was constantly expanding due to internal radioactive heat or a decrease in the gravitational constant, which results in the continents being moved farther away from each other as the Earth expands (Sudiro, 2014). Alternatively, contractionists believed that the Earth was cooling as it got older, resulting in contraction and shifting of the continents (Jeffreys, 1924). The problem with these fixist theories is that they each independently failed to explain different important geophysical observations.

Given the failure of the fixist geophysical models, German meteorologist Alfred Wegener proposed a new model in 1912 — continental drift. In Wegener's model the continents were not fixed in place, instead they moved around by plowing their way through the oceanic crust (Wegener, 1915). Unfortunately for Wegener, the idea of continents plowing their way through solid rock seemed ridiculous to geoscientists of the time, and his "mobilist" view was tossed aside and largely forgotten for several decades, leaving the aforementioned fixist theories to reign supreme. It would not be until Arthur Holmes published his theory of mantle convection in 1944 (Holmes, 1944) and Harry Hess identified sea floor spreading in 1960 (Hess, 1962) that Wegener's mobilist theory would be reborn in the form of plate tectonics. In addition to the previously mentioned researchers who were crucial to the development of modern plate tectonic theory, there is another man who played a key role. His name is John Tuzo Wilson (see Figure 1.10), a Canadian, and he is considered to be one of the most important figures in the development of this plate tectonics.

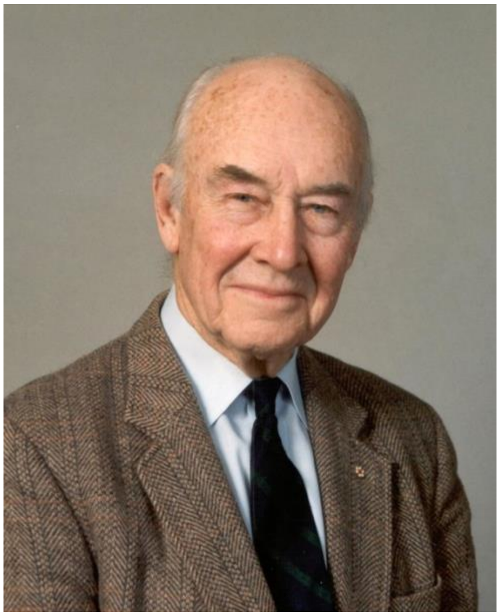


*Figure 1.10. Photograph of John Tuzo Wilson, taken in 1992. Tuzo is the famed Canadian geoscientist who helped to develop the theory of plate tectonics.*

John Tuzo Wilson, known internationally as 'Tuzo', was born on October 24, 1908 in Ottawa, Ontario. Sixty years ago, an international movement known as the "Revolution in the Earth Sciences" took place, with Tuzo acting as a key player in its launch (Garland, 1995, West et al., 2014). Tuzo, who is now a world-renowned geologist and geophysicist, had a life ambition to understand global geology. He was one of the most influential and imaginative Earth scientists of his time, and is regarded by many as the father of academic geophysics in Canada (Garland, 1995, West et al., 2014). In relation to plate tectonic theory, Tuzo was an interesting figure, as he was originally strongly opposed to the idea that continents could move. In fact, Tuzo was a very firm believer in the contracting Earth theory since it could provide a fairly strong explanation for mountain building (West et al., 2014). Several key events in Tuzo's life led to him changing his views, and resulted in one of the most important developments in the Earth sciences.

## Education and Influence

While in high school, Tuzo gained some of his first geological exposure through summer employment with the Geological Survey of Canada, which regularly employed students as junior assistants on survey parties. Through this work, Tuzo was provided with not only an introduction to geology, but valuable experience in woodcraft and wilderness travel (Garland, 1995). Upon completion of high school, Tuzo enrolled in the Honours Programme in Mathematics and Physics at the University of Toronto. Unfortunately, at the time there was no programme in geophysics, nor a convenient way of studying both geology and physics, so he continued to work on geological field parties in the summers. Interestingly, Tuzo found the instruction and experimentation in physics to be tedious and behind the times, despite major breakthroughs occurring at his own university. Regardless, he found more inspiration in his summer work until a notable shift in the Department of Physics. Professor Lachlan Gilchrist was asked by the Canadian Government to join an investigation regarding methods of geophysical mineral prospecting. This shift would cause Gilchrist to influence Tuzo in two major ways: first, as he employed Tuzo in the summer on geophysical focused investigations, and second by convincing the University to institute a programme in physics and geology. Consequently, Tuzo gained experience operating magnetometers and electrical field instruments, while also being able to study what he later recalled as "an ill-assorted mixture of geology and classical physics" (Garland, 1995).

After graduating as the first physics and geology student in Canada in 1930, Tuzo was financed by a Massey Fellowship to pursue a second B.A. degree at Cambridge. He made many connections there and recalls having to strongly reflect on how limited his own grasp of mathematics was. Tuzo attended Princeton for his Ph.D. studies, after being attracted by Professor M. Field's charisma and high standing as an Earth scientist at the time. Field would serve as a notable contributor to Tuzo's overall progression due to his ability to launch major research projects, despite limited financial resources, and convince young scientists to carry them out. Tuzo was assigned to Professor Taylor Thom, who, although regarded as a great teacher, was known to leave research students very much on their own. As such, Tuzo was assigned an area in the Beartooth Mountains in Montana to conduct his thesis research and given $200 to buy a car and live there for a summer. It was during this time that he realized many of the then current ideas regarding mountain building were very inadequate (Garland, 1995; West et al., 2014).

Upon graduation with his Ph.D. from Princeton, Tuzo joined the Geological Survey of Canada as an Assistant Geologist in 1936. At the time, the primary effort of the survey was conventional mapping of the country, with all members of staff leading summer field parties. First assigned in southern Nova Scotia in order to finish incomplete gold exploration-era map-areas. Although this region lacked the thrust-faulted terrain of the Beartooth Mountains, Tuzo would strongly benefit from this work by developing an interest in the overall geology of the Maritime Provinces, which would serve him well when he later studied the oceans. Additionally, it was through later work with the Survey in the Northwest Territories that he established air photos as a geological tool- an innovation for the time (Garland, 1995).

## Tuzo and Contractionism

After serving with the Royal Canadian Engineers in WWII, Tuzo accepted the position of Professor of Geophysics in the Department of Physics at the University of Toronto in 1946. There Tuzo would establish the 'Geophysics Laboratory' where research would apply physics to the broad problems of the Earth. He would conduct important research and help pioneer a wide array of topics such as geochronology, but his early work with the applied mathematician A. Scheidegger was among the most influential. Through this collaboration, the methods of failure of a cooling and contracting Earth were studied, as many island groups and portions of mountain chains on the continents were found to form well-defined arcs. Together, they were able to demonstrate that under certain conditions, the Earth, consisting of a hot core, rapidly cooling upper mantle, and an already cool crust, could fail in arcuate forms. Wilson and Scheidegger published a paper in 1950 that was extremely well received by the Earth science community, who had long sought a generalized theory of mountain building. This acceptance was in spite of the fact that the contracting Earth theory failed to explain repeated periods of mountain building. Interestingly, the apparent ability of the contraction theory to explain initial mountain formation is believed to have strongly hindered Tuzo's ability to accept continental drift, as Tuzo maintained his views for nearly a decade after he published this paper — even when challenged on the topic by other scientists (Garland, 1995; West et al., 2014).

## Transition to Mobilism

It remains unclear as to exactly why, but at some point, shortly after 1957, Tuzo abandoned his former belief that the continents were fixed and began examining the effects of large-scale displacements of continents and oceans. His transition to a mobilist viewpoint may be attributed to reading the work published by Harry Hess and Robert Dietz in the early 1960's. In fact, Tuzo's acceptance of ocean-floor spreading and continental displacement was first demonstrated by his contribution to discussion of R.S. Dietz's paper in 1961. It was at this point that Tuzo readily accepted most of the evidence provided by Dietz's comprehensive model of upper mantle convection and the spreading of the ocean floor from ridges, in addition to Harry Hess' early postulates. Tuzo can be quoted as saying "In two recent papers Dietz and Hess have made similar proposals in which, guided by new discoveries made about paleomagnetism and the ocean floors, have combined features of several older theories into one which appears to fit many observations" (Wilson, 1961). He was particularly welcoming of the fact that the two models of Earth behaviour he had helped develop could still be utilized aside from "admitting some features of compression in mountains".

Tuzo's foremost remaining objection stemmed from Dietz's inability to fully provide a mechanism for continental crust to thicken under continental shields. He further pointed out that if over time continents amalgamate material from the interior, the salic crust must thicken everywhere in order for isostasy to maintain continental freeboard. Dietz's vision foresaw the idea of 'underplating' of salic materials, but only around continental margins (Garland, 1995). This objection was almost fully answered shortly after, as the full significance of deep subduction zones and presence of relict subduction zones under continental interiors were acknowledged. This stark change in view highlights an admirable quality of Tuzo that made him such a good scientist: he was not afraid to change his stance on a subject he had devoted his life to when presented with new and better evidence.

The conversion of Tuzo's stance was further substantiated and finalized by a subsequent discussion of the Canadian Shield and related tectonics. At this point in time, Tuzo disclosed that "continental blocks can join and rift at random. The fact that two provinces of the Canadian Shield have been together during post-Cambrian time does not necessarily mean that they were formed close together or that the sediments lying on one province were derived from the province now beside it" (Garland, 1995). With his stance fully transformed, Tuzo then focused on studying the Atlantic Ocean. Once again returning to the Maritime provinces of Canada, he began investigating the major fault system present there. A system of left-lateral transcurrent faults he later referred to as the Cabot fault, which was according to be an extension of the Great Glen fault of Scotland based on similar senses of displacement. This research left Tuzo with no choice but to acknowledge the possibility of major continental displacement, as the apparent connection between the two systems yielded compelling evidence that the Atlantic Ocean was closed in pre-Jurassic time. This demonstrated a significant change in thought regarding his prior support of continental fixation (Garland, 1995).

## Hot Spots

It is clear Tuzo's stance had further shifted by early 1963, as he had not only accepted ocean-floor spreading and continental drift, but was an active researcher and contributor in propelling these theories. Notably, his analysis of the ocean island ages revealed both their extreme youth in comparison to continents, but also a trend

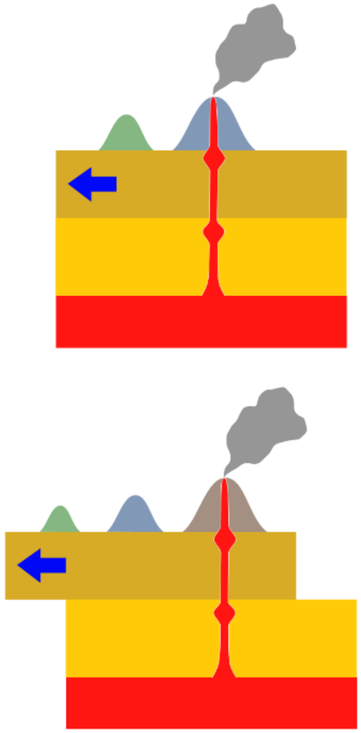
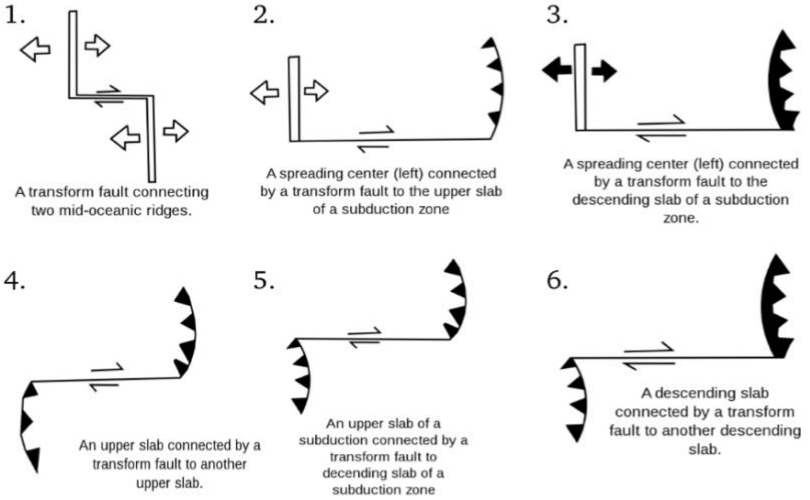


*Figure 1.11. Cartoon diagram of the formation of island chains from a mantle plume hotspot. One of Tuzo's main contributions to plate tectonic theory was his work on developing the idea of hotspots.*

toward older ages with increasing distance from a mid-ocean ridge. These discoveries would serve as strong evidence in confirming that ocean-floor spreading was occurring from these ridges, and accepted a system of mantle convection currents as the driving mechanism. Though the idea of plate tectonics had become an interesting and popular idea regarding the movement of the continents amongst geoscientists very quickly, there were several anomalies that had yet to be explained. One such of these enigmatic geological features was the presence of island chains along where there was no known mid-ocean ridge or fault. The most well-known and well-studied of these islands chains is Hawaii in the Pacific Ocean, which Tuzo became personally interested in after ascending Mauna Loa (West et al., 2014). In 1963, researchers at the time were struggling to piece together how the Hawaiian islands could be so geologically similar, yet so different in age. Tuzo offered a potential solution. Working from previous postulates by Menard (1960) and Runcorn (1962), Tuzo suggested that mantle convection currents could result in a mantle plume, in which hotter magma from the lower mantle is brought up near the surface, resulting in the formation of a volcano (Wilson, 1963). These volcanoes could then be moved away from the mantle plume if the upper mantle and crust move at a faster velocity than the lower mantle (Figure 1.11). Tuzo's idea was crucial to explaining the problem of island chains that were not near any mid-ocean ridges, and provided further evidence to support the budding theory of plate tectonics. This idea also complemented the work done by Vine and Matthews (1963), which would introduce the concept of a global framework of reference points provided by plumes or hot spots (Garland, 1995).

## Transform Faults

By the end of 1963, there was a general acceptance by the Earth science community regarding the main concepts of ocean-floor dynamics. Two types of plate boundaries were recognized: accreting boundaries, designated by proximity to mid-ocean ridges, and consuming boundaries that were designated by Benioff zones of deep-focus earthquakes, later known as subduction zones. However, the formulation of a global pattern of lithospheric plates remained unfinished, as not all plate boundaries fit within this model. Tuzo took the initiative to further concentrate on the study of the ocean floor, and subsequently spent a term studying at the University of Cambridge's Department of Geodesy and Geophysics in the winter of 1964-1965 (Garland, 1995). This environment would prove to be more than ideal, as he was accompanied by the likes of Fred Vine, Drummond Matthews, and Harry Hess. At this time, it was widely known and accepted that the major ocean ridges demonstrate frequent perpendicular offsets by fractures that are seismically active. Tuzo was able to recognize that the conventional theory of faulting, when applied to a medium that is conserved, must be altered as the ocean floor is non-conserved (Garland, 1995). From this idea, Tuzo generated arguably his most significant contribution to plate tectonic theory - the identification of transform faults. These faults are regions at which the plates move horizontally past one another, and the motion of the tectonic plates are transformed from one form to another (Figure 1.12). For example, a spreading centre with a large amount of vertical motion may be converted into horizontal motion at the ocean floor (Burke, 2011). Tuzo recognized that the existence of these faults at plate margins requires crustal displacement, and therefore could provide some of the strongest evidence to date in support of plate tectonics (Wilson, 1965). Tuzo's recognition of the transform fault as a type of plate boundary revolutionized the analysis of global plate motion kinetics. Tuzo would regularly teach audiences about transform faults and the trace of a hot spot, using a folded-paper model to represent the spreading ocean floor which he would then pass over a flame to represent the Hawaiian islands (Garland, 1995).



1. A transform fault connecting two mid-oceanic ridges.

2. A spreading center (left) connected by a transform fault to the upper slab of a subduction zone

3. A spreading center (left) connected by a transform fault to the descending slab of a subduction zone.

4. An upper slab connected by a transform fault to another upper slab.

5. An upper slab of a subduction connected by a transform fault to decending slab of a subduction zone

6. A descending slab connected by a transform fault to another descending slab.

*Figure 1.12. Simple cartoon diagram showing the different types of transform boundaries between different plate margins. Transform margins were first identified by Tuzo and helped to explain the movement of continental plates.*

## The Wilson Cycle

Tuzo once more returned to the area of the Cabot-Great Glen to study the north Atlantic Ocean. In his return he was able to form his third major contribution to the understanding of plate tectonics. Tuzo identified that there was strong evidence for the closing of an earlier Atlantic and reopening along a similar line (Garland, 1995). He also found that there were small areas of fossiliferous rock ‘left on the wrong side of the ocean’. From these observations Tuzo put forward another of his brilliant ideas in the form of the ocean basin lifecycle. This cycle, now referred to as the Wilson cycle (Figure 1.13), describes the process in which a continent will diverge to form an ocean basin and then converge back together to form a single continental landmass (Wilson, 1966). This idea was critical for understanding that the process of plate tectonics has occurred throughout all of recorded Earth history (Burke, 2011).

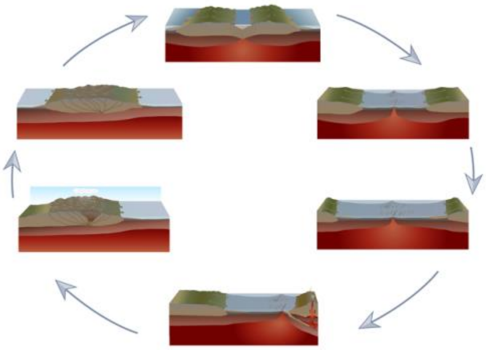


*Figure 1.13. Diagram showing the process of the Wilson cycle, whereby ocean basins open and close. Tuzo developed this idea after examining rocks on the Atlantic coast of Canada.*

## Legacy

Over the following two decades of his life, Tuzo would further contribute and substantiate his findings to the whole of the international Earth science society, all while undertaking many notable tasks and roles. He served as the principle of Erindale College (1967-1974), Director General of the Ontario Science Centre (1974-1985) and even as Chancellor of York University (1983-1986). In 1985, Tuzo would resettle at the University of Toronto, once again turning his full focus to global tectonics until his death in 1993 (Garland, 1995). Tuzo’s tenacious and unrelenting drive toward understanding the geophysical processes that govern the Earth are characteristics of a great scientist. He was passionate and curious, but not unwilling to change his views when presented with new information. Any Canadians reading should feel proud to know that one of the most important theories in the Earth sciences has roots that are inextricably linked to Canada and John Tuzo Wilson.

# Plate Tectonics and Aerial Photos

The applications and societal context of the knowledge gained from the plate tectonic theory are nothing less than immense. Through understanding how the Earth formed and the mechanisms behind continental drift, there are a wide array of societal and scientific implications. It has been previously established that plate tectonics is one of the most important developments in the history of Earth science as it allows researchers to understand how the Earth’s surface changes over time. During John Tuzo Wilson’s time studying plate tectonics, the principal method to study the movement of tectonic plates was through the use of magnetometers taking measurements at mid-ocean ridges (Dietz, 1961; Hess, 1962). Unfortunately, this technique is slow, expensive, and is constrained to measuring boundaries that are on the ocean floor. Therefore, it was extremely important to develop a new, more efficient and more effective method of measuring tectonic activity.

## Drones and Air-photos

This need has been met using a technique that

*Figure 1.14. Early aerial photograph taken of Hamilton, Ontario and Burlington, Ontario from a plane in 1959. Aerial photos are extremely helpful in mapping large geographic areas. Note the McMaster University campus near the mid to lower left-hand side.*

was also pioneered by John Tuzo Wilson - aerial photography. As the name may suggest, aerial photography is the process of taking detailed photographs from the air that can be used to analyze specific geologic features or to map a region (Natural Resources Canada, 2008). An example of an aerial photograph is shown in Figure 1.14. These photographs can be taken using a variety of instruments, such as balloons, planes, helicopters, and drones. The exact method used to take aerial photographs depends on the purpose of the study, size of the field site, accessibility of the area, and the required resolution of the photos. Given these criteria, unmanned drones are rapidly becoming the instrument of choice for geoscientists all around the world as they provide great dexterity, range, and resolution of images at a relatively low cost (Bonali et al., 2019; Angster et al., 2019; Sherwood, 2016; Behrman et al., 2019).

In fact, drones have recently been used to study volcanic-tectonic rifting in the Theistareykir Fissure Swarm of Iceland and to measure strike-slip rates of the Walker Lane shear zone in Nevada (Bonali et al., 2019; Angster et al., 2019). The island of Iceland sits on both an active hotspot and a divergent plate boundary, which makes it extremely prone to volcanism and seismic activity (Karson, 2017; Bonali et al., 2019). The use of unmanned drones allows geoscientists to map a larger area of potential seismic and volcanic activity than would be possible with ground-based fieldwork. This helps modern geoscientists obtain a better understanding of volcanic-tectonic processes on land and can allow them to make better models and predictions for future seismic and volcanic activity (Bonali et al., 2019). In contrast, the Walker Lane shear zone in Nevada comprises a complex system of faults that accommodates a large portion of the transform motion between the North American and Pacific plates (Angster et al., 2019; Koehler, 2019). Measurement of the strike-slip rates of faults in this zone allows geophysicists to predict the recurrence rate of earthquakes, and aerial photography using unmanned drones allows for a greater area to be studied, resulting in more accurate seismic recurrence predictions (Angster et al., 2019).

## Satellite Imagery

Although aerial photography has allowed geoscientists to map and analyze large field sites much more easily, it is still a challenge to analyze global-scale tectonic processes using a drone or plane. Recent technological advances have greatly expanded the geographic range of tools available to geoscientists, advancing past the atmosphere to space through the use of satellites as in Figure 1.15 (El-Mowafy and Bilbas, 2016; Shi et al., 2016; Koehler, 2019; Angster et al., 2019). Scientists with organizations such as NASA have managed to chart the motion of dozens of plates using signals to pinpoint locations and track tectonic plate movement from a constellation of orbiting navigation satellites. The data collected through use of these satellites will help scientists to better understand the motion of plates, an understanding that many hope will help predict future volcanic eruptions and earthquakes. Such a breakthrough would be revolutionary for society in a number of ways; helping those located in regions where high magnitude earthquakes are predicted to evacuate, or at the very least brace for impact, effectively saving lives (NASA, 1988).

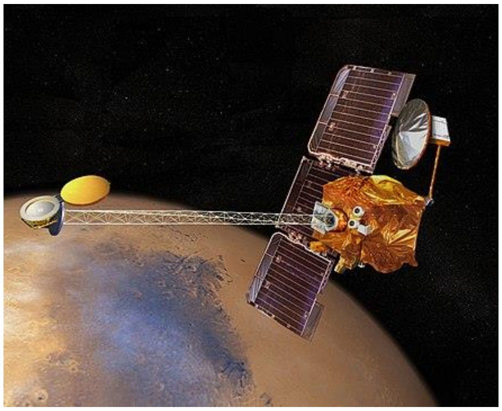


*Figure 1.15. Computer generated image of the Mars Odyssey satellite that was used to record volcanic activity on the surface of Mars. This highlights how far this technology has come, as satellites can now be used to map geologic processes on other planets than our own.*

Such usage of satellites falls within the confines of remote sensing, defined as the "continuous monitoring over a variety of spatial and temporal scales that can help to generate timely information" (Senay et al., 2015). Satellite imaging serves to provide a systematic and synoptic framework for the better understanding of the complex system of geophysical phenomena that often lead to natural hazards (Tralli et al., 2005). The use of satellite imagery in geoscience research has opened new avenues of study and allowed for questions that could not be answered to finally be addressed. This incredible and powerful tool would not be where it is today without the initial push from John Tuzo Wilson to use aerial photographs in studying plate tectonics. Like many of the great scientists of the past, Tuzo's work and contributions have made impacts beyond his own field of research and advanced geoscience altogether.

# Early Paleontology

"Our beautiful planet is indeed worthy of our study; it was once our cradle - it will soon be our grave..." - Gideon Mantell

Eighteenth century Britain was a time of development for the field of geology. Before the eighteenth century, fossils were thought to be acts of divine virtue and any person who spoke against this belief would be accused of heresy. By the eighteenth century, such theories were being questioned. Although religion still played a large role in the lives of the masses, some individuals were beginning look towards scientific logic. Such individuals founded The Geological Society of London in 1807, with the majority of this society composed of individuals in the higher class, who monopolized the powerful positions. As social class played a dominant role in the scientific community, it was difficult for the voice of middle-class scientists to be heard. The explosion of scientific findings turned geology into a competitive field, with interesting contributions from many scientists, including Gideon Mantell.

## Gideon Mantell

*Figure 1.16. Gideon Mantell in 1837. In his youth, he was perceived as having a style of "brilliancy and eloquence".*

In 1770, the county of Sussex, England, saw the birth of Gideon Mantell (Figure 1.16). Mantell was naturally drawn to geology from a young age. He explored local pits and quarries, leading him to uncover fossils of corals and fishes. At the age of fifteen, Mantell became an apprentice to a local surgeon. At the age of seventeen, after his father's death, Mantell arrived in London to study medicine with a bag full of fossils collected from Sussex (Cadbury, 2001).

As a shoemaker's son, Mantell was largely invisible to the scientific community, yet a certain meeting with a renowned geologist was about to set him on his future course. James Parkinson was a well reputable doctor and geologist whose work fascinated Mantell. Inspired by his work, Mantell decided to conduct a systematic study of the fossils in Sussex. He gained his diploma from the Royal College of Surgeons at the age of 21 and faced a heavy workload as the county doctor. He used his very minimal leisure hours to embark on geological expeditions. Mantell found many different species of ammonite, with one species being named after him, the *Ammonites mantelli*. Mantell began to slowly gain confidence and establish connections, allowing him to extend his knowledge beyond Sussex (Cadbury, 2001).

While visiting a quarry at Cuckfield in 1820, Mantell discovered giant bones that did not resemble the *Ichthyosaurus*, the only large fossil identified at the time. This creature was chunky and solid, uncharacteristic of the slender and hollow bones of *Ichthyosaurus*, suggesting that this was not a sea creature (Cadbury, 2001). This was further verified by the fact that the fossils were quite fragmented, which is likely for land creatures as they fall prey to other animals or are scrambled by wind and rain. He believed that the fossils belonged to a crocodile. One morning, he and his wife were performing medical rounds when she noticed a strange shape in the pile of stones on the side of the road. It was a flattened fragment of a giant tooth with "very remarkable character" and "unlike any that had previously come under" Mantell's observation (Mantell, 1851). This tooth was about an inch long, very smooth, worn out, blunt in shape, and brown in colour. This was clearly not the tooth of a crocodile, as it was flattened and had a grinding surface, which made it much more likely to belong to an herbivorous mammal. With more consideration, Mantell began to think that the tooth may have belonged to a lizard, but there were no known herbivorous reptiles (Mantell, 1833). Mantell was missing a fossilized jaw, which could provide clear evidence of whether the tooth belonged to a mammal or a reptile (Cadbury, 2001).

In 1821, Mantell had the opportunity to chat with Charles Lyell, which marked the beginning of an enduring friendship between them. Lyell shared news of huge reptilian bones in Oxford, which made Mantell's idea of a giant lizard seem less preposterous. In May 1822, Mantell published *Fossils of the South Downs*, which recorded any progress he had made with the fossils from Weald (Mantell and Mantell, 1822). He included a brief description of the herbivorous teeth under the heading "Teeth and Bones of Unknown Animals", as he wanted to avoid controversy by suggesting he had found an herbivorous lizard. Notably, this was the first attempted scientific description of a dinosaur.

He attempted to share these fossils at a meeting of the Geological Society, where they quickly shut down his ideas of an herbivorous lizard and claimed that these teeth belonged to either a large fish or a mammal. On June 18, 1823, Mantell shared his tooth with Cuvier, who suggested, to Mantell's dismay, that the teeth belonged to a herbivorous mammal and not a reptile (Cadbury, 2001). This defeat, along with increased financial problems, pushed Mantell into a deep depression, with his ambition being replaced by frustration and loss.

Despite the setbacks, Mantell continued to diligently search, and fruitfully found that the serrations on all the teeth did not match that of previous discoveries. Mantell reasoned that if he could prove that there was a replacement cycle in the teeth, the creature must be a reptile without the need for a fossil jaw. He spent the next few months accumulating a series of teeth, showing the graduation of young animal teeth to the late-stage teeth. Mantell decided to try his luck again with Cuvier in 1824, but this time with the younger teeth that had distinct serrations (Cadbury, 2001). Mantell received a response from Cuvier, clearly stating that they belonged to the order of herbivorous reptiles. This gave Mantell the encouragement he needed to keep pursuing his research. With Cuvier's support, he would not be discarded so easily by the English geologists in London (Cadbury, 2001).

To learn more about this reptile, Mantell travelled to London to visit the Hunterian Museum at the Royal College of Surgeons. His goal was to determine if any living reptile had similar teeth, which would allow him to gain a further understanding of the organism's jaw. When the fossil was compared to the iguana, a modern lizard, the similarities were striking but the raised indentations and markings did not quite follow the same pattern. The largest difference was the fact that the fossil teeth (Figure 1.17) were almost twenty times larger than the modern iguana teeth (Cadbury, 2001). This intrigued Mantell further, as his ancient beast may be over sixty feet long. In September 1824, Mantell began to prepare a scientific paper on his ancient animal, later deciding that he would name it the *Iguanodon* in December 1824. With continued good fortune for Mantell, Cuvier published a paper in 1824, highlighting his error in identifying the *Iguanodon* tooth. Due to this public acknowledgment, Mantell was rapidly admitted into the elite circles of London Societies, and was urged to attend the next meeting of the Geological Society. Mantell realized that in order to enter the world of opportunities he needed to be made a Fellow of the Royal Society. On February 10, his discoveries were shared with the Society, and this allowed him to become a Fellow. Mantell wrote in his diary that night: "It was with no small degree of pleasure that I placed my name in the Charter book which contained that of Sir Isaac Newton and so many eminent characters" (Brook, 2002). By 1825, Mantell had finally established supremacy in the field of geology, largely through his identification of a herbivorous species from a simple tooth (Cadbury, 2001).

Unbeknownst to Mantell, this was also the year a young anatomist named Richard Owen arrived in London, who would soon play a significant role in interpreting fossil reptiles.

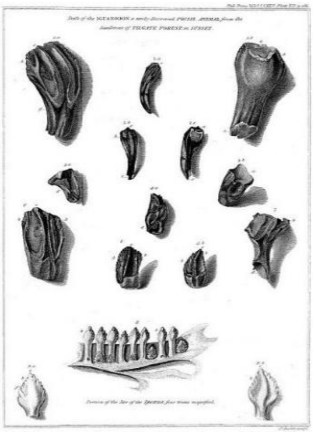


*Figure 1.17. Iguanodon teeth illustrated by Gideon Mantell in early 1825. A series of teeth with serrations are shown.*

## Richard Owen

In his childhood, Richard Owen had very little enthusiasm for studying and saw no point in taking lessons. In 1820, sixteen-year-old Owen became an apprentice to a local surgeon whose practice extended to prisoners in sick-rooms, and this is where Owen first received his introduction to the science of anatomy. His interest in anatomy grew, and in 1824, he went to Scotland's Edinburgh University to study medicine. Here, Owen was excited by extramural anatomy lectures, and realized that anatomy was not merely a tool of the surgeon to understand bodily functions and causes of death. Rather, it was the torch that would shed light upon the origin and extinction of species (Cadbury, 2001).

While in Edinburgh, Owen read papers about newly discovered dinosaurs by scientists like Mantell. This further fuelled his interest in the origin of species, and by the end of 1824, Owen had decided to develop a career as a surgeon in London (Cadbury, 2001). In April 1825 Owen arrived in London, where he had no friends, or even acquaintances; yet this was temporary, as his aspirations would change everything.

In 1826, Owen received his diploma from the Royal College of Surgeons. In less than two years since arriving in London, he had effortlessly made a place for himself in the privileged inner circle of wealthy and well-connected medical elite. During his visits to Paris, he became a welcome visitor to the Museum National d'Histoire Naturelle, where the extensive fossil collections amplified his intrigue and ambition (Cadbury, 2001).

## The Rivalry of a Lifetime

While Owen prepared the catalogues of Hunter's collection and familiarized himself with the anatomy of living animals, Mantell continued with his intensive study of fossils.By understanding the anatomy of creatures and classifying them, Owen hoped to make inferences about their place in nature as God's creation (Cadbury, 2001). Owen (Figure 1.18) hoped to use the subject of anatomy to counter the ideas of scientists that suggested the progression of organisms from one form to another based on homologies. Owen countered progressionist ideas of his rivals by highlighting the uniqueness of a specimen in Hunter's collection, or rather, the lack of the relatedness to other creatures (Cadbury, 2001).

In 1833, Mantell and his wife moved to Brighton, and this was where they created the first museum to exhibit the three known giant land reptiles, *Iguanodon*, *Megalosaurus*, and *Hjaeosaurus*. Mantell's success in Brighton led to many unexpected opportunities, such as the discovery of the lower extremities of the *Iguanodon*. For the first time, he was able to see the connected parts of the skeleton. Mantell then brought newly unearthed *Iguanodon* bones to Brighton, where he was able to better estimate the size along with finally confirming the identity of the teeth. He created his first provisional sketch of the *Iguanodon*, despite missing some key bones (Cadbury, 2001). Mantell wrote in his diary: "The past few months have been the most splendid in my existence and if fame and reputation could confer happiness, I ought to be happy." However, his medical practice was neglected and suffered greatly from circulating gossip, which stated that he was more committed to geology than medicine. Eventually, Mantell had to sell his fossil collection to the museum, including his precious *Iguanodon* (Cadbury, 2001).

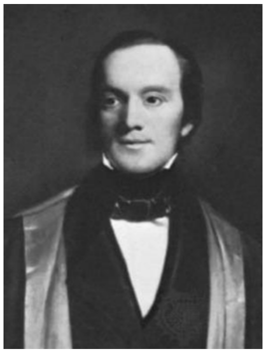


*Figure 1.18. Richard Owen in 1845. As a young man, Owen made a striking impression on people, and was thought to have possessed "great glittering eyes".*

In 1834, Owen was appointed as Fellow of the Royal Society and climbing higher on the ladder of success. With his sharp mind and skills, Owen manipulated power and annihilated the competition within each institution he joined. At the same time, evolutionist ideas were on the rise, and Owen solidified his belief that fossil reptiles would be his weapon against them (Cadbury, 2001). His new rival was none other than Mantell. Owen knew he could not easily challenge Mantell in the field, but he could claim Mantell's territory as his own.

1837 was a landmark year for Owen as he was chosen to be the figurehead of the British Association for the Advancement of Science. Although Mantell was the discoverer of the *Iguanodon* and had distinguished himself with the studies of giant reptiles, Owen was the one to receive recognition. Soon, Owen met a geologist who collected fossils from Mantell's favourite site, the Tilgate forest. He saw this as the perfect opportunity to enter Mantell's territory. With the invention of microscopes, Owen was able to compare the ancient *Iguanodon* teeth with teeth of the modern iguana in his report. It seemed to him that *Iguanodon* bones were more analogous to herbivorous mammals (Cadbury, 2001).

This report by Owen did not contain any particularly new findings (Owen, 1841), as they were all based on discoveries of other geologists, including Mantell. However, Owen used this platform to attack his evolutionist rivals. He insisted that the giant reptiles were created by God and ridiculed Mantell for attempting to seek similarities between ancient and modern reptiles. He even claimed that the reptile was inappropriately named. After reading the report, Mantell found it to be full of "unworthy piracy and ingratitude". Mantell wrote a letter to the *Literary Gazette* in 1841, in which he commented on Owen's statements (Mantell, 1841).

This began the competitive battle between Mantell and Owen.

Unfortunately, on October 11, 1841, Mantell was travelling by carriage to visit a patient when the coachman lost control of the horse. As Mantell attempted to regain control, he was flung to the ground and dragged across the ground for some distance. This severely damaged his spine, and eventually led to paralysis in his lower body (Cadbury, 2001). Owen likely heard about Mantell's misfortune and used this time to further advance himself in the field (Owen, 1894).

Owen realized that the consideration of size was important and came up with a new approach to describe the anatomy in a way that would make sense, as Mantell's calculation would have resulted in an organism that was too large to move. Owen measured the length of vertebrae and guessed their total number from head to toe, using mammal-like thick skin, rather than that of lizards. This led him to reduce the size of *Iguanodon* drastically from one hundred feet to twenty-eight feet (Owen, 1894).

In the winter of 1841, the sacrum of the *Iguanodon* was found, but despite his deepest desires, Mantell could not go see this discovery due to his paralysis, giving Owen the freedom to describe this finding. Owen noticed that the five sacral vertebrae in the lower part of the spine in the *Iguanodon* were fused exactly the same way as they were for the *Megalosaurus*. This fused sacrum would have provided the strength that the giant reptile needed to support its muscular tail and large body. The sea lizards, the flying lizards and the crocodile division all lacked this fused sacrum. Using these findings, Owen used the Greek words *Deinos* for fearfully great and *Sauros* for lizard to introduce the name *Dinosauria*. By coining this term and presenting them as the most advanced reptiles, Owen received all acknowledgment for their discovery, despite Mantell's work on this topic for years.

The only new feature of the report, according to Mantell, was the analysis of the sacrum (Mantell, 2010). In Owen's rewritten report of 1842, not only did he give Mantell negligible credit, but he also pointed out the absurdity of Mantell's size estimations of the *Iguanodon*.

In 1846, Owen used his support at the Royal Society to refuse consideration of Mantell's study of the *Iguanodon*. Interestingly, Owen himself was the chair at the Royal Society when his own paper on belemnites was proposed for the award. This paper was not original and had been described by Chaning Pearce almost four years earlier. Owen's unethical behaviour did not go unnoticed. The *London Geological Journal* commented on Owen's unscrupulous conduct, yet Owen had risen so high in power that he was immune to this criticism.

Despite being incapacitated, Mantell was still irresistibly drawn towards completing his understanding of the *Iguanodon*. His second book was published in 1844 and was quite a success (Mantell, 2010). He also began to receive fossils from his son Walter, who he had not seen for eight years. Walter had collected more than eight hundred specimens, including many rarities such as the complete skull of the large flightless bird, *Dinoris*. Reginald, Mantell's younger son, found superb fossil belemnites, providing proof that Owen's study of belemnites, which earned him the Royal Medal, was wrong. In 1848, Mantell prepared a talk, armed with evidence against Owen. After his talk, Owen "got up and made the most ungentlemanly and uncalled for attack upon it". There is record of "a most animated discussion in which all who took part made a resolute stand against Owen" (Mantell, 1851).

In March 1848, Mantell received a package from a stranger, and it included a fossil that he had dreamed of finding for over thirty years, an *Iguanodon* jaw.

This was a part of the lower jaw, over twenty inches long and had sockets for about eighteen identically shaped teeth with two tiny replacement teeth. These tiny replacement teeth were the elusive evidence needed to prove that the *Iguanodon* was reptilian. Mantell presented his finding to the Royal Society on 18 May 1848. He humbly admitted that the earlier fragments of bone and teeth had wrongly been attributed to *Iguanodon*, but it was yet another dinosaur, which he named the *Regnosaurus*. Right as Mantell finished his talk, Owen announced that a more perfect specimen of the jaw had already been found at Horsham, indicating that Mantell's findings were not the first.

Mantell partnered up with other scientists to find enough vertebrae to reconstruct the spine of the *Iguanodon* (Figure 1.19). Owen was becoming increasingly territorial about the *Iguanodon*, despite not being its original discoverer, and told Mantell that his own study was already complete. This further motivated Mantell, who devoted many hours and completed the entire study in January 1859, within a month of Owen's warning (Cadbury, 2001). Mantell presented his findings to the Geological Society and stated that many of the vertebrae that Owen had classified were incorrect and actually belonged to the *Iguanodon*. According to Mantell, the entire skeleton had been found, excluding the bones of the skull, sternum and lower forearm. Mantell went on to identify his sixth dinosaur around the end of 1849, challenging Owen's supremacy in the field of dinosaurs. Once again, Mantell was proposed for a Royal Medal but the committee refused because of Owen's influence. Owen stated that, "all Mantell had done was collect the fossils and let others work them out"! Upon hearing this, Mantell was enraged, writing "what a pity a man of so much talent should be so dastardly and envious"(Cadbury, 2001).

Mantell could no longer handle Owen's envy, as this was his life's work being debated, but Owen was not prepared to accept that his work on dinosaurs was built on Mantell's foundational work. Mantell requested to be reconsidered for the Royal Medal and a fourth meeting was held. Owen, once again, began to attack Mantell. This time, however, Mantell received support from Lyell, Cuvier and Buckland, and justice was served. Mantell was awarded the Royal Medal on 30 November 1949, with only Owen and one other member voting against him (Cadbury, 2001).

Owen then took credit for Mantell's carefully researched illustrations in a piece that was published by the Quarterly Review. Mantell was furious, and when he proved to the Royal Society that those illustrations were his creation, he received an apology from Owen. Mantell believed that "every one of the Members of the council present seemed to be convinced that Owen, for once, had been caught and exposed in his duplicity." Owen's monopolising spirit

*Figure 1.19. Bones of Iguanodon found in the Weald. The heavy damage incurred by these bones had initially made it very difficult to interpret them.*

resulted in numerous clashes with other scientists, and eventually, Owen lost his loyal allies (Cadbury, 2001). Owen has been described as a "social experimenter with a penchant for sadism and mystification"(Irvine, 1955).

In the summer of 1852, The Crystal Palace Company approached Mantell to see if he would oversee their new project: the first life-sized restorations of the dinosaurs (Cadbury, 2001). At last, Mantell could bring his visions to life, including that of the *Iguanodon*. But this was a year long project and Mantell was barely surviving. Mantell knew that his end was close but was not ready to leave just yet.

A few months later, on 10 November 1852, Mantell slipped on his stairs at home, barely crawling to his bedroom, where he took a full dose of opiates (Cadbury, 2001). The next day, he died of narcotic poisoning and was buried in Norwood. It was later discovered that the lower part of his backbone was very twisted, with some of the lower vertebrae along at right-angles to their correct position. Ironically, Mantell's lower spine was placed in Owen's museum. Shortly after his death, an anonymous letter was published in the *Literary Gazette* where Mantell was described as an "inadequate scientist" (Dean, 1999). All leaders of the geological community were shocked, but certain that Owen was the author.

Owen was denied presidency of the Geological Society at multiple occasions due to his "pointed and repeated antagonism" to Mantell (Lendler, 2019). Nevertheless, the Crystal Palace opportunity fell into Owen's lap, where he constructed the *Iguanodon* based on his own vision, completely ignoring Mantell's previous findings. It was Owen who received all of the credit for interpreting the *Iguanodon*, despite Mantell sacrificing his marriage, health and professional practice for this discovery (Cadbury, 2001). The only tribute to Mantell was a small plaque placed behind the model of the *Iguanodon*. It is extremely unfortunate that Mantell never got to witness the captivating impacts of his extraordinary discoveries.

# The Iguanodontian Brain

The search and discovery that Mantell began in the early 1800's has piqued the interest and curiosity of numerous scientists over the years. Today, modern paleontologists employ a variety of methods such as radiometric dating, computed tomography (CT), X-ray, and scanning electron microscopy (SEM) to examine ancient fossils. The reconstruction of Iguanodontian herbivores is a particular area of interest, specifically the three-dimensional construction of the brain tissues.

## Complex Behaviours of Iguanodontia

With the help of modern imaging techniques, Lauters et al., 2012 were the first to use the fragile cranial endocasts, hollow fossils of the brain, of two Iguanodontians, *Iguanodon bernissartensis* and *Mantellisaurus atherfieldensis*, to perform a comparative study on the inaccessible and unexplored areas of the brain. The best preserved skulls at the Royal Belgian Institute of Natural Sciences were scanned using CT imaging, a technique that generates a three dimensional image of an object from a series of X-ray images taken around a single axis of rotation (Lauters et al., 2012).

In extant reptiles, the endocranium reflects the forebrain surface morphology. Therefore, the endocast is assumed to be a considerably accurate representation of the shape of the most developed parts of the forebrain. Although the digital endocasts created from the natural specimens did not show many details of small anatomical features such as cranial nerves, a few important conclusions could be drawn (Lauters et al., 2012).

The olfactory tracts and bulbs appeared large and indicated a highly developed sense of smell in *I. bernissartensis*. Furthermore, cerebral hemispheres were enlarged and round, and a triangular peak was developed above the midbrain. These suggest spaces for well-developed pineal glands in the brain, which are present in extant birds (Lauters et al., 2012).

The endocranium of *M. atherfieldensis* was partially crushed, and thus the midbrain could not be accurately constructed. Similar to *I. bernissartensis*, it appeared that this species contained large olfactory bulbs. However, as the cerebral cavity was not as straight as *I. bernissartensis*, it appeared that the primitive flexures in the midbrain were better developed in *M. atherfieldensis*. The variations in the angles of primitive flexures, which are the bent regions of the brain during embryonic development, were likely a result of differences in skull size relative to eye size (Lauters et al., 2012). Moreover, the encephalization quotient (EQ), an estimation of the relative brain size for an organism's body size, was calculated for the two species. The estimates were found to be marginally greater for *I. bernissartensis* than extant non-avian reptiles, indicating larger brains and more complex behaviours than modern reptiles. Upon comparison, the EQ's of the two species were found to be significantly different from each other (Lauters et al., 2012). This suggests that although these species occupied the same territories in western Europe, their behavioural complexities may have been vastly different.

## The Intelligent Iguanodontia

Another study conducted by Brasier et al. in 2017 was the very first to present a report on the detailed mineralization of preserved Iguanodontian brain soft tissues. Soft tissues of terrestrial organisms, such as Iguanodontian dinosaurs, are rarely preserved compared to marine animals. Brain tissue is highly labile, and thus, it is extremely rare for the brain to become fossilized. Unexpectedly, a well-preserved braincase belonging to the *Iguanodon* was found on the intertidal exposures in Sussex, the county where Mantell spent his childhood. SEM was used for further analysis, revealing detailed structures such as blood vessels (Figure 1.20), meningeal fabrics, and cortical tissues, which had been replaced by calcium phosphate or moulded by iron carbonate (Brasier et al., 2017).

This specimen was found to have a body length of four to five metres, signifying that it may have belonged to either of the two *Iguanodon*-like taxa, *Barilium dawsoni* or *Hypselospinus fittoni* (Brasier et al., 2017).

The cranial endocast was found among fluvial sediments, which had been exposed by tidal erosion. The fossil bones found here appeared to have originated from a fine-grained, cross bedded siltstone, which formed the infill of a fluvial channel. There were many surrounding sedimentary structures, such as rippled sandstones with wood, bioturbated mudstone containing molluscs, and amber nodules with fossil inclusions. This suggests that the depositional environment was a seasonal wetland, with some occasional forest fires (Brasier et al., 2017). The cranial endocast may have been transported by longshore drift. At the same stratigraphic level, other *Iguanodon* fragments were found, including limbs and vertebrae, along with fossilized footprints and trackways.

The forebrain and hindbrain were preserved well, with heavy weathering of the ventral surface of the endocast. Optical microscopy along with SEM displayed a layered region, which appeared to consist of thin laminar sheets of phosphate that were molded into ribbon-like folds and troughs. There were some small spaces between these ribbons, which were filled with reddish brown, rod-shaped siderite crystals. These features were expected of the periosteum or meningeal matter, which form the protective outer coating seen in vertebrate brains. It is accepted that these ribbons represent the remains of bundles of fibrous collagen. There were several finely layered walls, which had their internal spaces infilled with microcrystalline siderite, and likely formed during early diagenesis. These tubes resemble blood vessels and, in some cases, penetrate the cortex as a form of blood supply. Beneath the meninges, there is an area that lacks the ribbon-like features and shows considerable complexity. This area has been interpreted as the remains of cortical tissue, otherwise known as grey matter (Brasier et al., 2017). These new findings allow the internal structure, including soft tissue arrangement, of the organism to be better known. This also enables the assessment of behavioural patterns and intelligence in the organism relative to others.

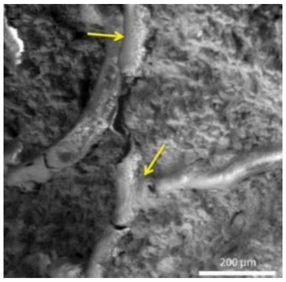


*Figure 1.20. SEM image of tubular structures, interpreted as blood vessels, on the exterior of the Iguanodontian cranial endocast. The arrows point to the branching of vessels.*

For soft tissue to be preserved in phosphate, a local anoxic environment is required as this promotes bacteria mediated mineralization. The fluvial system was likely associated with eutrophication through algal bloom, resulting in anoxia and the addition of phosphate to the water. This suggests that the death of this dinosaur occurred in close proximity to the eutrophic water (Brasier et al., 2017).

The encephalization quotient (EQ) was estimated to be 5.0 rather than the typical 0.8 to 1.5 from earlier studies, indicating that this organism was more intelligent than previously thought. Along with other anatomical findings, it is believed that the Iguanodontian may have possessed a complex range of locomotion skills along with social behavioral skills, which closely resemble their later Cretaceous descendant, the Hadrosaurs (Brasier et al., 2017).

The laborious and meticulous efforts of Mantell were undoubtedly crucial in laying the foundation for research on dinosaur fossils. The methods employed by the early geologists has allowed the modern Earth scientist to conduct in-depth studies and perform simulations of paleoenvironments and their life forms. Without the foundational work of Mantell, perhaps the *Iguanodon* would not have been as intimately explored by paleontologists as it is today.

# Inge Lehmann: The Woman Behind the Discovery of the Earth's Inner Core

Inge Lehmann (Figure 1.21) was born on May 13, 1888 at Osterbo by the lakes in Copenhagen, Denmark (Bolt and Hjortenberg 1994; Bolt, 1997). Lehmann was born into a good family which included many influential people in 1800s Denmark, including barristers, politicians, and engineers. Her family had a history of successful men; her father was a psychology professor at the University of Copenhagen, her grandfather laid out the first Danish telegraph line which opened in 1854, and her great-grandfather was the Governor of the National Bank (Bolt, 1997).

*Figure 1.21. Inge Lehmann in 1932.*

Growing up, Lehmann attended a school where boys and girls were treated equally (Hjortenberg, 2009). This school was run by Hannah Adler, the aunt of Niels Bohr, and served as the foundation for Inge's education (Bolt, 1997). At this co-educational school, Lehmann found a passion for math; her math teacher would even give her extra practice questions, which were more difficult than what the class was learning. Although her parents were concerned that she would not be able to handle the extra work, she exceeded their expectations by attending the University of Copenhagen in the autumn of 1907 to study math (Hjortenberg, 2009). Lehmann later remarked, "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" (Bolt, 1997). She passed her first examination at the University in 1910 and was admitted to Newnham College in Cambridge that fall for one year.

During a break from her schooling, Lehmann worked in an actuary's office as a 'computer' (Bolt and Hjortenberg; 1994). This is where she learned a lot about computation, which helped in her work with seismography later on (Bolt, 1997).

In 1925, Lehmann was appointed as the assistant to Professor N.E. Nörlund, Director of the geodetic institution Den Danske Gradmaaling (Bolt and Hjortenberg, 1994). This is where she was first exposed to seismography. Professor Nörlund was planning to have seismographic stations installed near Copenhagen, as well as in Ivigtut and Scoresbysund in Greenland. Through this work, she had the opportunities to meet many of the leading practitioners of seismology in Europe; Professor Beno Gutenberg, Professor E. Tams, Professor E. Rothé, Dr. van Dijk, and Dr. Somville to name a few (Bolt, 1997). In the summer of 1928, Lehmann obtained her master's degree in Geodesy from the University of Copenhagen after writing her thesis about seismological events (Bolt and Hjortenberg, 2001).

Lehmann accomplished many things in her 104 years on Earth. She was one of the founders of the Danish Geophysical Society, a Danish delegate and contributor at the International Union of Geodesy and Geophysics and was awarded the Bowie Medal by the American Geophysical Union in 1971 (Bolt, 1997). However, her greatest accomplishment is by far her discovery of Earth's inner core in 1936. This finding, among others, solidified her reputation as a well-respected seismologist and female scientist.

## History of the Earth's Core

In the centuries leading up to Inge Lehmann's discovery of the Earth's inner core, several attempts were made to model the Earth's interior.

The first model of the Earth's interior dates back as early as 1686, when Edmond Halley postulated that the core of the Earth was a 'nucleus' or 'inner globe', separate from the Earth's external shell (Tkalčić, 2017). His model, referred to as the 'Hollow Earth' model, depicted the Earth's core as a solid innermost sphere with two moveable magnetic poles, rotating separately from the rest of the planet (Tkalčić, 2017). Although this model was ultimately disproven by Pierre Bouguer and Charles Hutten in the 18th century, it introduced several revolutionary ideas that still persist in today's literature, such as the existence of 'a planet within a planet' (Tkalčić, 2017).

Following Halley's model, many scientists attempted to determine the radius and structure of the Earth's core. The debate as to whether the

Earth's core was solid or molten was particularly prevalent during the early 20th century.

In 1897, German physicist and geophysicist, Emil Wiechert, proposed that the Earth's interior comprised an iron core surrounded by a stony shell (Brush, 1980). Wiechert's two-shell model was based on theoretical considerations of the Earth's density, specifically, that the Earth's core had a significantly greater density than the Earth's crust (Brush, 1980; Tkalčić, 2017). While the idea that the Earth had a solid core was not uncommon at the time, Wiechert's model was unique in that it suggested that each shell had a constant density rather than a density that increased with depth (Brush, 1980; Tkalčić, 2017).

Geologist Richard Dixon Oldham proposed a very similar model to Wiechert in 1900 but did not reference any of Wiechert's work (Tkalčić, 2017). In his observations of seismographs over the next six years, Oldham made the first clear distinction between S and P waves, as well as surface waves (Tkalčić, 2017). He also noticed that P waves propagated more slowly in the core and that a shadow zone formed on the side of the Earth opposite to the epicentre of the earthquake (Tkalčić, 2017). In 1906, Oldham identified a discontinuity in the boundary between the core and its surrounding shell, which prompted him to update his model to give the core a smaller radius (Brush, 1980; Tkalčić, 2017).

Although Oldham is credited with officially discovering the Earth's core, discrepancies in his work ultimately lead to Andrija Mohorovičić being credited with the discovery of the core-mantle boundary in 1910 (Tkalčić, 2017). In 1914, Beno Gutenberg determined this boundary to have a depth of 2900 km, which varies only slightly differs from present-day estimates (Brush, 1980; Tkalčić, 2017).

Wiechert and Oldham created a strong argument for the Earth's core being solid, however, this idea was refuted by Harold Jeffreys in 1926 (Brush, 1980). Jeffreys, among other scientists, hypothesized the existence of a core based on S-wave deflection. Thus, they determined that the core could only be fluid to accommodate this (Bolt, 1997). Jeffrey's model was ultimately disproven following Inge's discovery.

The numerous flawed attempts at modelling the Earth's core over several centuries are a testament to how difficult it was for scientists to model structures that could not be observed. Despite their inaccuracies, these models served as the basis for the creation of Inge Lehmann's three-shelled Earth model. Additionally, the development of the modern seismograph proved crucial in creating an accurate depiction of the Earth's core as, even today, the only way to study the properties and characteristics of the Earth's core is through the study of seismic waves.

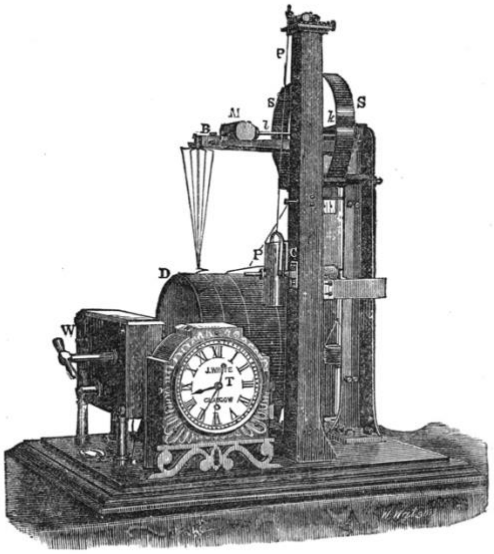


*Figure 1.22. Gray-Milne seismograph with recorder.*

## The Evolution of the Seismograph

Although the major breakthroughs in seismograph technology are commonly thought to have occurred during the late 19th and early 20th century, the earliest seismoscope was invented in 132 A.D. by Chang Hêng (Dewey and Byerly, 1969; USGS, 2020b).

The seismoscope went through many developments in the centuries following Hêng's invention, however, the mid-late 1800s signified the time that major changes were made to seismological instrumentation (Dewey and Byerly, 1969).

In 1875, M.S. De Rossi invented the first true seismograph, which recorded the relative motion of the pendulum with respect to time; before this point, scientists had only made variations to the seismoscope (Dewey and Byerly, 1969). This seismograph was further developed in Japan throughout the 1880s (see Figure 1.22) to become a practical research instrument (Dewey and Byerly, 1969). At the start of the 20th century, the first Wiechert inverted-pendulum seismograph was constructed (Dewey and Byerly, 1969).

Seismographs have a mass that is suspended by a spring and their inertia remains the same in space (USGS, 2020b). As the Earth moves, the mass stays still. The mass has a writing utensil attached to it, and the utensil marks on paper on a revolving drum; if the markings vary from a straight line, this indicates that there is an earthquake or something causing waves to travel through the Earth (USGS, 2020a).

At the time that Lehmann analyzed seismographs, they were all manual and could only measure in one direction. This means that she could not get the complete picture of wave motions since the seismograph could only measure from one direction (USGS, 2020a).

## Discovery of the Earth's Inner Core

During Inge's time as an assistant to Professor Nörlund, she learned that knowledge of the Earth's interior composition could be obtained from the observations of seismographs (Bolt and Hjortenberg, 1994). Her position at the geodetic institution also gave her access to data recorded at seismic stations from around the world (Lehmann, 1987).

Because there was no computer processing available at the time that Inge conducted her research, all of Inge's data and computations were organised 'by hand' (Bolt and Hjortenberg, 1994). Using oatmeal boxes filled with cards containing information on the times that earthquakes were registered in different locations, Inge was able to register the velocity of propagation of earthquakes all over the world (Bolt and Hjortenberg, 1994). She completed this work independently, with no help from assistants, which made the process tedious but allowed Inge to analyze every individual seismogram (Kölbl-Elbert, 2001). The fact that she, herself, noted the arrival times as well as the relative amplitude and shape of each seismic wave likely aided in her discovery of the Earth's inner core (Kölbl-Elbert, 2001).

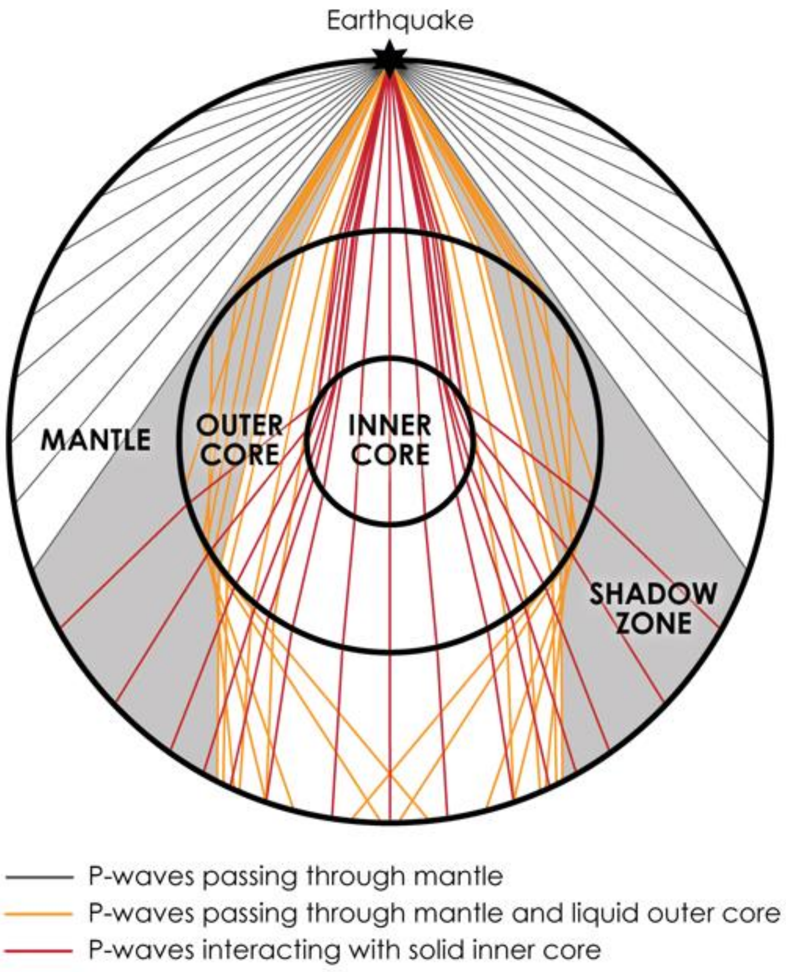


*Figure 1.23. Recreation of Inge Lehmann's three-shelled Earth model.*

Lehmann spent several years analyzing the seismic waves from earthquakes before officially proposing the existence of a solid inner core in her 1936 paper "P'". In her paper she used P to denote the seismic waves that traveled in the Earth's crust and mantle, and P' to represent the waves that passed through the mantle into the core and then back through the mantle again (Kölbl-Elbert, 2001).

Her analysis primarily focused on the seismograph readings from the 1929 earthquake in Buller, New Zealand (Lehmann, 1936; Kölbl-Elbert, 2001). This earthquake was of particular interest to Inge because of the unexpectedly large P-wave amplitudes in the shadow zones of the earthquake (Lehmann, 1936; Hjortenberg, 2009). Inge noted that these waves passed more slowly through the core of the Earth than through the mantle, which indicated that the Earth's core was not entirely fluid (Lehmann, 1936; Kölbl-Elbert, 2001). Thus, Inge Lehmann deduced that the core was not homogenous; rather, that there was an inner core surrounded by and outer core (Rousseau, 2013). Her three-shelled Earth model proposing the existence of an inner core can be seen in Figure 1.23.

One of Inge's greatest strengths was her ability to simplify complex problems. When creating her model, she adopted the simplified assumption that P and P' curves travelled at a constant velocity of 10 km/sec in the mantle and 8 km/sec in the core (Lehmann, 1936; Bolt and Hjortenberg, 1994). Adopting constant wave velocities proved invaluable in the creation of her model because it allowed her to use straight seismic rays as opposed to curved ones, and thus, calculate wave travel times using simple trigonometry (Bolt and Hjortenberg, 1994).

Inge's decision to omit unnecessary details is ultimately what helped her three-shell Earth model gain recognition and acceptance (Kölbl-Elbert, 2001). Although velocity in the mantle and core increases with depth due to the increasing density caused by increasing pressure, the values Inge presented were reasonable averages for each shell (Bolt and Hjortenberg, 1994; Kölbl-Elbert, 2001). Her model was elaborated upon in 1938 by Gutenberg and Richter, who estimated the core radius to be 1200 km and the mean inner core P velocity to be 11.2 km/sec (Bolt and Hjortenberg, 1994).

One final piece of information that is worth mentioning is the common misconception that in addition to discovering the existence of the Earth's inner core, Inge also discovered this core to be solid and surrounded by a molten outer core. This idea was only tentatively proposed by Francis Birch in 1940 and then well established by Keith Edward Bullen in 1946 (Bolt, 1997; Kölbl-Elbert, 2001). Though Inge's model did not investigate the properties of the Earth's core, it likely served as the foundation for Birch and Bullen's discoveries several years later (Hjortenberg, 2009).

## Prejudice Against Female Scientists

At the turn of the 20th century, there was still a lot of prejudice surrounding women in the science community.

Inge Lehmann was born into a privileged family, which allowed her to pursue an education that not many other young girls could. She attended a school where she was treated equally to boys and was given the opportunity to seek a post-secondary education both in Denmark and in England (Hjortenberg, 2009).

Despite the many opportunities that were afforded to Inge, however, she was still no stranger to sexism.

Her father and mother often commented on her not being 'strong enough' for extra math questions in her early schooling (Bolt, 1997). She also experienced intense culture shock upon her acceptance into the Newnham College in Cambridge, as she was exposed to the many harsh restrictions placed on young girls and women (Bolt, 1997). When she eventually returned home in December of 1911, she did not consider going back to school until almost seven years later, when she reattended the University of Copenhagen (Bolt, 1997).

Before Lehmann made a name for herself, her male colleagues often disregarded her research and ideas. One example of when this happened was four years before she published her work on the Earth's core. She had showed her findings to a male colleague, Dr. Harold Jeffreys, who showed no interest in her work at the time (Hjortenberg, 2009).

Unfortunately, he was not the first nor the last man to misjudge her and her work. Her nephew recalls she once told him, "You should know how many incompetent men I had to compete with – in vain" (American Museum of Natural History, 2020).

Note that Lehmann would only use her initial for her first name and her full last name rather than her full name. This is most likely because including her first name would have most certainly resulting in her peers disregarding her papers.

It should also be mentioned that she never married, likely because this would have ended her career as a scientist (Kölbl-Elbert, 2001). This implies that female scientists had to choose between their careers and having a family, which was common for much of the 20th century (Isen and Stevenson, 2010). This simply was not an option for Lehman, seeing as she continued with her career until her last publication at the age of 99 years old (Hjortenberg, 2009).

Despite the gender stereotypes that persisted at the time, Inge Lehmann was still able to establish her reputation as well-respected seismologist.

# The Development of Seismology

Inge Lehmann's discovery of the Earth's inner core was one of the most important geological breakthroughs of the 20th century, and one piece of technology that was critical to Inge's research was the seismograph. Although the seismograph went through many advancements even before Inge's analysis of seismic waves, it has continued to develop well into the 21st century. Furthermore, the application of geodetic technology to seismology has proved invaluable to studying the features of earthquakes and the interior structure of the Earth.

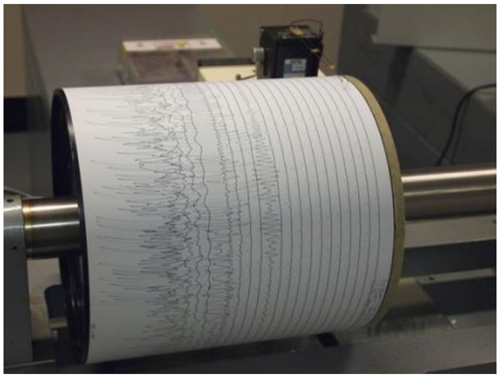


*Figure 1.24. Seismogram being recorded by a seismograph at the Weston Observatory in Massachusetts, USA.*

## The Modern Seismograph

One way in which seismographs have improved is regarding their accuracy (USGS, 2020b). This is for a plethora of reasons. The first is that scientists know more about the Earth than they did when Lehmann was making her discoveries. Her discoveries actually lead to improved seismography because scientists became better informed about the Earth's structure and composition, as well as how S, P, and L waves travel through it (USGS, 2020a).

Modern seismographs (as seen in Figure 1.24) can also measure waves that are coming from many different directions. This is done using three separate instruments to record horizontal waves; one horizontal seismograph records north-south waves, the second horizontal seismograph measures east-west waves, and the third is a vertical seismograph which measures vertical ground motions (USGS, 2020a). This combination of seismographs at a single seismograph station can tell seismologists, "the general direction of the seismic wave source, the magnitude at its source, and the character of the wave motion" (USGS, 2020a). Using data from other stations around the world, seismologists can find the precise location of an earthquake's epicentre.

## Application of Geodetic Techniques

Although geodesy has traditionally been used to determine the Earth's geometric shape, orientation in space and gravitational field, the application of modern geodetic techniques to seismology has the potential to greatly improve the monitoring of seismic activity (Torge and Müller, 2012; Xu, Gong and Niu, 2016).

Three high precision techniques that have shown great promise in the field of seismology are Global Navigation Satellite Systems (GNSS), Interferometric Synthetic Aperture Radar (InSAR), and satellite gravimetry.

GNSS comprises a network of satellites that provide global geo-spatial positioning information; since its implementation, GNSS has been an invaluable source of geodetic information for several decades (Torge and Müller, 2012; Xu, Gong and Niu, 2016). As of present-day, high-rate GNSS has the capability of resolving seismic waves generated by moderate-to-strong earthquakes up to thousands of kilometers away (Xu, Gong and Niu, 2016). Though GNSS is less sensitive than other seismic instruments, this can be advantageous in itself, as waveforms recorded by seismometers are easily distorted due to clipping and tilting of the sensor (Xu, Gong and Niu, 2016).

Another source of seismological geodetic data is InSAR, which is capable of making high-density measurements over large geographic areas using radar signals from Earth-orbiting satellites (Galloway, Jones and Ingebritsen, 2000). In addition to measuring changes in land-surface altitude at high degrees of measurement resolution and spatial detail, InSAR can be used to monitor crustal deformation, including seismic deformation across active fault belts (Galloway, Jones and Ingebritsen, 2000; Xu, Gong and Niu, 2016).

Finally, satellite gravimetry can be used to temporarily study the global gravity field and measure the coseismic deformations from different earthquakes (Xu, Gong and Niu, 2016). This is because mass migration and tectonic deformation cause fluctuations in gravity prior to earthquakes (Xu, Gong and Niu, 2016). It has also been proposed that the data from satellite gravimetry could potentially be combined with the observations of GNSS to model the coseismic slip distribution of an earthquake (Fuchs et al., 2015).

Each geodetic technique offers unique advantages, whether it be distinguishing between seismic waves, monitoring crustal deformation, or monitoring changes in gravity. The continued development of these techniques in combination with traditional seismological measurements is certain to further current understanding of the Earth's structure as well as improve the ability of seismologists to monitor earthquakes.

## Earthquake Prediction

Earthquakes occur when seismic energy that has accumulated along fault zones in the Earth's crust is rapidly released (Kanamori, 1978). Although the magnitude of an earthquake is determined by the amount of seismic energy that is released at the hypocentre, additional factors such as time and location can impact its overall severity (Kanamori, 1978).

Due to the often devasting nature of earthquakes (as seen in Figure 1.25), a natural objective of seismology over the last century has been to predict their occurrence.

Primarily, seismologists have attempted to study the occurrence of anomalies prior to earthquakes to determine a clear precursor (Knopoff et al., 1996). Some of these anomalies have included the ratio of seismic wave velocities, magnetic fields, resistivity, tilt, and emission of noble gases, however, they have all been incredibly difficult to document (Knopoff et al., 1996).

Despite the many advancements in seismology, seismologists have not yet been able to accurately predict the occurrence of earthquakes with respect to exact time, space, and magnitude window (Wallace, Davis & McNally, 1984; Kagan, 1997). Though the chance of ever being able to predict an earthquake by this definition is slim, it is possible for seismologists to predict the likelihood of earthquakes occurring in specific locations based on rates of historic activity (Knopoff et al., 1996). Furthermore, continued research into precursors, such as changes in the electromagnetic signals preceding major earthquakes, could yield new insights into earthquake prediction (Knopoff et al., 1996).

*Figure 1.25. Aftermath of the 2016 Amatrice earthquake.*

# James Dwight Dana: The Development of Permanence Theory

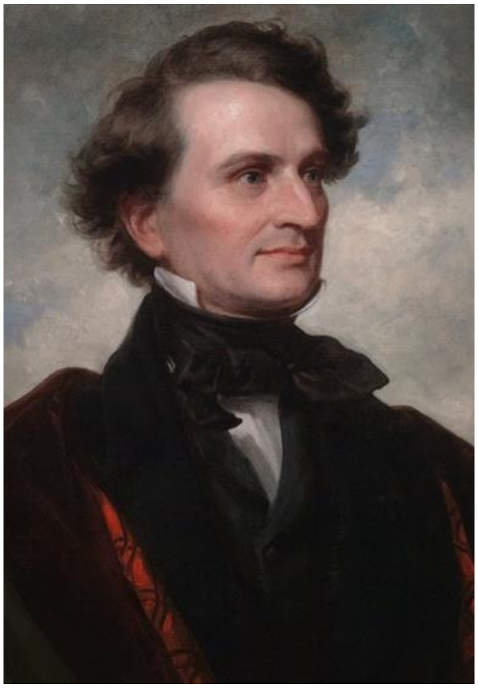


*Figure 1.26. James Dwight Dana (1813-1895), an American geologist and mineralogist.*

The goal of understanding the formation of the Earth has been a long-enduring pursuit. In particular, the inquiry into the origin of the Earth's continental features and processes has been an important objective in the field of geology, dating back to the sixteenth century (Romm, 1994). At present, the widely accepted notion regarding the morphological and topographic characteristics of the Earth is the theory of plate tectonics (Scarselli, Adam and Chiarella, 2020). However, it must be recognized that the path to arriving at this consensus involved centuries of foundational work and ideas put forward by certain individuals in the scientific community.

A key question of interest in the nineteenth century geosciences was regarding the formation of mountains, which are among the most striking features visible on the Earth's surface (Oreskes, 2001). Until the early eighteenth century, a common belief was that the morphological features on the Earth's surface were the products of sudden cataclysms — this doctrine was known as the catastrophism theory (Charlier and Upadhyay, 1987). Specifically, the catastrophist's interpretation was that a Biblical flood acted as the driving force in the formation of various structures on the Earth's surface (Meinhold and Celâl Şengör, 2019). However, with the rise of empiricism and uniformitarianism, this way of thinking did not prevail. Uniformitarianism, as theorized by James Hutton (1726-1797), emphasized that 'the present is the key to the past' (Meinhold and Celâl Şengör, 2019). It can be recognized that Hutton's novel approach provided the basis of investigations among later geologists; this principle was of utmost importance in the advancement of scientific postulates on continental theories, diverging from catastrophism.

One notable figure involved in this progression was American geologist and mineralogist, James Dwight Dana (1813-1895) (see Figure 1.26). Dana was an influential man of his time, shaping the system of geology with his comprehensive endeavors in mountain formation and continental development, along with numerous other remarkable contributions in other disciplines of the natural sciences (Williams, 1895). It is without doubt that Dana laid the necessary groundwork for many geologists that would follow and build upon his ideas, eventually leading to our current understanding of continental formation and processes.

## Dana's Early Life and Existing Continental Theories

Dana was born into a privileged family, providing him with numerous opportunities that fostered his scientific curiosity from a young age — this curiosity was evident in his early penchant for collecting and inspecting stones, bugs, and plants (Williams, 1895; Natland, 2003). Dana's exposure to teachers with a passion towards the natural sciences and natural history throughout his childhood played a large role in inspiring his lifelong devotion to searching for answers of the physical world (Williams, 1895). In conjunction with his favourable familial environment, it should be acknowledged that the time period in which Dana began his involvement in science coincided with the American industrial revolution. These societal and economic changes influenced a progression in the scientific community through the growth in travel and communication, which further facilitated Dana's potential for academic success (Natland, 2003). For these reasons, in retrospect, much of Dana's achievements can be attributed to his fortunate circumstances.

Throughout his boyhood, Dana was surrounded by religious ideologies adopted by his family (Dott, 1997). Despite pursuing a career heavily centralised on the natural sciences, Dana maintained these theological beliefs and rather honored his scientific pursuits as a faithful form of service to God, whom he believed to be "giving lessons to a man on a subject loftier than art, even his own transcendent wisdom in the great plan of creation" (Dana, 1856; Dott, 1997).

After having established a desire to study the natural world, Dana pursued a higher education at Yale College (Williams, 1895). During his years of study, he was taken under the wing of Benjamin Silliman, a renowned professor and figure in mineralogy and chemistry at the time (Williams, 1895). Silliman's influence greatly deepened Dana's interest in mineralogy; although Dana acquired a diverse set of qualifications under Silliman's teachings, his primary interests remained in geology and mineralogy, the areas of knowledge in which he would make his chief contributions. Additionally, following his graduation in 1833, Dana was granted an assistantship by Silliman. During this mentorship, Dana was not only able to broaden his skills as an author, teacher, and scientist, but he was also able to form networks of connections that would be of high value in his forthcoming independent years of study (Dott, 1997).

Prior to Dana's studies into continental development, the prevalent notion behind the origin of continental features was contraction theory, first suggested in the seventeenth century by the philosophers Rene Descartes (1596-1650) and Gottfried Wilhelm Leibniz (1646-1716), and advocated by numerous other geologists of the nineteenth century (Greene, 1982). The rationale behind contraction theory derived from the basis of the Kant-Laplace nebular hypothesis, which implied that if the Earth was initially formed from the coalescing of hot gases, it would undergo cooling and consequently, contract (Greene, 1982). This process of contraction was believed to cause deformation of the Earth's continuous outer surface. This idea was refined and translated into a geologic context with the work of Charles Babbage (1791-1871), an English mathematician, and English geologist Henry De la Beche (1796-1855), who elaborated on the theory in relation to continental development — the deformation of the Earth's surface, as a consequence of cooling over geologic time, would result in the formation of mountainous features (Williams, 1895). Several other variations of this notion were proposed by other geologists, however, these working hypotheses revolved around the general premise of contraction theory (Greene, 1982). With this, Dana began his own studies branching off these existing ideas, during an age that would one day be recognized as a momentous time in the history of geologic thought.

## Dana's Major Voyages

Dana's social and financial privileges allowed him to take advantage of many opportunities to embark on various expeditions across the world and conduct scientific observations at a broader level. There were two major expeditions that were integral in facilitating Dana's scientific discoveries and observations, particularly in the early stages of developing his main geologic theories.

After graduating from Yale College, Dana departed on a voyage across the Atlantic and about the Mediterranean on the U.S. Navy Frigates *Delaware* and *United States* (Williams, 1895). He primarily acted as a mathematics instructor to midshipmen. However, during the expedition, Dana took it upon himself to further his knowledge into mineralogy and crystallography. Throughout his travels, Dana made many scientific notes and observations, especially on the geological features of Minorca and Smyrna (Pirsson, 1919). Dana's findings led him to publish his first scientific paper *'On the condition of Vesuvius in July 1834'* in the *American Journal of Science*, which contained detailed observations of Vesuvius (see Figure 1.27) (Williams, 1895). This marked the beginning of Dana's formal involvement in the scientific community.

*Figure 1.27. Mt. Vesuvius, the continental feature that marked the beginning of Dana's formal involvement in geology.*

Dana was later recruited to join the Wilkes Expedition in August 1838, where he was assigned the fitting role of mineralogist and geologist (Williams, 1895). The Wilkes Expedition sparked Dana's curiosity in coral islands, cephalization, but more importantly, furthered his strong interest for volcanic processes and orogeny (Williams, 1895; Pirsson, 1919). The route started from the United States and travelled across the Southern Atlantic to the islands of the Pacific, before crossing the Pacific once again to the Sandwich Islands before returning back to New York (Williams, 1895). The voyagers first arrived on the island of Madeira, in Portugal, where Dana studied a dissected volcanic island (Pirsson, 1919). Later in 1839, Dana arrived in Chile, where he made detailed geological observations about the

Andes. He travelled with the vessel until Wilkes went on to explore the Antarctic seas; Dana spent this time exploring the geology of Southern Australia, which was the origin of his interest in coral reefs and islands (Pirsson, 1919).

Later in September, the expedition arrived in Hawaii, where Dana spent his time studying volcanoes, most notably Mauna Loa and Kilauea (Williams, 1895; Pirsson, 1919). Dana's intrigue in volcanic activity led him to ponder about mountain formation and continental development (Williams, 1895). It was during this particular expedition that Dana started to interpret igneous activity as a form of evidence for the origin of surface features via geophysical contraction, which was the prevailing theory at this point in time (Williams, 1895). Following the end of the expedition, Dana revisited the Hawaiian Islands in 1887 to conduct further geologic investigations, where he continued to build upon his prior observations. Based on his findings on the volcanic craters, Dana further inquired into volcanic processes and volcanic energy, and later published his ideas in '*Characteristics of Volcanoes*' (Williams, 1895).

## Permanence Theory

The culmination of Dana's observations over the course of his expeditions provided him with a large repertoire of empirical evidence at his disposal to formulate his version of contraction theory, which was to be formally known as permanence theory. In fact, these experiences, along with his high-level knowledge of mineralogy and geology, served as the backbone of Dana's permanence theory. Dana's claims followed the basic premises of the existing contraction theory, however, the distinguishing element of permanence theory was the proposed mechanisms behind the contractions and the stationary nature of continents and oceans (Dana, 1847).

Dana hypothesized that the Earth was once a molten globe which gradually cooled over time, and that there was an igneous fluidity to it (Dana, 1847; 1863). He believed that during this time, continents formed and were fixed in place as a result of low-temperature minerals solidifying (Oreskes, 2001). Subsequently, the high-temperature minerals solidified to form the ocean basins (Oreskes, 2001). Furthermore, he articulated that there was a source of heat at the center of the Earth, as demonstrated by the spheroidal form of the globe which demonstrated its once fluid state and the subsequent cooling over the exterior (Dana, 1863). He had also noted that in mine shafts, the temperature of the Earth varied based on depth, with higher temperatures located under the ground. Additionally, Dana's volcanic observations allowed him to conclude that volcanism was a result of melted rock being ejected through fissures. As such, he stated that the distribution of volcanoes across the globe also supported the existence of a singular source of internal heat (Dana, 1863). Moreover, he hypothesized that contractions were the consequence of the cooling that had taken place over time, which would account for the origin of the mountains, volcanoes, and other features on the Earth's surface (Dana, 1847; 1863). He attributed the differences in surface depression and elevation to unequal levels of contraction (Williams, 1895).

Dana believed that oceanic areas were the more igneous parts of the globe and thus experienced the greatest subsidence (Dana, 1847; 1863). Additionally, he claimed that fissurings and mountain elevations over continents were a result of contraction beneath the oceanic regions (Dana, 1847). This was further justified by the orographic changes taking place near continental margins or near the limit between contracting and non-contracting areas (Dana, 1847). Essentially, Dana proposed that the presence of islands and mountains would take place at lines of weakness and at areas of foldings and fractures (Williams, 1895). Previously, it was believed that there was a form of water or liquid lava that acted below the continents and expanded into a state of vapour causing mountains to form (Dana, 1847). However, Dana (1847) opposed this idea and stated that such force would be incapable of acting against the pressure of the igneous fluid to produce an eruptive force large enough for the orographic changes he observed.

Instead, he proposed that under a certain amount of tension, the primary effect would cause some areas of the crust to be drawn downwards (Dana, 1863). Additionally, as a secondary effect, lateral pressure on a subsiding portion of the crust would cause it to be pushed upwards. As such, either one mass could rise over another or folding could occur in parallel ranges (Dana, 1863). Dana also mentioned the possibility of both fractures and folds occurring simultaneously. However, the nature of the contraction would depend on the nature of the crust that was raised, the moisture and heat of the crust, as well as the moving power of the force acting on it (Dana, 1863). As a result of this, Dana stated that metamorphism, uplifts to a larger scale, and epochs of plications could occur (Dana, 1863).

Dana also postulated that the lateral pushing movement and tension within the crust were the result of folding of the Earth's crust and orographic changes (Dana, 1863). Consequently, depressions and fractures were predicted to take place when contraction occurs below a stiffened crust (Dana, 1847). Dana further suggested that depressions form as the result of lateral pressure, and the fissurings that form from the contractions would also produce violent earthquakes. It was also hypothesized that there was an increasing amount of tension over time which would result in minor oscillations and uplift.

Permanence theory was also closely associated with the concept of geosynclines, which refer to sedimentary basins found on continental margins (Oreskes, 2001). James Hall (1811-1889), another noteworthy geologist involved in geosyncline theory in Europe, suggested that the eroded materials from continents accumulated in marginal basins which caused the basins to recede (Oreskes, 2001). Hall proposed that as more material accumulates, the weight of the sediment results in it being converted to rock through heat, and results in the formation of mountains (Oreskes, 2001). In contrast, Dana argued that the piles of eroded material were the result of subsidence rather than the cause of it (Oreskes, 2001).

Another source of evidence that was paramount in developing Dana's ideas was the Moon, which he used as an analogy of the Earth (Oreskes, 1999). With the use of telescopes, Dana observed the moon to be a cooled igneous surface with no water, and thus no vegetation, soil, or sedimentary deposits (Dana, 1846). He was particularly interested in lunar craters that he identified near large mountains, describing such craters to be an analogue of those found on Kilauea in the Pacific Islands, which he had studied during the Wilkes Expedition. He stated that both were large, open craters with a ledge raised slightly above the base which was filled with open lava, and this led to his conclusion that the volcanoes found on the Moon were volcanoes similar to the ones observed on Earth (Dana, 1846).

Furthermore, Dana contrasted the Earth with the Moon, which had already undergone cooling (Dana, 1846; Williams, 1895). Dana postulated that the Earth and the Moon must have been subjected to the same phases, although Earth would have had water present during its initial contraction. On the Moon, it was observed that approximately one third of the hemisphere facing Earth had no evidence of volcanism (Dana, 1846). Dana therefore suggested that this area must have cooled first and the regions with higher volcanic presence must have experienced a greater degree of contraction (Dana, 1846). When applying the same logic with Earth, Dana noted that the interior of continents, for the most part, were free of volcanoes, whereas the ocean had many igneous islands (Dana, 1846). Thus, he concluded that the continents must have cooled first, thereby resulting in the oceanic crust experiencing greater subsidence and forming ocean basins (Dana, 1846).

## The Legacy of Permanence Theory

Dana's permanence theory was generally well-received by the scientific community, and was upheld over the following 25 years after its proposal (Oreskes, 1999).

The reason behind the widespread acceptance of Dana's theory among a plethora of working hypotheses in the nineteenth century can be largely credited to his thorough revision of observations, skillful communication of ideas, and meticulous attention to detail, evident in his published papers (Greene, 1982). Additionally, permanence theory was recognized as one that most successfully elaborated upon the many ideas put forward by previous geologists, such as that of Elie de Beaumont's and the aforementioned individuals, Charles Babbage and Henry de la Beche (Greene, 1982). Dana's work on general uplift and mountain formation allowed for a wider synthesis of data among forthcoming geologists such as Eduard Suess (1831-1914) and Marcel Alexandre Bertrand (1847-1907) (Dott, 1978). With this, and the inevitable emergence of new evidence, permanence theory was ultimately dismissed. Nevertheless, Dana's legacy as a pioneer in the field of geology remains; in other respects, Dana's seemingly remarkable ability to dichotomize his religious beliefs and scientific outlook in his academic pursuits, in hindsight, can be praised, and merely highlights his eminence in the natural sciences.

# Plate Tectonic Theory and the Hawaiian Islands

Contraction theory beganto be heavily contested in the early twentieth century (Oreskes, 2001). One line of evidence that acted as a major driving force in the discreditation of this theory was the discovery of radiogenic heat in the Earth's crust, as outlined in the book 'Radioactivity and Geology' by Irish physicist John Joly (Joly, 1909; Greene, 1982). Joly, along with other physicists, advocated for the geologic role of "convection and accumulation of radio-thermal energy [on] the surface features of the globe" and deemed the concept of global cooling as implausible due to its inconsistencies with the newly established radioactive properties of rocks and minerals (Joly, 1909, p.116; Oreskes, 1999). Other discrepancies such as in the field mapping of the Swiss Alps and the Appalachians challenged the assumptions of contraction theory (Oreskes, 1999). It was not until 1912, largely attributed to the work of Alfred Wegener (1880-1930), that one unifying theory accounting for these untended observations was formulated — this marked the beginning of an eminent paradigm shift in geology.

## Alfred Wegener and Harry Hess

Alfred Wegener (1880-1930) was a primary contributor to plate tectonic theory, being the first to allude to the idea of plate tectonics in his theory of continental drift. Wegener postulated that there was once a supercontinent, Pangea, which eventually broke apart as continents migrated across the Earth's surface and the corresponding interactions between continents resulted in mountain and volcano formation (Oreskes, 2001). Wegener first developed this hypothesis when he noted the jigsaw-like nature of the continents (Oreskes, 2001).

While the basis of Wegener's theory is universally accepted today, its initial reception in the 1920 to 1930s was on the contrary (Oreskes, 2001). The response was especially poor in the United States, where American ideologies of 'good science' championed the diversity of multiple theoretical explanations and empiricism (Oreskes, 2001). Moreover, his theory directly contradicted widely accepted scientific theories such as that of John Pratt's isostasy and uniformitarianism (Oreskes, 2001). It was not until the 1950s that the scientific community began to consider the credibility of Wegener's theory.

Later on, Harry H. Hess (1906-1969) proposed the theory behind sea floor spreading which shed light on the viability of Wegener's continental drift theory. While Hess was creating a topographic map of the sea floor, he discovered flat-topped mountains, now named guyots (Oreskes, 2001). Guyots developed as the top of volcanoes were eroded by wave action when they sank due to ocean subsidence; the discovery of guyots was particularly significant, as it supported the idea that ocean basins had been geologically active (Oreskes, 2001). Hess hypothesized that there were magmatic intrusions due to mantle convection that was driving the crust apart at the crests of mid-ocean ridges and creating new crust (Hess, 1962). Hess postulated that the continents rode passively on the mantle and away from ridge crests as they drifted, rather than moving through the oceanic crust (Hess, 1962). Following Hess' work, and further developments, the mobility of continents and the theory of plate tectonics was established. Hess and Wegener's work supported the idea that the continents drifted apart over time rather than being permanently fixed as Dana and permanentists had previously suggested.

## Paleomagnetism and the Hawaiian-Emperor Chain

Paleomagnetic data has supported the idea that continents have migrated throughout time (Oreskes, 2001). The Earth has a dipole magnetic field, and over the past 600 million years, its polarity has reversed thousands of times (Hess, 1962; Merrill, McElhinny and McFadden, 1998). Earth's magnetic field is a vector and is thereby associated with a magnitude and direction. At the time of a rock forming from cooling lava at mid-ocean ridges,

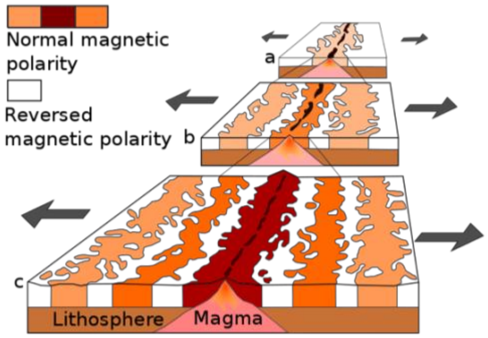


*Figure 1.28. Diagram depicting the magnetic reversals observed in the lava flows at mid-ocean ridges.*

primary magnetization occurs, which provides information regarding the external magnetic field (Merrill, McElhinny and McFadden, 1998).

A 'zebra stripe' pattern of magnetic signatures is found along the ocean floor, where magnetic zones correspond with either the magnetic polarity of present-day Earth or the reversed polarity of the past (Oreskes, 2001). The lava flows found on the ocean floor are thought to be instantaneous representations of the magnetic field at the time, due to the fast-cooling properties of lava (Merrill, McElhinny and McFadden, 1998). It was observed that the zebra stripe pattern of the ocean floor had alternating magnetic polarities that corresponded with Earth's recorded magnetic field reversals. The patterns suggested that hot magma was being produced at the crest of the mid-ocean ridge and flowed sideways (Oreskes, 2001). As the magma cooled, it preserved the current magnetic polarity of the Earth (see Figure 1.28). Since the paleomagnetic record preserved in lavas of the ocean floor corresponds to the recorded magnetic field reversals, this demonstrates that hot magma was being produced and cooled at the crest of the mid-ocean ridge (see Figure 1.28). Moreover, the magnetic anomalies are symmetrical on both sides of the ridge, supporting the idea that the ridge is spreading apart (Oreskes, 2001).

Mid-ocean ridges and subduction zones at plate boundaries are where the majority of volcanic activity occurs. However, volcanism can also be associated with regions away from plate boundaries, in hot spots; hotspots are high-heat flow regions within tectonic plates, fed by underlying mantle plumes, from which magma can be supplied during seamount formation (Tarduno and Cottrell, 1997; Torsvik et al., 2017). The Hawaiian Islands exemplify this phenonmenon, as a mostly-underwater mountain range that stretches across 6000km from the Lōʼihi volcano to the Emperor Seamounts in the northwest Pacific (Torsvik et al., 2017). Towards the northwest, the formations get progressively older — the Hawaiian Islands are the youngest, while the Detroit seamount is dated to be approximately 81 to 75 millions of years old (Ma), and the Meiji seamount greater than 82Ma (Torsvik et al., 2017). This chain is currently the best-identified source for studying the relationship between mantle convection, plumes, and tectonic plate movement (Tarduno and Cottrell, 1997). A particular feature of interest in this chain is a prominent bend which formed around 43Ma (see Figure 1.29) which initially was suggested to have originated from sudden plate movement confined to a fixed hotspot region sourced by mantle plumes (Tarduno and Cottrell, 1997; Torsvik et al., 2017). Initially, paleomagnetic studies aiming to reproduce this bend by modelling the movement of the Pacific plate assumed a stationary hotspot; however, this assumption failed to reconstruct such features, and it was speculated that the bend was associated with a non-fixed hotspot (Tarduno and Cottrell, 1997; Torsvik et al., 2017).

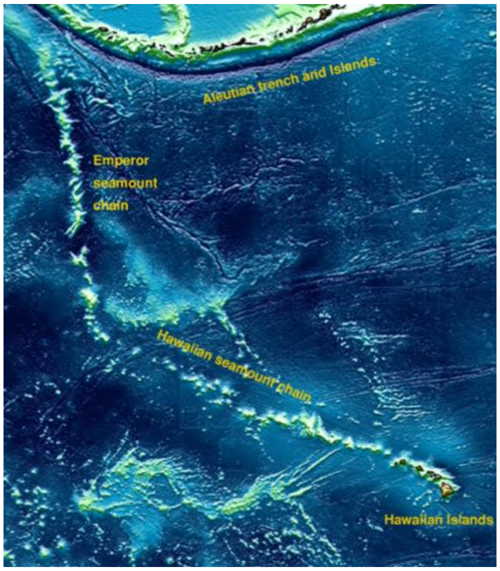


*Figure 1.29. Map showing the Hawaiian-Emperor chain and the prominent bend which formed around 43Ma.*

Specifically, the paleolatitudes of the island chains failed to correspond to that of Hawaii's present day latitude of 19.4°N (Tarduno and Cottrell, 1997; Torsvik et al., 2017). Instead, in such paleomagnetic studies, it was determined that the younger seamounts exhibited northward offsets of 8$^{o}$ to 2$^{o}$ to Hawaii, while the older seamounts demonstrated a paleolatitude of approximately 15$^{o}$N of Hawaii (Torsvik et al., 2017). The paleomagnetic data of the seamounts illustrated the mobile nature and southward-movement associated with the Hawaiian hotspot (Torsvik et al., 2017). With this, the current tentative theory on the formation of the chain was developed, specifically, that the island chain was produced as a result of tectonic plate motion in conjunction with a drifting hotspot (Torsvik et al., 2017). This supports the notion of the dynamic and mobile nature of the Earth's surface, as previously hypothesized by Hess and Wegener.

Paleomagnetic investigations into the Hawaiian-Emperor Chain have provided insight into the likely origin of the bend in the chain. Although a consensus on the exact driving force has yet to be achieved, at present, it is believed that the directional change of the Pacific plate around 47 Ma and the moving Hawaiian hotspot during the Late Cretaceous and mid-Eocene contributed to the bend formation (Torsvik et al., 2017). With further investigations into the Pacific plate through the use of advancing geologic methods such as seismic tomography, the cause of this enigmatic bend very well may be determined. Ultimately, this would deepen our knowledge of plate tectonics, and above all, our understanding of the Earth's fascinating past.

# Chapter Two

## EARTH AND CLIMATE

> “Teaching children about the natural world should be seen as one of the most important events in their lives.”
>
> -Thomas Berry

# Permian Extinction Cause

Imagine the Earth of the Permian age - teeming with life. Lush rainforests blanket the warm and humid regions of the supercontinent Pangea. Insects are crawling and buzzing through the forests. Plant-eating reptiles and amphibians are grazing the trees. Therapsids, the first mammal-like creatures, are hunting for their next prey. The primitive reptiles inhabit the warm deserts of northern and central Pangea. Meanwhile, the oceans were ruled by fish. Trilobites scuttling across the sea floors and coral reefs are flourishing. Life in the Permian age was thriving for around 48 million years, until the unthinkable happened. The Permian Extinction, known as the Great Dying, was the largest mass extinction in Earth's history. Almost 250 million years ago, life endured the worst catastrophe Earth has ever seen. Our planet, a bastion of life in a cold and dark universe, was the closest it's ever been to complete annihilation. How did Earth's nurturing environments become so hostile that over 90% of Earth's life on land and sea vanished forever?

In order to answer this question, it is important that today's society of scientists approaches this puzzle as a practice of global geology. To better understand this global extinction on land and sea, we must be able to correlate the evidence found all over the globe to aid us in explaining this narrative of ancient history. This will require that we understand the temporal and spatial characteristics of the geological evidence we collect from the various locations from around the globe.

## London, England

We will begin this journey of global geology in London, England. The Earth has a rich fossil record spanning as far back as 550 million years. Long before we knew this, geologists of the 1800s in England started identifying rock formations and fossils contained within. One of the grandfathers of geology and the producer of the 'Map That Changed the World', William Smith, was among the first people to recognize the gap in fossils at what is now known as the Permo-Triassic boundary (Winchester, 2001). This boundary marked Earth's most devastating extinction of all time. Smith's protégé and nephew, John Phillips, who took part in many of Smith's expeditions, published his own book in 1860 called *Life on Earth: its Origin and Succession*. In this book, using Smith's principles of identifying rock and fossils, Phillips gave names to regions of the strata associated with different geological eras. These names may sound familiar because they are still used today as follows: Palæozoic, Mesozoic, Cænozoic (Phillips, 1860).

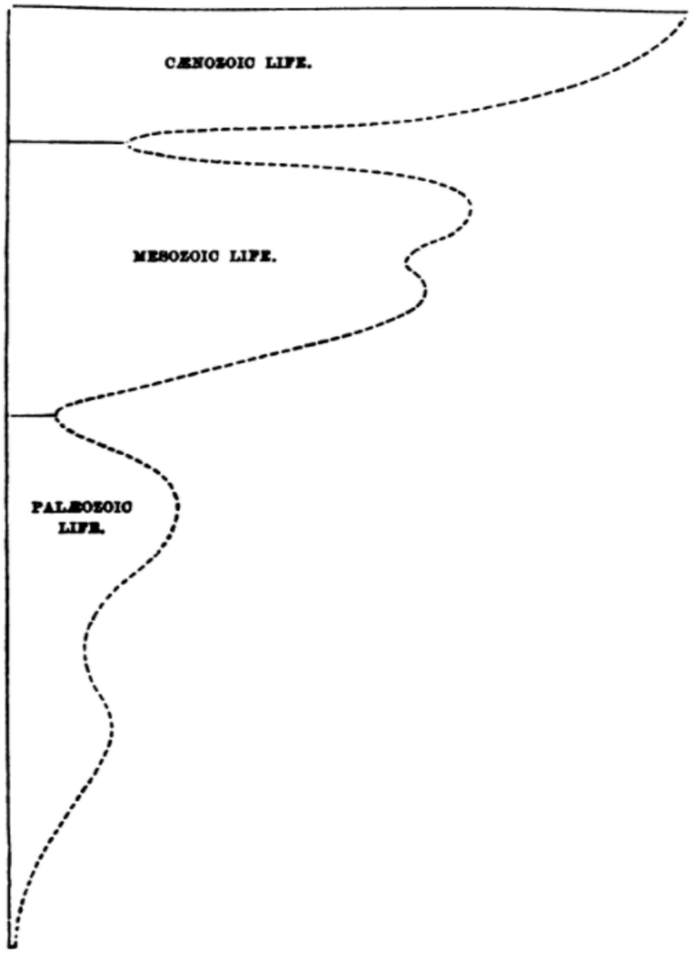


*Figure 2.1. John Phillip's famous diagram on page 66 of his book 'Life on Earth: its Origin and Succession'. This diagram depicts the changes in biodiversity over the course of the Phanerozoic period. Despite the progress humanity has made since 1860 in terms of our knowledge of Earth and its vast history, the assertion of two substantial reductions in biodiversity that Phillips depicted have stood the test of time (Phillips, 1860).*

Each geological era was marked by a substantial change in the types of fossils; these major changes coincide with the most recent major extinctions that Earth has experienced. In his book, Phillips produced a diagram (see Figure 2.1) that shows the change in biodiversity over time and he depicts two major reductions in biodiversity, one at the end of the Palæozoic and the other at the end of the Mesozoic. Phillips had discovered the Permian Extinction and the Triassic Extinction. To this day, geologists and paleontologists still struggle to understand how the accuracy of this diagram was achieved. This major discovery was important because it guided geologists trying to better understand this drop in diversity, to the Permo-Triassic geological boundary where it was first observed. If this drop in diversity can be observed in other locations on Earth and the pattern is not just local, then it is likely not a coincidence.

## Southern Alps, Italy

Today, the Alps is the highest and most extensive mountain range in Europe. In the Permian age, however, the Alps were not yet what they are today. In fact, the Southern Alps were located adjacent to the Tethys Ocean when Pangea was still in formation.

In 1962, a study conducted by Wilson et al. discovered something very interesting. In their study, they examine the fossil record of the Permo-Triassic boundary which helped create a means to reliably correlate the land and sea Permo-Triassic boundaries. This model was used to first confirm that the fossil record shows a similar drop in biodiversity to that seen in other countries, but they also discovered something they weren't expecting. They discovered that the major drop in biodiversity was marked by a thin layer of sediment which contained >95% fungal cells (*Reduviasporonites*) and woody debris. Seeing that *Reduviasporonites* is a wood-degrading fungus, this fungal spike is indicative that the wide scale extinction of marine biodiversity in the late Permian age may have also occurred to plant life as well (Wilson et al., 1962).

In 1973, the first multidisciplinary study was conducted on the Permo-Triassic boundary and it was conducted in the Southern Alps. Using stratigraphy-sedimentology facies analysis and paleontology, Assereto et al. examined the Werfen Formation where the Permo-Triassic boundary is located in the Southern Alps. The study suggests that in the Late Permian, the area of the Southern Alps was once likely an epeiric sea that graded eastward into a highly saline epicontinental sea where limestone accumulated. The study also shows there was an oceanic regression occurring in the late Permian, implying a more humid climate and hotter temperatures (Assereto et al., 1973). This finding was huge at the time because it pointed future scientists in the direction of the Southern Alps, a prime location to examine facies and the strata from the Permo-Triassic boundary to better examine the changes in marine environments during the Permian age. This study was also influential in the sense that it suggests that global warming occurred during the late Permian, which also guided future research.

Studies in the Southern Alps continued and in 1988, a major stride forward was made in a study conducted by Magaritz et al. highlighting the carbon-isotope shift at the Permo-Triassic boundary. The results of this study suggest that the carbon isotope ratios in marine carbonate rocks have been shown to shift gradually at the Permo-Triassic boundary. This is characterized by a large $\delta^{13}C$ depletion in sections of the Southern Alps that likely spanned millions of years during the late Permian and early Triassic. This result implies a massive decrease in biological production and rate of burial of organic matter which aligns with previous drops in biodiversity in past studies (Mararitz, 1988).

Building on this major finding, a paper from Wignall and Hallam in 1991 was the first to suggest that anoxia may have been the causal mechanism for Permian Extinction. In the same region of the Southern Alps where significant $\delta^{13}C$ depletion was observed, the strata had fine laminations containing low diversity, yet fine-scale sedimentary structures were preserved. This pattern could possibly suggest oxygen-restricted deposition inhibiting a bioturbating infauna (Wignall and Hallam, 1992).

As it turns out, a study conducted five years later in 1996 by Wignall and Twitchett supported this hypothesis by measuring the radioactive decay ratios thorium and uranium. Typically, anoxic conditions yield higher uranium values resulting in Th/U ratios of less than 2. The strata located in the southern alps near the Permo-Triassic boundary, specifically the Mazzin member and the Siusi member, both resulted in anoxic Th/U ratios at both low and high paleolatitudes (see Figure 2.2), implying widespread benthic anoxic conditions in the Late Permian oceans (Wignall and Twitchett, 1996). At the time of its publishing, the work done by Wignall and Twitchett had enormous implications for the theories in question. The smoking gun for the Permian Extinction was still being disputed. Many thought that it could have been a result of an extraterrestrial body hitting Earth, some thought it was primarily due to ocean level regression, and others thought it could be volcanic activity. Regardless of what exactly occurred, there was highly suggestive evidence showing the causal mechanism of this extinction to be linked to wide scale anoxic conditions in Permian oceans. Their work would go on to guide future research on a global scale.

## Southern China

The next stop on our global geological journey is Southern China. The Permo-Triassic boundary in Southern China was a source of confusion for quite some time there as well. An American geologist by the name of Amadeus William Grabau was among the first to study the Permian and Triassic formations in Southern China. Grabau started as a professor at Rensselaer Polytechnic Institute, then Massachusetts Institute of Technology, as well as Columbia University in New York before leaving for China. Upon arrival in China, he was appointed as a professor at Peking National University. There, he conducted geological surveying and published many books (Rafferty, 2007). One of his most prominent being *Stratigraphy of China*. In this book, he focussed much of his studies in Meishan of Changxing where the formations of the Permo-Triassic boundaries were well exposed. In 1923, Grabau first took notice of Changhsingian faunal beds (Grabau, 1923). Grabau's work was important because he laid much of the groundwork in this region and catalyzed the work of other geologists in Southern China. For this reason, Grabau is often referred to as the father of Chinese geology (Rafferty, 2007).

By 1985, a study conducted by Yin Hongfu made use of ammonoids and conodonts zonation in the more complete sequences known across the Permo-Triassic boundary in all of Southern China. Using the associated bivalves, this study was able to provide parallel zonation which could permit inter-continental correlations in the absence of ammonoids (Hongfu, 1985). This allowed for a better understanding of the biologic sequence of events and the biostratigraphic relationship between the Permian and Triassic sequences in the world, such as the ones discovered in the Southern Alps of Italy.

A couple years later, in 1987, a study conducted by Jin-wen et al. took a different approach to examining the faunal beds. The study noticed a large amount of crystals of α-quartz in the late Permian faunal beds which typically represent acidic eruptive rocks, from volcanic ash, for example. The loss in biodiversity seen in the faunal beds was correlated with the volcanic eruptions which also coincided with the time of mass extinction of Permian marine invertebrate faunas (Jin-wen et al., 1987). This paper, among many others, hypothesized that volcanic activity was responsible for the Permian Extinction. Where could volcanism occur on a scale large enough to cause an extinction event of this magnitude?

## Siberia, Russia

The The Siberian Traps is among the most far-reaching large igneous provinces (LIPs) on earth. It was created by a mantle plume over 250 million years ago and is located in modern day Siberia, Russia. The Siberian Traps remains the prime suspect of the Permian Extinction over 250 million years ago.

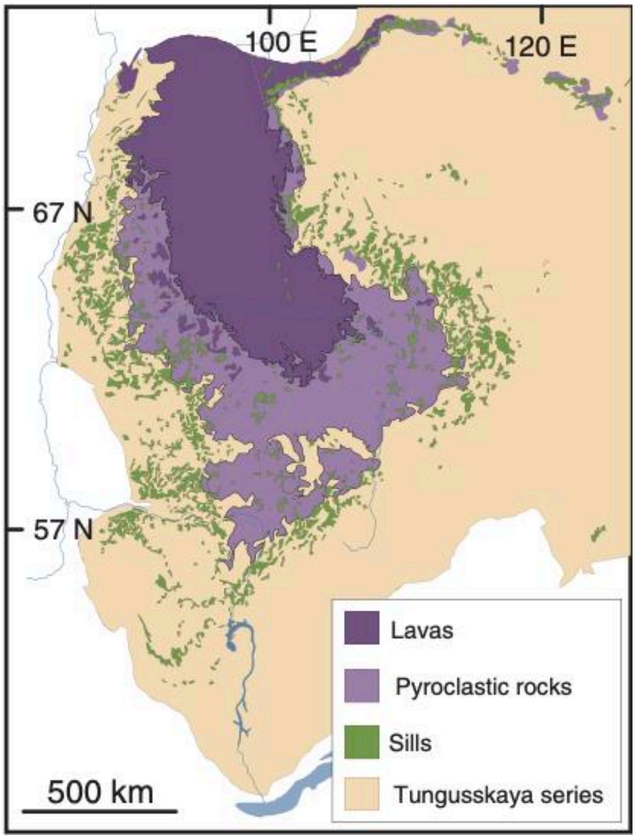
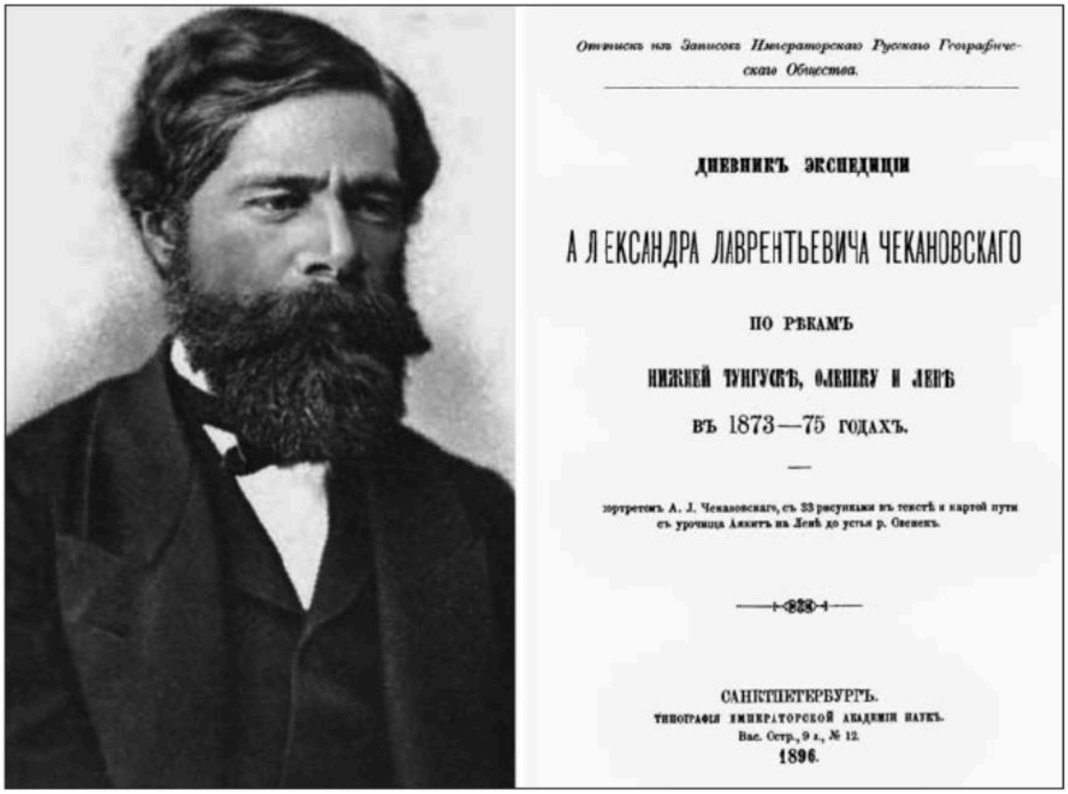


*Figure 2.2. This map depicts the region in modern Russia where the Siberian Traps are located. The different types of volcanic load are colour coded which can be seen in the legend in the bottom right corner. The scale of the Siberian Traps LIP can be seen in the bottom left corner. (Burgess, Muirhead, and Bowring, 2017).*



*Оттискъ изъ Записокъ Императорскаго Русскаго Географическаго Общества.*

ДНЕВНИКЪ ЭКСПЕДИЦІИ

АЛЕКСАНДРА ЛАВРЕНТЬЕВИЧА ЧЕКАНОВСКАГО

ПО РѢКАМЪ

НИЖНЕЙ ТУНГУСКѢ, ОЛЕНЕКУ И ЛЕНѢ

ВЪ 1873—75 ГОДАХЪ.

портретомъ А. Л. Чекановскаго, съ 33 рисунками въ текстѣ и картой пути
съ урочища Аякитъ на Ленѣ до устья р. Оленекъ.

САНКТПЕТЕРБУРГЪ.
ТИПОГРАФІЯ ИМПЕРАТОРСКОЙ АКАДЕМІИ НАУКЪ.
Вас. Остр., 9 л., № 12.
1896.

*Figure 2.3. This image depicts Aleksander Piotr Czekanowski (1833-1876) in the last years of his life (left). Alongside is the title page of his main work (right) (Czekanowski, 1896). This publication contains Czekanowski's diary entries from his Siberian expeditions in 1873-1875, published 20 years after his death by*

The Siberian Traps were first discovered by a Polish geologist by the name of Aleksander Czekanowski who had been exiled by Russian authorities to Siberia for his participation in organizing the Polish January Uprising in 1863. Many years later, in 1873, he led an expedition to northern and eastern Siberia where he discovered numerous exposures of basalt lava floods. Czekanowski wrote a diary outlining the details of his discovery during his exhibition between the years of 1873-1875. In it, he wrote "the discovery of previously unknown area of igneous rocks of so large extent that it exceeds the size of any other of its kind" (Czekanowski, 1896). It was clear to Czekanowski that this must represent something significant in earth's history. Upon returning from his expedition, he was pardoned by the government of Russia but the financial stress caused by his expedition worsened his mental disorders and he committed suicide by taking a large dose of poison on October 18, 1876 (Czekanowski, 1896). As a result, his work remained unpublished for 20 years before being published in 1896 by Fryderyk Schmidt under the title 'Diary of the expedition on the rivers Nizhny Tunguska, Olenek and Lena in 1873 – 1875' (see Figure 2.3). Schmidt was a renowned geologist, as well as a member of the Imperial Academy of Science in 1874, so he was in the position to widely promote the work of Czekanowski's exile research (Czekanowski, 1896). The widespread promotion of Czekanowski's work was not for nothing. Research on the Siberian Traps LIPs continued for many years but it would require time before major breakthroughs were made.

In 1959, Ivanov and Pirozhnikov published one of the first papers to offer a paleontological perspective on the Siberian Traps LIPs. Prior to the publication of their paper, various different rock formations were previously identified in Siberia. These rock formations go by the name of the Khardakhsky formation and the Arydzhangsky formation. During their research, Ivanov and Pirozhnikov examined the flora in the outcrops of Khardakhsky formation and examined phyllopods in the middle section of the Arydzhangsky formation. Using the data they collected, they were able to apply their knowledge of fossil identification, which allowed them to be one of the first to substantiate where the Permo-Triassic boundary lies within the Khardakhsky and Arydzhangsky formation boundaries (Ivanov and Pirozhnikov, 1959). This discovery paved the way for more research to be conducted on the Permo-Triassic boundary. Research continued and as technology continually became more advanced, more conclusive evidence started connecting the Siberian Traps to the Permian Extinction. By the early 1980, scientists began forming hypotheses linking the Siberian Traps to the Permian Extinction. A paper published in 1991 was among the first to beg the question, did the volcanism of the Siberian Traps coincide with faunal mass extinction at the Permo-Triassic boundary worldwide. This study uses laser-heating of $^{40}$Ar/$^{39}$Ar to interpret the timeline of the eruptions which they determine to occur for ~900,000 years beginning at about 248 million, which coincides with the mass extinction at the Permo-Triassic boundary 249 million years ago (Renne and Basu, 1991).

# Sills of the Siberian Traps

By the early 2000s, it had become clear to scientists that the end of the Permian period was marked by intense global warming and that the emplacement of the Siberian Traps was the likely culprit causing the Permian Extinction. Despite this, the causal mechanism for this catastrophe remained to be disputed for quite some time. In 2006, a study used the Deccan Traps LIP in India as an analogue to the Siberian Traps LIP. That study suggests that the lavas from the Siberian Traps likely lack the dissolved $CO_2$ content required to drive a significant global warming event (Self, 2006).

In 2009 a new theory was proposed for the causal mechanism of the Permian Extinction. A paper published by Svensen et al. hypothesized that heating of Tunguska Basin sediments in Siberia via the ascending magma caused sill intrusions (see Figure 2.4) that played a key role in triggering the Permian Extinction. The extensive field work they carried out in 2004 and 2006 suggested that the heating of organic-rich shale and petroleum via the sill intrusions led to greenhouse gas and halocarbon generation in sufficient volumes to cause global warming and atmospheric ozone depletion. The contact metamorphism of organic matter and petroleum could have generated more than 100,000 Gt of $CO_2$. Additionally, heating experiments of petroleum-bearing rock from Siberia suggests that methyl chloride and methyl bromide were also significant components of the erupted gases (Svensen et al., 2009). This finding was an enormous stride forward because it explains how the Siberian Traps were able to change atmospheric gas composition to cause global warming and atmospheric ozone depletion; a finding that could not be explained by the emplacement of extrusive lava flows, alone. A recent study published by Burgess and Bowring in 2015 has since demonstrated high-precision geochronological evidence that the timing of the Siberian Traps major volcanic event aligns well with the geological records of when the Permian Extinction occurred. Using uranium-lead dating with $^{238}U$ to $^{206}Pb$ ratios governed by a half-life of 4.47 billion years, the researchers were able to describe the emplacement of sills into the shallow crust which began at the start of the mass extinction and continued for at least 500,000 years into the early Triassic. This model is not only consistent with the theory that the emplacement of the Siberian Traps triggered the Permian Extinction but it also suggests a role for magmatism in suppression of biotic recovery

*Figure 2.4. This photograph depicts a basaltic sill intrusion at the Yellowstone River in Yellowstone National Park in Wyoming, USA. This would be similar to the sills found at the Siberian Traps where the sills are in contact with organic-rich sediments, like coal. The result of sill intrusions adjacent to the sedimentary layers produces metamorphic aureoles from contact metamorphism, a process which liberates gases such as carbon dioxide and methane from the host rock (Werner, 2006).*

well after the extinction event (Burgess and Bowring, 2015). Another major finding of this study is that about two thirds of the total volume of lava erupted around 300,000 years before the onset of the Permian Extinction based on fossil records (Burgess and Bowring, 2015). This finding can be best explained by another paper published by Burgess et al. in 2017. The Burgess paper uses carbonate carbon records to hypothesize that the sill intrusions emplaced at the beginning of Stage 2, characterized by widespread lateral transport of magma intrusions (see Figure 2.5), satisfies the criteria to qualify as the trigger mechanism for the Permian Extinction (Burgess and Muirhead, 2017). This aligns with the previous studies and explains why the Siberian Traps were erupting for 300,000 years prior to the start of the End-Permian biotic crisis seen in the fossil records.

In 2018, 10 years after publishing his paper first suggesting the importance of sills as contributors to the extinction event, Svensen et al. contributed yet more convincing evidence to support this theory. Almost 300 deep boreholes that intersect the emplaced sills in the region of Tunguska Basin in East Siberia were examined in this study and thermal one-dimensional modelling was completed for some of the boreholes (Svenson et al., 2018). What was observed was metamorphism of marls and rocks containing organic matter such as coal resulted in 4.0–9.2 times more $CO_2$ generation compared with the sill degassing mantle $CO_2$ alone. This finding truly emphasizes the importance of the composition of the sediments into which sills are intruding. It is critically important because a sill network intruding into volatile-poor sediment will likely not result in volatile production on the scale required to drive an extinction event. This conclusion agrees with the theory of the Permian Extinction being triggered by the Siberian Traps LIP. This also suggests that it was the formation of volcanic sill networks that ultimately triggered the sequence of events starting with substantial greenhouse gas emissions, driving global warming and atmospheric ozone depletion, leading to warmer global temperatures, ocean acidification, and anoxic conditions on land and sea (Svensen et al., 2018).

Now, imagine Earth in the present day of the Holocene. Our planet is still a bastion of life in a cold and dark universe and we as humans are still surviving here on Earth but this likely wouldn't be if the Permian Extinction hadn't left any mammalian-like survivors. So how did /Earth's nurturing environments become so hostile that over 90% of Earth's life on land and sea vanished forever? By correlating the geological evidence around the world, we know that it was likely not one cataclysmic event, but rather a slow sequence of events rooted in the causal mechanism of copious greenhouse gas emissions. It is possible that $CO_2$ release during formation of the Siberian Trap lava flows was accentuated by the emplacement of sill networks causing contact metamorphism. Today, anthropogenic $CO_2$ production is occurring at an extremely rapid rate due to industrialization. If this continues for long enough, this could cause the Earth's atmosphere to surpass a critical $CO_2$ threshold. We have already observed global warming, ozone depletion, and severe ocean acidification in recent years. Species could start dying off in a trophic cascade and before we know it, we may start experiencing a phenomenon similar to the Permian Extinction in our brief age of human existence on Earth unless drastic measures are taken to reduce our carbon footprint.

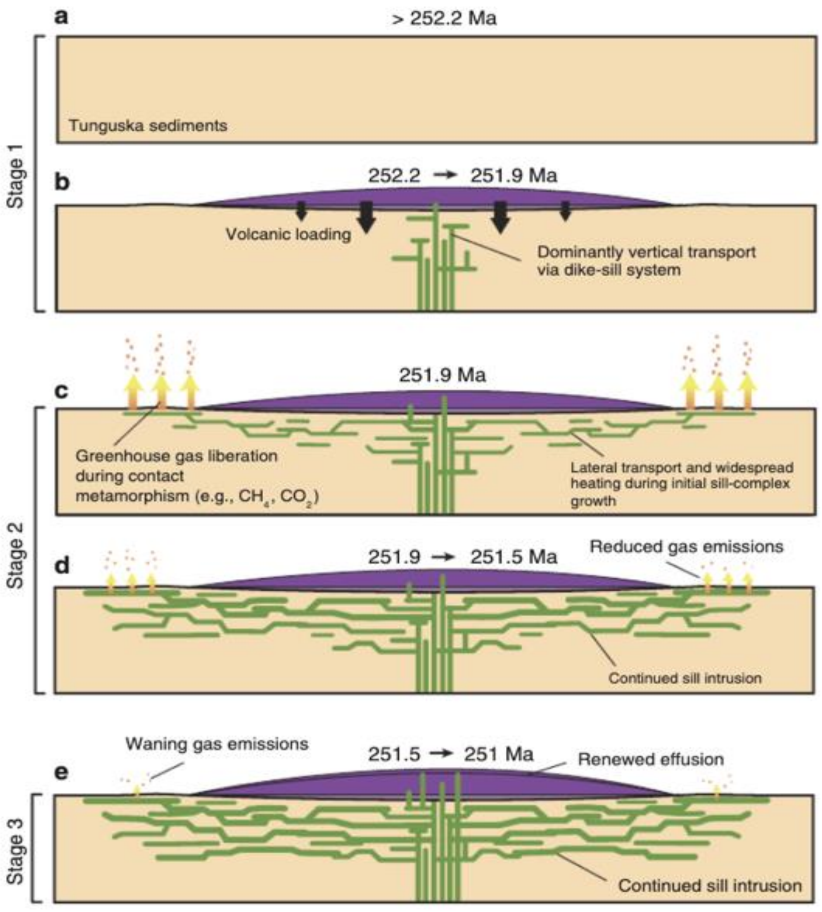


*Figure 2.5. This image illustrates a series of images of the hypothesized time series of Siberian Traps LIP emplacement. Stage 1 is characterised by pyroclastic eruptions followed by lava fissures. Stage 2 is characterised by the slowing of extrusive lava flows and the onset of widespread sill complex formation. Stage 3 was marked by the re-emergence of extrusive lava flows and the continuation of sill formation. C) shows the point in Stage 2 where most greenhouse gas emissions are released (Burgess and Muirhead, 2017).*

# Anthropogenic Climate Change: A Historical Lens

Humans have wondered about Earth's processes and climate for as long as civilizations have existed. As early as the 3rd century BCE, Greek astronomer-geographers Eratosthenes and Ptolemy began to determine that the Earth's climate was related to the inclination of the sun. Ptolemy's system in particular included fifteen climatic zones by the lengths of their longest day, which he also expressed as latitude (Edwards, 2011). The consensus in early schools of thought was that the natural world is, and would continue to be, balanced in equilibrium (Weart, 2004; Edwards, 2011). For many years, this would guide our understanding of the climate. However, the field would undergo a paradigm shift that would implicate human actions in the warming of the planet. This chapter offers an overview of anthropogenic climate change, its pioneers, and their motivations. While there are gaps in our knowledge of climate science through time, the history of anthropogenic climate change frames what today is an issue of global concern.

*Figure 2.6. Joseph Fourier, French physicist and early climatologist who suggested the greenhouse effect (Louis-Léopold Boilly, 1810).*

## Early Modern Perspectives on Climate Change

The story of anthropogenic climate change begins during the late 17th century in England (Edwards, 2011). A time of great social and political upheaval (White, 2018), the 17th century brought religiopolitical tensions and warfare to Europe (Kenny and Smyth, 1997). Following the scientific revolution, science was a burgeoning field, yet fraught with religious influence and societal doubt. Despite the forces of religion, English polymaths were determined to lay the foundation of climate science and build on ancient perspectives (Halley, 1687; Edwards, 2011). Some pointed to sunspots as sites which could potentially provide hints about long-term climate shifts (Weart, 2004). However, there was no large-scale and systematic data collection for upper air at the time, so these early meteorologists could only infer the structure of above-ground atmospheric circulation. Theorists at this time were limited to a purely conceptual understanding of the climate system as an equilibrium (Edwards, 2011).

## Joseph Fourier and the Greenhouse Effect

Scientists continued to explore the global energy system as a balanced structure. However, in 1807, the heart of the Industrial Revolution, French scientist Joseph Fourier (see Figure 2.6) would dismantle this notion. A member of the prestigious École normale supérieure, he began to explore how Earth received and emitted radiation and its effects on global climatic variation (Edwards, 2011). Fourier and many other 19th-century theorists were beginning to recognize the Earth's surface temperature was much higher than would be expected given the amount of radiation it receives and emits (Fourier, 1822). Investigating the factors responsible for the average temperature of planets, Fourier's initial belief was that infrared (IR) radiation emitted from heated surfaces carries heat energy into space (Weart, 2004). However, this was not supported by his own mathematical model; it calculated a far lower temperature (Weart, 2004). Hence, Fourier noted that Earth's atmosphere was trapping some heat by intercepting part of the IR radiation emitted from the surface (Fourier, 1822; Weart, 2004). Drawing an analogy between Earth and its atmosphere to a box with a pane of glass, the Frenchman spoke of the greenhouse effect (Weart, 2004); his 1822 book even referenced the word "serre", meaning "greenhouse" (Fourier, 1822; Edwards, 2011). While the notion of the "greenhouse effect" had not yet gained traction, Fourier's work laid the foundation for future research on this phenomenon. He also reinforced the notion of natural world balance with his principle of radiative equilibrium (Edwards, 2011).

## John Tyndall and the Carbon Dioxide Theory of Climate Change

The mid-1800s saw an increasing relationship between science and technology (Layton, 1971). In both Europe and America, many were realizing the opportunities afforded by experimental equipment to provide precise empirical data (Layton, 1971). A notable figure at this time was British scientist John Tyndall (see Figure 2.7), a professor of physics at the esteemed Royal Institution of Great Britain (Jeans, 1887). Tyndall was a staunch advocate of climatology. Motivated by his hope of increasing the cultural authority of science, he sought to diminish the influence of religion and its practitioners on the general population (Fyfe, 2008).

Tyndall wondered how the atmosphere may control the Earth's temperature yet was stymied by the popular scientific opinion of the time that all gases were transparent to infrared radiation (Weart, 2004). He remained unconvinced. In 1859, Tyndall conducted an experimental study which found that while most atmospheric gases, like $O_2$ and $N_2$, were transparent to IR radiation, the gas let off by coal was opaque (Weart, 2004). Importantly, he observed that $CO_2$ was opaque as well and thus had the potential to influence the planet's radiation balance (Weart, 2004). While in relatively low concentration at the time, atmospheric $CO_2$ stores were sufficient to absorb upwelling infrared radiation and re-radiate heat energy to the air and surface, in turn maintaining a higher temperature (Weart, 2004). By 1861, Tyndall had concluded that geophysical cycles which involve heat-trapping gases were, at least in part, responsible for major climatic change (Tyndall, 1861). He presented his findings at a prestigious Bakerian Lecture of the Royal Society (Tyndall, 1861), reaching an elite audience. At this time, it was still immensely useful to gain the support of the academic elite in order for widespread acceptance and dissemination of Tyndall's ideas (Barton, 1990).

Tyndall continued his work with a focus on the prehistoric ice age, a growing controversy among scientists of the day (Weart, 2004). Noting the geological deposits and landforms in northern Europe and the United States, his research and advocacy helped scientists accept that northern regions had been buried kilometres deep in continental ice sheets in recent geological time (Weart, 2004). He implicated water vapour as $CO_2$ was present in relatively low concentration. Tyndall attributed greenhouse gases (GHGs) to long-term negative impacts of human practices, such as agriculture. He also associated GHGs with the prehistoric ice age, hypothesizing that a drier atmosphere would result in an ice age (Weart, 2004).

## Late 19th Century Perspectives

After Tyndall's early work on glaciation, determining the mechanism by which it occurred was a driving force in climatology, riddled with controversy. Thomas Chrowder Chamberlin, American geologist and founder of the *Journal of Geology* suggested that carbon dioxide in particular was the fundamental driver of global climatic changes on geological time scales (T.C. Chamberlin, 1897, 1898; R.T. Chamberlin 1928). Chamberlin argued that periods of high volcanic activity released large amounts of $CO_2$ warming the Earth (Edwards, 2011). Further, during slow weathering processes, atmospheric $CO_2$ would combine with calcium in igneous rock to form $CaCO_3$ and carbon would also be absorbed by organic matter. In periods of low volcanic activity, the opposite would occur (Edwards, 2011). By the early 20th century, this theory was generally rejected as Anders Ångström and others concluded that water vapour's effects on Earth's temperature outweighed that of $CO_2$ (Ångström, 1923, 1929); thus, they argued that changes in $CO_2$ levels had virtually no effect on global temperature (Edwards, 2011).

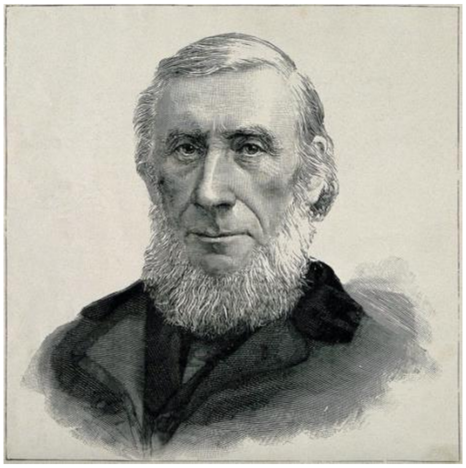


*Figure 2.7. John Tyndall, British scientist and member of the Royal Society (Elliott and Fry, 1973). Tyndall was the first to attribute changes in global temperature to carbon dioxide.*

On the opposite side of this controversy was Swedish scientist Svante Arrhenius, who, in 1895, built on Tyndall's earlier work (Weart, 2004). He hypothesized that if the amount of atmospheric $CO_2$ changed via volcanic eruptions, the temperature would rise incrementally (Weart, 2004). He estimated the amount of heat retained by carbonic acid and water vapour, noting how they contribute to Earth's surface temperature (Edwards, 2011). Warmer air would hold more moisture, and thus humidity, thereby greatly enhancing warming. The opposite would be true if all $CO_2$ were to be absorbed (Weart, 2004). Arrhenius was among the first scientists to link the concept of "positive feedback" with climate, building on notions put forward British geologist James Croll in the 1870s (Weart, 2004).

While Arrhenius could estimate the immediate effects of changing $CO_2$ levels, he sought to better understand the compounding factors to produce a valid theoretical model (Weart, 2004). Soon, he was able to announce that cutting the amount of atmospheric $CO_2$ could induce an ice age due to feedback (Weart, 2004). As Arrhenius' colleague Arvid Högbom helped compile estimates for $CO_2$ cycles through natural geochemical processes, he realized that the rapid industrialization earlier in the century contributed to GHG emissions to the atmosphere at roughly the same rate as natural processes emitted and absorbed the gas (Weart, 2004). Arrhenius' 1896 paper calculated that doubling atmospheric carbon dioxide would raise global average temperature by 5–6°C (Arrhenius, 1896; Weart, 2004; Edwards, 2011). The declaration was opposed by many, as the notion that humans could perturb the atmosphere to such extents was not considered reasonable by the scientific community and public at-large (Weart, 2004). Ångström provided experimental infrared evidence to suggest that water vapour had a greater role relative to carbon dioxide, leading many scientists in the 1910s to believe that Arrhenius' speculation was wrong altogether (Ångström, 1923, 1929; Weart, 2004). Further, there was hope in technological advances, including industrialization, for the betterment of society; the argument that it may have in fact been detrimental was resisted (Weart, 2004).

## 20th Century Perspectives

By the turn of the century, it had long been acknowledged that vast global climate changes had occurred in the past, but there was still objection about its origin (Weart, 2004). Professional scientists did not consider climatology to be a true science, especially given that climate models and weather prediction were not sophisticated (Weart, 2004). Analog models, such as using bowls and globes with cloudy fluids, or dishpan models, were increasingly popular to understand climate (Edwards, 2011). The turbulent patterns produced by rotating these models strongly resembled atmospheric motions. While these analog models were limited in their capabilities, they helped demonstrate the fundamental principles of climate on a global scale, including fluid motion (Edwards, 2011). However, meteorologists now finally had enough reliable weather records to test these principles (Weart, 2004).

While many early climatologists incorporated aspects of geology, physics, and mathematics, most thought that climate had nothing to do with biology. However, a Russian geochemist, Vladimir Vernadsky, thought differently (Weart, 2004). He acknowledged that the volume of materials produced by human industry was approaching the scale of geological processes. Examining organismal biochemical activities, Vernadsky concluded that the oxygen, nitrogen, and $CO_2$ which make up the Earth's atmosphere were put there largely by living creatures (Weart, 2004). His 1920 paper argued that living organisms constituted a force for reshaping the planet comparable to any physical force. It was not widely circulated, and most did not consider it to be credible (Weart, 2004).

Early mathematical models of climate attempted to isolate determining factors between incoming solar energy and outgoing heat (Edwards, 2011). Soon, it was found that astronomical cycles played a role in climate. Reviving and building on Adhémar and Croll's 19th century hypothesis that orbital cycles caused ice ages by reducing insolation, Milutin Milanković put forward the notion that three astronomical cycles could explain recurring climatic changes in the 1920s (Edwards, 2011). These cycles were the eccentricity of Earth's orbit, axial tilt, and the precession of the axis. Interactions among these cycles would cause variations in the amount of insolation of up to 20-30% at a given latitude (Edwards, 2011). He also suggested that these cycles do not alter overall planetary insolation much themselves but can still cause large changes in albedo (Edwards, 2011). Regardless, Milanković's interacting astronomical cycles soon were considered a principal cause of the ice ages, alongside other factors like variations in the carbon cycle (Edwards, 2011).

In 1938, English steam engineer Guy Stewart Callendar spoke before the Royal Meteorological Society in London to challenge the scientific consensus of the time regarding the causes of climate change (Callendar, 1938). An outsider to the scientific community, Callendar was merely a follower of weather statistics; however, Callendar had gathered convincing evidence over time (Weart, 2004). Following new, more sensitive measurements which disproved Ångström's argument, he used basic climate modelling (Edwards, 2011) to argue that human industry, specifically the burning of fossil fuels, emitted millions of tons of $CO_2$ into the atmosphere which was changing the climate (Weart, 2004). It does not come as a surprise that Callendar was a steam engineer earning a livelihood designing objects which emit water vapour, not carbon dioxide. Regardless, this effectively revived the carbon dioxide theory of climate change amongst the scientific community (Edwards, 2011).

## Global Circulation Models

Basic numerical climate modelling conducted by Ångström and his predecessors provided a rudimentary understanding of the climate (Bjerknes, 1906, 1910; Woolward, 1922). Their methods were imprecise and led meteorologists to abandon numerical modelling for the next two decades (Edwards, 2011). Technological advances became the foundation of weather and climate modelling, a central pillar of climate change science, from the 1940s onwards (Edwards, 2011). During World War II, there was a push to advance scientific research in weather prediction to inform battle plans and even control the weather (Kwa, 1994, 2001). This research continued after the war—military agencies and civilian weather services used digital computers to undertake computerized numerical weather prediction (NWP) (Edwards, 2011). The success of NWP led to efforts to make global circulation models (GCMs) for long periods, such as the atmospheric aspect of climate (Edwards, 2011). These GCMs used the same techniques as early NWP models but extended them to the hemispheric or global scale, using full, unsimplified equations to compute atmospheric motion (see Figure 2.8) (Edwards, 2011). Since these models require accurate parameterization of physical processes, considerable political and scientific controversy arose with regards to the weightings of parameters, the scientific integrity of models, and legitimacy (Edwards, 2009, 2011).

## Sounding the Alarm

Technological and methodological advances allowed for the forecasting of future climate warming. This caught the public's eye. By the start of the 1970s, the global climate alarm had been sounded. To the scientific community, it was clear that human activities were significantly contributing to global warming. There was a strong theoretical basis for anthropogenic climate change, and evidence, specifically measures of atmospheric carbon dioxide, was being rigorously gathered (Peterson, Connolley and Fleck, 2008). Climate science had become highly politicized, a sensationalistic topic of the media and a public focus. This brewed the perfect storm for misinterpretation.

In 1972, American climatologist f Murray Mitchell culminated a series of publications aimed at organizing global temperature records. Mitchell had observed a period of global cooling between the 1940s and 1970s, seemingly contrary to mounting evidence for global warming (Peterson, Connolley and Fleck, 2008). At the same time, authors had begun to discover the negative climate forcing of aerosols. Air pollution was producing aerosol compounds which increased atmospheric albedo and reflected a greater proportion of incident solar radiation. Rasool and Schneider were the first to include this in a basic climate model, concluding that a fourfold increase in aerosol concentrations would be sufficient to induce a global ice age (Rasool and Schneider, 1971). This sparked concerns among scientists and media alike—articles such as Science Digest's "Brace Yourself for Another Ice Age" in 1973 became commonplace alongside an increasing consensus that the planet was entering a period of glaciation (Vogel and Lazar, 2010). This had particular ramifications among a public which, only recently, had warmed to the idea of anthropogenic climate change. The pathway toward mitigating anthropogenic effects on climate significantly derailed.

*Figure 2.8. Climatologists using an early digital computer to run a global circulation model (Everett Collection Historical, n.d.). These models were central to forecasting anthropogenic effects on climate.*

It was only until James Hansen, a compatriot of Mitchell, conducted more rigorous modelling in 1978 that the true interplay between the greenhouse effect and aerosols was revealed. Hansen recognized that more empirical data was required for precise modelling. Using aerosol data from the 1963 eruption of Balinese volcano Mount Agung, Hansen accurately replicated the temporal and spatial scales of aerosol distributions in the atmosphere (Peterson, Connolley and Fleck, 2008). This was crucial to understanding the correct degree of negative forcing produced by aerosols. By the end of the 20th century, the question of whether aerosol cooling or the greenhouse effect would prevail was clear: the planet was en route to significant anthropogenic warming. A polarizing figure unafraid to be an activist, Hansen would go on to testify to the United States Congress promoting the urgency of the climate crisis (Besel, 2013). The significance of anthropogenic actions to the warming of climate would remain a topic of scientific and public urgency.

## Conclusion

The history of climate science is one of controversy and influence. Our understanding of anthropogenic climate change has not evolved linearly over time. Yet, it is the digressions in theory, driving forces of religion and industry, and the multitude of unique contributing individuals which has enriched our knowledge of the subject. It is a testament to the fact that science, contrary to what we might hope, is not practiced in a vacuum.

# Climate Modelling

At present, climate models are critical to our understanding of anthropogenic climate change in both a retrospective and predictive capacity. Unlike the preliminary models developed in the 1960s and 1970s, current models are integrative and examine aspects of climate and society to provide a holistic view of the Earth's climate. In particular, the models of today have a finer resolution, greater complexity, and are more realistic than their predecessors. Examining the features and uses of these models, specifically the Earth System and Integrated Assessment Models, is central to understanding the modern climate science toolkit.

## Earth Systems

The first numerical climate models simulated single, and later, multiple physical aspects of the climate system, such as the atmosphere or ocean. Contemporary Earth System Models (ESMs) involve both physical processes and interacting biogeochemical cycles (Flato, 2011). ESMs use an interdisciplinary approach and consider the ecosystem functions, atmospheric chemistry, and nutrient cycles which impact the ongoing processes driving the climate (based in physics and thermodynamics).

ESMs divide the planet into a series of grid cells, often on the order of 100km in diameter, and vertical layers, which divide the ocean and atmosphere for more precise simulation (Flato, 2011). The core of an ESM is its physical model, a computer code which approximates the solutions to complex differential equations. These sets of mathematical equations, initially developed by Joseph Fourier, are based on properties of thermodynamics and fluid motion which dictate the flow of energy throughout the system (Fleming, 1999; Heavens, Ward and Mahowald, 2013). The physical model operates uniquely in each grid cell and represents 'physical' processes such as precipitation, heat transfer, and winds. However, there are countless such processes that operate on far smaller scales which cannot be resolved in a grid cell. To address this, smaller-scale phenomena such as cloud formation are simulated using parameterizations, which assume these processes to be a function of average larger-scale mechanisms (Heavens, Ward and Mahowald, 2013). Superimposed on the physical model are a series of biogeochemical cycles, ranging from dynamic vegetation models to atmospheric chemistry (Sellar et al., 2019). By coupling biogeochemical phenomena with physical processes, ESMs are able to examine feedback loops which are central to climate change (Sellar et al., 2019). Rather than studying unforced changes in climate over time, this ensures that impacts of natural and anthropogenic activities are evaluated (Heavens, Ward and Mahowald, 2013). While these simulations can take months to complete, as they require massive computing power (Jones, 2019), exponential advances in computational capabilities have been central to increasing the complexity of ESMs.

Since ESMs do not incorporate the influence of anthropogenic activities, they are particularly useful for modelling paleoclimatic conditions prior to the industrial revolution (Haywood et al., 2019). This provides a process-oriented explanation of how past climatic conditions arose and is especially useful in identifying the effects of feedback loops over time. Moreover, ESMs fill gaps in discontinuous paleoclimatic data, which allows us to better understand how natural forces have influenced climate in the past (Haywood et al., 2019).

A major constraint of ESMs is the inherent trade-off between resolution and complexity. Climate modelling is a technology-limited field in that the capability of models is largely dependent on computational power. As a result, there are both pressures to improve resolution for more granular analysis and to incorporate a greater number of biogeochemical processes which may be responsible for climate change. The computational cost of these improvements is especially large—an increase in resolution from 200km to 20km, for example, requires a ten-thousandfold increase in power (Flato, 2011).

## Integrated Assessment Models

Integrated Assessment Models (IAMs) are the most recent advancement in climate modelling, describing both the natural physical phenomena of the Earth and the influence of socioeconomic factors. These models simulate the development of human activities with respect to energy, economy, and population to predict anthropogenic forces on climate. IAMs incorporate a variety of scientific and non-scientific disciplines to add the anthropogenic dimension to the climate system.

Similar to an ESM, an Integrated Assessment Model is centered on a physical climate model which represents flows of energy through the Earth-Atmosphere system in layered grid cells (see Figure 2.9). The physical climate model is responsible for determining modulations to the climate system which are caused by human activity. IAMs are complex, and often involve the coupling of many individual physical models (referred to as component 'modules') which in combination represent the full climate system. A similar process is used to simulate anthropogenic impacts—often multiple economic, population, and industrial models are added, producing emergent properties which arise from the interaction of each module. A contemporary IAM for example, combines the E3ME macroeconomic model, which calculates a series of econometric relationships based on real-world data, with the FTT model of technology diffusion that determines the environmental intensity of technology (transport, electivity, households) over time (Mercure et al., 2018).

The primary function of IAMs is to inform decision-making about climate policy on a regional and global scale. By projecting the influence of anthropogenic activities, notably the contribution of greenhouse gas emissions, IAMs can be modified based on the outcomes of potential climate policies, providing policymakers with a relatively accurate prediction of how they differ. IAMs also allow for cost-benefit analyses which cannot be performed on ESMs. Since IAMs project the impact of anthropogenic activities on natural phenomena *and* the impact of climatic changes on humans, the projected consequences of policy decisions can be determined in terms of monetary or social impact. However, at present, integrated models are only able to provide effective feedback on potential policy decisions over a scale of about 5-10 years (Weyant, 2017).

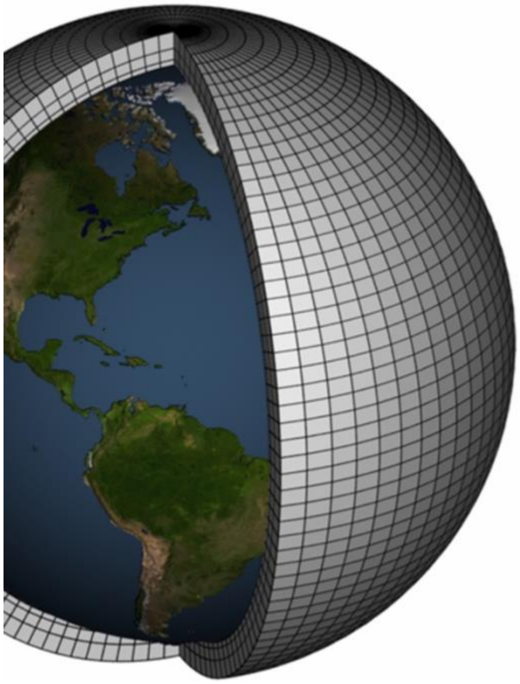


*Figure 2.9. Grid cell system used for simulation in Integrated Assessment and Earth System Models (NOAA, 2012). By representing the atmosphere and oceans as a series of layered cells, differential equations and parameterizations can be performed at a finer resolution.*

IAMs are subject to a unique set of criticisms because they focus on assessing the climate system in terms of human impact. Many authors have expressed concern about the relatively 'arbitrary' nature of these models, which require modellers to make subjective decisions. For example—are the mean outcomes or potential extreme outcomes of climate change more significant? Modellers are also tasked with deciding whether to express the results of simulations in terms of monetary or social impacts and the scale of analysis (regional versus global) (Weyant, 2017). There are also concerns with modelling climate policies. Since climate policy is of relatively recent interest, there are few data against which to evaluate IAMs or to parameterize the effects of policy on human actions in the model (Weyant, 2017).

## Conclusion

Contemporary climate models are diverse in structure and function, with adaptable components. This means that they can be used for a variety of purposes, from reconstructing paleoclimates and mass extinctions, to forecasting global warming and the impacts of climate change on society. Climate modelling is a centrepiece of the modern climate science 'toolkit' and plays a central role in understanding and evaluating anthropogenic climate change. Improvements to computational power in future years will propel advances in modelling resolution and complexity, enabling us to predict the future and analyze environmental decisions with ever-increasing precision.

# Determining the Age of the Earth

It is difficult to grasp time in the range of billions of years as a species that considers itself lucky to reach the age 100. As such, it was not an easy process in science to arrive at the current age of the Earth as 4.5 billion years old. This discovery took the work of multiple generations of creationist and scientific academics, as well as many fierce debates between them, to come to this final conclusion. This endeavor also spurred major developments in almost all fields of science over multiple centuries.

## Original Creationist Perspectives

*Figure 2.10. An artist's rendition of God separating the land from water during the Biblical six days of Creation.*

When the bible alone is used, the age of the Earth is determined to be the same as the age of humans, give or take a few days (Ussher, 1650). As such, an age of approximately 6000 years was supported by early postulates made by Christian scholars. In 1650, when the Irish bishop and chronologist, James Ussher, used the Hebrew Bible to date the Earth (Ussher, 1650), they found that the Earth's Creation took place in 4004 BC on the evening of 23 October (Ussher, 1650). Similar ages preceded Ussher's chronology, however not to the same precision, which earlier chronologists believed could not be achieved (Ussher, 1650). Given the dominance of Christianity at this time and Ussher's status as a clergyman, his dating was well supported (Numbers, 2000). By 1701, his date in 4004 BC was published in bibles and remained there for three centuries (Numbers, 2000), which undoubtedly had a major influence on Christian beliefs.

In the 18th century, many novel geological discoveries were made which compelled Creationists to accept and support an age older than 6000 years, for example the findings of Reverend James Douglas (Montgomery, 2012). In 1785, Douglas presented *A Dissertation on the Antiquity of the Earth* to the Royal Society of England (Montgomery, 2012). Works like these contrast so-called young-Earth and old-Earth creationists based upon their extent of scientific acceptance. Douglas, for example, was an old-Earth creationist, whereas Ussher was a young-Earth creationist. Douglas argued in his dissertation that the world was in fact old, like the age's scientists suggested (Douglas, 1785). Although his work suggested no timeframe during which Creation took place, Douglas used fossil discoveries to place Creation at earlier than 4004 BC (Douglas, 1785). Douglas used fossilizing organisms of known age to estimate mineral replacement rates. He then used these rates in conjunction with completely fossilized organisms, which could in no possible way be of origins younger than 4004 BC, thus making the argument that more time would have necessarily passed after the organisms had died than could have been suggested by young-Earth creationists (Douglas, 1785). In addition, Douglas made mention of fossils found on the Isle of Sheppey which were noticeably unlike the modern organisms living there. He claimed that it would have been impossible for these fossils to drift to the island by natural marine transport and stated that considerable amounts of time would have passed since those organisms lived there (Douglas, 1785). Douglas then stated his agreement with an argument growing in popularity at the time; that the Biblical six days of creation (Figure 2.10) were in fact six expanses of time, wherein the first four do not adhere to the typical solar day. This would still align with the Bible, because before day 4, when God created the sun, the conventional measure of a day could not be used (Douglas, 1785). This argument is part of the Day-Age Theory supporting old-Earth creationism (Montgomery, 2012).

As geological bases for an old Earth grew in popularity, the Gap Theory became popular like the Day-Age Theory. This theory states that between the first two verses in Genesis, there exists a large period of time where the Earth grew to support life, but after God watched his Creation grow evil, he destroyed the Earth and started anew (McIver, 1988). This theory allowed for the second Earth to have existed for as long as science suggested, because it suggests that the six days of Creation took place long after the Earth itself came to be (McIver, 1988). The acceptance and popularity of these theories among creationists resulted in a reduced audience for young-Earth scholarly content and by the year 1802, when François-René de Chateaubriand published *Genius of Christianity,* it was not well supported (Montgomery, 2012). De Chateaubriand recounted reasons for which nature was a product of God's Creation and he claimed that a major source of the Earth's beauty is its appeared antiquity (de Chateaubriand, 1802). For this reason, God could not have Created the Earth in a young state, because it could not have been as beautiful and charming, which would be a flaw in His divine creation (de Chateaubriand, 1802). As such, de Chateaubriand claimed that the Earth's age could not be determined through its supposedly deceiving appearance (de Chateaubriand, 1802). Over half a decade later in 1857, when the British naturalist Philip Henry Gosse published *Omphalos*, he made a similar argument that the Earth's age was an illusion, just like Adam's belly button, which was purely appearance worthy, because he was motherless (Gosse, 1857). Based upon the cyclical nature of life on Earth in which death is followed by rebirth, Gosse did not believe that there was any true beginning to this cycle, meaning that it must have always been so since creation (Gosse, 1857). His arguments were not respected by the public, especially one which stated that God had implanted rocks with fossils in order to appear older (Montgomery, 2012). Both de Chateaubriand and Gosse were proponents of the Appearance of Age theory, which allows for all of the physical signs pointing to an antique age of the Earth being discredited as decorations by God (Pfahler, 2005).

Since they were first developed, Gap and Day-Age Theories and the Appearance of Age Theory have continued to be used by creationists to describe how the features of the Earth pointing to its age align with their faith and very few creationist contributions to the discussion on the age of the Earth have been made since the theory that the biblical flood deposited all of the Earth's strata was proposed and discredited (Montgomery, 2012).

In the 1600s to 1700s, biblical answers to earthly phenomena were easily acceptable to the public (Montgomery, 2012). However, looking back to the early and mid 1800s, it is clear that literal interpretations of the Bible were no longer sufficient given their inability to answer the biggest questions in science. Hence, we begin to see the paradigm shift to a more observation-based approach

## Early Developments from a Scientific Lens

One of the first true geologic pioneers who suggested an incredibly old Earth was James Hutton, who is well known today as the first to propose uniformitarianism. Hutton had a keen interest in rocks as well as natural processes, and most of his research in the mid to late 1700s was devoted to studying structural features around the world (Britannica, 2020). He was one of the first to recognize the Earth as a dynamic planet, in which its materials are constantly being transported, consolidated, broken, and displaced again in a cyclic fashion (Hutton, 1788). Additionally, Hutton also realized that the internal heat of the planet was a fundamental force that caused expansion of the crust, producing the mountains we see today (Hutton, 1788). These ideas and more are linked to the theory of uniformitarianism, which states that the geological processes that go on today, like erosion and deposition, are the exact same as those that operated in the past. While he did not coin the term, he was the first to really develop this framework. From it, he concluded the Earth must be much older than the age proposed by theologians, as the thick layers of sediments exposed on Earth's surface must have taken millions of years to be deposited (American Museum of Natural History, 2000). In 1788 he published his findings in a paper titled, *Theory of the Earth; or an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of Land Upon the Globe*. This was a turning point in geology, as it consolidated much of what had been discovered independently about strata, fossils, and Earth materials into a unified geological theory (Britannica, 2020). It was also controversial at the time, as it opposed the concept of a 6000-year-old Earth (Britannica, 2020). This idea of an ancient Earth shaped by slow but consistent mechanisms was one of the first truly revolutionary concepts that gave birth to modern geology, as well as rejected theological doctrine (American Museum of Natural History, 2000). Other well-known scientists would use Hutton's framework to expand and build their own ideas.

## First Estimates

Charles Darwin had great interest in proving the Earth was old in the favour of his Theory of Natural Selection (Rognstad, 2020). As such, during an international voyage in 1831, Darwin collected geological evidence using Charles Lyell's *Principles of Geology* (Rognstad, 2020), and observed that the geological processes that had visibly taken place would require much greater time than the current scientific and biblical theories on the Earth's age would allow for (Darwin, 1859). He observed cliff faces and commented on the amount of time and energy that would be required to erode them to such an extent. He also evaluated stratigraphy, noting the enormous time that it would take for the deposition of a single stratum, as well as the time delay between the deposition of successive strata (Darwin, 1859). He proposed a length of time in the order of hundreds of millions of years that would occur over the course of the erosion of the chalk cliff face (Figure 2.11) in the Wealden region of England (Darwin, 1859). The age of the Earth implied by this discovery was not eagerly accepted by scientists like Lord Kelvin, who was at the forefront of physics at the time, whose own theories on the age of the Earth were founded by new developments in thermodynamics (Rognstad, 2020).

*Figure 2.11. Chalk cliff face near Wealden district UK, from which Darwin estimated the Age of Earth.*

Soon after Darwin's *On the Origin of Species by Means of Natural Selection*, Kelvin published *On the Secular Cooling of the Earth*, in which he made calculations of the age of the Earth based upon the assumption that it formed as a molten sphere that had since been cooling (Kelvin, 1864). An Early hot but cooling Earth like in Kelvin's hypothesis is shown in Figure 2.12. Kelvin made this assumption based upon the hotter temperature of the inner Earth at increasing depths (Kelvin, 1864). The age he produced using this information, as well as his assumed melting point of early Earth rocks being between 7000° and 10000°F, was between 20 million and 400 million years (Kelvin, 1864). In the following years, scientists initially were too intimidated by Kelvin's stature to counter this age, including Darwin, whose theory was directly challenged by Kelvin's (Rognstad, 2020). Eventually, the role of conduction in Kelvin's calculations was heavily criticized, because suspicions were mounting that the inner Earth had had large proportions of liquid rock, such that convection currents would play a major part in the cooling of the Earth (Rognstad, 2020). In 1899, Kelvin revisited his proposed age, adjusting the temperature of melting rock by using experimentally determined temperatures and the densities of solid and liquid diabase — this time producing a range between 20 to 40 million years of age, with the exact number likely being closer to 20 million (Kelvin, 1899). This new range garnered little support from the scientific community, because it contradicted the widely accepted notion of an upper limit in the hundreds of millions (Rognstad, 2020).

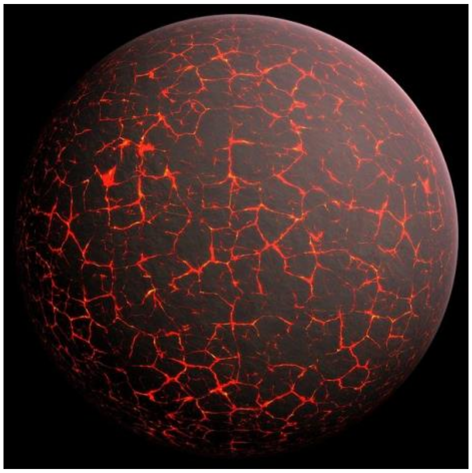


*Figure 2.12. Hypothesized early cooling Earth.*

As part of his lesser works, in the late 1800s, Charles Darwin's son George Darwin (from here on called G. Darwin) attempted to contribute to the age of the Earth discussion by determining the age of the Earth-Moon system (Hughbanks, 1919). G. Darwin suggested that the Earth-moon system loses energy through friction between the rotating Earth and the water pulled by the lunar tides (Hughbanks, 1919). Because of this friction, the Earth's revolution has slowed, and the Moon has grown farther away from the Earth (Giedd, 2005). G. Darwin calculated the length of time it would have taken to increase the Earth's rotational period to 24 hours (from an original faster rotational speed), assuming that the Moon was a mass split off from the early Earth, and that their system's age is similar to the Earth's (Giedd, 2005). G. Darwin did not have much faith in his calculation, considering it produces a lower estimate of the Earth's age at 56 million years (Giedd, 2005). Surprisingly, G. Darwin's work to prove the antiquity of the Earth was later used as a foundation by creationists to argue the Earth's youth (Giedd, 2005). A creationist named Thomas Barnes, for example, wrote about how the commonly proposed recession rate of the Moon from the Earth would place the Earth within the Roche limit (the closeness that would result in the Moon falling apart into a planetary ring) if the system's age had been older than in the thousands of years range (Barnes, 1982).

## Radiometric Dating In the 1900s

The first concrete method used to accurately determine the age of the Earth was radiometric dating. The development of this technique began in the early 1900s, when Ernest Rutherford and Frederick Soddy discovered that some elements decay radioactively in predictable ways through the process of nuclear fission (Elias, 2015). In 1904 Rutherford began to postulate that this decay could be used to measure geologic time (Elias, 2015). In 1906 research began to determine the rate of decay of uranium, which would end up being the key element used to estimate the age of the Earth.

An American scientist named Bertram Boltwood heard Rutherford speak at a conference in Yale and was inspired by his findings (Kovarik, 1932). At this time, he was already very interested in rare-earth metals, and began to investigate the decay of uranium. He was the first to realize that small amounts of lead were always found in uranium containing rocks (Kovarik, 1932). This suggested that lead was not radioactive and that it is in fact the final product of uranium radioactive decay. In 1907 he published a study that proposed that the age of rocks could be determined by analyzing lead-uranium ratios in the rock (Boltwood, 1907). While the half-life of uranium, 4.5 billion years, was not known to scientists at this time, one of Boltwood's associates, Ellen Gleditsch, had found the half-life of radium. Boltwood had previously discovered that radium was another product of uranium decay and was able to extrapolate the half-life of uranium used for his calculations from this known value (Boltwood, 1907). He examined 20 lead containing samples, in which most were dated at 500 million years old - already much greater than the accepted age of the Earth at the time, which was between 20 and 100 million years. Most significantly, one of the samples he inspected was a Ceylonese thorianite rock dated at 2.2 billion years old (Boltwood, 1907). This estimate would later be found to be too generous, as some of the lead found in this specific rock was generated from thorium. This element similarly splits to produce lead, giving the appearance of a larger daughter product to original element ratio. Still, this was a radical change in the thinking at the time (Brush, 1989). By 1915, 1.6 billion years was the most frequently proposed age of the Earth by physicists, based on the works of prolific geoscientist Arthur Holmes (Holmes, 1946).

The technique of radiometric dating would continue to develop throughout the early 1900s, but would take time to be fully accepted by the whole scientific community, with considerable resistance by geologists in particular (Brush, 1989). This was because the time scale proposed by radiometric dating was far longer than estimates based on geologic sequencing as well as geologic rates like the amount of sodium introduced to the oceans via streams (Brush, 1989). At the time, geology was still primarily grasped by the principle of uniformitarianism, and the theories proposed by physicists were not consistent with the observable rates of Earth's processes. With their methods, geologists had a rough time scale in the order of 100 million years, with the alternative radiometric time scale being far too long and as a consequence suggesting incredibly slow rates of sediment accumulation. It would take the work of prominent geologists like T. C. Chamberlin to change the minds of these dogmatic geologists. He showed that geological evidence could be reinterpreted to agree with the radiometric dating (Chamberlin and Chamberlin, 1921). For example, sodium would be introduced to the sea more rapidly in the modern world due to the increased elevation of continents as well as being augmented by human activities like mining (Brush, 1989). Nuanced thinking like this encouraged geologist to rethink their strict uniformitarianism assumptions in order to be congruent with the admittedly hard to dispute radiometric time scale (Brush, 1989).

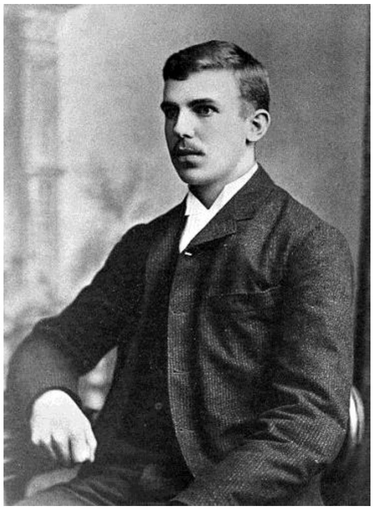


*Figure 2.13. Picture of Ernest Bohr Rutherford, who along with Frederick Soddy proposed the "disintegration theory of radioactivity," at McGill University. In 1908 he received The Nobel Prize in Chemistry for his work.*

In the coming decades, different scientists would continue to study radioactivity in order to refine the technique and produce the most accurate estimate for the age of the Earth. In 1922, Chamberlain combined radioactive dating with his planetesimal hypothesis and theoretical biology to propose a time scale of 4.26 billion years (Chamberlin, 1922). In that same year, astronomer Henry Norris Russel examined the ratios of uranium, thorium, radium and lead in rock samples to investigate the age of Earth's crust (Russell and Jeans, 1921). By accounting for some of the lead being released by thorium, he had an upper limit of 8 billion years and a lower limit of 1.1 billion years for the planet. The mean of the two values is 4 billion years, which he suggested as the most reasonable order of magnitude for the age of the Earth (Russell and Jeans, 1921). In his last contribution to the radiometric field, Rutherford (Figure 2.13) continued to look at uranium ratios along with the relative age of the sun, which these uranium samples would have originated from, and concluded that the maximum age of the Earth might be 3.4 billion years (Rutherford, 1929). This estimate of around 3 billion years would be continuously supported by the findings of physicists and astronomers over the next 30 years, with constant revision to theories focused on how the solar system developed, like the velocity of celestial bodies (Brush, 1989). In

1951, Pope Pius XII gave his blessing to the radiometric determinations of the age of the Earth in his address to the Pontifical Academy of Sciences (Brush, 1989), supporting that the oldest minerals appeared to be "at the most five thousand million years."

This would all lead to early 1956, when a scientist named Claire Patterson used meteorites for isotopic dating, assuming that this material must have formed at about the same time as the Earth and would contain uranium with the same isotopic composition (Patterson, 1956). Additionally, these samples would be much less affected by Earth's processes over time and therefore would be the best materials to derive an estimate from. With this technique he proposed that the Earth was 4.55±0.75 billion years old (Patterson, 1956), which was confirmed in the coming years by various researchers. This value has stayed relatively constant into the modern day, with the current estimate at 4.54 billion years, within the error originally accounted for in Patterson's work (Brush, 1989).

# Insights from the Oldest Rocks Discovered

Radiometric dating has continued to be the cornerstone for determining precise ages of Earth's oldest minerals. While rocks and minerals give insight into the age of the Earth and continually support the timescale proposed by scientists in the latter half of the 20th century, they also give important information about the conditions of early Earth. From this, we get a better sense of how life may have evolved on Earth as well as the rates of geological processes occurring on and under its surface, like crustal growth and tectonic movements (Valley et al., 2014).

In early 2014, geoscientists dated the oldest terrestrial material found on Earth, a zircon crystal with an age of 4.4 billion years, the oldest mineral in the world (Valley et al., 2014), found in Jack Hills, Western Australia. Once again, dating these minerals has given further evidence to support the age of the Earth at 4.5 billion years. On this note, homogenization of Earth's crust and the existence of a magma ocean have not been dated directly. However, these processes must have occurred before the formation of this zircon sample (Wilde et al., 2001). As such, with an age of the Earth at 4.5 billion years, and a zircon dated at 4.4 billion years, it can be concluded that the solidification of the magma ocean and Earth's mantle occurred relatively quickly after the Earth was formed (Valley et al., 2014).

Another important feature of these zircon crystals are their oxygen isotopic contents, which give us information on the magmatic, fluid and thermal history of the crust (Mojzsis, Harrison and Pidgeon, 2001). This is because the exchange rate for oxygen is slow in zircons, which allows the oxygen composition of the protolith rock to be consistent even after high grade metamorphism (Watson and Cherniak, 1997; Mojzsis, Harrison and Pidgeon, 2001). The quantity of heavy oxygen isotopes varies depending on the conditions of formation, and thus can be used to postulate what the environment may have been like. When a group of researchers examined a set of zircon crystals dated between 3,910- 4,280 million years, they found they had heavy oxygen ($^{18}O$) compositions of around 7-11% (Mojzsis, Harrison and Pidgeon, 2001). Based on this data, Mojzsis et al. suggest that these zircons had originally come from magmas containing recycled continental crust produced in the presence of water. This conclusion then suggests that Earth's hydrosphere would have been established within about 200 million years of terrestrial core formation at 4.5 billion years (Mojzsis, Harrison and Pidgeon, 2001).

While ancient zircon crystals embedded in igneous rocks can provide pertinent information on the early Earth, zircon found in 'younger' rocks can give us an idea of when life first evolved on its surface. The timescale of this event has been quite difficult to pin down, as deposits from the Eoarchean period tend to be quite rare and poorly preserved (Tashiro et al., 2017). However, there is an extremely valuable structure found in Labrador, Canada called the Saglek Block, which contains the oldest supracrustal rocks in the world. These metasedimentary rocks are is intruded by Uivak Gneiss, which was dated to be greater than 3.95 billion years old using uranium-lead ratios in zircons (Shimojo et al., 2016). What really makes this metasedimentary rock interesting is its inclusion of graphite (pure carbon), which can be used as an indicator of organic life. Light carbon ($^{12}C$) is the primary isotope sequestered by organisms, and as such graphite containing high amounts of light carbon is associated with the decay of these creatures (Mojzsis et al., 1996). This is our best source of evidence, as fossils of early life would be incredibly small and likely to be destroyed by metamorphic processes over time. A team of researchers from the University of Tokyo investigated the graphite contained in many parts of the Uivak Gneiss including samples from pelitic rocks, conglomerates, carbonate rocks, and chert nodules (Tashiro et al., 2017). They determined the concentrations and isotopic compositions of graphite samples using a graphite combustion method along with analyses of carbon isotope ratios relative to a Vienna Pee Dee Belemnite standard. Based on these methods they found that the graphite found in the rock has a biogenic origin, making it the oldest evidence of life discovered so far on the planet (Tashiro et al., 2017). Additionally, the isotopic signatures analysed indicated that the lifeforms that ended up producing this graphite were autotrophs, as the fractionation of the isotopes would most likely result from an organism using the reductive acetyl-CoA pathway or the Calvin cycle for energy (Tashiro et al., 2017).

While so far, we have only mentioned terrestrial materials, lunar samples have also been studied, as the inception of the Moon and the Earth are undoubtedly linked together. Despite being collected decades ago, scientists are always announcing new findings through their analyses of moon rocks. For example, in 2013 Hui et al. found significant amounts of water using infrared spectroscopy (Figure 2.14) in two lunar anorthosites retrieved in the Apollo 15 mission, which took place in 1971 (NASA, 2017). One of these anorthosites, known as the Genesis Rock, is among the oldest we have, with an estimated age of 4.1 billion years (Schaeffer, Husain and Schaeffer, 1976). While water had been previously found in lunar samples, this was typically attributed to processes like meteorite impacts or solar-wind implantation (Hui et al., 2013). The samples examined most recently however would have originally been part of the lunar magma ocean and later the primary crust, and as such would avoid contamination from these mechanisms. They found that these anorthosites had a water content greater than 5.0 parts per million, suggesting that the highland upper crust was not anhydrous, and contained appreciable amounts of indigenous water during its formation (Hui et al., 2013). This has important implications as it may contradict popular models of the Moon's formation, which involves an impact event between proto-Earth and another large celestial body. If this was the case, the disk generated from the impact that would later form the Moon would be incredibly hot and would release volatiles into space due to vaporization (Nakajima and Stevenson, 2018). However, the high water content of the early Moon suggested in studies like these seems incompatible with models of volatile release. If this is the case, it means that the events leading to the formation of the Moon and the Earth may need to be re-examined, which could result in even more alterations in our understanding of the early Earth (Nakajima and Stevenson, 2018).

Dating ancient rocks is the first step in unlocking the story of Earth's past. By using the dates of these rocks along with other features of their composition, we get a sense of not only when these rocks were formed, but additionally what kinds of conditions led to their formation. Unfortunately, these kinds of samples are incredibly rare, and as such scientists are always re-examining what little they do have in the hopes of unearthing new pieces of information. Since the use of radiometric dating for determining the age of the Earth, the tool has provided insight into many conditions of our Earth's far past. Already, in the past few hundred years our understanding of the early Earth has changed radically, and it is likely that the continued conviction of geologists, physicists and astronomers will foster amazing new developments into the future.

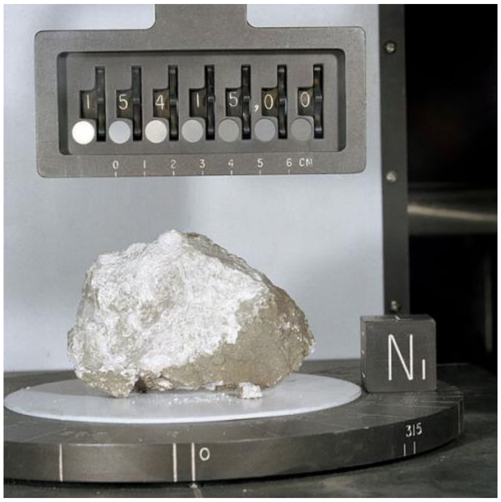


*Figure 2.14. Picture of the Genesis Rock, which was recovered from the Moon in the Apollo 15 mission.*

# The Queen of Science

Born on December 26, 1780 on the coast of Scotland, Mary Fairfax, or Mary Somerville as she would come to be known (see Figure 2.15), was designated the "Queen of 19th Century Science" by the London Morning Post (Patterson, 1974; Speese, 2013). Over the course of her life, she published numerous books and original research, received significant commemoration from the European academic community, and would even go on to have her name listed second on the election ballot for new members of the American Philosophical Society in 1869, two places ahead of Charles Darwin (Patterson, 1974). While her contributions to science speak magnitudes, her road was not easy; Somerville had to navigate the strictly enforced gender norms that served to confine her, and multitudes of other women, to the domestic sphere. Despite the challenges posed by both societal and familial influences, Somerville overcame these adversities to pursue and communicate a broad range of scientific disciplines, to eventually become the muse of the word "scientist" (Fara, 2008).

*Figure 2.15. A sketch of Mary Somerville contained within her personal recollections, as published by her daughter, Martha Somerville, after her mother's passing in 1872 (Somerville, 1874).*

Growing up in Scotland, Somerville was more likely to be found exploring or collecting fossils and shells on the coastline than inside practicing needlework or handwriting as was customary for young women of the time (Chapman, 2016; Somerville, 1874). This was perhaps a testament to her insatiable curiosity, as learning how to write and maintain accounts was of little interest to her (Chapman, 2016). An avid reader from a young age, Somerville had no familial incentive to begin learning mathematics and science (Patterson, 1974). Remarkably, it was a puzzle that catalyzed her fascination with mathematics and physics, although prior to that, geometric aspects of art had always appealed to her (Chapman, 2016). Her parents were greatly opposed to her endeavours to self-educate and would confiscate her candle every night to prevent her from accessing the household's limited book collections, among which was her personal favourite, Euclid's *Elements* (Chapman, 2016; Lamprecht, 2015; Somerville, 1874). Throughout Somerville's upbringing, it was thought that women were incapable of abstract thought and were likely to become delusional following exposure to algebra and geometry (Chapman, 2016; Lamprecht, 2015). Her father even went as far as threatening to put her in a straitjacket if she was found with mathematics textbooks, out of concern she would find a similar fate as another woman in the town who supposedly "went raving mad about the longitude" (Somerville, 1874).

The limited access to formal education she was privy to at an all-girls boarding school focused predominantly on tedious activities like memorizing words and their order in the dictionary, which understandably, Somerville thought to be "very inefficient"; she left boarding school after one year (Somerville, 1874). Somerville reflected on this arduous time of her life in her autobiography, expressing frustration at the gendered basis of education during the 18th century, as she "thought it unjust that women be given a desire for knowledge if it were wrong to acquire it" (Somerville, 1874).

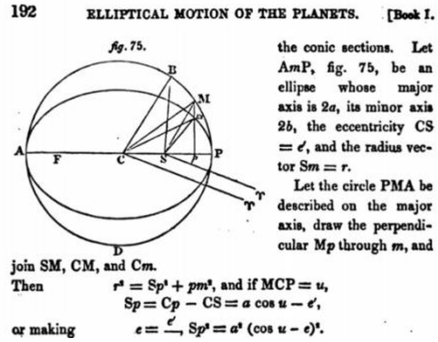
After the marriage and passing of her first husband and distant relative, Samuel Greig, Somerville obtained significant financial independence that enabled her to pursue intellectual avenues as she deemed fit, opening the floodgates to quench her thirst for knowledge (Chapman, 2016; Lamprecht, 2015; Somerville, 1874). Her second husband, Dr. William Somerville, was proud of his wife's intellectual endeavours and vastly more supportive than the first, enabling the now Mary Somerville to study openly which propelled her scientific career forward (Chapman, 2016). Counter to Mr. Greig, Dr. Somerville often transcribed important journal articles for his wife, as his occupation and gender provided him access to the exclusive, male-only societies of the time (Chapman, 2016). Following Dr. Somerville's appointment to the Army Medical Board, the couple moved from Edinburgh to London in 1816 and became integrated into the academic society of the capitol almost immediately (Patterson, 1974). Shortly afterwards in 1817, Dr. Somerville was made a fellow of the Royal Society (Patterson, 1974). Through his avid support, Mary Somerville was able to indirectly reap the benefits of such an exclusive society, which was most significant seeing as science and peer collaboration were inextricably linked at the time; for one to contribute to the emerging fields of natural philosophy, connections to other researchers, societies, and organizations were absolutely necessary. With the essential financial resources and academic connections, Mary Somerville quickly became a notable member of the scientific community.

## Early Works

With the industrial revolution coming to a close in the early part of the 19th century, there was a drive to communicate important scientific findings to the working-class population, a movement Mary Somerville was recruited for given her newfound prominence in the elite academic societies of Europe and aptitude for science communication (Brock, 2006). Therefore, the Society for the Diffusion of Useful Knowledge commissioned Somerville to translate Pierre-Simon LaPlace's *Mechanique Celeste*. However, her 1831 work *Mechanism of the Heavens* (*Mechanism*) transcended the translatory purpose, as foundational concepts in the field of gravitational physics were clearly derived and explained, complete with relevant diagrams (see Figure 2.16) and formulae (Brock, 2006; Chapman, 2016).

Somerville received a plethora of commendations for her translation, most markedly was LaPlace's declaration that Mary Somerville was the only woman in England who could not just understand his work, but also correct it (Patterson, 1974). *Mechanism* was promptly adopted by the academic community, as it was used by Reverend Dr. William Whewell to teach upper-level science at the University of Cambridge, likely making Somerville the first female author of a university textbook (Chapman, 2016). Amidst the accolades, Somerville and her husband were invited to spend a week in Cambridge's Trinity College, making Mary Somerville the first woman to be housed under the same roof that had once sheltered Isaac Newton (Patterson, 1974). Surprisingly, a prominent society in the British capitol, the Royal Society, also celebrated *Mechanism's* success, voting unanimously to erect a marble bust in Somerville's likeness in the Great Hall, while Somerville herself was still barred from entering on the basis of gender (Patterson, 1974; Fara, 2008). This remained the case until 1904, which was the year the first woman was permitted to speak at the Royal Society, 32 years after Mary Somerville's passing in 1872 (Fara, 2008).

*Mechanism* propelled Mary Somerville into the realm of popular science writing and it was not long before her second text, *On the Connexion of Physical Sciences* (*Connexion*), was published in 1836 (Baker, 1948). A vast range of topics were discussed, ranging from geomagnetism to atmospheric heterogeneity, and unlike *Mechanism*, *Connexion* was equation free and was aimed at a more non-specialist audience (Chapman, 2016). While positive critique from her academic colleagues was abundant, the general public also took well to her text; Somerville was offered a pension by Sir Robert Peel, on behalf of the House of Commons, to commemorate her notable scientific merit (Brock, 2006; Patterson, 1974). She was not without critics though; MP Charles Buller advocated vocally against Somerville's pension, arguing that her work did not constitute a civil reward (Brock, 2006). Despite this, reviews of *Connexion* were largely positive, most noteworthy being William Whewell's commentary of *Connexion* which featured the first print appearance of the word "scientist".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the conic sections. Let **A*m*P**, fig. 75, be an ellipse whose major axis is $2a$, its minor axis $2b$, the eccentricity $CS = e'$, and the radius vector $Sm = r$.

Let the circle PMA be described on the major axis, draw the perpendicular $Mp$ through $m$, and join SM, CM, and $Cm$.

Then $r^2 = Sp^2 + pm^2$, and if $MCP = u$,

$Sp = Cp - CS = a \cos u - e'$,

or making $e = \frac{e'}{}$, $Sp^2 = a^2 (\cos u - e)^2$.

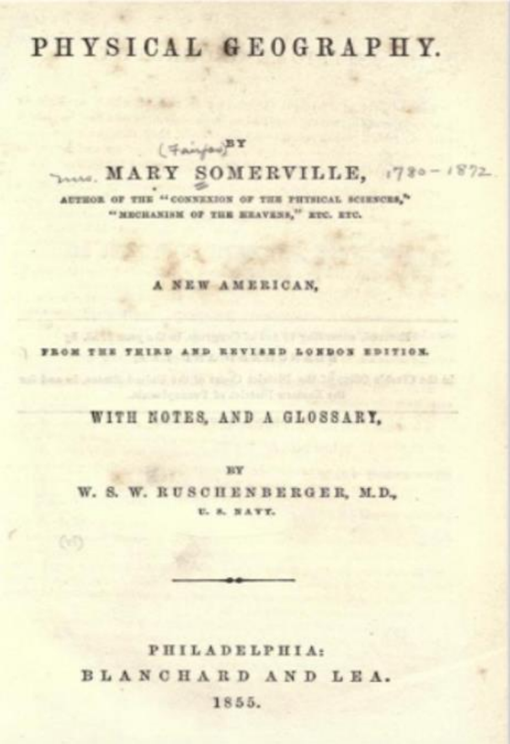
*Figure 2.16. An example of the mathematical translations and figures employed in Mechanism of the Heavens to increase reader comprehension (Somerville, 1831).*

## Physical Geography

*Connexion* served as a natural progression for the creation of Mary Somerville's third text, *Physical Geography*. Dedicated to her mentor and close friend, Sir John Herschel, "heat" is a reoccurring theme in *Physical Geography*, presenting ideas central to the modern heat budget concept although going into depth on a multitude of other topics like cloud formation and early plate tectonics (Sanderson and Somerville, 1974; Chapman, 2016; Somerville, 1855). After her second husband's illness necessitated a move to more moderate Italian climates, Somerville did not author a book after *Connexion* for a number of years, focusing instead on her family and adjusting to a new way of living (Lamprecht, 2015). The first edition of the text was eventually released in 1848 and served to link the formative and modern periods of geography; *Physical Geography* was published prior to geography being officially recognized as a discipline in much of Europe (Sanderson and Somerville, 1974; Baker, 1948). As a result, Somerville has been referred to as the "first English Geographer" and *Physical Geography*, the first English geography textbook (Sanderson and Somerville, 1974). Somerville adopted a more holistic view of the subject, setting the foundations for the later development of the discipline of geography as a whole (Sanderson and Somerville, 1974; Lamprecht, 2015).

*Physical Geography* was similar to *Connexion* in that she did not simply summarize the research of others but rather aimed to answer "why" the results were obtained, identifying unifying themes present in nature in the process (Sanderson and Somerville, 1974; Lamprecht, 2015). Geology was a rapidly advancing subject in the 1840's, which made encompassing the amassing findings in a textbook particularly difficult (Chapman, 2016). The text built on the work of more than 50 cited individuals, among which were prominent geologists Charles Lyell and Robert Murchinson, two close companions of Somerville's and "fellow scots" (Lamprecht, 2015). To keep pace with the evolving field of geology, Somerville did not stop after one edition but alternatively, constantly modified the text in conjunction with the rapidly advancing natural sciences scene in the mid 19th century, the length and footnotes growing with each successive edition (Sanderson and Somerville, 1974; Baker, 1948). Six editions of the text were published during her lifetime and a seventh released shortly after her death, with each version containing the most up to date information that was accessible and pertinent to the contents of the book (Baker, 1948; Lamprecht, 2015). The cover page (Figure 2.17) is an excerpt from the third edition of the text.

Consisting of 33 chapters and an extensive appendix culminating to nearly 600 pages, *Physical Geography* was a vast account of the world, its relationship to the solar system, geological forces, surface features, and floral and faunal distribution (Somerville, 1855). On the first page of chapter one, Mary Somerville set the stage for the coming chapters, establishing that the text would include "a description of the earth, the sea, and the air, with their inhabitants animal and vegetable, of the distribution of these organized beings, and the causes of that distribution" (Somerville, 1855). Chronologically, chapters I-XIV focused on terrestrial features, chapters XV-XXI were predominantly about the oceans, the atmosphere was discussed in chapter XXII, plant and animal geography was contained within chapters XXIII-XXXII, and the final chapter was about "man" (Somerville, 1855). In the text, explorers and men of science are frequently referred to, and served as a significant source of information for Somerville; she attributed much of the book's novelty to such individuals for their academic contributions (Somerville, 1855).



PHYSICAL GEOGRAPHY.

(Fairfax) BY
Mrs. MARY SOMERVILLE, 1780-1872
AUTHOR OF THE "CONNEXION OF THE PHYSICAL SCIENCES,"
"MECHANISM OF THE HEAVENS," ETC. ETC.

A NEW AMERICAN,

FROM THE THIRD AND REVISED LONDON EDITION.

WITH NOTES, AND A GLOSSARY,

BY
W. S. W. RUSCHENBERGER, M.D.,
U. S. NAVY.

PHILADELPHIA:
BLANCHARD AND LEA.
1855.

*Figure 2.17. The cover page of the third edition of Physical Geography by Mary Somerville (Somerville, 1855).*

Critics of the book attempted to reduce the text to a summary of others research; this, however, is incredibly dismissive to the significance and calibre of science contained within *Physical Geography*. In addition to Somerville laying the foundations for the heat budget theory, she was one of the first to draw connections between the topography and resource availability of a region to the associated industrial value (Baker, 1948). Thus, sections of the book serve as analogues to modern demography, as Somerville explores "the influence of man on the material world" (Baker, 1948; Somerville, 1855). Political geography too, made its debut in *Physical Geography*, with Somerville referencing and alluding to societal factors contributing to human distribution and relative economic values of the regions discussed (Baker, 1948).

Beyond the introduction of new geography subdivisions, the manner in which Somerville described the natural world was revolutionary. Her stance on creation challenged the idea that Earth and humankind originated simultaneously and alternatively believed that our planet existed long before ourselves, an idea that was not yet completely accepted (Speese, 2013). Counter to other popular science writers at the time, Somerville focused on conceptually understanding as opposed to dominating the natural world (Speese, 2013). Likewise, her description of the physical processes governing the Earth and the natural world was not centered around humans, rather she placed greater significance on invisible forces unseen to man and ancient history contained in the geologic structures around her and below the surface (Speese, 2013). Analysis of the language present within Physical Geography revealed that she employed a "feminine scientific sublime," a style more oriented towards plurality and holism rather than ego and control, thereby resulting in an unparalleled portrayal of the interconnectedness and balance of the natural world (Speese, 2013). Her taxonomical prose was heavily influenced by poets, scientific and Roman alike, offering her readership a blend of empirical and elegance (Speese, 2013). The cadence of *Physical Geography* is reminiscent of both science and poetry, a dichotomy that parallels the balance between the known and the unknown when it comes to our understanding of the Earth and its processes (Speese, 2013). Thus, both the essence of the ideas presented in *Physical Geography* and the communication of such ideas was innovative, with Somerville's unique writing style capturing an angle of Earth history and physical processes that was new to academia.

While *Physical Geography* unified the natural sciences through an identification and discussion of prevailing interdisciplinary concepts, this book was not as successful as *Mechanism* or *Connexion* (Baker, 1948). Central to the success of her text was the recognition of geography as a distinct subject. Geography was not recognized as a university subject until 10 years after the date the seventh, and final, edition was published (Baker, 1948). Prior to the establishment of contemporary geography, geologists were claiming many of the concepts present within *Physical Geography* as their own, amalgamating geology and geography in both post-secondary education and academic discourse alike (Baker, 1948). Both disciplines were even combined into one academic organization, with the early Geographical Society dealing with affairs pertinent to both geology and geography (Baker, 1948). The lack of initial popularity of the book made it easy for mal-intending individuals to plagiarize her work; a number of smaller, cheaper versions of the text appeared in circulation without any credit to Somerville (Baker, 1948). The failure of the book was no fault of its contents because after 1851, *Physical Geography* gained more traction within the European academic community and Somerville along with it (Baker, 1948). Numerous awards were bestowed upon her for the text, the inaugural gold medal of the Geographical Society of Florence and the Patron's Medal of the Royal Geographical Society being most distinguished (Lamprecht, 2015; Patterson, 1974).

## Physical Geography and Heat

With the increased prominence of Mary Somerville and *Physical Geography*, concepts presented within the text began to rise to the forefront of the European academic community. Of notable interest in *Physical Geography* was the introduction of revolutionary ideas similar to today's "heat budget" theory, which had not been explored extensively prior to Somerville's work. Building on the work of scholars like von Humboldt, H. W. Dove, and Matthew Fontaine Maury, Somerville recognized the pivotal role of solar energy in geophysical processes, as such heat was a reoccurring motif in *Physical Geography* (Sanderson and Somerville, 1974; Chapman, 2016; Lamprecht, 2015). At the time it was believed by many that light rays and radiation were mutually exclusive (Sanderson and Somerville, 1974). Mary Somerville and Sir John Herschel also shared these beliefs; heat rays and ultraviolet rays are referred to as "calorific rays" and "chemical rays", respectively, throughout *Physical Geography* (Sanderson and Somerville, 1974; Somerville, 1855).

The introduction of these fundamental heat concepts begins with an explanation of the dependency of Earth's surface temperature on the revolution of the Earth (Somerville, 1855). While most of the theories on heat in this period were based on solar radiation, Somerville acknowledges that the global climates remain relatively stable, with minimal and predictable changes (Somerville, 1855). However, the exploration of Earth's net heat balance stands apart with respect to its scientific significance; Somerville explains that while "the same quantity of heat is annually received from the sun, and annually radiated into space, it follows that all climates on Earth are stable, and that their changes, like the perturbations of the planets, are limited and accomplished in fixed cycles," which was not a widespread or generally discussed concept in atmospheric and climatic sciences at the time (Somerville, 1855). As well, Somerville proceeds to elaborate that it "is possible, however, that the earth and air may be affected by secular variations of temperature during the progress of the solar system through space, or from periodical changes in the sun's light and heat, similar to those which take place in many of the fixed stars" (Somerville, 1855). Her discussion of thermodynamics and influential factors is evident, making *Physical Geography* quite a progressive account of heat and energy on Earth.

Chapter XXI continues to expand upon the importance of solar radiation and its relationship to absorption, illustrating Mary Somerville's awareness and consideration of the conservation of energy (Somerville, 1855). Somerville acknowledges that that manner with which solar rays and the net energy fluxes impact seasonal changes and recognizes the effect of the tilt of the Earth on seasons; this is suggestive of Sir John Herschel's influence in Somerville's writing (Somerville, 1855). Radiation is considered to be "the principal modifying cause of temperature", and it is pronounced that "temperature depends upon the property all bodies possess, more or less, of perpetually absorbing and emitting or radiating heat" (Somerville, 1855). These powerful statements clearly show the development of theories around the manner of heat transfer, storage, and the processes behind net changes observed. The groundwork laid for modern heat and energy and its applications to geography and earth sciences was undeniably one of the most important subjects introduced in *Physical Geography*.

# Heat and Energy Budget

The concept of "heat" as we know it did not emerge into prominence until the aftermath of World War II (Miller, 1968). The definition of "heat" gradually developed and slowly led to the concept of the heat budget being an essential term in physical geography (Miller, 1968). While the heat budget certainly existed prior to its common usage in physical geography, it went from being overlooked to standing out as a key concept (Miller, 1968). One of the major hindrances in the recognition of a heat budget and energy transfer in geography is the continual pattern of reliance on summaries (Miller, 1968). Smaller heat fluxes contribute to the global heat budget; however, these were often overlooked in observational temperature data (Miller, 1968). A broad perspective concerning both the global and microscale thermodynamics is being increasingly acknowledged, which allows for new developments on the planetary heat budget to be considered (Miller, 1968).

## Development of Heat Concepts

One of the precursory concepts that led to an understanding of the heat budget was the consideration of solar climate. Examining the relations between the sun and warmth led to further hypotheses developing around the impact of solar radiation, with the ultimate goal of translating these observations into one unified equation that could account for the global heat budget: however, a major downfall was the reliance on thermometer shelters, which are enclosures to protect measurements from external factors such as solar heat and wind (Miller, 1968). As such, phenomena from the Earth's surface and the atmosphere were often neglected (Miller, 1968). The modern interpretation of "heat" emerged as regional and global methods were connected to larger patterns through smaller experiments (Lockwood, 1996).

## The Definition of "Heat"

The historical definition of heat was primarily based on kinetic energy in the context of chemistry and physics (Day, Doige and Young, 2010). Now, "heat" is defined as the energy transferred between a system and its environment as a consequence of temperature differences across a system boundary (Day, Doige and Young, 2010). Heat transfer between a system and the surrounding environment has the goal of reducing the internal energy of whichever body has an initial higher temperature, and to increase the temperature of the other body which has a lower initial temperature (Day, Doige and Young, 2010). Heat is one of the two ways in which energy can be modified within a system or environment, the other being work (Day, Doige and Young, 2010). The processes of radiation, conduction, convection, latent heat, specific heat, heat capacity, and adiabatic transfer are all foundational in physical geography.

While many modern definitions of climate change and the greenhouse effect mention heat being trapped or stored in the atmosphere, this is an inaccurate depiction of the heat transfer through radiation which is occurring (Day, Doige and Young, 2010). Upon completion of the energy transfer, "heat" can no longer be used, as there is no transfer taking place; this means that heat cannot truly be stored (Day, Doige and Young, 2010). Heat cannot be trapped, held, contained, or stored, and implications of substances holding heat better than others are also incorrect. What many textbooks commonly refer to as "heat" could be more accurately described as the internal energy of a system.

## The Energy Budget

Earth's global energy budget is now based on technological advances which measure incoming and transmitted radiation, along with the mean flow and global perturbations in energy flow (Trenberth, Fasullo and Kiehl, 2009).

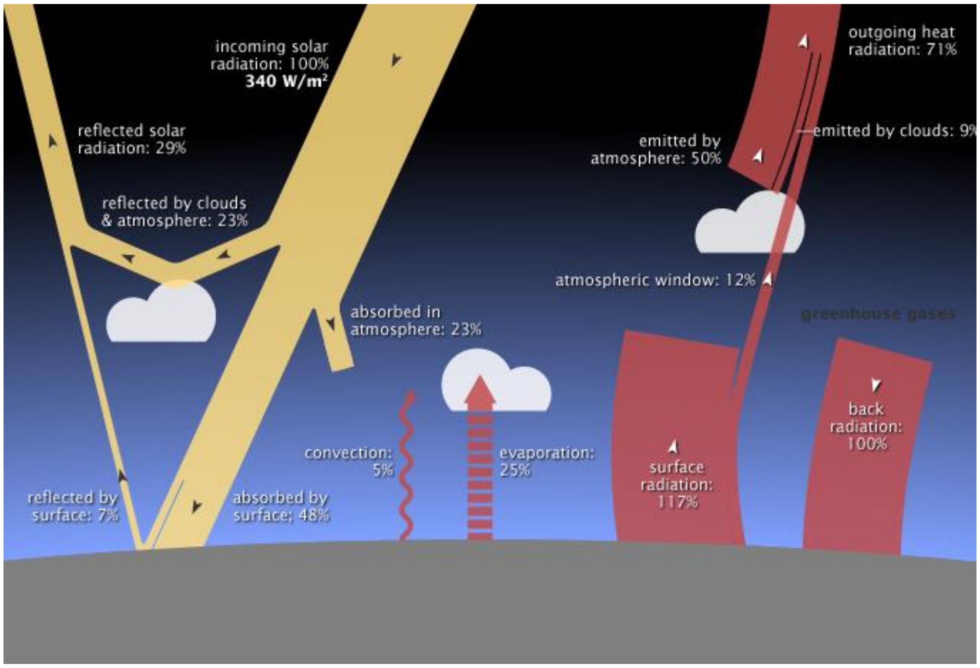


*Figure 2.18. A depiction of the broad energy transfers occurring between the atmosphere and Earth's surface, with arrow size showing the relative importance of the energy flow. This NASA illustration was generated based on data from CERES flux estimates by Norman Loeb and adapted from Trenberth et al. 2009. (Lindsey, 2009)*

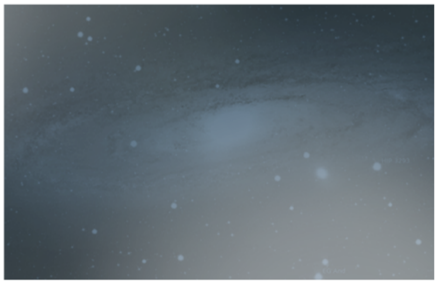
Estimates for the global energy budget have progressed significantly since the origin of the heat budget theory, which simply accounted for energy balance with the equation $R_n = \lambda E + H + A$, where $R_n$ is the radiative flux of energy, E is the energy lost by latent heat transfer, H is the energy lost by heat transfer to the atmosphere, and A is the energy flux (Lockwood, 1996). Nowadays, the estimates for the global mean energy budget involve a complex consideration of heat fluxes (see Figure 2.18), which illustrates the factors impacting the global annual mean energy budget (Trenberth, Fasullo and Kiehl, 2009). The weather and climate of Earth arise from the equilibrium between incoming solar radiation and its distribution, as incoming radiant energy can either be absorbed or reflected (Trenberth, Fasullo and Kiehl, 2009). As such, considering the energy balance and conversions is very important to considering climatic implications through estimates of the global mean energy budget based on radiative computations (Trenberth, Fasullo and Kiehl, 2009). These estimates are primarily based on modern technology allowing for datasets from satellite measurements, which provide the most accurate radiative models and measurements (Trenberth, Fasullo and Kiehl, 2009).

Global energy and heat budgets are often applied to considerations of climate change. At the most fundamental level, Earth's climate is controlled by solar energy; the net flow of energy in and out of Earth's system is maintained by the surface and atmosphere radiating heat into space, which prevents a constant heating effect from the solar radiation (Gillard, 2017). To understand how the energy transfers occurring in the Earth's system can impact climate change, new instruments such as Clouds and the Earth's Radiant Energy System (CERES) can be implemented through satellites (Gillard, 2017). CERES can provide top-of-atmosphere datasets to allow for the most accurate energy budget calculations by observing how much solar radiation is incoming compared to the reflected solar radiation and thermal emissions (Gillard, 2017). The CERES project has been collecting data on Earth's energy budget since the 1990s in conjunction with technology such as the Visible Infrared Imaging Radiometer Suite, which can assist with the analysis of surface and atmospheric properties (Gillard, 2017). Analysis can then be performed on greenhouse gases and their impact on the balance between absorption and reflection that leads to both short and long-term climatic changes (Gillard, 2017).

While the concept of heat in physical geography can be misinterpreted due to its similarities to other thermal concepts in various disciplines, the energy transfer between systems plays an essential role in our modern understanding and interpretations of climate, geographical trends, and global energy changes. Heat flux and transfer in systems have numerous localized applications, but the current focus lies in the concept of Earth's energy budget, which plays an increasingly important role in climate science.

# Chapter Three

## EARTH SURFACE AND BEYOND



> “The Earth is the cradle of humanity, but mankind cannot stay in the cradle forever.”
>
> -Konstantin Tsiolkovsky

# Space Exploration and Lunar Origins

The second half of the 20th century was marked by the continually high tensions present between the Soviet Union and the United States. Fortunately for science, such conditions brought much attention to scientific advancement, as both superpowers continually competed in order to demonstrate the superiority of their respective ideologies. This competition was the catalyst for the space race, as both groups looked to establish supremacy beyond Earth's atmosphere. While this was the primary motivation behind space exploration (Kennedy, 1961), it also led to several discoveries about our own planet, and how it came to be the way it is today. However, these discoveries did not occur directly following the Apollo Space Program; it took over a century of incorrect hypotheses followed by analysis of the lunar samples to generate a widely accepted theory that is still under scrutiny today. The gradual development, competition, and cooperation surrounding these theories is a testament to nature of the scientific method.

Analyzing the history of the Earth has proven to be difficult. The Earth's geological processes mean that terrestrial features are constantly in a dynamic state. Whether the driving force is the movement of plates, volcanic action, or erosion, the geological record is constantly being rewritten. Consequently, finding geological structures that have been unaltered since the origin of the Earth is a difficult task. However, the relative lack of such intense action on the Moon means that geological features on the Moon have not been altered to the same degree. This has led to planetary scientist Julianne Gross referring to it as a "time capsule" for the solar system (Resnick, 2019). Hence, studying features of the Moon enables us to extrapolate conditions that are representative of the time of its formation.

## Theories of Lunar Origin

Space exploration would facilitate analysis of Moon rocks in an unprecedented manner. This information was believed to be able to provide the key to finally determining what led to the formation of the Moon. Following the Apollo missions, the leading theory that would ultimately emerge was the Giant Impact Hypothesis. This theory proposed that the Moon originated from the collision of protoplanet, Theia, with the early Earth (Stevenson and Halliday, 2014). However, as is often the case in science, this theory is merely one of a set of constantly evolving theories. The Moon landing enabled the Giant Impact Hypothesis to come forth, yet the theory was—and somewhat still is—in competition with some of its predecessors. There were three major, widely accepted theories as the likely explanations for the formation of the moon (see Figure 1). These preceding theories were in the mind of the scientists designing the lunar missions. From their perspective, the aim was to find information on the Moon that would be able to reveal where the truth lies amid these theories. Ultimately, the Moon landing did not function as a simple breakthrough that elucidated the origins of the Moon. It did not enable one theory to immediately come forth and dominate. However, it would provide us with pieces of the early Earth puzzle that are being put together decades after that famed giant leap for mankind.

## Binary Accretion

The oldest of the three major preceding theories was that the Earth and the Moon originated as a binary system. That is, the two formed together through synchronous accretion of material in the solar nebula along with the other terrestrial planets of the solar system. The theory was temporarily abandoned early in the 20th Century, as initial versions of the theory implied a common chemical and physical composition between the and Earth and the Moon. However, this theory was altered and brought back into discussion by Dutch astronomer Gerard Kuiper. He argued that the early conditions of the Moon were hot (Kuiper, 1954). As a result, melting and differentiation could lead to it possessing an iron core (NASA, n.d.). The details of this theory varied between what were termed the American and Russian schools of thought. The former suggests a large solar nebula with a fast rate of accretion associated with increased temperatures and melting, similar to the views of Kuiper. Whereas the latter suggested the opposite, a slower rate of accumulation and colder conditions (El-Baz, 1975). The Russian school of thought regarding the energy of the Moon was similar to the views of American scientist Harold Urey. In 1955, Urey would write criticisms of the beliefs of Kuiper that appeared rather direct. This led to a controversy that would be known as the hot Moon/cold Moon debate (Royal Society of Chemistry, 2009). Interestingly enough, this debate would soon reach a resolution provided by the Apollo missions. Analysis of Moon rocks detected the presence of basalt (see Figure 3.1): evidence of volcanism which favoured Kuiper's hot Moon stance (Royal Society of Chemistry, 2009).

*Figure 3.1. Lunar rock sample collected from the Apollo 11 mission. It is a basaltic rock which favours the hot-moon hypothesis by Kuiper.*

While most found this to be undeniable support for Kuiper, Urey was not convinced. Regardless, this was not the only source of rivalry between Kuiper and Urey (See Figure 3.2). While Kuiper was a supporter of binary accretion, Urey developed and championed for another one of the three major 20th Century theories for the formation of the Moon: The Lunar Capture Theory.

## Lunar Capture Theory

The Lunar Capture Theory states that the Moon was once an independent celestial body in our solar system, that was then captured by the Earth's gravitational field and kept in orbit. This theory supports the iron imbalance in the composition of these two celestial bodies (Mitler, 1975). This theory was strongly favoured by Thomas Jefferson Jackson See, a major astronomer at the time (Brush, 1982). See proposed that the early Moon was formed in outer parts of the solar system near Neptune. He then believed that it lost energy due to its interplanetary position, eventually to the point where it was captured by Earth's orbit. The existence of retrograde satellites near Jupiter and Saturn could not be explained by the other two theories (Brush, 1982). This provided support for the Lunar Capture Theory. As mentioned, another rather distinguished scientist who advocated for this theory was Harold Urey.

In the 1960s, several scientists developed criteria which must be fulfilled in order for lunar capture to be possible. They included the initial conditions of the celestial system, the lunar orbit entering the Roche limit, and the capture occurring within 1 Ga due to the extrapolation of tidal dissipation (Brush, 1982). All of these criteria seem quite improbable. However, Urey, being the pioneer of this theory, justified its validity. In response to the first criterium, Urey explained that there have been several celestial bodies analogous to the Moon, meaning it is feasible that the Earth could capture one. He defended the second criterium by hypothesising that there may have been several smaller protomoons that were proximal to the Earth at one point that then amalgamated. Lastly, Urey was proposing that the moon was captured as the Earth was being formed. This meant that the rate of tidal dissipation at the time of capture was greater than that of today. This nullified the third criterium, as it suggests the moon could have been captured over 1 Ga (Brush, 1982).

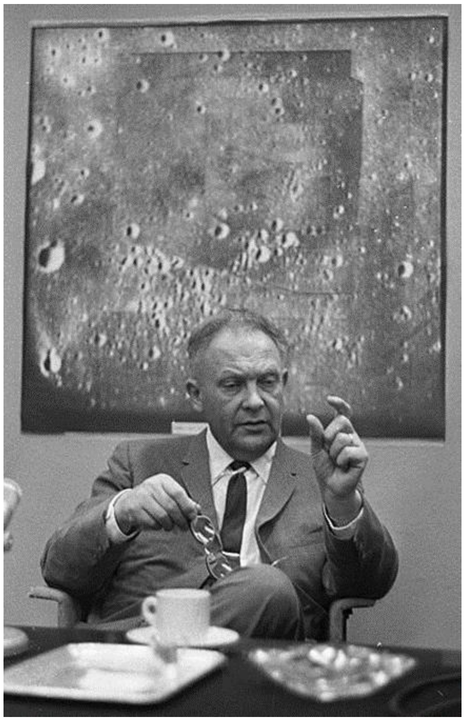


*Figure 3.2. Gerard Kuiper in front of a photo of the lunar surface.*

Another significant doctrine proposed by Urey was that the Moon was never in a molten period. This is significant, since a cold Moon could provide much more information regarding the early Earth and solar system than a Moon initially in a molten phase (Urey, 1955). However, this hypothesis contradicts notions already proposed by Gerald Kuiper. As previously mentioned, Urey wrote a rather critical paper denouncing Kuiper's work. Some of the claims Urey made in this paper included that if the Moon were molten at one point, its insulation would allow for a molten core today. Due to the number of radioactive isotopes present in the solar system at the time, the amount needed to melt the Moon during its formation would be insufficient (Urey, 1955). These all contradict Kuiper's work and support the cold moon and Lunar Capture Theory.

## Origin by Fission

The last of the major theories of the 20th Century regarding the formation of the Moon is the fission theory. This theory was proposed in 1879 by George Darwin: the son of Charles Darwin. The theory suggests that the Moon and the Earth were once one body that fissioned and spread apart to form the system observed today (Wise, 1966). In its first iteration, this theory proposed a system where the equatorial centrifugal force of an Earth with an intense speed of rotation was sufficient to overcome the force of gravity (See Figure 3.3). This effect was compounded by solar tides, in order to enable some mass to separate from the Earth to form the Moon.

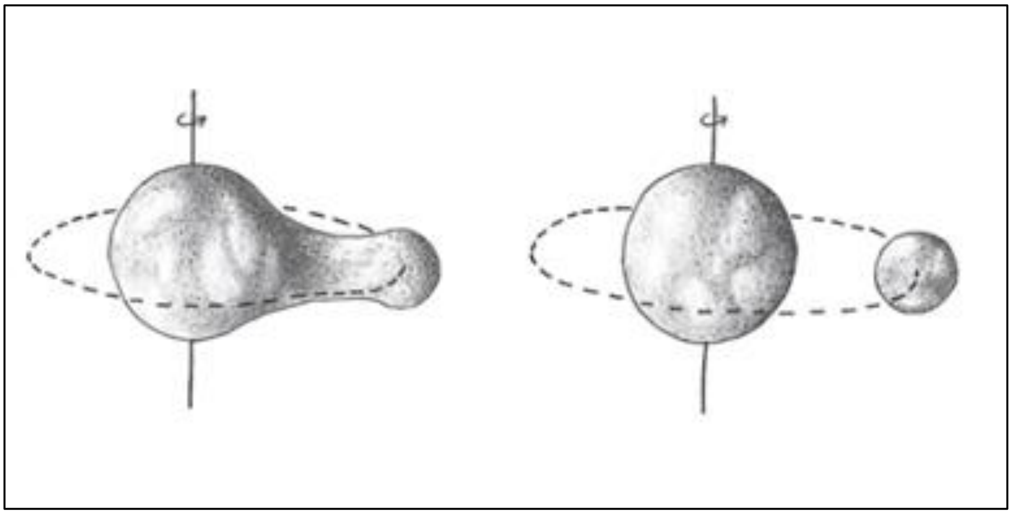


*Figure 3.3. An artist's rendition of the Lunar Origin by Fission Theory.*

Suggesting that the Moon originated from the surface of the Earth also explained its lower density, as it would largely consist of mantle material if it had formed in this manner. Osmond Fisher added on to this theory in 1889, by speculating that the Pacific Basin marks the site from which the bulge that became the Moon split, remaining a core element of this theory (Wise, 1966). Nevertheless, this theory eventually became the least favourable of the three, due to calculations that suggested it would be impossible. In 1909, Forest Ray Moulton demonstrated that there would not be sufficient angular momentum for such fission to occur. In 1930, Harold Jeffreys calculated how tidal frictions would limit the height of a tidal bulge. Each of these were cemented as major problems that the theory could not overcome for most of the century. However, there were some additions to the theory to address this problem, such as the increase in angular acceleration that would be associated with the formation of the core. Regardless, the discourse on this topic went back and forth for the majority of the century. There were still gaps present in each of the theories that could not be explained. For instance, none of the theories convincingly explained why the Earth was the only terrestrial planet with a moon of such size (Royal Society of Chemistry, 2009).

## The Giant Impact Hypothesis

Before and after Apollo, there was no scientific consensus on the origin of the Moon, as evident by conference proceedings and journal papers in the years prior to and following the landing (Wise, 1966; El-Baz, 1975; Hartmann and Davis, 1975). In an interview with William K. Hartman, the scientist credited with coauthoring the first paper proposing the Giant Impact Hypothesis, he describes the conditions of the scientific community on this topic following the Apollo missions. He mentions how after a series of papers were written on the subject in the mid 1970s, there was a state of "limbo" in which nothing was happening, until leading scientists in the field decided to call a conference in order to cement the findings that were made. The product of this would be an increased enthusiasm towards discussing lunar origin, and the emergence of the Giant Impact Hypothesis as the leading theory (Hartmann, 1998).

Although the paper by Hartmann et al. published in 1975 gets most of the credit as the earliest proposition of this theory, it was discussed decades earlier by Reginald A. Daly. Daly, in 1946, suggested that collision with a planetoid could be sufficient for the ejection of matter that could form the moon (Daly, 1946). In addition, a group of Soviet scientists, including Viktor Safronov, in the 1960s produced plenty of work regarding the processes of accretion in the solar system that were relevant to the work of Hartmann. However, there was not much flow of information between the Western world and the Soviets, and thus the cooperation that is believed to be so crucial to the scientific process was hindered. Fortunately, some translations were performed by a US-funded Israeli agency that enabled Hartmann to have access to the work of Safranov, which was utilized in his eventual paper (Hartmann and Davis, 1975; Hartmann, 1998). As stated earlier, it is true that the political conditions at the time were favourable for scientific advancement, as it led to increased government and public support via funding and policy changes. However, here we see an instance where competition between the Soviet Union and the United States stunted international cooperation and, as a result, scientific progression. Nevertheless, there were multiple papers being published at the time on the topic (Hartmann, 1998). This was a consequence of the increased knowledge about the moon that was obtained due to Apollo. For instance, information regarding isotopic differences between the Moon and the Earth. One notable difference between the structure of the Moon and the Earth is the composition with respect to iron. The Moon's composition is marked by a clearly lower amount of iron when compared to that of the Earth's (Palme, 2004). The paper by Hartmann et al. proposed how the collision of a large body with the Earth could have resulted in the ejection of crust and upper mantle material (see Figure 3.4). The ejected material would be part of the accretionary material that would give rise to the Moon. This functioned as a potential explanation for the lower iron content in the Moon as the Earth's mantle contains a lesser amount of iron than the remainder of the Earth.

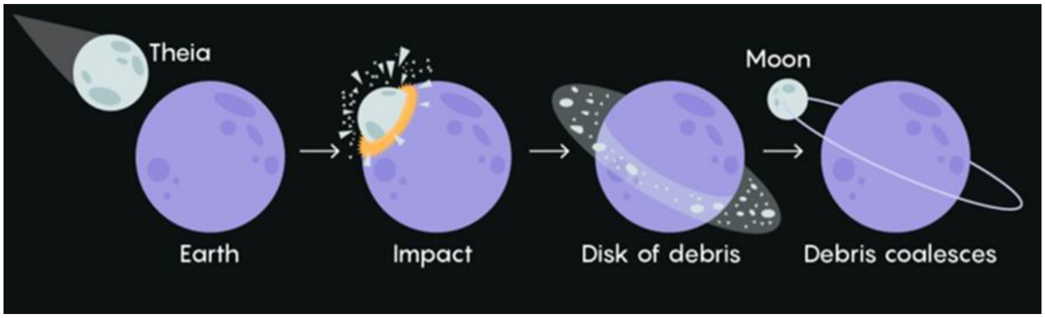


*Figure 3.4. An animated representation of the progression of the Giant Impact Theory.*

The significance here is that the scientific community had various ideas surrounding the origin of the Moon prior to, and throughout the 20th Century. There were many scientists involved with working towards answering such questions, and they were tied together through this common goal, multiple theories, and associated arguments. It is clear that Apollo was not definitive evidence of anything, but rather pieces of the puzzle that allowed scientists to make progress in the theories that they had been developing for a century. If one considers the ideas that pre-exist the modern theories discussed here, it could be argued that the Giant Impact Hypothesis was millennia in the making. As humanity's knowledge expanded, there were more and more arguments made that enabled progression towards understanding the truth. The Apollo missions were one step in this process that provided crucial information that has led to discoveries years after they were conducted. For instance, a paper comparing lunar and terrestrial ratios of oxygen isotopes in 2001 revealed consistencies with the Giant Impact Theory (Wiechert et al., 2001). The story is not entirely complete yet as there are still arguments to be made for other theories and nothing is certain, yet it is clear that lunar exploration played a vital role in this process.

# Modern Applications of Space Exploration

In the recent past, the National Aeronautics and Space Administration (NASA) has performed many missions to gain a further understanding of natural processes on Earth. For instance, in 2004 the Tropospheric Emission Spectrometer, or TES mission was launched to study the Earth's troposphere and ozone. These data were further used to study carbon dioxide levels on the entire planet (McGregor et al., 2020). As of now, NASA has several missions ongoing that aim to study natural phenomena on Earth. It is often said that space exploration is an unnecessary use of tax dollars, since there are still many issues to be addressed within our own atmosphere. However, many of NASA's current missions are studying processes on the Earth using satellites to make many advancements in fields such as climatology, environmental science, and environmental physics.

## The Magnetospheric Multiscale

One major natural process being studied using space missions is reconnection of the celestial magnetic fields, more commonly known as magnetic reconnection (Garner, 2015). This phenomenon is a process involving energy from a magnetic field being converted into plasma. These magnetic reconnections are quite common on the surface of the Sun, and are the results of solar flares (Biskamp, 1996). As of now, we have little understanding of this process, but an ongoing NASA mission called MMS, or Magnetospheric Multiscale, has enhanced our understanding of this phenomenon occurring on the Earth (Garner, 2015).

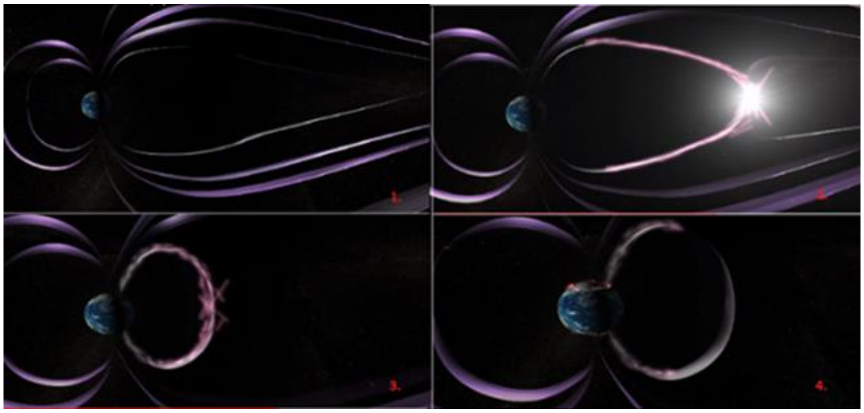


*Figure 3.5. A diagram of the phases of a magnetic reconnection. Notice the outflowing and inflowing inner field lines reconnect. This is followed a jet of plasma towards and away from the celestial body and the formation of new internal field lines.*

The basics of a magnetic reconnection are as follows; in some regions of a celestial body, such as the Sun, outflowing magnetic field lines and inflowing magnetic field lines can come in close proximity to one another. Occasionally, these lines can reach a point where they reconnect. At this point, the external field lines have been cut off while the internal field lines form a novel form of magnetic field lines (See Figure 3.5).

Simultaneously, the energy from the field lines is converted to kinetic energy in particles, which form a plasma that is jetted towards and away from the celestial body (Masuda et al., 1994). On March 12th, 2015, NASA launched the Magnetospheric Multiscale mission to research this phenomenon on Earth. This mission involves four identical spacecrafts that orbit the Earth in areas where they suspect magnetic reconnections would be present. On the Sun side, these spacecrafts are analyzing the energy released from magnetic reconnections at the Sun. It is hypothesized that this released energy may influence the Earth's magnetic field. On the night side, these satellites are analyzing magnetic reconnections strictly produced from the Earth's magnetic field. It is believed that these reconnections produce the auroras, or Northern and Southern Lights (Garner, 2015).

The study of this process can be quite useful, considering its societal impacts. After all, magnetic reconnections can lead to large amounts of energy being released, which can damage technological infrastructure and pose a threat to ongoing missions. For instance, reconnections can lead to loss in satellite and airline communications, can impede our ability to collect solar energy (Shea, 2018), and can emit radiation posing a threat to manned missions to the Moon, and perhaps Mars eventually. From a more local perspective, it has been observed that these magnetic reconnections have had effects on the energy sector through fusion energy here on Earth. Originally, it was predicted that magnetic fields confined plasma which allowed fusion to occur. Devices capable of producing a magnetic field to confine plasmas, called tokamaks, were produced. However, these devices failed to confine them. Due to this occurrence, this process was researched, and it was later discovered that twisted magnetic fields were responsible for containing plasma. This twisting of magnetic field lines did not occur in the tokamaks. This suggests that for a plasma to be contained, there must be twisted magnetic fields present. In short, although tokamaks could produce a plasma via a magnetic reconnection, the fields it utilized were not twisted. This resulted in the energy being dissipated (Hesse and Cassak, 2020).

Therefore, not only is the study of magnetic reconnections an active field of modern science that still has many aspects to be discovered, but the study of it has several implications on both the societal and collective level of inhabitants on Earth.

## Soil Moisture Active Passive

Observing phenomena such as magnetic reconnection is clearly beneficial, and can lead to many innovations in fields such as natural sciences. However, NASA has many ongoing missions that directly benefit all human populations. One of which is called the Soil Moisture Active Passive mission, or SMAP. The mission statement for SMAP is to improve weather forecasting capabilities, monitor droughts, predict floods, improve crop yields and to observe water, energy, and carbon cycles (Greicius, 2015). It does so in a quite unique manner. After the launch on January 31, 2015, it took about 3 months for the satellite to get into a stable orbit. After this, the boom of the satellite extends and a 6-metre gold reflector unfolds (See Figure 3.6*)* (Tate, 2015). Embedded in the reflector there is an L-band high-resolution radar, and an L-band radiometer. These are devices that emit and sense microwaves (1-2 GHz in this case), used to detect soil moisture (Schwank et al., 2009). Once in position, the satellite's reflector simultaneously begins to rotate at about 13 rpm, and emit microwaves through its L-band high-resolution radar (Fournier et al., 2016). As the satellite continues to orbit, the microwaves emitted map the moisture present in the topsoil (about the first 10cm of soil from surface level) over a 9 km$^2$ area per rotation. At this rate, SMAP can map the topsoil moisture levels on the entire planet in 2-3 days (Entekhabi et al., 2013).

This type of satellite undoubtedly has several applications directly related to the wellbeing of Earth's inhabitants. One major application is its ability to predict floods and droughts. This is achieved since agricultural droughts are defined as the lack of moisture in soil, which is directly measured by SMAP. In contrast, floods can be predicted by measuring previously saturated soils prior to storms (Callery, 2020). Another utilization of SMAP directly related to the health of many is its ability to predict crop yields. By producing soil moisture maps of the Earth, it becomes apparent to agriculturalists whether there will be a good harvest or not, and how to prepare for poor harvests (Government of Canada, 2015). Although this mission was designed for soil moisture detection, it was soon noticed that the radiometer on SMAP was capable of detecting ocean winds in storms, neglecting the effects of rain. This gives SMAP a clear advantage over other ocean wind sensors, that do not perform as well under very high winds, or very rainy conditions. Compared to the most prominent hurricane validation source, the Stepped Frequency Microwave Radiometer (SFMR), SMAP's data was in agreement up to 65 m s$^{-1}$ during hurricanes such as Hurricane Patricia (Meissner et al., 2017). This validates that the SMAP satellite is effective at mapping storm conditions and soil moisture alike.

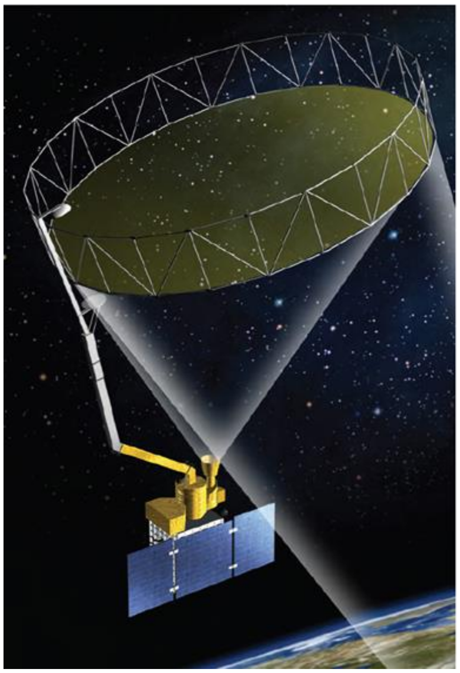


*Figure 3.6. An artist's rendition of the SMAP satellite.*

Quite evidently, space exploration has been a useful technique, both in the past and present, that enables us to study many natural processes on Earth. As of now, it appears that space exploration will continue to be a prominent aspect in science, continually making revolutionary advancements in our understanding of our constantly dynamic planet.

# The *HMS Challenger* Expedition: Taking Oceanography to New Depths

## Mapping the Ocean

Although mapping out ocean depth was of particular interest in the eighteenth and nineteenth century, this interest was actually quite new to society at the time (Murray, 1895). Oceans have been vaguely understood throughout history and did not interest scholars until the seventeenth century. Prior to the seventeenth century, society was more interested in what lay beyond the horizon of the oceans, marine life, and the phenomena related to the surface of the seas as these aspects influenced travel and trade. Sounding weights, used from the seventeenth to the twentieth century to measure depth, date back to the Neolithic era with lead variations appearing soon after, however, early sounding weights are believed to have been used for navigational and fishing means rather than tools for scientific exploration (Galili and Rosen, 2009). As sounding technology for depth determination was improved, the ability to explore greater depths became exploited. Ocean sounding data eventually enabled French geographer Philippe Buache to make the first map with ocean depth contours in the early eighteenth century (Murray, 1895). These early topographic maps of the sea floor were poor in detail but continuous seafloor mapping expeditions such as the Challenger expedition enabled the creation of more topographic seafloor maps and improved accuracy of pre-existing maps. Representation of the data collected by the Challenger expedition was based off of the novel marine charts of Philippe Buache (Murray, 1895).

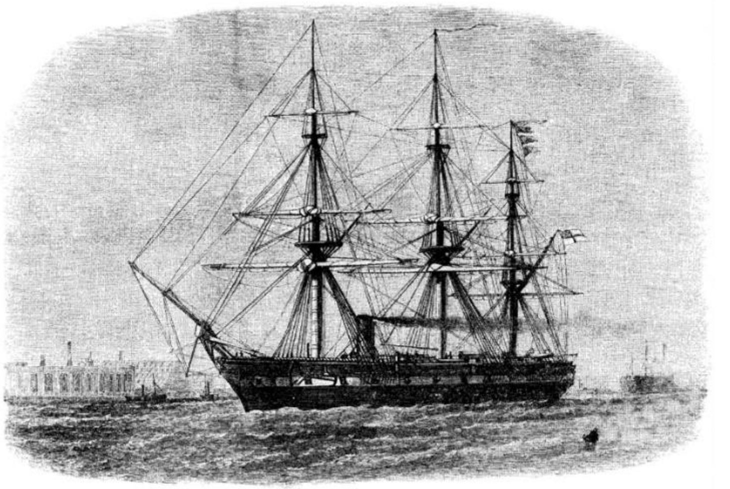


*Figure 3.7.* HMS Challenger *out at sea*

## Setting Sail to the *HMS Challenger*

The mid 1800s in Scotland was a period of great intellectual advancements and higher education from which many foundational fathers of science arose (Redfern, 1888). It was during this time that a man named Charles Wyville Thomson was raised. Thomson strayed from his father's path of being a surgeon, when he developed a great attraction to zoology and botany which placed him as the head of the natural history department at the Queen's University Belfast in Northern Ireland (Redfern, 1888). Through his correspondence with other professors, Thomson learned of many cases in which the Azoic hypothesis, that life did not exist a few hundred fathoms below the ocean surface, was disobeyed (Redfern, 1888). The Azoic hypothesis was proposed in 1843 by a naturalist named Edward Forbes and was based on calculations and reasoning. At a depth of 50 fathoms, the sun's light becomes cut off and thus, there would be no plants for animals to feed on (Thomson, 1877). Additionally, at a depth of 1000 fathoms, an animal would have to bear the weight of 1 ton per square inch which was not believed to be possible (Thomson, 1877). Despite this, however, fishermen were finding life at deeper and deeper depths and doubts that the Azoic hypothesis was true began to emerge. Realization of how little was known about the ocean placed Thomson in a position to conduct original research which he had yearned for and could not get with a surgical profession (Redfern, 1888). Additionally, during the mid 1800s, underwater telegraph cables were beginning to be built thus giving practical value to uncovering what lay below the sea's surface (Thomson, 1877). Charles brought forth an idea of a large-scale scientific investigation while collaborating on a project with the vice president of the Royal Society, Dr. Carpenter (Redfern, 1888). Upon approval and after some preliminary small-scale investigations on the small warships, *Porcupine* and *Lightning*, the most thorough scientific exploration of its time, the Challenger expedition, commenced (Thomson, 1877).

The Challenger expedition marked the beginning of modern oceanography. Prior to the departure of a nearly four-year voyage, 16 of the 18 guns of the 2306 ton warship were removed and replaced with fully equipped scientific laboratories and work rooms (Thomson, 1877). A scientific team was assembled which consisted of Thomson, as scientific director, 3 naturalists and a chemist (Thomson, 1877). One of the naturalists, John Murray, specialized in pelagic organisms and marine deposits and was left in charge to finish the Challenger data collection and publications after Thomson's death (Redfern, 1888).

The goals of the Challenger expedition were very broad and all encompassing. The objectives included determining the physical conditions of the deep sea, the chemical composition of the water at various depths, the distribution of organic life, and the characteristics of deep-sea deposits (Thomson and Murray, 1885).

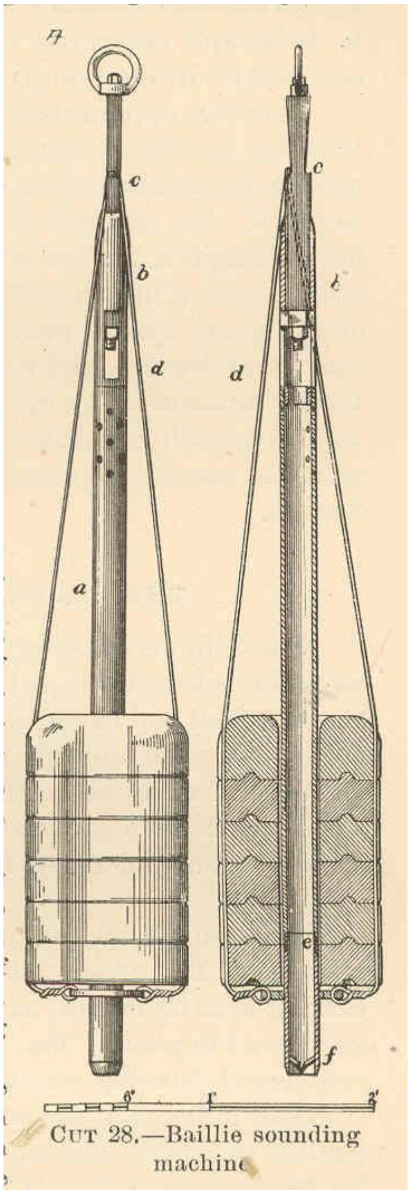
## Quest to Find the Deepest Oceans

The data collected by the ship's crew resulted in the discovery of new sediments and aquatic species. Not only were the crew of the ship successful in their exploration of the ocean at never-before-seen depths but, their novel methods paved the way for the future of oceanography (Seibold and Berger 2017). In 1872, when the *HMS Challenger* (Figure 3.7) left the port of Sheerness England to begin its long journey around the globe, scientists had been attempting to map out the depth of the oceans and seas for over two thousand years (Murray, 1895). Aristotle, one of the first to begin mapping out the depths of seas, set the path for other scientists to set sail with the goal of finding the greatest ocean depth (Murray, 1895). As more and more recordings of greater depths were being observed, a topographic map of the sea floor began to form. To locate the deepest point on Earth, scientists relied on the fourteenth century theory that the deepest ocean trenches were located near the coast of mountain ranges while coastal mountains were thought to serve the purpose of preventing the "invasion of the ocean" on land (Murray, 1895). Prior to the exploration of Marianas trench, observations of extreme ocean depths were observed off the coast of mountains in Norway, Iceland, and the islands of Flanders, thus further supporting the theory of the relationship between sea depth and proximal orography (Murray, 1895).

## Tools and Methodologies

To conduct research, the crew of the *HMS Challenger* modified methodologies and tools previously used from other small scale expeditions. However, since this scale of investigation was the first of its kind, many hurdles had to be overcome when taking measurements at extreme depths.

*Figure 3.8. Baillie Sounding Machine used on the* HMS Challenger



Cut 28.—Baillie sounding machine

Sounding machines were used throughout the journey, whenever conditions permitted, to determine the depth of the seafloor. The process of sounding involved sinking a lead weight attached to a line (Thomson, 1877). Depth was recorded by various colors of buntine markers spaced along the length of the line (Thomson, 1874). An impulse felt by the operator indicated that it had reached the bottom and a sample of the ocean floor could be brought up with the lead for confirmation (Thomson, 1874). Original models of sounding devices involved covering the lower portion of the lead with tallow, animal fat, to capture sediments; however, there have been many iterations since, and the type used on the *HMS Challenger* had a structural component, such as the open tube centre shown in Figure 3.8 for collecting sediments (Thomson, 1874).

Although these techniques had been used successfully in the past, sounding at extreme depths, such as what was done on the *HMS*

*Challenger*. presented a number of challenges. For instance, a heavier weight and thus stronger line was required to perform deep sounds (Ritchie, 2000). Additionally, since an impulse is impossible to detect after reaching a certain depth, the timed interval method was Ritchie, 2000). This method involves timing the amount of time it takes between each buntine marker. A sudden increase in the time between buntine markers indicates the sounding lead has reached the bottom (Ritchie, 2000).

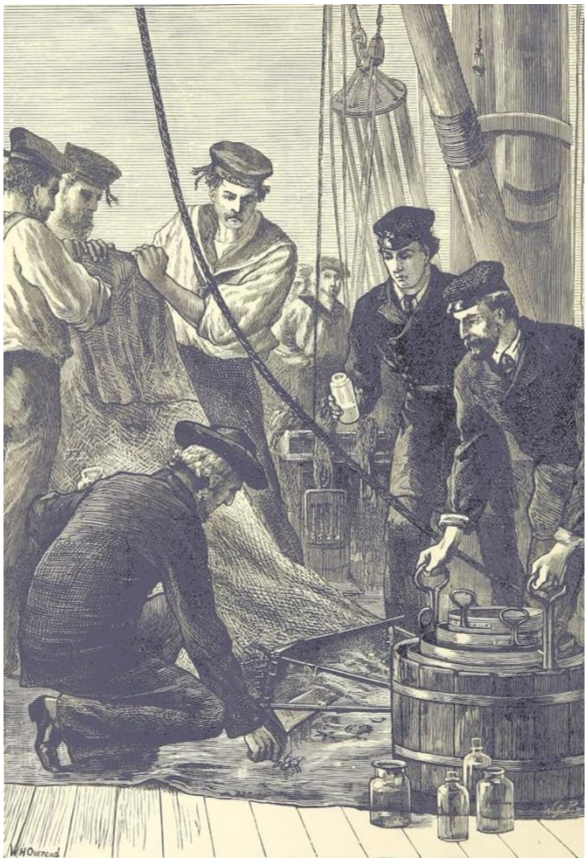


*Figure 3.9. Crew of the* HMS Challenger *examining creatures brought up from the sea floor*

To obtain more information about the seafloor besides the small amounts of sediment brought up with soundings, dredges were used. These functioned by scraping a section of the seafloor into a bag-like structure to collect sediment and deep sea life (Figure 3.9). Bags for dredging were divided into 2 sections - a lower portion made up of very fine twine, which could collect all but the finest muds, and an upper thickly netted twine (Thomson, 1877). Upon removal from the sea, sometimes with the aid of steam donkey engines, contents were closely examined and specimens were preserved and added to a collection (Thomson, 1877).

## Sedimentology

During the expedition, sea floor samples were taken across the globe, however, samples taken from the Pacific Antarctic Ridge and the Chile ridge produced the most unexpected results (Dekov et al., 2010). As expected, sediment samples taken from shallower depths consisted of sands containing varying percentages of shells and calcium carbonate (Murray and Renard, 1891). Based off the work from past scholars, it was generally accepted at the time that the higher presence of sands and gravels near shore were a result of the erosion from wave and tidal action (Murray and Renard, 1891). These shallow marine sediments are then deposited in deep sea marine environments as a result of sediment transportation (Murray and Renard, 1891). Depths of 160 fathoms and 210 fathoms revealed coral muds with high calcium carbonate percentages upwards of 86% (Murray, 1895). Surprisingly, a high percentage of iron and manganese containing sediments were collected in the region (Murray, 1895). Blue muds, which derive their colouration from the presence of iron sulphide, were taken from varying depths along with green and red muds which get their colouration from potassium iron silicates (Sirisha, 2017). Another discovery of particular interest was the evidence of volcanic activity in the sediment samples. Volcanic mud, smectite and volcanic conglomerates were found at a variety of depths while volcanic sand was found to be only present in shallower depths (Murray, 1895). Minimal carbonate sediments were integrated in the volcanic sediment layers and deep red clays containing pumice were observed to show traces of the carbonate of lime found at shallower depths (Murray, 1895). Uniform layers of red clay were hypothesized to have been formed in the deep sea by some process in which the calcium carbonates are removed from the clay (Murray and Renard, 1891). The origin of volcanic sediments on the ocean floor remained a mystery to the *HMS Challenger* crew and the geologists who later analysed their findings. The volcanic sediments were thought to have been possibly transported from subaerial and submarine volcanic eruptions by aeolian and fluvial processes (Murray and Renard, 1891). However, one observation on the cruise showed volcanic rock so fresh in texture, that the crew speculated that it may not have been produced from higher elevation but rather through the subsidence of the sea floor (Thomson, 1877).

Samples collected from the greatest depths consisted of oozes and clays (Figure 3.10) (Murray, 1895). Most depths below 2000 fathoms contained globigerina ooze and the deepest globigerina ooze was sampled from 2700 fathoms (Murray, 1895). Globigerina ooze greater than 3000 fathoms (Murray, 1895). These samples were handed over to the British Museum and the Natural History Museum following their analysis by John Murray, Professor Renard, and Sir greater than 3000 fathoms (Murray, 1895). These samples were handed over to the British Museum and the Natural History Museum following their analysis by John Murray, Professor Renard, and Sir Wyville Thomson (Dekov et al., 2010).

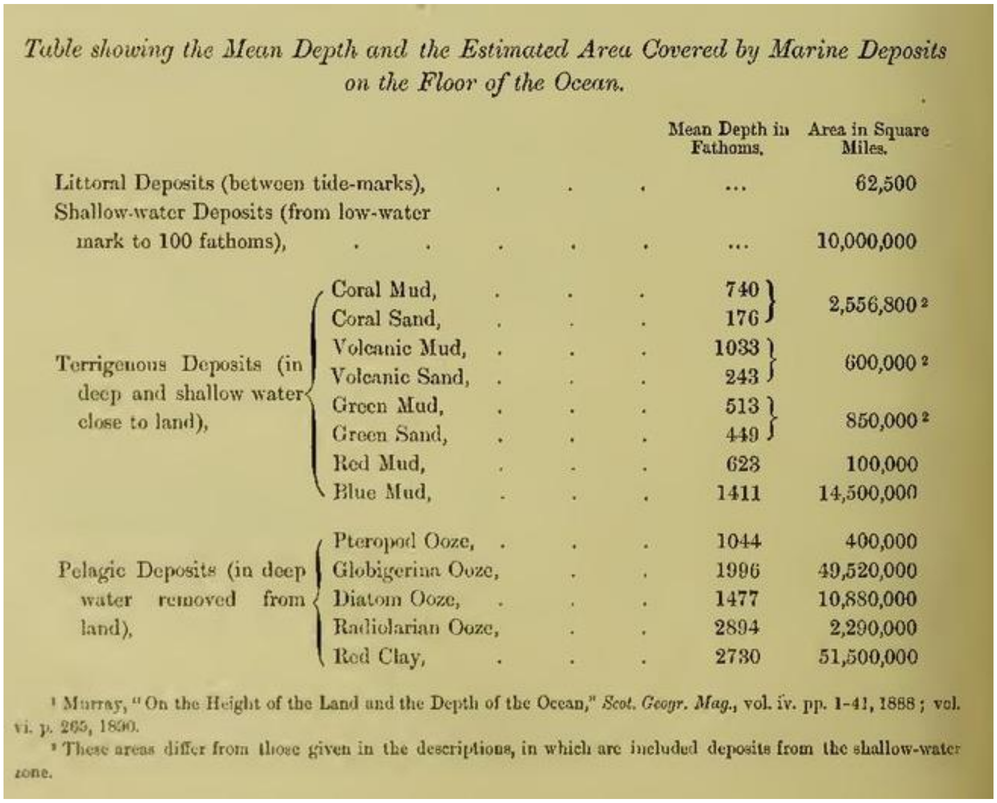


*Table showing the Mean Depth and the Estimated Area Covered by Marine Deposits on the Floor of the Ocean.*

| | | Mean Depth in Fathoms. | Area in Square Miles. |
|---|---|---|---|
| Littoral Deposits (between tide-marks), | | ... | 62,500 |
| Shallow-water Deposits (from low-water mark to 100 fathoms), | | ... | 10,000,000 |
| Terrigenous Deposits (in deep and shallow water close to land), | Coral Mud, | 740 | 2,556,800[2] |
| | Coral Sand, | 176 | |
| | Volcanic Mud, | 1033 | 600,000[2] |
| | Volcanic Sand, | 243 | |
| | Green Mud, | 513 | 850,000[2] |
| | Green Sand, | 449 | |
| | Red Mud, | 623 | 100,000 |
| | Blue Mud, | 1411 | 14,500,000 |
| Pelagic Deposits (in deep water removed from land), | Pteropod Ooze, | 1044 | 400,000 |
| | Globigerina Ooze, | 1996 | 49,520,000 |
| | Diatom Ooze, | 1477 | 10,880,000 |
| | Radiolarian Ooze, | 2894 | 2,290,000 |
| | Red Clay, | 2730 | 51,500,000 |

[1] Murray, "On the Height of the Land and the Depth of the Ocean," *Scot. Geogr. Mag.*, vol. iv. pp. 1-41, 1888; vol. vi. p. 265, 1890.

[2] These areas differ from those given in the descriptions, in which are included deposits from the shallow-water zone.

*Figure 3.10. Sediment sample data taken from the seafloor during the Challenger expedition*

## Debate on Ocean currents

During the voyage of the *HMS Challenger*, a major debate about ocean circulation took place between Dr. Carpenter and a Scottish physical scientist named James Croll. Carpenter believed, based on *Challenger* temperature data, that ocean currents were a result of the uneven distribution of heat throughout the ocean (Argus, 1875). More specifically, that cold water flows from the poles to the equator via a deep undercurrent. On reaching the equator this water heats up and rises to the surface (Argus, 1875). The warmer surface water then flows as a surface current, back to the poles thus producing a cycle. Carpenter's theory circulated the scientific community and gained specific attention from Croll, who strongly disagreed (Mills, 2011). Croll thought that current was caused by the wind as he believed that there was no way that ocean circulation could be produced just by the application of heat (Mills, 2011). This friction prompted Carpenter and his colleague to test his hypothesis by placing current drags into various depths of water (Argus, 1875). Near the surface, the drag flowed one way, while deeper down, it flowed in the opposite direction, thus seeming to support his theory (Argus, 1875). Additionally, the two layers had different densities - one resembling Mediterranean water, while the other resembling Atlantic water (Argus, 1875). The results of this experiment did not however sway Croll and the bitter disagreement remained, with correspondence taking place through *Nature* journal editorial letters, until after the voyage (Mills, 2011). It wasn't until 1976, that Carpenter combined both hypotheses into one (Mills, 2011).

## Marine Life

Marine life that was collected using trawls and dredges during this investigation were examined, classified, and meticulously preserved and stored inside the ship throughout the voyage (Thomson, 1877). The crew of the *Challenger* found no shortage of marine life, many of which had never been seen before, which far surpassed the depth predicted to be sterile of life by the Azoic hypothesis (Thomson, 1877). This finding highlighted how remarkable life forms can be, and called for a new definition of habitable zone to be set.

## The Beginning of Modern Oceanography

The voyage of the HMS Challenger and what many would call the beginning of modern oceanography was initiated by the innate desire for knowledge and was made possible by political and social pressures of the 1800s. Prior to this ground-breaking exploration, what lay below the surface of the sea was largely unknown. The data collected by the crew of the HMS Challenger clarified many scientific disputes including theories that life ceased to exist below a few hundred fathoms and that ocean currents were caused solely by wind. This scientific expedition provided abundant evidence that life was plentiful at far greater depths than ever predicted and that arctic and equatorial water temperatures were a major driving for ocean circulation. Furthermore, the novel technologies used aboard the HMS Challenger led to the creation of seafloor topographic maps, with depth recordings never seen before. As well, the patterns of sediment composition and distribution across the ocean floor gave evidence that perhaps the seafloor was not as static as once believed. Ultimately, the Challenger expedition provided a fundamental understanding of the sea and paved the way for the future of oceanography.

# Modern Oceanography

## Seafloor Mapping Technology

Following the exploration of the *HMS Challenger* and developments to marine technology in world wars 1 and 2, the field of oceanography and the technologies used to map the ocean saw major advancements (Seibold and Berger, 2017). The switch from traditional sounding technology to echo sounding resulted in numerous discoveries pertaining to the history of the Earth, most importantly plate tectonics and mid ocean ridges (Seibold and Berger, 2017). Current technologies used in the field of oceanography include sonar, submersible watercrafts, remotely operated vehicles, and deep-sea sediment cores (de Ronde and Stucker, 2015; Dembicki, 2017). These technologies serve many purposes and are most often used to create contour maps of the ocean floor and to collect seafloor sediments, ultimately serving the purpose of creating a more in-depth image of the deep seas. Figure 3.11 shows an example of how contour maps can be created using modern sonar technology.

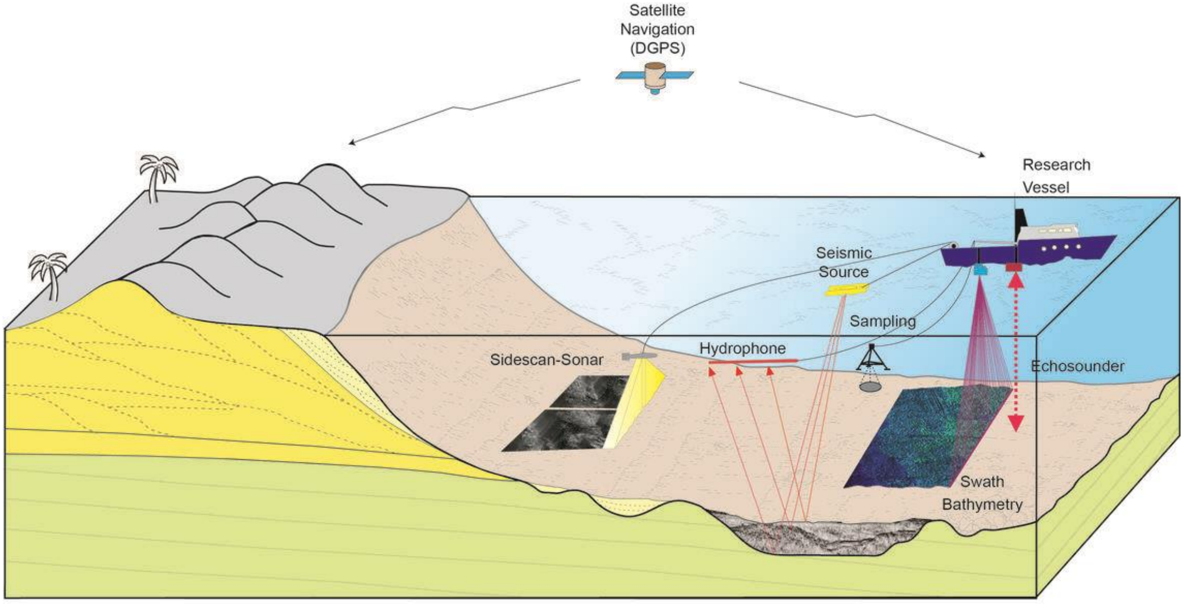


*Figure 3.11. Modern sea floor mapping technologies*

In the twentieth century, sonar replaced traditional methods of ocean sounding (Seibold and Berger, 2017). This acoustic technology uses transducers to send multiple sound waves from the vessel to the sea floor. Distance is calculated from the time it takes for the sound waves to return to the vessel after reflecting off of the seafloor (Harris and Baker, 2012). Depth data is then coupled with global positioning system information to create a map of the sea floor (Harris and Baker, 2012). Temperature of deep-sea water poses difficulties in sonar sounding as ultrasonic waves are reflected in cold water. To adjust to this effect, lower frequencies around 12 kHz are used to map extreme depths of the ocean, whereas frequencies greater than 100 kHz are used in shallow water (Harris and Baker, 2012). Although lower frequencies enable soundings of the seafloor at greater depths, this ability comes at the cost of reduced spatial resolution (Harris and Baker, 2012). Higher sonar frequencies are thus preferable in shallower depths. To increase image resolution and refraction of sound waves in water, either remotely operated or submersibles may be deployed to perform sonar sounding closer to the sea floor (Baggeroer, 2001).

While traditional lead weight sounding technology allows for simultaneous sampling of the seafloor, sonar sounding can indicate probable sediments depending on the strength of the echo received by the ship. Harder sediments reflect sound waves with more clarity while softer sediments such as muds and sands reflect weaker echoes (Harris and Baker, 2012).

A piston coring device is often used alongside sonar technology when seafloor sediment samples are desired (Dembicki, 2017).

## Oceanography and Climate Change

The applications of oceanography, and in particular seafloor mapping, are numerous and are of utmost importance when it comes to understanding climate change and the dynamic processes that occur on Earth. Despite its vast applications however, the sea is inherently challenging to study and hence, only a small fraction of it has been directly mapped - the majority of our current data is based on satellites (Wölfl et 77al., 2019). Recent climatic changes and increased frequency in environmental disasters have renewed interest in oceanography in the hopes to use sea mapping data to deepen our understanding of these events. For example, bathymetric data is not only important for understanding the relationship between mid ocean ridges and earthquakes, but it can also tell us about the morphology of the ocean floor and how it is linked to the formation of tsunamis, aiding in the prediction of natural disasters (Wölfl et al., 2019). Oceanography can also model ocean circulation which is useful for predicting how climate warming will impact sea level rise and weather (Wölfl et al., 2019). Furthermore, while oceans are excellent at slowing down climate change by acting as massive carbon sinks, it is well recognized that the oceans are also taking the most detrimental hit from the changing climate. Dissolved carbon dioxide alters the water chemistry and increases ocean acidity (Doney et al., 2009). Ocean acidification reduces the amount of available carbonate, thereby making it difficult for coral reefs and other marine organisms to form and maintain strong skeletons or shells (Figure 3.12) (Doney et al., 2009).

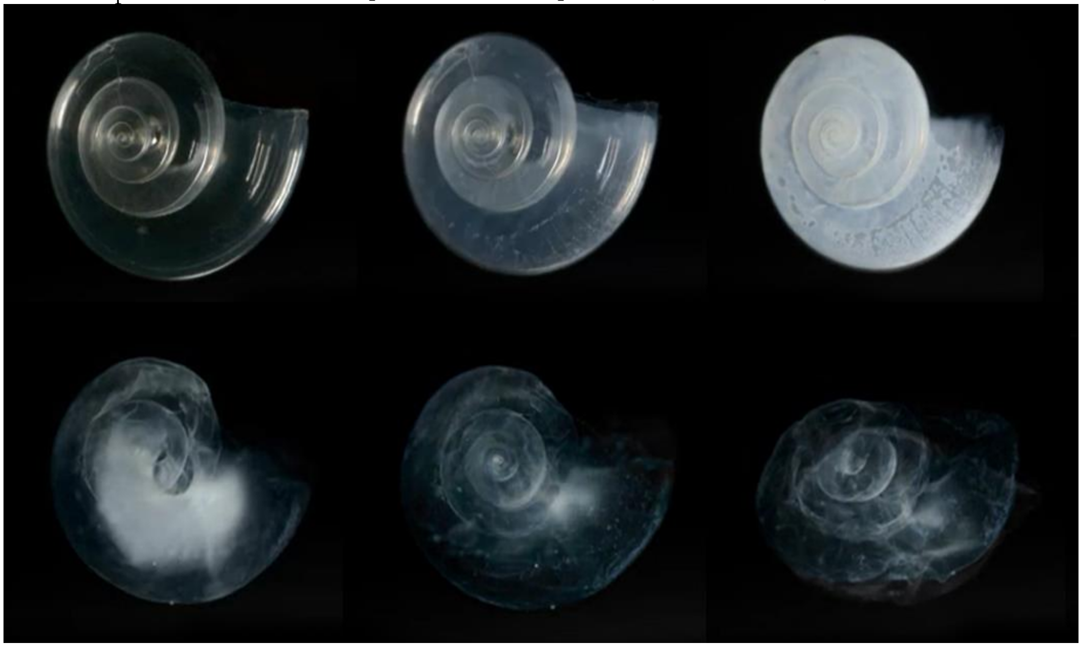


*Figure 3.12. Pteropod shell dissolved in seawater adjusted to an ocean chemistry projected for the year 2100*

Data from the Challenger expedition has been very useful for analyzing the effects of climate change, albeit some data had to be removed due to possible biases of the technology of the time. A recent paper by Gebbie and Huybers (2019) compares the temperatures of the sea, before and after the onset of anthropogenic climate change, from measurements taken by the Challenger in the 1870s and from the 1990s World Ocean Circulation Experiment. Significant differences between these two data sets revealed patterns of ocean warming in surface oceans and the deep Atlantic, while in the deep Pacific Ocean, cooling was noted (Gebbie and Huybers, 2019). It is suggested that this cooling is due to the Pacific ocean's delayed response from the Little Ice Age which occurred from 1300-1870 (Gebbie and Huybers, 2019). Another comparative analysis study found a 76% reduction in shell thickness of some foraminifera between the time of the Challenger expedition and the present (Fox et al., 2020). This change in composition is likely due to anthropogenic climate change (Fox et al., 2020)

Overall, the sea is a very dynamic portion of the Earth and therefore constant data collection is vital for better understanding the world we live in. Despite exploration of the ocean being of little interest to early scientists, the development of oceanography has led to important discoveries in Earth science and its exploration continues to reveal new discoveries and applications.

# Perspectives of the Moon Through History

Space and the sky have piqued the curiosity of humanity for centuries. From today's insatiable desire to find life elsewhere in the universe, to ancient civilizations observing the sky without the burden of light pollution, the mysteries of space have interested humankind throughout time. Not only has space been used as a subject of study, however, the night sky has historically been used as a tool for navigation, timekeeping, and spiritual practices (Canadian Space Agency, 2020). Nowadays, technological tools prove incredibly useful when studying astronomy, though generations prior to these inventions still found valuable ways to make scientific discoveries and advancements. One resource in particular has proved time and time again to be immensely useful when seeking to learn more about space, be it during the 1500s or now. That resource can be found right beneath our feet — the study of terrestrial geology has made countless impacts on the study of astronomy, and nowadays, planetary geology. The Geological Society of America, established in 1888, created its Planetary Geology Division in 1981, which is known through two mottos: "When one planet just isn't enough!", and "The GSA Division with the biggest field area!" (The Geological Society of America, 2020a; GSA Planetary Geology Division, 2020). The field of planetary geology is one rapidly evolving, and many discoveries within this discipline could not have been made without knowledge of the Earth's geology.

*Figure 3.13. Da Vinci's View of the Hills of Tuscany*

## The Renaissance Period

The Renaissance (roughly the 14th to the 16th century) was a vital time period in the history of Europe, marking a transition from the Middle Ages to modernity (Soergel, 2005). Landscape art emerged as an independent genre in this time. In other words, artists began to routinely paint illusionistic, 3-dimensional landscapes that were the subject of art, rather than a backdrop for religious or historical narratives (Rosenberg, 2001). Linear, or geometric perspective, in which objects on a picture plane within a mathematical framework, expanded this art style (Rosenberg, 2001). This perspective was essential to the expansion of landscape backgrounds, extending space into deep perspectives of broad landscape and producing a sense of unification of space, or spatial isotropy (Rosenberg, 2001). This art style was used to illustrate the shape, volume, size, position, and more of an object in landscape, adjusting for various linear coordinates across the picture plane to depict the object more accurately (Rosenberg, 2001).

## Leonardo da Vinci

One mind that spearheaded this art style and was instrumental in this time period of creativity and scientific discovery was the mind of Leonardo da Vinci (1452-1519). Living in Italy during the height of the Renaissance allowed him to explore freely both creatively and scientifically under the guidance of the best minds at the time. Part of his genius and his impact comes from his multifaceted discoveries, documenting his research in art, engineering, geology, astronomy, and the human body in his surviving notebooks - a collection of roughly 6000 pages of notes and sketches (Kemp, 2008).

According to da Vinci, geometry is the key to understanding the powers of all of nature, and that the complexity of nature is founded on the geometry of natural law (Rosenberg, 2001). In August of 1473, he drew a scenic view in Tuscany (Figure 3.13). This piece was vital to the history of artwork and geology for several reasons. Firstly, it was the first known artistic rendition of a pure landscape, as opposed to the background of a painting, produced in the West (Rosenberg, 2001). Secondly, as stated in the description of the drawing in his notebook, da Vinci proposed that the strata in the area were deposited in the sea that once covered the area, and that other sediments had been deposited by rivers in flood when the sea was lower. This theory opposed the Universal Flood theory that reigned supreme at the time due to the church's beliefs in creationism (Rosenberg, 2001). As for its impact, this drawing foretold what future geologists would study and develop theories about, later serving as tools for describing Earth's stratigraphy along with applying them as an analog for other terrestrial planets (Rosenberg, 2001).

In Leonardo's time, it was believed that the universe was conceived as the work of an omnipotent and purposeful creator - a way of thinking pushed by the influential church (Kemp, 2008). This God-made universe was thought to be an all-inclusive sphere composed of four elements that had concentric regions assigned to them: Earth occupied the centre while water, air, and fire would each be a layer surrounding the earth in that respective order (Kemp, 2008). Leonardo had grown up with this conception based on ancient traditions and, for the most part, accepted it. In explaining phenomena, however, da Vinci did not refer to hypothetical unknown agencies but to the activities of nature, and he did not fail to reject widely accepted theories by his strictly empirical and experimental methods (Kemp, 2008). One of these rejections came to be when he was studying astronomy, specifically the Sun and the Moon. In his notebooks, he stated, "the moon has no light of itself, but so much of it as the sun sees it illuminates" and "that the illuminated part we see as much as faces us" (da Vinci, 1508). These excerpts from da Vinci's notebooks were fundamental for science, as he describes the phenomenon of planetshine prior to it being proven by further astronomers. Additionally, he stated in his notebooks that "The Sun does not move. The sun has substance, shape, motion, radiance, heat, and generative power: and these qualities all emanate from it without its diminution. The sun has never seen any shadow," (da Vinci, 1508). This theory that da Vinci had would later be similarly stated by Galileo Galilei (1564–1642) in 1632 after using his invention of the telescope to develop his findings (Edgerton, 1984). However, for Galileo, his statement would be condemned as heresy since the church viewed the theory of heliocentrism as an attack on faith. This goes to demonstrate how impressive da Vinci's discoveries were, because not only were many of them correct or almost correct, they were proposed decades or even centuries before they were actually proven by improved science.

## Origins of the Moon's Craters

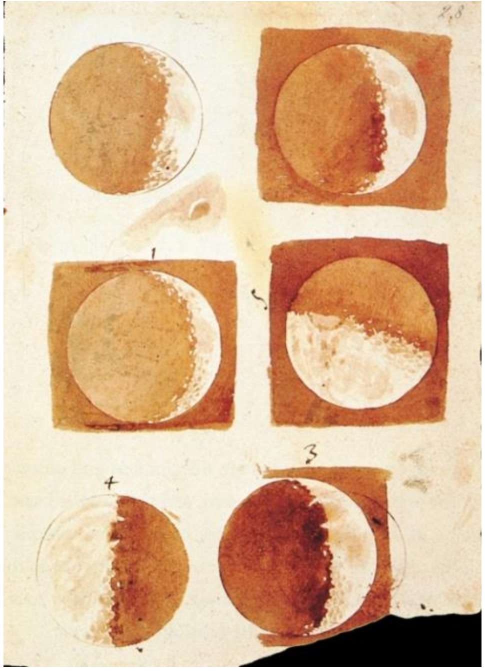


*Figure 3.14. Galileo's first drawings of the Moon, upon his postulation that the surface of the Moon was not, in fact, smooth, as was previously thought.*

Despite their incredible value to the scientific community at the time, very few scientists had access to the private notebooks and manuscripts of Leonardo da Vinci (Edgerton, 1984). Despite this, however, significant discoveries stemming from those of da Vinci's were still subsequently made. Though da Vinci designed potential telescopes, Galileo Galilei's invention of functional telescopes aided greatly in his observations of the Moon's surface in 1610. Galileo employed the same use of perspective principles as da Vinci when observing the Moon, and proceeded to make drawings, as seen in Figure 3.14, once again demonstrating the connections between the Renaissance period of art, as well as the development of science at the time (Edgerton, 1984). When creating these drawings of the Moon, Galileo stated that he believed the surface of the Moon was not smooth, uniform, or a perfect sphere, but rather an uneven surface full of cavities and projections, going on to compare them to mountains and valleys on the Earth (Edgerton, 1984).

Subsequently, in Robert Hooke's (1635-1703) 1665 book, *Micrographia*, the craters of the Moon's surface were once again observed, and analyzed (Hooke, 1665). To build upon the observations of Galileo, Hooke described the Moon's craters as 'pits', and hypothesized that these craters were caused by motions within the Moon, analogous to earthquakes occurring on the Earth. Furthermore, Hooke speculated that these craters could also be the cause of volcanism, with features of the Moon appearing very similar to that of Earth (Hooke, 1665). Galileo's prior invention of the telescope aided Hooke greatly in theorizing these causes of the Moon's craters. Hooke felt so strongly about the geological similarity between Earth and the Moon, that he stated "...I am apt to think, that could we look upon the Earth from the Moon, with a good Telescope, we might easily enough perceive its surface to be very much like that of the Moon." (Hooke, 1665).

As the disciplines of both geology, as well as astronomy, continued to develop, as did theories surrounding the origins of craters of the Moon. Throughout the 19th century, the most generally accepted theories at this period of time would attribute the creation of lunar craters to volcanism (Koeberl, 2001). The impact craters of the Moon were compared to those of volcanic craters on Earth, particularly that of Mount Vesuvius. Despite volcanism theories prevailing during this time period, there were still some members of the scientific community who were vocal in favour of the craters having their origins as impact craters (Koeberl, 2001). One particular reason, however, as to why these theories were generally unaccepted at the time was likely due to one having being postulated by German astronomer Franz von Paula Gruithuisen. Gruithuisen stated that he had seen inhabited cities, cows grazing on meadows, as well as a temple on the Moon as well, leading to his impact crater theory being met with extensive skepticism (Koeberl, 2001). Theories surrounding the causes of craters on the Moon were ever evolving, with terrestrial features being used as analogues for the reasoning of the vast majority of these theories.

*Figure 3.15. An oblique aerial photograph of Meteor Crater, Arizona, USA.*

## The Planetary Geologic Hypothesis Method

Grove Karl Gilbert (1843-1918), an American geologist and early pioneer for planetary geology, published an article in 1896 that fundamentally changed how the geologic scientific method would be applied (Baker, 2014). Gilbert proposed "...that tentative explanations are always founded on accepted explanations of similar phenomena", providing reason to why terrestrial analogs are so commonly used in planetary geology and how they provide geologists with their most effective resource for the invention of potential hypotheses (Baker, 2014). The actions of forming such hypotheses, following their consequences and testing those consequences comprise integral parts of effective geological practice in regard to the understanding of planetary surface (Baker, 2014). This method had many implications in planetary geology and is a method used in modern science.

Later in his career, as the chief geologist of the United States Geological Survey (USGS), Gilbert examined the Meteor Crater in Arizona, also known as the Barringer Crater (Figure 3.15). The Meteor Crater is one of the best preserved and most well studied impact craters on Earth (Chapman, 2007). Gilbert observed the crater and declared that it was the result of an explosion of volcanic steam, of which most agreed (Koeberl, 1999). This, however, was contrary to Gilbert's beliefs surrounding craters on the Moon, being that lunar craters could have only been formed through impact. This lunar hypothesis was not taken rather seriously in the scientific community, as Gilbert was a geologist, as opposed to the professional astronomers that filled the field at the time (Koeberl, 1999). Despite this, Gilbert still made incredible contributions to the field of planetary geology that would later show their importance. Due to these irreplaceable contributions to planetary geology, where he recognized the importance of a planetary perspective in solving terrestrial geological problems, the Geological Society of America created the G.K. Gilbert award in 1983 (The Geological Society of America, 2020b).

## Eugene Shoemaker — The Father of Planetary Geology

Born in 1928, Eugene Shoemaker is commonly known as the father of planetary geology, having made many foundational contributions to the studies of impact cratering (Ahrens, 1997). Shoemaker first developed interest in the Moon's craters while employed by the US Geological Survey (USGS) in 1948, studying volcanic rocks during the Cold War with the aim of identifying uranium deposits (Ahrens, 1997). Upon visiting Meteor Crater in northern Arizona in 1952, near the site of his volcanism studies, Shoemaker considered the prior hypothesis of Gilbert's surrounding the origin of the crater. Shoemaker, however, contested Gilbert's theory, and believed that the origin of the crater was due to the impact of a meteorite, and that craters found on the Moon are of the same cause (Kieffer, 2015). Shoemaker then discovered coesite, a form of silicon dioxide, in the Meteor Crater, meaning that the crater could not have been caused due to volcanism, as coesite had never been found in a volcanic environment. This means that the contrary argument to Gilbert's, that the crater was a meteorite impact crater, would be accepted (Kieffer, 2015). The discoveries that Shoemaker made regarding impact craters and their physical properties would prove to have extensive applications in the developing field of planetary geology as well.

In 1956, Shoemaker, along with fellow geologist Robert Hackman, published a paper using terrestrial geological principles, such as Steno's law of superposition, to create a basis for a time scale of lunar geology (Shoemaker and Hackman, 1962). Through observations of the stratigraphic layers of a crater on the Moon, as well as other surface features such as topography and impact ejecta, Shoemaker and Hackman created a timeline for the geology of the Moon. This was done largely using principles and analogues from terrestrial geographical studies (Shoemaker and Hackman, 1962). This paper of Shoemaker's in particular helped greatly in developing the field of planetary geology, through the application of terrestrial geology to celestial bodies as opposed to postulates of astronomy or physics (Kieffer, 2015). Though it had been used in lunar studies in the past, Shoemaker's emphasis on analogical reasoning was further supported by the developing understanding of terrestrial features of the time (Shoemaker, 1961). This work by Shoemaker helped pave the way for the rapidly developing fields of lunar and planetary geology.

Following Shoemaker's very influential paper, he was given the role of establishing the USGS' astrogeology program, creating a significant alliance between NASA and the USGS, and giving Shoemaker the opportunity to begin training astronauts (Kieffer, 2015). Though, due to medical reasons, Shoemaker was unable to be an astronaut himself, he believed that a geologist would be best suited for making observations of the Moon's surface. Furthermore, this hands-on studying of the Moon's surface would help in providing geological information pertaining to the history of the Earth, as well as that of the Moon (Shoemaker, 1962). In preparing astronauts for lunar missions, Shoemaker emphasized that geological education, as well as knowledge of lunar landing surfaces was vital to ensure safety and effectiveness of manned missions (Shoemaker, 1962). Another valuable aspect of Shoemaker's astronaut training involved hands-on learning about Earth's geology, in the same place in which Shoemaker had his breakthrough discovery just years prior, Meteor Crater. Figure 3.16 shows Shoemaker leading an astronaut training trip to Meteor Crater in May of 1967. Shoemaker's work with NASA was furthered in his development of the Ranger and Surveyor missions, both unmanned missions with various goals, such as observation, sample-collecting, and practice for manned missions (Shoemaker, 1962). Shoemaker's development of geological techniques for use on the Moon helped not only to further the knowledge of the Moon's geology,

*Figure 3.16. Shoemaker leading a NASA astronaut training trip in 1967, describing the rim ejecta and geology of Meteor Crater.*

but subsequently the knowledge of the histories of both Earth, and the Moon (Shoemaker, 1962).

Shoemaker went on to also apply the lunar, and terrestrial properties he studied to other celestial bodies such as moons of Jupiter and Neptune (Kieffer, 2015). Shoemaker's discoveries provoked paradigm shifts in the geological community, particularly surrounding the backgrounds of impact craters on both Earth, and the Moon. Shoemaker made an exceptional contribution to the geological community, as well as the discipline of planetary and lunar geology. Shoemaker was the first recipient of the Geological Society of America's G. K. Gilbert Award, in 1983 (Kieffer, 2015).

# Life Beyond Earth

As humankind continues to learn more about space and the universe, as well as our Earth, terrestrial analogues find new relevance in the search for extraterrestrial life. Furthermore, as advances in technology further our understanding of, and capability for interplanetary travel, astronomers and astronauts seek to travel to other planets within our solar system, with Mars being the likeliest candidate to sustain living inhabitants. However, in order to better understand planets other than our own, and their ability to potentially harbour living organisms, we must look towards our own planet first.

For Earth to be able to sustain life is something very special. The specific region of the Milky Way Galaxy with which the Earth maintains its orbit is referred to as the habitable zone, or more colloquially the 'Goldilocks Zone' (Gowanlock and Morrison, 2018). This zone is defined as the proximity of a planet to its host star, such that it can maintain the presence of liquid water. With this in mind, the Earth's solar system is considered to be a model in the search for habitable exoplanets (Gowanlock and Morrison, 2018). Applying knowledge of geological qualities of the Earth is necessary in the search for life elsewhere in the universe, with the presence of water being of particular interest. This search for water, however, does not revolve solely around liquid water on the surfaces of planets; geological features that indicate past running water are also important indicators of a planet's capability of sustaining life, or history of potential lifeforms (Carr, 2012). Knowledge of fluvial, deltaic, and oceanic environments on Earth, and their respective geology can be observed to other planets, in the same way they are studied on Earth.

## Water on Mars?

One planet that has recently been of interest for exploration is our very own Red Planet. Research into the geological processes operating on Mars continues to rely on interpretation of images and other data returned by unmanned orbiters, probes, and landers (Chapman, 2007). Such interpretations are based on our knowledge of processes occurring on Earth. Terrestrial analog studies therefore play an important role in understanding the origin of geological features observed on Mars (Chapman, 2007). For instance, satellite observations of the morphology of the surface of Mars have shown similar terrestrial features to those found in river valleys, deltas, and lake beds on Earth (Carr, 2012). Figure 3.17 portrays a delta on Mars, indicating the presence of water on the planet in the past. Playas (dry lakes) are a type of lacustrine system which despite their dry conditions are characterized by an active hydrological cycle (Chapman, 2007). Therefore, playas on Mars have significant implications for the planet's hydroclimatic history. Photogeologic surveys have identified possible paleoshorelines in the northern plains and crater lakes, which would imply that conditions suitable for stable oceans and lakes must have existed at some point in Mars' history. This is significant because such sites would have changed to playa environments, owing to the decline in the water budget, and eventually

*Figure 3.17. A delta structure found on Mars in the Eberswalde crater.*

desiccating completely (Chapman, 2007). Therefore, Earth's geological history can be used as an analogue for studying the pasts of other planets, with knowledge of erosional surfaces on Earth helping to uncover the potential undocumented geological history of other planets (Carr, 2012). Through using knowledge of erosional surfaces associated with flowing media and bodies of water on Earth, it can be postulated that running water and bodies of water once existed on Mars.

## Mars' Geologic Structures

Another analogical application on the Red Planet includes analyzing impact craters. Martian impact craters appear morphologically similar to terrestrial craters at the resolution of imagery currently available (Chapman, 2007). Detailed analysis of the mineralogy and structure of terrestrial impact craters provides clues to the features we should look for with future missions to Mars. Mars Global Surveyor imagery reveals widespread sedimentary deposits and thermal infrared analysis suggests that the major compositional units are basalt and andesite (Chapman, 2007). While in the past, terrestrial craters were used as an analog for lunar craters, they can also now be applied to Martian craters in order to understand how environmental conditions affect crater formation, along with understanding the geologic structures and history of the Red Planet for the potential of human exploration and habitability.

## Exoplanets

With technology having developed enough for satellites to capture images of planets and their orbits beyond our solar system, researchers are using Earth's orbit and terrestrial conditions to look for exoplanets that could possibly sustain life. Recently, NASA's Transiting Exoplanet Survey Satellite (TESS) discovered its first Earth-sized planet in its star's habitable zone (Gilbert et al., 2020). NASA's Spitzer Space Telescope was used to confirm the planet's size and zone, but future missions will be necessary to identify whether the planet has an atmosphere and, if so, determine its compositions. The planet, named TOI 700 d, receives 86% of its star's energy and while the exact conditions on TOI 700 d are unknown, scientists can use current information, such as the planet's size and the type of star it orbits, to generate computer models and make predictions (Gilbert et al., 2020). Researchers at NASA's Goddard Space Flight Center modeled twenty 3D potential environment models of TOI 700 d to gauge if any version would result in surface temperatures, pressures, surface types, and atmospheric conditions suitable for habitability (Gilbert et al., 2020). Another exoplanet that scientists have discovered is Kepler-1649c, located 300 light-years from Earth and most similar to Earth in size and estimated temperature (Vanderburg et al., 2020). This exoplanet is only 1.06 times larger than Earth and receives 75% of the amount of light that Earth receives from our Sun, making it likely that its temperature is similar to that on Earth. However, its star is a red dwarf, and therefore life can be difficult to sustain due to the star's tendency to flare up (Vanderburg et al., 2020). The atmosphere of the exoplanet is still unknown; therefore, astrobiologists will need more information about this planet in order to gauge whether it has the potential to sustain life. Earth's orbit, atmosphere, and planetary environment are used as a model for searching for life potential in these exoplanets and beyond,. It can then be presumed that when we finally are able to observe these exoplanets more closely, we can use the geological features of Earth as an analog for our search for life beyond the Milky Way.

Considerable discoveries about the world around us have been made thanks to the vital contributions of astronomers and geologists in the past. In understanding the history of our own planet through geological discoveries, we can formulate hypotheses about the moons and planets around us with heightened degrees of accuracy as time passes. Whether it be with craters, fluvial formations, geologic composition, or the ability to sustain life, scientists are learning so much about distant planets thanks to founding figures in science, and art alike.

# Conclusion

Those who ponder the history of the Earth are prone to feeling small. It is likely that you too, dear reader, felt this way while reading our book for one or many reasons. What made you feel this way might have been the lives of scientists of the past dedicated to the cause, or the billions of years of natural processes which shaped the planet, or maybe it was the expanse of space outside our atmosphere. Whatever the reason, you are not alone.

While you may just be a speck on a giant, ancient rock, you can rest assured that since the dawn of humanity, countless other specks have felt the same way. In fact, how small we are has been a limiting factor in coming to understand something as big as the Earth in many cases explored over the chapters of this book. While you might have felt small, you probably later felt inspired by the brilliant minds who overcame their stature to discover the truth.

What is the truth? For some brilliant minds, just a short while after their small time on this big Earth, what truth they had put everything into finding was no longer so. We humans are often just as wrong as we are small. Even the truths that are in this very book might be proven wrong before long. Just as we are specks on a giant rock are our truths specks in eternity. From history we know it is the ones who dare to be wrong who write the truths.

*-Finn Korol-O'Dwyer*

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