History of the Earth

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Special Thanks

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Sarah **Symons**

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Foreword

This book is the outstanding creation of a group of second-year Honours Integrated Science (iSci) undergraduate students at McMaster University (graduating class of 2025). Each entry in the book was conceptualized, researched, written, and illustrated by a pair of students as part of their academic 'deliverables' for a program module entitled 'History of the Earth'. Dr. Sarah Symons and I developed this module in 2010 with the objectives of introducing interdisciplinary science students to the fascinating wonders of Earth history and encouraging them to consider how scientific ideas have been generated, the cultural, societal, and economic conditions that have influenced the development of scientific thought, and the importance of individual and team personalities and experiences. There is no better topic than Earth history through which to explore the history and development of scientific thought given its interdisciplinary nature that integrates concepts from biological, chemical, and physical sciences as well as mathematics. One of the greatest interdisciplinary scientists of all time, Charles Darwin, utilized his understanding of geological processes, the movement of land masses, and the significance of extinct fossil species to develop his revolutionary theory of evolution at a time when theological ideologies prevailed. We can learn a great deal about the evolution and future of modern science by studying those who have made significant contributions to science in the past.

I am a scientist who has always been fascinated by the history of our planet – particularly the changing environmental conditions recorded in the rocks and sediments exposed on its surface. Unravelling the mysteries trapped within ancient materials has captivated me and I have been very fortunate to spend my career seeking clues that reveal the extent of former lakes, oceans, and ice sheets and their relationships to changing climate and environmental conditions. However, the research I have conducted has merely scratched the surface of reconstructing past environmental change and we have much yet to learn about the world we inhabit and its past if we are to better manage its future changes. I hope that by researching, writing, and producing this book, a new cohort of scientists that understand both the importance of understanding Earth history and the complex way in which scientific thought is developed, has been created.

This book provides a wonderful introduction to Earth history and how we have developed our understanding of our planet's origins, past conditions, and possible future. It records the explorations of our students into the history of science through investigations into the evolution of our planet, the processes that shape its surface, and the evolutionary history of its inhabitants. These explorations include considerations of how we have learned about the origin of life on Earth as well as the loss of species through extinctions, how the contributions of early geoscientists provided the foundations of our current ideas and approaches, and how discoveries were made regarding the many dynamic processes active within and upon the Earth's surface. This book also addresses the ways in which controversial theories regarding the origin and shaping of the Earth over time have stimulated the questioning of pre-existing ideas and the initiation of innovative approaches and investigations. It is a pleasure to read, and I hope it will stimulate you to dig deeper into Earth's history and the lessons we can learn as guardians of its future. Enjoy – I am incredibly proud of this contribution our students have made toward enhancing our understanding of the 'History of the Earth'.

Dr. Carolyn Eyles, McMaster University
August 18, 2023

Introduction

For as long as human beings have existed, we have been curious. Curious to understand the miraculous ways the world works. Curious to learn how and why we have come to be the creatures we are. To answer these questions, humans have often chosen one of two strategies: looking to the stars or looking to the ground below us. Before space exploration, those that looked to the stars found stories in constellations to try to explain what they saw on Earth. But those that looked underneath what was around them, noticing geologic phenomena, fossil remains, and patterns throughout the Earth, uncovered more than stories; they found history.

From the earliest geologists to modern paleontology, our history continues to grow. Throughout this book, we will dive into every aspect of our Earth's history, from the origins of life to the creation of continents, glaciers, and mountains. As humans often do, we will start with an anthropocentric perspective towards history, beginning with the origin of us. What do we know about the beginning of life on Earth, and how have we gained this knowledge? Just as life starts, from the soils and waters of the Earth, it ends. It leaves traces, biomarkers, fossils, and glimpses into the past. From the ordered stratigraphic layers, a dated history can be traced back to the earliest creatures of our world. Who is to say these same strategies and biomarkers will not reveal the evolution of life outside the Earth?

As we discover the history of Earth's creatures, we will gain an appreciation for what preserves their history—rocks. The rocks, minerals, and soils that makes up every part of our world tell an even more powerful story of creation. From climate change to mountain building, Earth's geologic history is rich. Our understanding of this landscape would be incomplete without the help of the founders of geology, who rarely get the recognition they deserve. Their stories will be told alongside their discoveries.

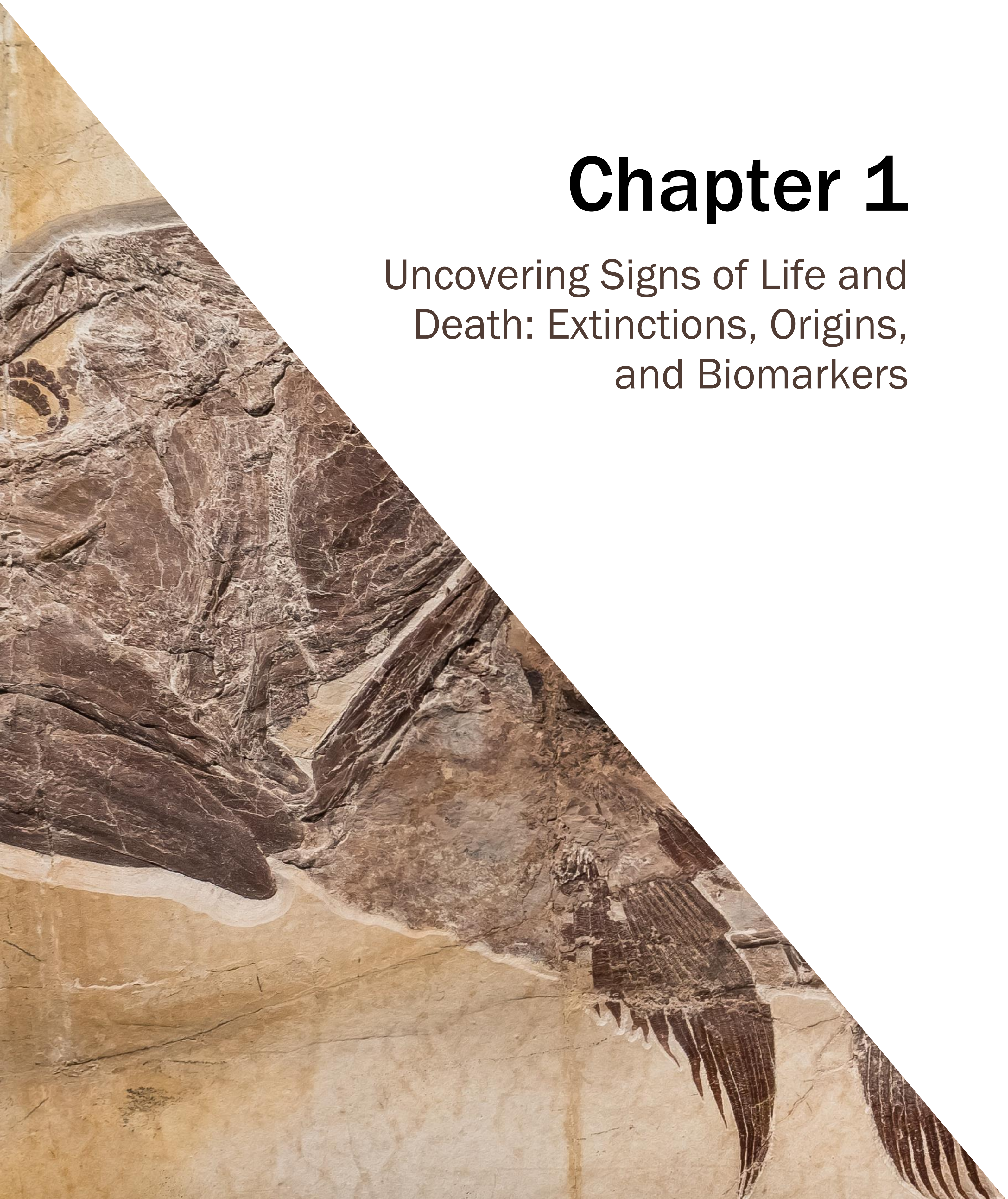
The history of our modern landscape is dynamic. Since its birth, Earth has remained active and ever-changing. While the scale of movement, power, and change that occurs through Earth's processes may seem unfathomable to humans, it places us in awe of our world. Understanding the movement of plate tectonics, molten rock, and glacial processes

Our knowledge about the Earth and its wonders has not always been so clear. Conflicting theories, perspectives, and controversies has long plagued our history. But these diverse perspectives must be appreciated, for these new, creative, and far-fetched theories are what led us to the discoveries we now know to be true. Evidently, humanity has only scratched the surface of the wonders that surround us, but our curiosity is alive and well. We hope, as you progress through the chapters of this book, that your curious spark for what has come and what is to come, is kindled into a flame.

Welcome to the History of the Earth.

Chapter 1

Uncovering Signs of Life and Death: Extinctions, Origins, and Biomarkers



Introduction

Humans, in their egocentric nature, were far more concerned with the origins of life than rock when they began their journey to understand the history of the Earth. The first theories of the origins of life are documented throughout the myths and legends of Indigenous peoples around the world. As humanity grew and civilizations appeared, religions began to put forth their own stories of life's beginnings. It was then only natural for science and scientific thought to be heavily influenced by religious dogma.

The first indication of life before us has always been, and continues to be, fossils. From myths and legends to Genesis and the catastrophic biblical flood, fossils have been at the heart of all of life's origin stories. The first fossils were generally misidentified as extant animals from the time as prehistoric or extinct animals were unfathomable. Through comparative analysis of fossil anatomy, conclusions could begin to be drawn surrounding the relationships of various living creatures and the creatures that must have once existed to link them. Soon enough it was clear that the depth of life's history was much vaster than we could imagine. Entire species, or what seemed like worlds, appeared to have been created, destroyed, and preserved within the geologic stratigraphy.

Much of our understanding of prehistoric life remains incomplete due to the limitations hindering fossilization. However, the missing puzzle pieces of the history of life on Earth continue to be uncovered. The newest technologies, analyses, and theories will continue to shape what we know to be true about our own evolution and the origins of all life on Earth. In Chapter 1, we will investigate fossils through their organic synthesis, how they explain extinctions and origins, and examine the future of paleontology and its potential for reshaping the history of life on Earth.

Alvarez's Extinction

The Alvarez Hypothesis, the idea that an asteroid was the sole cause of the sudden mass extinction of dinosaurs, is scientific theory deeply ingrained in the general public's knowledge of paleontology. While the Alvarez Hypothesis represents an astute analysis of elements in the K-T Boundary, a section of rock associated with the Late Cretaceous extinction event, it certainly does not represent a conclusive or even complete evaluation of the Late Cretaceous extinction event. The Alvarez Hypothesis is not the culmination of hundreds of years of paleontology, it is just one part of our current understanding. By evaluating the history of research into the Cretaceous extinction event, it can be shown exactly where the Alvarez Hypothesis fits into modern paleontology.

Scientific discussion of extinction began in the mid 1600s. By that time, there was a clear distinction between rocks and fossils but there was not a clear understanding of what a dinosaur was. At this period in time, paleontology was still strongly guided by scripture, and many naturalists of the time were collecting and publishing research to reconcile geological evidence with the Bible (Rudwick, 1985). Advancements around extinction and extinct species played a significant role in creating modern paleontology. The first step in extinction research was proving that some of the fossils that had been uncovered corresponded to an extinct species of animal.

The Discovery of Extinction

Predating the ideas of mass extinctions, there existed a debate on whether extinction as a concept existed. Extinction was observed very early on in paleontology as fossils were dug up that did not correlate to any living animal. Explanations for such fossils were sparse and unscientific. Extinction was not treated as a serious scientific idea as it implied that some animals are inherently flawed and unsuited for life, which contradicted the Bible and the idea that, in the beginning, God created a perfect Earth. As stated in the Bible: "God saw everything that he had made, and indeed, it was very good. And there was evening and there was morning, the sixth day." (The Bible, Genesis. 1:31). Prior to the mid 1700s there were several arguments to discredit fossils that seemed to prove extinction, the most common being that the species represented by the mysterious fossil was not extinct, rather it simply had not been discovered yet. In this period, much of South America, Africa, and parts of western North America were unexplored by Europeans. Pure coincidence was also used as a rebuttal, as a fossilized Mastodon, discovered on the banks of the Ohio River, was thought to be a mixture of the remains of an elephant and a hippo rather than a unique extinct species (Rudwick, 1985).

Georges Cuvier (Figure 1.1) was the first to question these arguments. Irrefutable evidence for extinction came from his paper *On the species of living and fossil elephants* (Cuvier, 1799). At the time, Cuvier was the world's leading expert in comparative anatomy. He studied animals as if they were machines, where every part of the animal served a specific purpose and could be correlated to its mode of life. Cuvier was more concerned with the specific parts of the animal rather than their general characteristics. In his paper, Cuvier compared the bones of extant and extinct elephant species bone-by-bone. This meticulous juxtaposition revealed that the anatomical differences between mammoth bones and Indian and African elephants were too great for them to be the same species. This implied that mammoths were an extinct species and, by extension, that species could go extinct (Rudwick, 1985).

Figure 1.1: Portrait of Georges Cuvier, the scientist that proved that extinction is possible in the late 1700s.

Following his landmark paper, Cuvier sought to explain the mechanism of extinction. It was known that mammoths were well-adapted to the cold and that gradual changes to their environment would have triggered a migration of the species. Cuvier proposed the only method of extinction was a sudden and drastic event he named a 'revolution' (Rudwick, 1985).

The Nonquestion Phase

From the early 19th century to the early 20th century, there was a lack of public interest in mass extinction research, leading to this period being known as the 'Nonquestion Phase'. However, a key few scientists continued to progress and advance Cuvier's ideas. William Buckland (Figure 1.2) produced a theory of catastrophist geology to explain ancient mammal bones found in caves (Benton, 1990). He proposed a universal flood that may have caused these extinctions. Buckland, unable to conclusively determine the causes of these catastrophic extinction, stated that a potential "astronomical" event such as "a change in inclination of the earth's axis" would have been the only possible cause for a catastrophic event (Buckland, 1824).

In contrast to the catastrophism espoused by other thinkers at the time, Charles Lyell proposed that extinctions were non-catastrophic and were on a more species level rather than global. Lyell's book *Principles of Geology* (1830) challenged commonplace beliefs regarding the Earth's age and provided evidence of the Earth being more than 6000 years old. An older earth made Lyell's smaller scale non-catastrophism viable. Lyell believed that species relied on the environmental conditions and any changes to environmental conditions could have led to extinction (Benton, 1990).

Figure 1.2: Portrait of William Buckland, one of the first scientists to theorize about catastrophic geology leading to mass extinction events, in 1883.

Research on dinosaur extinction began to decrease in the mid 19th century as Charles Darwin saw the decrease of ammonite fossils at the end of the Cretaceous period as simply a gap in the fossil record (Darwin, 1859; Benton, 1990). The Darwinian viewpoint became prevalent leading to a decrease of research in the mass extinction of dinosaurs. Some non-Darwinian models in the late 19th century stated that evolution was directed and in patterns in favour of more advanced animals, leading the primitive dinosaurs towards extinction (Benton, 1990).

The last key theory before the more professional era of Late Cretaceous extinction research was racial senility, the theory that groups of animals became too long lived and their evolutionary novelty dried up. This view stated that dinosaurs simply "ran out of the genetic variability that was necessary to survive" (Benton, 1990). During the period in which racial senility was seen as the clear theory, research and publications regarding the Late Cretaceous extinction began to skyrocket. Subsequently, this increase in research led to a great variety of new theories and ideas. The public also became more aware of the extinction debate and new theories began to permeate pop culture (Benton, 1990).

Arguments for a Gradual Extinction

It is worth mentioning that racial senility as a mechanism of extinction is not entirely unfounded and has played a role in the understanding of the Late Cretaceous extinction since it was proposed. A more modern version of this theory is a decrease in dinosaur diversity at the end of the Cretaceous. One of the first papers discussing this decrease in diversity is Axelrod and Bailey's paper *Cretaceous Dinosaur Extinction* (1968) claiming climatic changes caused dinosaur diversity to gradually decline.

Centering Cretaceous extinction research around a gradual decline in dinosaur diversity and population was common in extinction research during the early 20th century. Extinction ideas in this period did not even discuss the possibility of an instantaneous global catastrophe as the cause. Weiland's paper *Dinosaur Extinction* (1925) proposed the predation of dinosaur eggs by small mammals gradually brought dinosaurs to extinction. Other gradual extinction theories include the progressive replacement of dinosaurs by mammals, climatic cooling, and disease (Benton, 1990).

Movement away from gradual extinction

thinking was brought on as more dinosaur fossils were discovered, making it obvious the sample size of known dinosaur species was too small to draw meaningful conclusions (Russell and Tucker, 1971). Additionally, very few of the proposed methods of gradual extinction could have caused dinosaurs to become extinct at the rate observed in the fossil record, ushering in ideas for more dramatic mass extinctions.

Magnetic Reversals

Discovery of a historical sedimentological record within the Gubbio region of Italy allowed the Alvarez group to begin to form their extraterrestrial impact hypothesis. Dating historical items require precise methodologies to be effective. In the 1970s, Walter Alvarez and his group discovered deep-water limestone containing planktonic foraminifera in the Gubbio area of Italy (Alvarez, et al., 1977). This limestone was undisturbed by erosion, leading to a phenomenal record of the Late Cretaceous and Palaeogene periods. Particularly, these limestones allowed for the analysis of the historical reversals of magnetic fields and demonstrate a continuous record of the K-T boundary, something previously not possessed or properly researched and understood (Alvarez, 2009).

Figure 1.3: Luis Alvarez (Left) and Walter Alvarez (Right) at the layer of sediment at the K-T boundary in Gubbio, Italy.

Magnetic polarity stratigraphy allowed for the examination of the how the Earth's magnetic field impacted the deposition of these deep-water limestones. It was shown that throughout the deposition Earth's magnetic field reversed many times. Magnetic reversal stratigraphy is quintessential for correlating and dating rocks as well as aiding in radiometric age dating (Alvarez, 2009). To make accurate measurements with this method, the sediment must be magnetically stable, have strong magnetism, and be contained in continuous, homogenous layers. The sediments deposited in the Gubbio sequence were left near perfect, possibly due to the low rate of sediment deposition (Alvarez, et al., 1977).

Specifically, a 1cm layer of clay discovered by Luterbacher and Premoli Silva (1962) led to substantial innovations in investigations into the K-T boundary. This clay was geochemically studied under a microscope by the Alvarez group and revealed a sudden mass extinction of all planktonic foraminifera at the time of deposition. In tandem with this, iridium was discovered within the clay. Iridium is exceedingly rare on Earth's surface, as it only originates from the Earth's core and extraterrestrial sources like comets and asteroids. The large amount of iridium within this rock could only be due to an impact from a comet or asteroid (Alvarez, 2009). The explanation that this iridium could have only come from an extraterrestrial impact led to the commonly accepted Alvarez Hypothesis, in which the mass catastrophic extinction of the dinosaurs was caused by an asteroid (Alvarez, et al., 1980).

Overview of the Alvarez Hypothesis

The idea that an asteroid was responsible for the extinction of the dinosaurs comes from Luis and Walter Alvarez's paper *Extraterrestrial Cause for the Cretaceous-Tertiary Extinction* (1980). The Alvarez paper states three results that support this theory: that there is a significant increase in the concentration of iridium in sediment deposited during the Cretaceous extinction, that the iridium is from an extraterrestrial source, and that the iridium did not come from a nearby supernova explosion.

This study was conducted by studying the layer of sediment deposited during the late Cretaceous extinction (K-T boundary) in Italy (Figure 1.3). 12 sediment samples were taken from the boundary and surrounding strata and were tested for traces of 28 different elements.

The Alvarez team found that 27 of 28 examined elements had uniform patterns of abundance throughout the layers, but the abundance of iridium increases by a factor of 30 at the K-T boundary. This curious result was confirmed in another part of this experiment conducted at Stevns Klint in Denmark with 7 samples, and showed an increase in the abundance of iridium by a factor of 160, from ~0.26 ppb background abundance to 41.6 ppb abundance at the boundary. The paper elucidates on the natural abundance of iridium and concludes that its prevalence in the boundary is too high to have been deposited naturally and therefore its origin is undoubtedly extraterrestrial.

At the time, a supernova being the cause of the extinction was gaining traction amongst the scientific community and could have been the method of deposition for the iridium. A paper by Russel and Tucker (1971) explains that a nearby supernova approximately 100 lightyears away could deposit 10^{22} joules of energy into our atmosphere in less than a week. This would cause devastating environmental effects, including modifying atmospheric circulation globally, changing Earth's albedo, disrupting the ozone layer, and generally increasing the frequency and intensity of storms as well as lowering temperatures.

Alvarez addressed the supernova theory with another sub-experiment. Using an approximation for how much iridium would be blown off a supernova, it was estimated that the star would have been 0.1 lightyears, or 9.46 x 10^{11} km away from earth. Given the population of stars on the shell, there is a miniscule 10^{-9} probability that a star went supernova within the last 100 million years. Additionally, the Alvarez team realized that in a supernova, the ratio of iridium atoms should be in a 10^3 ratio with plutonium-244 atoms. Gamma ray analysis of Italian sediment samples did not detect any plutonium-244. This negative result prompted the Alvarez team to speculate that an asteroid would be the only extraterrestrial source that could supply this iridium.

By eliminating supernovae as a potential extraterrestrial cause of extinction, an asteroid was the most likely explanation for the iridium. The paper finished by estimating the radius of the asteroid that would have hit the earth to spread the observed concentration of iridium would be about 10 km. They conclude by outlining their next steps, being to find the crater that this asteroid made and to investigate whether an asteroid could be responsible for the other known mass extinctions (Figure 1.4).

Controversy Surrounding the Alvarez Hypothesis

While the Alvarez Hypothesis is widely regarded as the explanation for the mass extinction of the dinosaurs, many historical and modern scientific sources have argued against it, stating that the science of the Alvarez group was "weak" (Officer, 1996). These criticisms are not a recent phenomenon; they were prevalent from the moment of publication. Through a mixture of science and politics, the impact hypothesis has been questioned and examined from a variety of angles (Officer, 1996).

Upon publication, the Alvarez group's hypothesis was immediately questioned as it went against a large pre-existing body of knowledge regarding the Late Cretaceous extinction.

Figure 1.4: Artistic rendering of the potential impact of the asteroid in the Yucatán Peninsula that may have led to the mass extinction of the dinosaurs.

A poll conducted at the Society of Vertebrate Paleontologists meeting in 1985 by New York Times writer Malcolm Browne found that only 4% of the 118 paleontologists surveyed believed that an impact could have led to a mass extinction event (Browne, 1985; Officer, 1996).

The Alvarez group did not accept the scientific criticism as valid, openly displaying their bias. Upon hearing about dissenters, the Alvarez group tried to block their promotions and discredit their research referring to it as "scientific nonsense" (Officer, 1996). Furthermore, in an attempt to minimize controversy, departments avoided researchers promoting theories that contradict the Alvarez Hypothesis. This began a ripple effect in which younger scientists, wanting to get on the bandwagon and receive promotions, began promoting the impact hypothesis. Given that arguing against the impact hypothesis may lead to a lack of employment, it makes sense that scientists would align themselves with Alvarez, in turn giving the impact hypothesis much more credibility in the eyes of the public (Officer, 1996).

Alvarez's control over the scientific community has led to a lack of public knowledge regarding other theories as well as impeding scientific progress in his own field of research. Luis Alvarez, a Nobel Prize winning physicist, put down paleontologists stating that they are "not very good scientists", further entrenching Alvarez as a self-proclaimed infallible source and unwilling to acknowledge other hypotheses (Glen, 1994). As Alvarez's hypothesis was easily digestible to the public, it quickly spread through the world and became common knowledge; an asteroid is easier to explain, and more interesting, than a series of volcanic eruptions causing the mass extinction of the dinosaurs (Glen, 1994).

Additionally, *Science Magazine*, a major scientific journal, appeared to show heavy bias in favour of the impact theory. Between 1991 and 1993, eleven articles supporting the hypothesis were published while only two articles against the hypothesis were published. The bias became so evident that the earth science community stopped submitting papers to *Science* that contested the impact theory. Interestingly enough, the editor of *Science* at this time was from Berkeley, the same institution Alvarez attended (Officer, 1996).

Research into the Cretaceous mass extinction has not brought us to the definite correct answer for the extinction of the dinosaurs. The vast collection of research and knowledge in this area provides a few key assumptions that must be made when considering mass extinctions. It is important to note that the Alvarez hypothesis was not conclusive evidence for an asteroid-caused mass extinction. Its significance was to be proved later when other key discoveries were made, such as the crater being found in Mexico. As one body of literature grew to support the Alvarez hypothesis, so did another body that did not support it. Finally, the suppression of such literature has led to serious detriment to the field by allowing bias to affect the scientific consensus.

Alternative Theories Surrounding Dinosaur Extinction

The Alvarez Hypothesis enjoys widespread acceptance in modernity. However, it is not the only theory considered as viable. A famous paper written by Gerta Keller in 2008 contested the widely accepted Alvarez hypothesis and stated that the impacts of the asteroid were overstated and could not have resulted in the mass extinction of the dinosaurs. Her hypothesis is that volcanic eruptions from the Deccan Traps (Figure 1.5) may have led to the Late Cretaceous extinction (Keller, et al., 2008). The Deccan Traps are an igneous continental flood basalt province in India and are one of the largest volcanic features in the world. The Deccan Traps formed a shield volcano made up of thousands of layers of flood basalt. The largest Deccan trap eruption occurred near the end of the Cretaceous, leading to an alternative hypothesis in which this eruption caused the mass extinction event (Sen, 2001). Chronogeological analysis has determined that the main phase of Deccan Trap eruptions began a quarter of a million years before the Cretaceous extinction, suggesting that Deccan Trap eruptions caused the extinction of dinosaurs instead of an asteroid (Schoene, et al., 2015).

Environmental impacts from the eruption of large igneous flood basalt provinces are well documented and could have led to a catastrophic event causing the mass extinction (Black and Manga, 2017). The influx of CO_2 into the atmosphere, causing a greenhouse effect, through the eruption of the Deccan Traps could have led to an unlivable atmosphere for fauna and caused the mass extinction of the dinosaurs (Caldeira and Rampino, 1990). Additionally, some of the findings in the Gubbio region of Italy were found to be biostratigraphically incomplete. Additional stratigraphic analysis of magnetic reversals in Spain and Tunisia found that there were Cretaceous fauna above the K-T boundary, leading to doubts regarding the accuracy of the original findings in Gubbio. A lack of a dramatic decline in species richness does not bode well for the Alvarez hypothesis as these 'survivors' contradict the belief that the majority of life was wiped out by a single impact (MacLeod, 2014). Specifically, Keller's work in El Kef, Tunisia found a great abundance of fauna, specifically benthic forminafera, that was unquestionably above the K-T boundary. This suggests that the mass extinction could not be explained through a single impact, as indicated by the abundance of iridium, and must have been due to a variety of factors that could have originated from volcanism. Additionally, the surviving species showcase a slow recovery of the ecosystem, meaning it is unlikely that a single impact from an extraterrestial object could have such long-lasting effects on ecosystems (Keller, 1988).

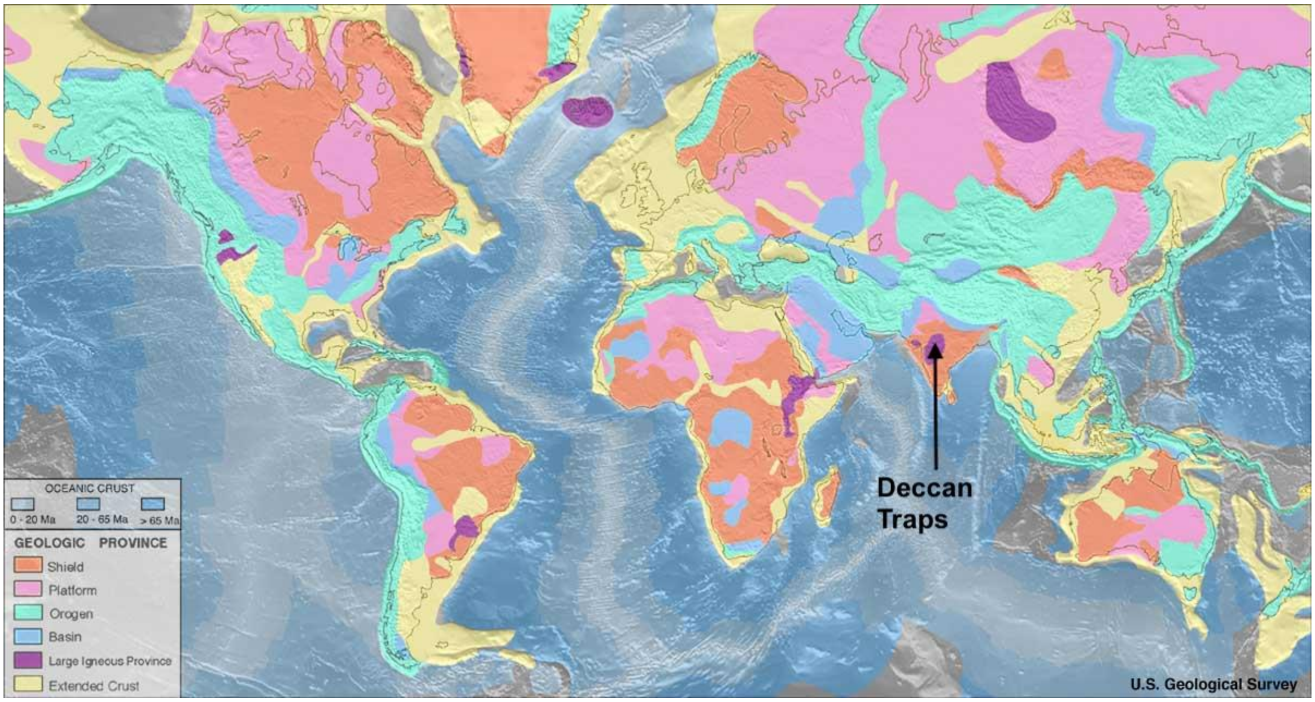


Figure 1.5: Map of the world highlighting geologic provinces. The Deccan Traps are labelled in purple as large igneous province in India.

While the Alvarez hypothesis may appear true in the public's eye, Gerta Keller's work proves there still remains great turmoil within the scientific community regarding the extinction of the dinosaurs.

Reduction of Diversity

The broadening of scientific research in this field, as exemplified in the popularization of the Deccan Traps hypothesis, has also put forward other theories, circumstances, and criteria pertaining to the late Cretaceous extinction. New data points to the potential of a gradual extinction once again.

As previously mentioned, small sample size is one of the main factors affecting the consensus regarding the decline in dinosaur diversity towards the end of the Cretaceous period. Modern researchers use computer modeling and data on known dinosaur genera to investigate this. Wang and Dodson's 2006 paper *Estimating the Diversity of Dinosaurs* used an abundance-based coverage estimator to produce an estimated diversity of dinosaurs from a known diversity. It indicates that despite the known diversity of dinosaurs decreasing towards the end of the Cretaceous, their estimated diversity is constant (Wang and Dodson, 2006). On the contrary, Condamine, et al. 2021 use a process-based speciation and extinction model to show that dinosaurs were in decline 10 million years before the late Cretaceous extinction event. These two contradicting articles exemplify the lack of a consensus regarding the demise of the dinosaurs.

New dinosaur species are being discovered at a rate of 1 dinosaur per 1.5 weeks (Brusatte, et al., 2015). That new data is being used to determine whether the extinction of the dinosaurs was abrupt or gradual, whether there is a sole cause or multiple causes of extinction, and whether the primary cause is an asteroid impact, volcanism, temperature changes, or sea-level fluctuations (Brusatte, et al., 2015).

Modern Doubters

Despite widespread acceptance of a mass extinction event caused by either a meteor or other events, there remains groups of people that deny the existence of dinosaurs or deny the currently accepted scientific circumstances surrounding their existence. The belief that dinosaurs roamed the Earth at the same time as humans is highly prevalent in creationist spheres. The limitations of science communication are clearly evident as a proportion of the population does not acknowledge basic scientific findings as valid (Williams, 2009). Discussions of mass extinction theories cannot begin when the foundational understandings of the Earth's histories are not agreed upon. Modern discourse of the Alvarez Hypothesis, the Keller Hypothesis, or any other modern theories will be limited by portions of society refusing to acknowledge and accept scientific findings.

Archaeopteryx and the Origins of Life

In 1861, the impression of a singular feather was found in Bavarian limestone, and presumed to be from the first bird species (Owen, 1863). This discovery came just two years after the publication of Darwin's *On the Origin of Species*, providing evidence for his theory of natural selection (Darwin, 1859a). The fossil discovered in Bavaria reinforced Darwin's theory of evolution, as a potential missing link in the fossil record. This feather provided a transitional species between dinosaurs and birds that Darwin had hoped for; this species was first described by Hermann von Meyer, who gave it the name *Archaeopteryx lithographica* (Owen, 1863; Thanukos, 2009).

The discovery of the first *Archaeopteryx* feather and Darwin's theory of evolution were highly debated throughout the late 1800s, sparking dispute between the people of science and the Church (England, 2017). Despite this, Darwin was able to continue his research and collaborate with many naturalists. One such naturalist was English biologist Thomas Henry Huxley, nicknamed "Darwin's bulldog" in the media for his wholehearted defence of Darwin's work (Kampourakis and Gripiotis, 2015).

Archaeopteryx acted as evidence for natural selection, fuelling the flames of debate on the origins of life in the 19th century.

The Origins

Charles Darwin is considered the father of modern evolution (Figure 1.6). His publication *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*, hereby referred to as the *Origins*, is considered to be the founding book of evolution (Boero, 2015; Tanghe, 2019). The first edition of Darwin's the *Origins* was published in 1859, with 5 subsequent editions published between 1859 and 1872 (Darwin, 1859a; 1872). In this text, Darwin was able to identify various evolutionary patterns, such as natural selection and ecological ultimate processes, leading to the development of the theory of evolution (Boero, 2015). Though the *Origins* contained many descriptions and ideas of ecological principles and processes, none were formalized until later on in time, and Darwin was not initially credited with these discoveries (Boero, 2015).

Darwin considered himself a naturalist, as he studied natural history: the overlap between ecology and evolution. In contrast, reductionists kept the two disciplines separate, making it more difficult to observe and understand the natural phenomena that can only be explained by the interaction between disciplines. Darwin's thoughts on evolution in the *Origins* consisted of the intersection between the theory of evolution and ecology, through the principle of natural selection (Ayala and Fitch, 1997). He questioned whether variations and adaptations in species could occur over the course of many generations, describing early ideas of evolution. Further, if this did occur, he wondered if variations with an advantage over others would have a better chance at reproducing, demonstrating natural selection and survival of the fittest (Ayala and Fitch, 1997). He focused on the overall concept of evolution rather than human evolution specifically, explaining that his reasoning surrounding human evolution may appear frivolous, though he did explain that sexual selection was a crucial force in the origin and evolution of humans (Bajema, 1988). Darwin supported his theory of evolution from common descent by pulling evidence from various scientific disciplines, including paleontology, geographical distribution, classification, morphology, and embryology (Tanghe, 2019).

The initial publication of the *Origins* created controversy across the United Kingdom, most notably the clash between the Church and

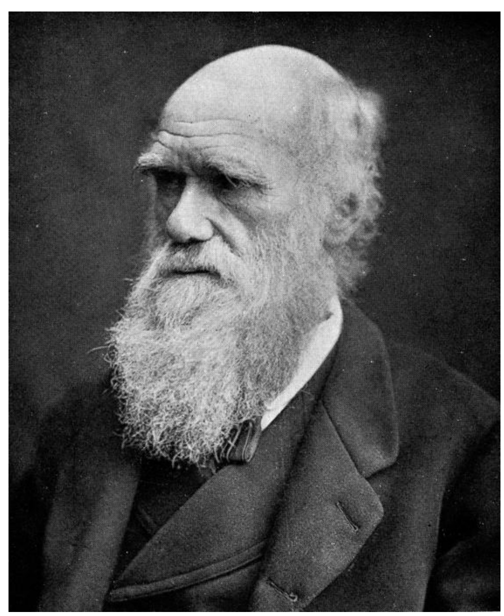


Figure 1.6: Charles Darwin lived from 1809 – 1882 (Martinez-Reina, 2022). Throughout his lifetime, he published 6 editions of his book the Origins *with a focus on the theory of evolution.*

scientific community (England, 2017). The Bishop of Oxford, Samuel Wilberforce, argued strongly against Darwin and his views on science. He initially attempted to demean Darwin in front of the British Association in Oxford by critiquing his theory of evolution. Thomas Huxley, a supporter of Darwin's theory and publication, later refuted Wilberforce's statements, with the help of others, such as English botanist Joseph Hooker. This confrontation is known as the Huxley-Wilberforce debate, which focused on the reception of Darwin's theory (Kampourakis and Gripiotis, 2015). Huxley was able to refute the obscurantism that Wilberforce and the Church had imposed on the scientific community. Though Huxley spoke a powerful speech, it is thought that Hooker may have had a greater influence on the debate than Huxley (England, 2017).

In the *Origins*, Darwin critiqued his own work and ideas on the grounds that the fossil record was incomplete. He noted that a transitional species directly connecting modern species to their common ancestor would have been undeniable evidence for his theory, explaining that the gaps in the fossil record were a glaring imperfection (Thanukos, 2009). Most environments are poor locations for fossilization, leading to this lack of evidence; these transitional fossils were not located in areas of suitable deposition for fossilization to occur. Darwin devoted a chapter of the *Origins* to a description of the nature of the geological record and explained why key transitional fossils may never be found, (Thanukos, 2009).

Archaeopteryx lithographica

Two years after the publication of the first *Origins*, in 1861, the oldest discovered feathered animal was found in Solnhofen lithographic limestone in Bavaria, also known as Lagerstätten. This fossil is considered to be the missing link proving the Darwinian theory of natural selection, aiding in the completion of the fossil record (Wellnhofer, 2010). Found in the strata of the Oolitic series, specifically from the Oxfordian stage of the Jurassic, this species was first described by Hermann von Meyer. The impression of a single feather, a type of trace fossil, was described by von Meyer, a German anatomist, in *Jahrbuch für Mineralogie* (*Journal of Mineralogy and Geochemistry*). He dubbed the specimen *Archaeopteryx lithographica* (Figure 1.7) (Owen, 1863; Skedros and Brand, 2011).

On November 9th, 1861, a meeting of the Mathematico-Physical Class of the Royal Academy of Sciences was held in Munich. In this meeting, Professor Andreas Wagner shared the discovery of *Archaeopteryx lithographica*, hoping to prove that this fossil was a long-tailed feathered pterodactyl, giving it the name *Griphosaurus*. His health prevented him from viewing the fossil and he passed before completing his research (Owen, 1863).

Another lithographic stone of Solnhofen was in the possession of Häberlein of Pappenheim, which contained the most important parts of an *Archaeopteryx lithographica* skeleton (Wagner, 1862). Skeletons demonstrated both saurian and avian skeletal characteristics, such as the *Archaeopteryx's* tail and feathers, respectively (Wellnhofer, 2010). The fossils were adorned with feathers, specifically on the tail of the dinosaur and on its anterior limbs, resembling those of birds. The tail of the dinosaur was not birdlike but rather resembled those of the Late Jurassic flying reptile (pterosaur) *Rhamphorhynchus* (Wagner, 1862; Frey and Tischlinger, 2012).

Figure 1.7: The first trace fossil of Archaeopteryx lithographica *discovered in 1861, which was first described by Hermann von Meyer.*

The relationship between *Archaeopteryx*, birds, and pterosaurs is best quantified through their anatomies. *Archaeopteryx* was approximately the size of a rook or of a peregrine falcon, with quill feathers on its tail and wings, and finer feathers on the side of its body, as well as a claw bone as the unguiculate digit of its wing (Owen, 1863). Anatomically, dinosaur and pterosaurs share tail shape and proportion, however, differ in the presence of a furculum in the *Archaeopteryx* skeleton. *Archaeopteryx's* wings share the form and proportions of *Gallinaceous* birds, based on their state of preservation (Owen, 1863).

In 1868, Huxley argued in favour of Darwinian evolution, and the relationship between birds and dinosaurs, with the missing link between them being *Archaeopteryx* (Figure 1.8) (Huxley, 1868a; Wellnhofer, 2010). He also commented on Richard Owen's *On the archeopteryx of von Meyer, with a description of the fossil remains of a long-tailed species, from the lithographic stone of Solnhofen*, published in 1863, stating that Owen's identification of bones and their locations were incorrect. Through his observations and reconstruction of the *Archaeopteryx* skeleton, Huxley believed that some *Ratitae* were closer relatives to both birds and reptiles than the dinosaur (Huxley, 1868a).

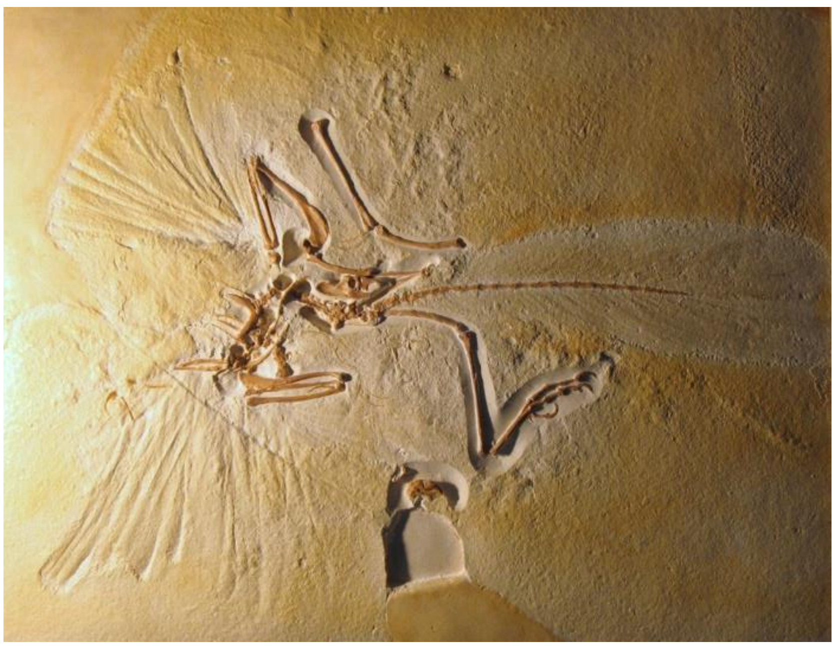


Figure 1.8: The Archaeopteryx *London Specimen was discovered in 1861, which provided a transitional state in the fossil record and reinforced Darwin's theory of evolution.*

Archaeopteryx fossils were preserved in Bavarian Lagerstätten, of which there are two kinds: concentration and conservation Lagerstätten (Nudds and Selden, 2008). Concentration Lagerstätten are deposits with a high number of fossils, though they may not be complete or well preserved. On the other hand, conservation Lagerstätten contain obrution or stagnation deposits, allowing for optimal fossilization conditions. Obrution deposits ensure rapid burial by fine-grained sediments, while stagnation deposits occur in anoxic, hypersaline conditions that reduce microbial decay. *Archaeopteryx* was fossilized in concentration Lagerstätten in obrution and stagnation deposits, with optimal conditions to preserve feathers (Nudds and Selden, 2008).

Proponents and Deniers of Darwin's Work

The two years between the *Origins'* first publication and the discovery of the London *Archaeopteryx* proved a difficult one for Darwin and his associates. The book attracted massive attention from proponents and critics alike and sparked some of the 19th century's most heated philosophical debates. Perhaps the most glaring fault with Darwin's earliest theories of evolution in the *Origins* was the lack of evidence in the geologic record of transitional forms (Gawne, 2015). That is, there were little to no known instances at the time in which a fossil was unearthed containing properties of both ancestral and modern organisms; for his theory to be truly convincing to the many skeptics of his time, Darwin needed a morphological median between known species.

Lack of evidence supporting Darwin's proposed evolutionary mechanism lent him a complex relationship with palaeontology (Herbert, 2005). His logic in several editions of the *Origins* stated that there must have been evolutionary "missing links" that connected modern organisms with prehistoric life. For Darwin, however, this was not a fault in his own theory; it was evident that the fossil record was largely incomplete (Friedman, 2009; Allmon, 2016). Up until the sixth and final edition of *Origins*, Darwin commented on the incompleteness of the geologic record, nodding especially to sedimentary unconformities that hindered the analysis of fossils. Further, he explicitly highlighted the poorness of palaeontological collections across all editions of the *Origins* (de Ricqlès, 2010).

Darwin was among the most forgiving of critics to the *Origins'* first edition. The theory of natural selection garnered harsh criticism and backlash as it challenged the Creationist religious dogma of the 19th century with seemingly no geologic evidence (Lack, 2013; Gawne, 2015). In the year following the publication of the first *Origins*, Richard Owen left an anonymous, hostile review of Darwin's work in the *Edinburgh Review*, effectively dubbing himself a major opponent to the theory of natural selection (Owen, 1860). In a similar fashion, Samuel Wilberforce left a scalding review of the first *Origins* in 1861, highlighting not only the clash between the theory and theology of the time, but also the lack of factual evidence to support it (Ruse, 1975). Sentiments concerning the poor evidence behind the *Origins* were echoed by European scientists including Albert von Kölliker of

Germany and Jean-Pierre Flourens of France (Huxley, 1894).

Reception of Darwin's work was not all bad, however. The discovery of the *Archaeopteryx* London Specimen fuelled conversations between Darwin and his associates, like Scottish geoscientist Hugh Falconer and German palaeontologist Frederich Rolle, surrounding Darwin's prediction of an incomplete fossil record and the nature of transitional forms (Archibald, 2017). The specimen effectively swayed some scientists of the time to gravitate toward Darwin's theory of natural selection. Extensive correspondence between notable figures in palaeontology and Darwin reveals that while he never overtly expressed the transitional status of *Archaeopteryx lithographica*, the evolutionary value of the specimen was not lost on him (Gawne, 2015). In a letter to Darwin, Falconer (1863) expressed his excitement about *Archaeopteryx*, announcing, "Had the *Solenhofen* [*sic*] quarries been commissioned—by august command—to turn out a strange being à la Darwin—it could not have executed the behest more handsomely—than in the Archaeopteryx." He further claimed the specimen to be "the dawn of an oncoming conception à la Darwin."

In his reply to Falconer, Darwin (1863a) expressed his "wish to hear about the wondrous bird," announcing, "the case has delighted me, because no group is so isolated as Birds." Darwin echoed these ideas in correspondence with American geoscientist James Dwight Dana (1863b), calling "The fossil Bird with the long tail & fingers to its wings […] by far the greatest prodigy of recent times." The evidentiary significance of *Archaeopteryx lithographica* was clear in Darwin's private correspondence with his colleagues (Gawne, 2015). Not only did Darwin seem to support the idea that Archaeopteryx's discovery was a fascinating case in transitional palaeontology, but he also claimed that bird-like fossils would be found in the geologic record in letters dating prior to the publication of the first *Origins* (Kritsky, 1992). Notably, in his response to Falconer, Darwin recalled mentioning to a colleague that "a fossil bird would be found," in the geologic record, "with end of wing cloven" (Darwin, 1863a). This refers to a more dated exchange with Scottish geologist and dear friend Sir Charles Lyell, known for his work on geological principles and the concept of uniformitarianism (Mayr, 1972). In his letter to Lyell just one month before the publication of the first *Origins*, Darwin (1859b) stated his belief "that if ever fossil birds are found very low down in series, they will be seen to have a double or bifurcated wing," a description matching that of *Archaeopteryx lithographica*.

Reception of Darwin's work followed a characteristic slew of praise and backlash. For every endorsement of his theory, a heap of criticism from opposing academics and theologians ensued. This was no different for the theory of natural selection and the transitional state of *Archaeopteryx lithographica*, regardless of Darwin's public views on the latter (Gawne, 2015). Following Wagner's initial description of *Archaeopteryx lithographica* in 1862, a handful of scientific heavyweights expressed concerns that Darwinists would use the London Specimen to stifle doubts from the public about the theory of natural selection. The same specimen of *Archaeopteryx lihtographica* was described by Andreas Wagner and Richard Owen with vastly different interpretations (Gawne, 2015; Foth and Rauhut, 2020). Wagner denied the transitional characteristics of the fossil, stating that the specimen was a reptile with ornamental feathers in 1862 for the Annals and Magazine of Natural History (de Beer, 1954; Foth and Rauhut, 2020). On the other hand, Owen asserted that *Archaeopteryx* was a bird with some skeletal features that resembled those of a reptile just one year later per Philosophical Translations of the Royal Society (Foth and Rauhut, 2020). Within a single year, *Archaeopteryx lithographica* was described as both strictly bird and strictly reptile. Both polarized descriptions disallowed the London Specimen to act as the transitional fossil needed to substantiate Darwin's claims (Gawne, 2015).

Darwin's Bulldog

Of all the staunch defenders of Charles Darwin's work, T.H. Huxley is notable for his tenacity. He is known for displaying wholehearted support of Darwin in writing and lecture, even though his attitudes surrounding Darwin's work began with some speculation (Bartholomew, 1975). At times throughout his career, his defence of Darwin's theories of evolution seemed more assertive than those from Darwin himself.

Huxley's views on evolution did not always perfectly complement those of Darwin. In fact, the pair had a series of fundamental disagreements that stemmed from Huxley's views prior to the publication of the *Origins* in 1859 (Bartholomew, 1975). While Huxley acknowledged that there was some form of succession of species over time, he fundamentally disagreed with Darwin's ideas surrounding evolution and the mechanism by which organisms changed over time (Schwartz, 1990; Galera, 2017).

After the first *Origins* was published, Huxley (Figure 1.9) remained cautiously optimistic that Darwin's theory would take hold, leaving a favourable review of the first edition in the *Times* in 1859 and later delivering a lecture about the theory at the Royal Institution in 1860 (Galera, 2017).

The same thought process is said to have been applied by Huxley to *Archaeopteryx lithographica*. He did not initially announce that the specimen was the single transitional form needed to confirm the theory of natural selection, but his transition to this position was gradual and was not completely evident until the late 1860s (Desmond, 1984).

His first notable publication concerning avian evolution and the status of Archaeopteryx lithographica in 1868, titled On the Animals which are Most Nearly Intermediate between Birds and Reptiles (Huxley, 1868b). In the paper, Huxley suggested a close relationship between birds and reptiles. It is worth noting, however, that whether Huxley was referring to a direct link between modern birds and dinosaurs is a subject of modern palaeontological debate (Switek, 2010). Nevertheless, the turn of the decade brought Huxley closer to the idea that birds and reptiles shared a more prominent evolutionary relation than before, and the significance of Archaeopteryx lithographica began to take hold in his work (Gawne, 2015).

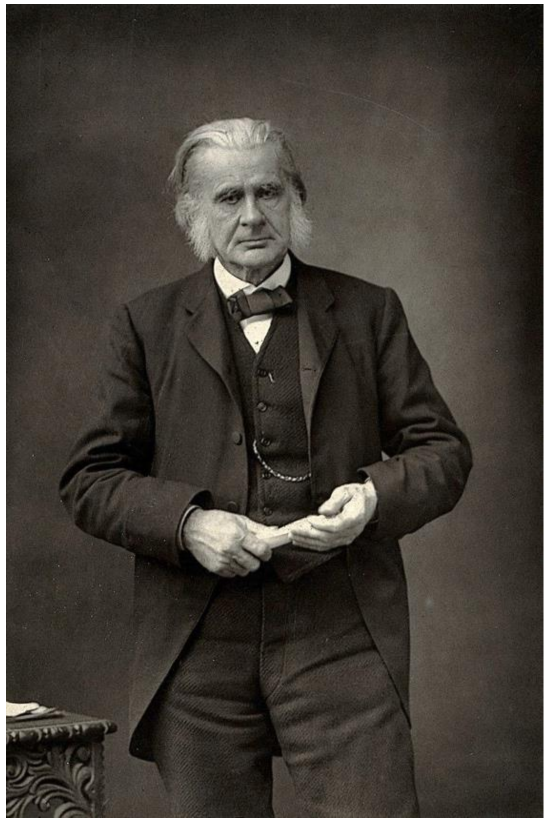


Figure 1.9: Thomas Henry Huxley became known after his death as "Darwin's Bulldog" for his staunch defence of Darwin's work throughout his academic career.

In the same year, Huxley challenged Owen's 1863 description of the London Specimen in his paper, Remarks upon "Archaeopteryx lithographica". In doing this, he highlighted a series of glaring analytical faults in Owen's original publication on the specimen. This furthered his support of Darwin's evolutionary theory by discrediting the scientific prowess of Owen's work (Huxley, 1868a; Gawne, 2015). Into the 1870s, Huxley had not only solidified his public support of Darwin's evolutionary theories, but he had also used other specimens (including the birdlike dinosaur Hypsilophodon) as "evidence of a further step towards the bird" from prehistoric reptiles (Huxley, 1870). While the use of *Archaeopteryx lithographica* in Darwin's own publications of the *Origins* was never explicit, biologists like Huxley used it to substantiate developing theories of evolution.

To claim that the contributions of Charles Darwin to evolutionary ideas in the 19th century are anything short of paradigmatic is an understatement. The contribution of the elusive London Specimen can be viewed through the same lens. *Archaeopteryx lithographica* allowed geoscientists and biologists of the time to observe physical evidence of "descent with modification" (Darwin, 1859a), a lithified substantiation of one of the most influential scientific theories on Earth.

21st Century Lagerstätten

Although the Lagerstätten were an important discovery in the late 1800s, these rocks continue to provide *Archaeopteryx* fossils to this day, with the most recent discovery in 2010 (Rauhut, Foth and Tischlinger, 2018). To date, there are 11 confirmed *Archaeopteryx* fossils. These fossils, along with other discovered species, continue to influence dinosaur taxonomy and the understanding of evolution. (Rauhut, Foth and Tischlinger, 2018; Kaye, et al., 2019).

New Lagerstätten and *Archaeopteryx*

The 12 possible discoveries of *Archaeopteryx* were found in various strata, allowing for the determination of their age with respect to one another by dating the strata. The newest specimen currently thought to be *Archaeopteryx* was discovered in limestone at the Kimmeridgian-Tithonian boundary, where Lagerstätten are commonly found (Fürsich, et al., 2007; Rauhut, Foth and Tischlinger, 2018). This fossil has been found to be much older than other *Archaeopteryx* fossils, which have all been discovered to be closer to the surface while remaining within Tithonian sediment, with an approximate age of 45 Ma (Fürsich, et al., 2007; Rauhut, Foth and Tischlinger, 2018).

Each of these fossils has been vital in the documentation of *Archaeopteryx* as well as the determination of what avian predecessors resembled. One key identifiable bird feature found on *Archaeopteryx* is long, its robust forelimbs, though there is still some debate as to whether *Archaeopteryx* was actually a bird (Kaplan, 2011). Many other small, feathered dinosaurs have been discovered, however, their relation to modern birds is still debated. One of the most recently discovered fossils that may provide evidence of avian ancestry, is *Xiaotingia zhengi*, a fossil found in 2011 dating back to the Late Jurassic. It too was surrounded by many feather trace fossils (Figure 1.10) (Kaplan, 2011). After much analysis, it was determined that *Xiaotingia zhengi* was more likely to be part of the *Deinonychosauria* clade rather than the *Avialae* clade, though it is an example of how new discoveries of the 21st century from Lagerstätten around the globe lead to questions and modifications of classification.

Lagerstätten have played a great role in the preservation and discovery of new species and specimens of *Archaeopteryx*. It is also important to understand their impact on palaeodiversity. Lagerstätten preserve a diverse range of fossils, but many of their genera do not overlap with other formations (Walker, Dunhill and Benton, 2020). They have allowed for the identification of various paleoenvironments and paleoecosystems that are not generally preserved within other rock types, further encouraging the identification of new species. Lagerstätten are also able to preserve smaller fossils more easily, such as the *Archaeopteryx*, due to taphonomic filters that prevent the preservation of larger remains (Walker, Dunhill and Benton, 2020).

Modern Archaeopteryx Taxonomy

The taxonomy of *Archaeoptryx* has been questioned with recent fossil discoveries, with the hope of determining whether they are all part of a single species, *Archaeopteryx lithographica*. Some of the specimens discovered have been classified as other species, *Archaeopteryx bavarica*, or assigned a new genus, *Wellnhoferia* (Senter and Robins, 2003). Through element length regression analyses, it was determined that the *Archaeopteryx* specimens varied proportionally, indicating that fossils were all within the growth series of a single taxon caused by various allometric effects and that other taxa should be considered junior synonyms for *Archaeopteryx lithographica* (Senter and Robins, 2003).

The clade to which *Archaeopteryx* belongs is also debated, whether it be part of the *Deinonychosauria* clade, a sister-taxon to the *Avialae*, or the *Avialae* clade itself. Though it has generally been determined that *Archaeopteryx* should reside in the *Avialae* clade, it had many deinonychosaurian features that, through the discovery of other specimens and species, allow for further comparison and determination of its true clade (Xu and Pol, 2014).

Due to the lack of fossils of Middle and Late Jurassic Archaeopteryx and other birdlike species, there is much still unknown about their evolution. Continued discovery and analysis of these specimens may provide modern paleontologists with a greater understanding of the fossil record and how dinosaurs and birds have evolved, as well as determine the origin of flight and of flight-associated characteristics (Hartman, et al., 2019).

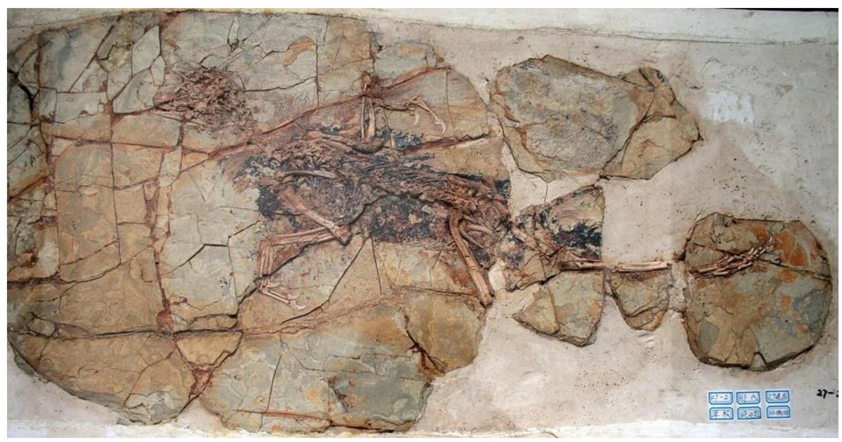


Figure 1.10: A fossil of the Xiaotingia zhengi *was unearthed, which dates back to the Late Jurassic, and caused the re-evaluation of* Archaeopteryx *as the first bird species.*

Georges Cuvier's Influence on Natural Science

The Enlightenment marks a time in the history of science when research methods transitioned to using experiments and human experience as evidence, rather than biblical texts. The revolutionary perspective that reason provided authority was set ablaze across Europe as an increasingly literate population became interested in refining their understanding of the Earth (Guerlac, 1955). Other factors, such as urbanization, accelerated the developments as socialization contributed to the dissemination of academic information (Guerlac, 1955). This shift in societal perspective set the stage for rapid productivity across the fields of science as the social climate was favourable for those inquiring about the world's unanswered questions.

Figure 1.11: Portrait of Georges Cuvier, founding father of paleontology. Painted by François-André Vincent in 1795.

Amidst the age of the Enlightenment, Georges Cuvier (Figure 1.11) was born in the town of Montbéliard, France in 1769. From a young age, Cuvier excelled across a range of subjects. This development was acknowledged and closely supported by his bourgeois family, who admired education (Rudwick, 1997). His keen interest in learning new topics was often facilitated through the examination of maps and a fondness for reading. At the young age of 10, Cuvier discovered a copy of *Historiae Animalium* by Swiss naturalist Conrad Gessner, igniting his fascination for natural history (Lee, 1833). This marked the beginning of Cuvier's dedication to solving the undiscovered questions of the Earth.

His passionate pursuit of knowledge continued into his adolescence, leading to recognition by Duke Charles, uncle to the King of Würtemberg, who proposed that Cuvier enrol at the *Académie Caroline of Stuttgart University* in Germany free of expense (Lee, 1833). Beginning at the age of 14, Cuvier spent four years studying at *Stuttgart* with a general focus on administration, the faculty that allowed him to continue his inquiry into natural history (Coleman, 2013). During his education, Cuvier's exposure to numerous instructors and the work of previous like-minded natural scientists set the foundation for his future scientific studies in the fields of stratigraphy, paleontology, and comparative anatomy (Lee, 1833). For instance, he received guidance from instructor Carl Kielmeyer who taught him the technique of dissection and provided Cuvier with his principal ideas of philosophical natural history (Coleman, 2013).

Stratigraphy

Upon graduation, Cuvier had no money to his name as he waited to be appointed to an academic institution. So, in July of 1788, he took a job at *Château de Fiquainville* in Normandy as the tutor to the son of a Protestant noble (Lee, 1833). It was during this time that he began to study and gain an interest in natural history and mineralogy. We can see this in his letters to Christian Pfaff, his friend from *Stuttgart*, where he described the layers of flint nodules in chalk he observed (Rudwick, 1997).

Cuvier later began working with Alexandre Brongniart, an instructor at *École des Mines de Paris*, to study the layers of strata of the region around Paris. By using his knowledge of fossils, as well as extant and extinct species, Cuvier was able to date the layers of strata he observed. The oldest stratigraphic layer was chalk and flint containing fossils of marine organisms, which Cuvier noted to be deposited in some type of fluvial environment (Cuvier and Brongniart, 1835). However, the exact conditions at the time of deposition were unknown to Cuvier. The next layers were an orderly succession, also indicating a fluvial environment. The layers included plastic clay, coarse limestone, gypsum, marine sandstone, and siliceous limestone, with most layers containing mollusks and other fossils from the Jurassic and Cretaceous periods. The original names of the formations embodied the interpretation of a sequence of alternating marine and freshwater deposition (Cuvier and Brongniart, 1835). Cuvier termed the last "regular" and "orderly" layer the "freshwater formation," which contained shells of organisms now living in freshwater (Cuvier and Brongniart, 1835). The youngest layer Cuvier observed differed from the orderly succession earlier on. It was a layer of detrital silt, which Cuvier noted to be confined to the floors of river valleys. It was here that he found fossilized bones of elephants and noticed that this layer was "very modern" compared to other formations (Cuvier and Brongniart, 1835).

Their work culminated in a monograph highlighting their findings, which was published as a preliminary version in 1808, with the final version published in the *Mémoires* of the *Institut de France* in 1811. The final paper placed fossils at the forefront of their research and was primarily descriptive with parts of the publication, including Cuvier's interpretation of his findings (Figure 1.12) (Rudwick, 1997). This influential monograph, along with William Smith's work during the same period on a map of England, was used to establish the discipline of stratigraphy.

Extinction

During Cuvier's time in Normandy, he came across Henri Alexandre Tessier at a meeting surrounding agricultural topics. Cuvier recognized Tessier as the author of many famous articles in *Encyclopédie Méthodique* and, following the meeting, began to converse with Tessier on his current geological research (Rudwick, 1997).

As they became closer, Tessier introduced Cuvier to his colleagues in Paris. He entered into correspondence with several naturalists and was invited to Paris to talk with them about their work (Coleman, 2013). Through these connections, he managed to obtain a junior position with Jean-Claude Mertrud, the chair of Animal Anatomy at the *Muséum National d'Histoire Naturelle* (Eigen, 1997). Little did Cuvier know that this small position would become his professional home and place him at the center of the world for natural history.

At this time, it was known that fossilized bones and teeth were found scattered across both the Old World and the New. However, the identification of these fossils and their geographical location remained unknown (Lee, 1833). Scholars such as Louis Jean-Marie Daubenton and George-Louis Leclerc attempted to create theories that could explain their observations, however, they were unsuccessful. Cuvier, on the other hand, had an advantage over his predecessors. He observed the skeletal remains from the Netherlands and concluded that the living African elephant was not the same species as the Indian elephant, which was previously proposed at the time (Fenton, 1933). He also noted that the teeth and jaws of mammoth fossils, as well as the unknown 'Ohio animal,' did not resemble those of an elephant, so they must be extinct (Fenton, 1933).

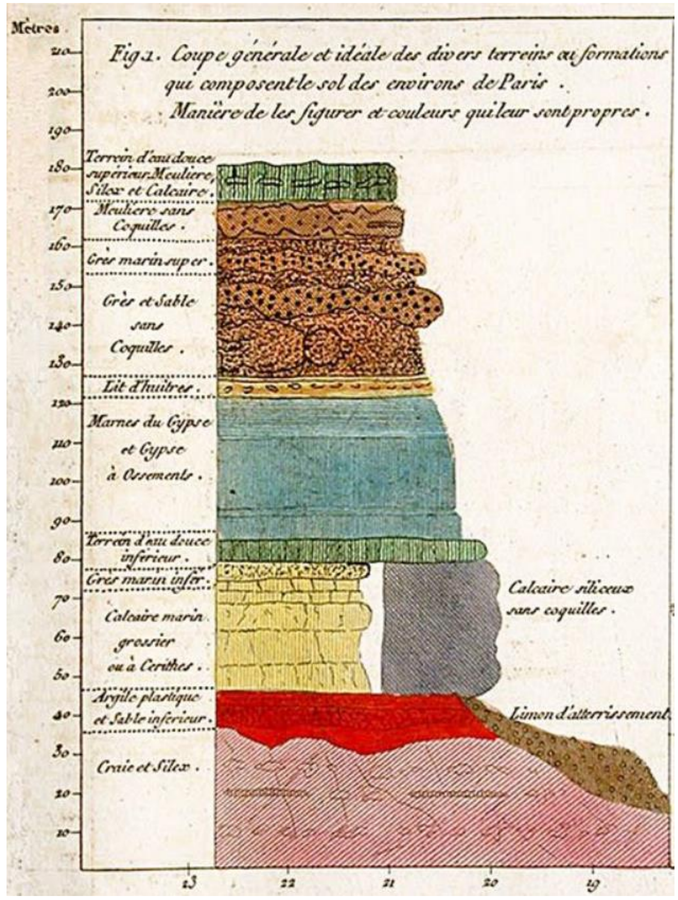


Figure 1.12: Georges Cuvier's illustration of the types and properties of strata in the Paris Basin that was published in his 1811 paper. The distinct layers with unique fossils helped Cuvier understand more about stratigraphy while developing his theory of catastrophism.

He presented his first paper just a year after his arrival in Paris, laying out his argument surrounding the extinction of species. His lecture and published paper caused a great deal of controversy. Among his scientific evidence, he confidently rejected the opinions of predecessors, stating that their observations were not precise or accurate (Lee, 1833). This was quite the claim for a 26-year-old with next-to-no scientific achievement to his name.

He presented his work as a demonstration of the importance of comparative anatomy in establishing the "theory of the Earth," now known as geology (Hooykaas, 1970). What Cuvier did not know was why he never saw any alive mammoths or the 'Ohio animal,' or why he never found a fossilized human bone. To address this question, he theorized a "prehuman world" that was destroyed by some sort of catastrophe (Coleman, 2013).

As Cuvier continued his work at the *Institut de France*, he received a new arrival full of engravings from Paraguay. The engravings depicted fossilized bones that Cuvier assembled into a skeleton (Rudwick, 1976). He named this unknown mammal *Megatherium*, or "huge beast," and concluded that this skeleton must have been yet another extinct animal (Figure 1.13) (Fenton, 1933). His comparisons between this unknown extinct animal and the extant giant sloth were meticulously presented in his second paper in 1796 titled *Notice sur le squelette d'une très grande espèce de quadrupède inconnue jusqu'à présent*, where he detailed similarities of specific bones and projections (Rudwick, 1976).

At the time, critics dismissed Cuvier's theory of extinction; they thought that the bones he found belonged to alive elephants that were 'in hiding' on the Earth. Cuvier, on the other hand, rejected this idea immediately as he knew that these animals would be impossible to miss due to their large size (Pietsch, 2012). Therefore, although Cuvier faced backlash, his work on the *Megatherium* and mineralogical evidence from Paris allowed him to propose that past geological changes caused the extinction of species. In doing so, he demonstrated the necessity of understanding paleontology and stratigraphy to describe the history of the Earth and the evolution of life forms.

Correlation of Parts

Perhaps Cuvier's most seminal contribution to the field of paleontology and geology was his observations noted in his 1798 publication *Tableau élémentaire de l'histoire naturelle des animaux*, which presented what we know as the principle of the correlation of parts (Cuvier, 1798). Through his analysis of fossils, he noted that the teeth of many animals allowed them to be skillful at pursuing and catching their prey. Further, he discovered a relationship between the skeleton of an animal and their locomotive and sensory organs. He stated that the relations of organs are necessary for the existence of the animal (Simpson, 1983). Hence, there must be a structural and functional significance to each body part, which must be correlated with other parts, or else the species will not survive.

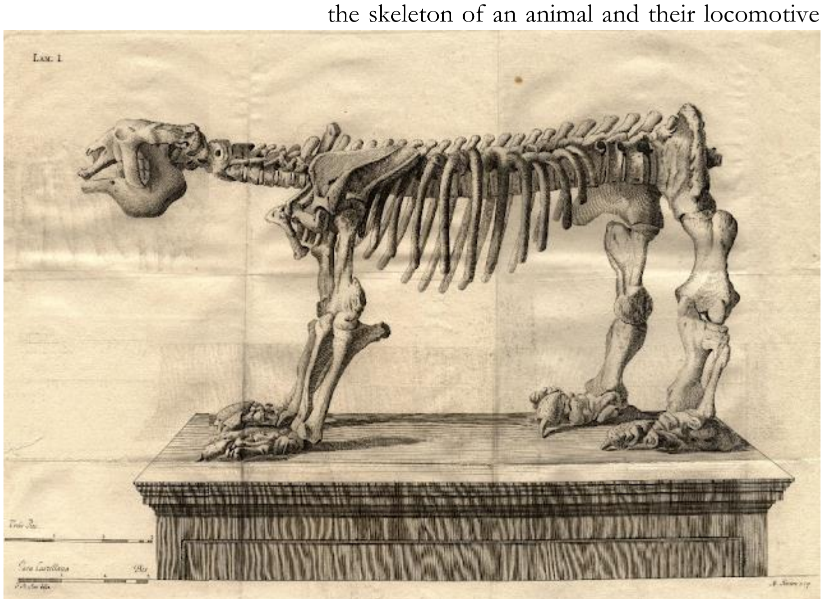
Following this publication, Cuvier used his principle to aid in the reconstruction of fossils. The fossils of quadrupeds he received were not complete skeletons but rather scattered pieces that needed to be put together (Fenton, 1933). Moreover, deposits of fossilized remains often contained several species mixed together, so Cuvier ran the risk of combining the remains and producing fictitious species (Pietsch, 2012). Thus, by using his principle, Cuvier believed that he could avoid this problem and used it to provide evidence that favoured his theory of extinction.

Later, when Cuvier discovered a fossil resembling a marsupial, he correctly predicted that the fossil should also contain specific pelvic bones (Lee, 1833). His momentum of successfully using his principle gave him hope that he could create a law-based framework for natural history. He was confident that his work paved the way for anatomy to be expressed as mathematical laws, no different than Isaac Newton's laws of physics (Lee, 1833). In his same 1798 paper, he emphasized the predictive power of his principle. He believed his principle allowed scientists to determine the class, sometimes even the genus, of the animal to which it belonged just after inspecting a single bone (Pietsch, 2012).

Due to his profound belief in his principle, he included these ideas in his scientific readings, *Leçons d'anatomie comparée*, published between 1800 and 1805 (Rudwick, 1997). Additionally, he emphasized this idea in *Le Règne Animal*, which is considered to be his most admired work. This publication in 1817 marked the start of classifying organisms, as Cuvier organized all animals into four distinct categories: vertebrate animals, molluscous animals, articular animals, and radial animals (Cuvier, 1817).

Looking back at the time, the functions of many body parts were unknown, so using Cuvier's principle would be impossible. Instead, we see that the high accuracy of his predictions related to fossils came not from his principle but from his extensive knowledge of comparative anatomy. Nevertheless, although Cuvier exaggerated the power of his 'mathematical'

Figure 1.13: Sketch of the skeleton of the Megatherium *by Georges Cuvier that was published in 1796. This species was one of many organisms that helped Cuvier propose his theory of extinction.*



principle, his work was still central to the fields of comparative anatomy and paleontology.

Catastrophism and Mass Extinction

When tasked with theorizing a process to explain the structural development of Earth, the doctrine of catastrophism was a prominent geological school of thought that many scientists at the beginning of the 18th century supported (Hooykaas, 1970). Although the theory has many different intricacies within its interpretation, the general view of catastrophists is that geological phenomena directly result from extreme events throughout the history of the Earth (Palmer, 2003). Furthermore, these events are thought to have been caused by violent forces that are not currently taking place or not on the same scale as current environmental events (McGrew, Alspector-Kelly and Allhoff, 2009). Due to his active support of the theory throughout his career, Cuvier was recognized as one of the principal proponents of the transient acceptance of catastrophism.

Despite Cuvier's association with catastrophism, his interpretation of the theory diverged from his predecessors in the field, such as Gregor Razumovsky and Déodat de Dolomieu (Palmer, 2003). Cuvier thought that their view of the development of the Earth was not based upon observable processes, which caused them to "dream up so many extraordinary conjectures and made them commit errors and lose themselves in contradictions, so that the very name of their science … has long been a subject of mockery" (Cuvier, 1825, p.22). Accordingly, the work that Cuvier performed in support of catastrophism was restricted to observable cases in which further extrapolations and conclusions could be made (Hooykaas, 1970).

Through his amassed knowledge of comparative anatomy and paleontology, Cuvier began to establish his support for the theory of catastrophism as an explanation for the mass extinction of past life forms. When assessing the distinct features of elephant skulls from Ceylon (Sri Lanka) and Cape of Good Hope (South Africa), Cuvier remarked on differences in the shape of the teeth, profile, and proportions (Figure 1.14) (Rudwick, 1997). Considering the differences between the two samples and the lack of similarities with the skulls of extant species, Cuvier insisted the two specimens were extinct species. Early evidence of his support of catastrophism is documented in his 1799 paper *Mémoire sur les espèces d'éléphans tant vivantes que fossils*. Throughout his publication, Cuvier urges that fossils distinct from extant species indicate previous extinction. His explanation continues by connecting incidents of extinction to a past world that was destroyed by a catastrophe (Cuvier, 1799).

When considering all of Cuvier's avenues of study, his work with stratigraphic sequences at the Paris Basin alongside Brongniart perhaps led to his most recognized support for catastrophism. Together, the pair of scientists identified consistent trends in the strata and discovered numerous sections of rock layers which had no fossils, with surrounding layers containing traces of fauna (Rudwick, 1997). From these observations, Cuvier and Brongniart theorized that the distinct transitions in stratigraphic layers possessing and lacking fossil evidence indicated new geological environments that followed sudden catastrophes. Cuvier also employed his fossil reconstruction techniques to identify that the structures of the animals recorded in the lower strata were distinct from extant fauna. In his publication titled *Discours sur les révolutions de la surface du globe, et sur les changemens qu'alles ont produit dans le régne animal* in 1825, Cuvier attributed the large time gaps in the fossil record to catastrophic events leading to the mass extinction of species (Rudwick, 1997). In his later work, Cuvier's perspective on catastrophism led him to further theorize that the sudden changes resulting in mass extinction were immensely powerful since "no slow action could have produced these sudden effects" (Cuvier, 1825, p.22).

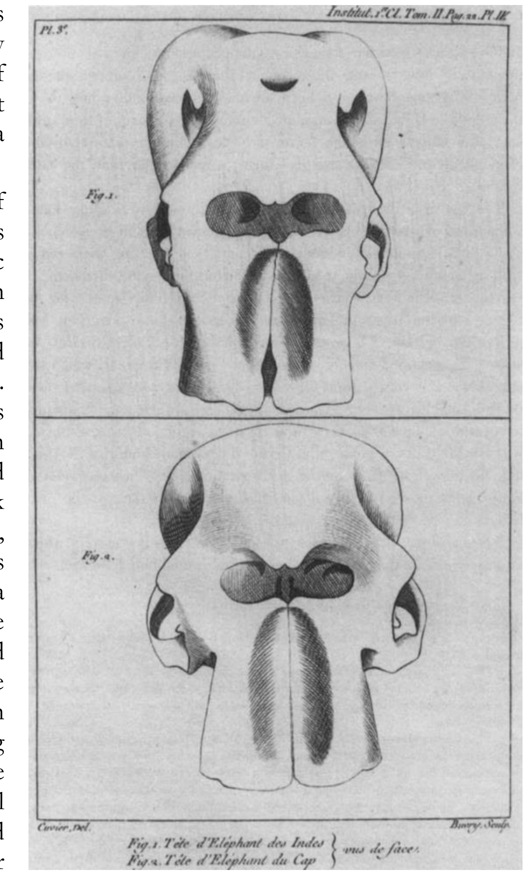


Figure 1.14: Sketches of elephant skulls from Ceylon (top) and the Cape of Good Hope (bottom), currently known as Sri Lanka and South Africa, respectively. These were published in his 1799 paper to support his theory of catastrophism.

At the time, Cuvier's scientific reputation allowed catastrophism to become a notable doctrine that attempted to explain geological events of the Earth. Ultimately, in the years that followed Cuvier's contributions, his theory was overruled by the Uniformitarian principle (Patton, 2014). Despite the criticism that catastrophism received as the field of geology evolved, Cuvier's evidence-based approach for supporting previous theories was an essential step for geology and science as a whole.

Religion and Science

Cuvier grew up in a Lutheran environment, and at *Karlsschule*, the elementary school he attended, religion was a key part of his education (Lee, 1833). For the lion's share of his life, Cuvier was a devout Lutheran who was deeply anchored to his Protestant faith. As a result, he founded the Parisian Biblical Society in 1818, which aimed to print and distribute Bibles (Taquet, 2009). His religious practices continued until the death of his eldest daughter Clementine, in 1827. At this time, he became completely distraught and devoted himself to the faith of Clementine (Lee, 1833).

The strong Lutheran environment and Cuvier's deep faith in these ideas begs the question if religion influenced his scientific approach. Similar to other naturalists at the beginning of the 19th century, Cuvier believed in the Principle of the Conditions of Existence (Taquet, 2009). He thought God had created the planet with various organisms, and each organism had a goal-directed plan when created (van der Meer, 2008). Although he believed in the supernatural design theory, Cuvier also recognized the criticisms of the design argument by Immanuel Kant, a German philosopher (van der Meer, 2008). Kant argued that there was no empirical method to determine such existence of God, and therefore, no assumptions can be made surrounding the creation of the universe. When Cuvier came across something he disliked, he built new theories to explain his ideas. Although Cuvier was careful not to include any religious ideas or references in published works as a young author, as he grew older, religion played a larger role in his academic career.

In 1807, Cuvier theorized that the most recent catastrophe on Earth that caused mass extinction was the biblical flood (Taquet, 2009). He emphasized that this catastrophe could be explained in *Genesis* and presented these ideas in a report titled *Théorie de la surface actuelle de la Terre* (Cuvier, 1807). Although there was no evidence at the time, in 1823, William Buckland published *Reliquiae diluvinae*, which contained observations on organic remains in caves. Buckland aimed to provide evidence of a biblical flood, using Cuvier's previous work to support his ideas (Buckland, 1823). Cuvier, on the other hand, was quite skeptical of the evidence, noting that Buckland did not have all the elements to support his theory. Through letters with colleagues, Cuvier noted the biblical flood theory had many flaws and continued to uphold his guiding principle of only using facts for research (Taquet, 2009). Therefore, while religion was a key part of Cuvier's life, it is clear that he took great care to separate facts related to natural history and geology from any references to theological interpretations.

Modern Imaging Approaches in Paleontology

While Georges Cuvier's remarkable approaches to fossil analysis allowed him to compose esteemed theories regarding species extinction, many consider his work with recovered specimens as the origin of vertebrate paleontology (Van Reybrouck, 2012). The exceptional advances that Cuvier made in the field of paleontology during his career provided insight into the plethora of conclusions that could be drawn from the study of fossils. In the generations of scientists that have followed Cuvier, scholars in the field of paleontology have been able to provide answers to questions regarding historical climates, evolutionary biology, and geomorphology. To correspond with the rapidly advancing discipline of paleontology, the assortment of techniques and technologies used to perform fossil analysis have also evolved in parallel (Whybrow, 1985).

Synchrotron-based Imaging

Studying the internal and chemical structures of paleontological specimens provides valuable information regarding the biosynthetic processes that occurred within the structure of organisms. Furthermore, chemical analysis of fossils allows for the differentiation of the biochemical conditions an organism endured when alive, compared to those generated by taphonomic processes during fossilization (Edwards, et al., 2013). Traditionally, approaches to retrieve this information involved mechanical polishing, preparation, and partial destruction of fossil samples (Pakhnevich, et al., 2018). This acute experimental technique requires precision and ultimately results in permanent damage to the fossil. To avoid the destruction of valuable fossil specimens, synchrotron rapid scanning X-ray fluorescence (SRS-XRF) imaging can be used to analyze the elemental distributions of specimens in their embedding matrix without altering the sample.

During an SRS-XRF experiment, the specimen is mounted to a computer-controlled raster stage that can move vertically and horizontally (Edwards, et al., 2013). The imaging process begins as a fixed horizontal X-ray beam, in the energy range of 2.1-17 keV, that induces fluorescence in the object of interest. The range in potential energy during XRF imaging allows for the creation of 'high-Z' and 'low-Z' environments. In high-Z conditions, XRF imaging is optimized for X-ray emission of higher atomic weight elements such as calcium, iron, zinc, and lead. Conversely, low-Z conditions optimize for X-ray emission of lower atomic weight elements, including silicon, phosphorous, sulphur, and chlorine (Edwards, et al., 2018). The interaction between the incident beam and the specimen produces fluoresced X-rays that project to a silicon drift diode detector which absorbs the incoming radiation. The detector is positioned at a 90° angle to the incident beam and a 45° angle to the sample surface to decrease scattering. Considering the fixed position of the incident X-ray beam, the stage moves in a computerized sequence in the two-dimensional plane to scan the entire object (Edwards, et al., 2018). The data is rapidly processed at the end of each scan line, permitting as many as 16 elemental maps to be overlayed and visualized during the analysis (Edwards, et al., 2018).

Applications

SRS-XRF imaging has revealed previously unknown chemical data in several paleontological studies. For one of the rare fossils of the Archaeopteryx discovered in the Solnhofen limestone, SRS-XRF analysis uncovered valuable information regarding the chemical composition of the feathers and bones (Bergmann, et al., 2010). In addition to analyzing the 150-million-year-old fossil considered as evidence for the dinosaur-avian lineage, elemental inventories were obtained to show that portions of the feather region were not topographic impressions, as previously interpreted (Bergmann, et al., 2010). Prior interpretations of impression fossilization suggested they resulted from the colonization of bacilliform bacteria and initiation of early lithification below the feathers. However, synchrotron imaging of the Archaeopteryx revealed that portions of the feather area could be attributed to the living tissue of the organism. This was based on the elemental content that was distinct from the embedding geological matrix (Figure 1.15). Specifically, magnified regions of the barb patterns of the feathers displayed traceable iron concentrations that closely track the feather structure, indicating that the feather patterns are not simply topographic impressions (Bergmann, et al., 2010). Using a similar approach to the Archaeopteryx study, SRS-XRF imaging was used to investigate the reptile fossil *BHI-102* found in the 50-million-year-old Green River Formation (Edwards, et al., 2011). Recorded SRS-XRF data of the skin of the reptile displayed levels of copper and sulphur. Furthermore, mapping the oxidation states revealed that components of the sulphur content existed as organic sulphur in the form of cysteine. This detected presence of cysteine within the skin of the reptile was compared to the absence of cysteine from the surrounding matrix to conclude that the sulphur content within the fossil was not exogenic (Edwards, et al., 2011). Within the same study, the results from SRS-XRF imaging were further supported with Fourier Transform Infrared mapping, an alternative mapping technique. The combination of modern analyses provides evidence that the fossilized proteinaceous skin of the *BHI-102* specimen is not an ordinary impression, mineralized replacement, or carbonization but rather fragments of the organism's original chemical structure.

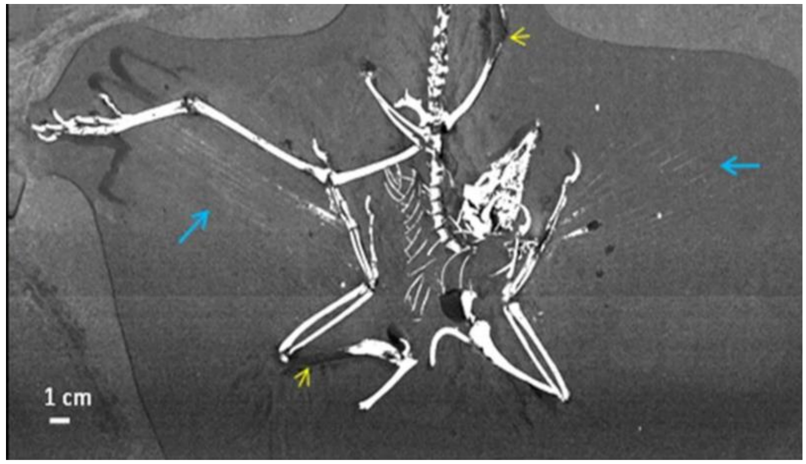


Figure 1.15: SRS-XRF map of the Thermopolis Archaeopteryx. *The imaging displays the distribution of rachises of the flight feathers (blue arrows) and areas of reconstruction (yellow arrows). Further imaging on the rachis area revealed fine barb detail identified in iron mapping.*

Ultimately, the non-destructive and high-resolution properties of SRS-XRF imaging offer an analytical approach that can reveal the chemical code of past life. With the continuous development of modern approaches to paleontology, the frontiers of understanding within the field continue to expand upon the seminal contributions of Georges Cuvier.

The Emergence of Geological Biomarkers

Petroleum has been used by humans for nearly six millennia. As early as 3800 B.C, ancient Sumerians used asphalt, a by-product of petroleum, in inlaying (Rossini, 1960). Stemming from this entrenchment in civilization, throughout history the origins of petroleum have been postulated. This fundamental question led to the discovery and research of biomarkers over 5700 years later.

The Greek philosopher and scientist Aristotle (384-322 BC) is acclaimed for the development of scientific reasoning using inductive-deductive methods to establish universal truths. Pioneering the study of natural sciences, the Aristotelian worldview formed the basis of biological theorization well into the eighteenth century (Walters, 2006). Among the doctrines he established was his theory of vitalism, which posited that life is a product of a vital force specific to living organisms that are only found inside living things and thus cannot be explained by physical or chemical factors (Coulter, Snider and Neil, 2019). Though there is evidence of petroleum use since biblical times, it had long gone undiscussed in classical literature. In his 1268 treatise *Opus Tertium*, English philosopher Roger Bacon (1220-1292), deplored the lack of attention towards the origin of oil and bitumen in natural philosophy (Bacon and Brewer, 1859).

During the renaissance two opposing theories arose. In his 1546 text *De Natura eorum quae Effluunt ex Terra*, German physician Georgius Agricola (1494-1555) proposed that, akin to other minerals such as gypsum, bitumen formed from condensed sulfur deep within the Earth (Agricola, 1546). This theory relied on Aristotle's vitalistic theory to reason that there was no biological origin for bitumen among other minerals (Walters, 2006). Another German physician, Andreas Libavius (1555-1616), argued that bitumen originated from ancient tree resins in his 1597 text *Alchemia* (Andreas, 1597). These early discussions chronicle the inception of what is among the longest disputes in science, spanning nearly 400 years: whether petroleum was formed biogenically from organic sediments belonging to now-dead organisms, or from abiogenic processes far below the Earth.

Throughout the 18th century, the discovery of fossils in coal deposits provided evidence that popularized similar biogenic origin theories for petroleum. However, the topic remained controversial as the proponents of abiogenesis supported prevailing ideologies among elites at the time. Though credation is debated, in 1757, Russian scientist Mikhail Lomonosov (1711-1765) theorized that crude oil and bitumen arise from coal via pressure and heat underground, which forms from the percolation of biological materials over tremendous periods of time (Kenney, 1996).

In 1789, Antoine-Laurent Lavoisier (1743-1794), French nobleman and chemist, established the foundations of modern chemistry in his textbook *Traité élémentaire de Chimie*, providing a basis for bringing the theories of vitalism into question (Greco, 2005; Lavoisier, 1789).

By the beginning of the 19th century, a variety of theories explaining the genesis of petroleum as a biological derivative emerged. At the same time, with the introduction of modern chemistry, many vitalists became divided over the nature of vital forces. Up to this point, it was believed that organic materials were only formed in living organisms and were thus products of 'vital activity' (Liebig, 1842). The concept of vitalism became an ever-present explanation used out of eagerness to interpret and understand phenomena that could not be sufficiently explained at the time. Vital forces were thought to regulate chemical reactions between organic compounds, similar to physical forces of chemical affinity and gravity in matter (Liebig, 1842). By recognizing the soul as a guiding force over living matter, vitalism provided a scientific foundation that allowed scientists to oppose the increasing secularization of science. Its adoption allowed religion and the church to be reflected and reaffirmed in the scientific ethos during times of great piety. Vitalism could not be directly proven due to its metaphysical nature. Its inability to falsify and interpretive nature allowed the concept to resist criticism. Vitalism prevailed until scientific disciplines progressed to provide verifiable alternative explanations, enabled by the advent of organic chemistry.

A modern understanding of petroleum formation began with Canadian geologist and chemist, Thomas Hunt's (1826-1892) theory in the 1863 Canadian Geological Survey, where he established that petroleum formed from ancient sediments saturated in organic matter. Hunt proposed that organic Paleozoic deposits in North America were products of marine biota transformed into bitumen, via similar processes to coal formation (Hunt, 1863). A variety of geologists studying Devonian shales across the United States would later echo Hunt's findings during the 19th century (Lésquereux and Worthen, 1870; Newberry, 1873).

During the 18th and 19th centuries, debate around vitalistic thought grew (Greco, 2005). Urea was discovered in urine by Dutch chemist Herman Boerhaave (1668-1738) in 1727, in his book *Elementa Chemiae*, he presented a procedure for its purification. He also presumed urine was possibly produced by the kidneys to align to vitalist thought (Kurzer and Sanderson, 1956). In accordance with vitalism, organic molecules could not be produced by inorganic molecules. Organic substances could only be produced by living organisms which possess a vital force from which they originate. This theory built on previous notions of vitalism by applying it to the emerging discipline of chemistry and was proposed in 1809 by Swedish chemist Jöns Berzelius (1779-1848) (Jorgensen, 1965).

Vitalism persisted largely in scientific ethos until 1828, when German chemist Friedrich Wöhler (1800-1882) synthesized urea, an organic component of urine, from solely inorganic molecules (Figure 1.16) (Kurzer and Sanderson, 1956).

$$Pb(OCN)_{2(aq)} + 2NH_{3(aq)} + 2H_2O \rightarrow Pb(OH)_{2(s)} + 2NH_4(OCN)_{(aq)}$$

$$NH_4(OCN)_{(aq)} \xrightarrow{\Delta} NH_{3(aq)} + HOCN_{(aq)} \rightleftharpoons (NH_2)_2CO_{(aq)}$$

Figure 1.16: Three-step synthesis reaction for urea from the heating of aqueous lead cyanate and ammonia (left).

Wöhler's synthesis of a carbon-based compound *in-vitro* signified the beginning of organic chemistry as a discipline.

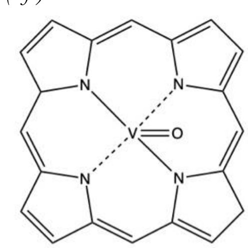
Because urea is only produced *in-vivo* by living organisms, Wöhler disproved the popular theory of vitalism through his artificial synthesis with inorganic molecules. Inadvertently, Wöhler's experiment provided a scientific basis for the inorganic theory of petroleum formation. Scientists argued that petroleum was generated from inorganic processes by proving organic matter can be produced by inorganic constituents (Brocks and Grice, 2011).

In 1866, French chemist Marcellin Berthelot (1827-1907) hypothesized that inorganic carbides react with water to produce petroleum after observing differences in densities and states of matter in petroleum (Berthelot, 1866). In 1877, Dmitri Mendeleev (1834-1907), celebrated Russian chemist, explained that petroleum deposits are dependent on plate tectonics rather than sediment, putting forth the 'metal carbide theory' which built on Mercellin's hypothesis (Mendeleev, 1877). Mendeleev believed Earth's core was composed of iron and that water had migrated towards Earth's core. Water would react at high pressures and temperatures deep within the Earth's crust to produce acetylene, which later condenses to form hydrocarbons found in petroleum (Mendeleev, 1877). Mendeleev reasoned that artificial irons develop hydrocarbons when dissolved in chlorohydric or sulphuric acids occurring in Earth's depths (Becker, 1909).

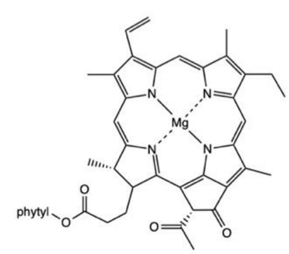
This theory was especially appealing as it provided an explanation for the widespread prevalence of petroleum reservoirs, implying a global process occurring at great depths (Brocks and Grice, 2011). In 1906, American geologist Richard Oldham (1858-1936) who had discovered S and P seismic waves, compared data from many earthquakes. Oldham found discontinuities in travel times for S-waves at ~120° from the epicenter indicating refraction from a denser inner core (Oldham, 1914). This discovery added greater validity to Mendeleev's metal carbide theory, increasing the acceptance of an abiogenic origin of petroleum within Earth's core (Becker, 1909).

In the 20th century, the biogenesis hypothesis attained broader acceptance with the progression of geological and chemical sciences, disproving the previously accepted metal carbide theory. These advances enabled the use of novel experiments and scientific methodologies, generating substantiated evidence and explanations that surpassed the approach of induction and deduction from general observations used prior.

The first of these experiments to provide strong evidence for the organic origin of petroleum was made by the German organic chemist Alfred Treibs (1899-1983) in his seminal porphyrin experiment in 1936. Treibs isolated a vanadyl-porphyrin complex, a red-coloured sedimentary porphyrin, from bituminous black shale, discovering the carbon-nitrogen skeleton was identical to chlorophyll *a* II, a green pigment in plants Figure 1.17) (Brocks and Grice, 2011). Using previous degradation experiments with chlorophyll *a* II and vanadyl-porphyrin complexes, Treibs correlated these derivatives to his isolated sample using absorption values by spectroscopy (Treibs, 1936). He was able to conclusively present that vanadyl-porphyrin pigment was derived as the final degradation product from a biogenic precursor which lost



vanadyl-porphyrin complex



chlorophyll a

Figure 1.17: Molecular structures of a vanadyl-porphyrin complex (top) which is a derivative of chlorophyll, and chlorophyll a *(bottom).*

multiple functional groups and had its central magnesium ion replaced by vanadyl oxide (Treibs, 1936). This enabled Treibs to determine the degradation pathway of chlorophyll *a* in sedimentary environments, establishing the presence of porphyrins as indisputable biological signatures in sedimentary organic matter (Brocks and Grice, 2011). Treibs is considered the father of organic geochemistry and biomarkers. His work provided the background knowledge necessary for later growth in the field through the application of new techniques developed in subsequent decades.

Concurrently, various global field studies found strata high in organic matter universally present in petroleum-rich sedimentary basins. Kerogen, an organic sediment observed as ubiquitous in these basins was found to originate from living organisms, being transformed from its original chemical composition. Moreover, it was established that gas and oil are formed from kerogen if buried and subjected to pressure and heat (Hunt, 1961; Tissot, 1969; Walters, 2006). Subsequent studies expanded on Treib's findings by widening the scope of hydrocarbons beyond porphyrins. By the 1950s, the accumulation of evidence supporting biogenesis as the origin of petroleum marked the end for the majority of abiogenesis supporters, concluding a 400-year-old debate.

Petroleum: a Research Reservoir

Crude oil is a complicated combination of thousands of distinct hydrocarbons and heteroatoms (Brocks and Grice, 2011). It was not until the early 1960s that separation and detection techniques such as computerized gas chromatography and mass spectrometry (GC, GC-MS), as well as elemental analysis became commercially available that significant strides in the research of petroleum were made. These techniques allowed for the separation, identification, and visualization of organic compound distributions in sediments and crude oils, confounding prior science (Bianchi, 2021).

Parker D. Trask (1899-1961) was an influential geologist in the progression of organic geochemistry, known for finding geological correlations between organic matter in sedimentary rocks and petroleum source beds. Forms of bed or rock with high enough organic matter content can produce and expel sufficient hydrocarbons which accumulate oil or gas (Al-Areeq, 2018). The American Petroleum Institute and United States Geological Survey collected 35,000 core samples from source beds across the country (Trask, 1942). By comparing the properties of sediments at 200 and 500-foot distances from oil zones, Trask and his colleagues found characteristic properties of petroleum source beds including the contents of nitrogen, bitumen, carbonate and organic carbon, colour, texture, and reduction and assay numbers (Trask, 1942). These studies found a means for geologists to ascertain commercially viable source beds from outcroppings. This proved to be an extremely lucrative and cost-effective discovery for the petroleum industry (Trask, 1942). With the confluence of novel analytical techniques and profitable findings, the petroleum industry quickly recognized the potential for biomarker research, becoming the driving force of the field for the remainder of the 20th century (Brocks and Grice, 2011).

In 1964, British chemist Geoffrey Eglinton (1927-2016) established the biological marker, or 'biomarker', concept by investigating experimental approaches to elucidating the origins of terrestrial life and the time of its first appearance in pre-Cambrian oil shales. Eglinton established the analysis of the geological record in ancient sediments based on the chemical nature of its organic matter. This sedimentary organic matter was posited to be attributable to fossil organisms with small molecules of biological significance (Eglinton, et al., 1964). Biomarkers were a term used to denote organic substances exhibiting resistance to chemical transformation with a molecular structure indicative of an exclusive product of biological processes occurring in significant amounts (Eglinton, et al., 1964). Specific categories of compounds such as porphyrin pigments, long-chain fatty acids, and alkanes could be used as biological markers as they were evidenced to have high stability in geologic conditions over extended durations of time. He argued that such molecules can give insight into the biological history of the region at its time of deposition. Effective biomarkers have high structural specificity and vast distribution in nature (Eglinton, et al., 1964).

In 1966, by likening biomarkers to micro- and macrofossils regularly used by geologists, Eglinton expanded his biomarker theory, introducing the "chemical fossil" concept: organic molecules that were constituents of once-living organisms that remained unchanged or slightly transformed from their original structure (Eglinton, et al., 1964). Such geochemically stable compounds are typically secondary metabolites derived from mechanisms of less stable pathways and can be seen as signatures of the preceding metabolisms that synthesized them (Eglinton and Calvin, 1967). At the time, biochemists had only just started determining the major constituents of extant organisms within the previous decade. With limited access to the concepts he was pioneering, Eglinton posited multiple applications of chemical fossils, including: insight on the origins and development of (extra)terrestrial life, taxonomical classification, paleoenvironmental analysis and reconstruction; arrangement of chemical fossils in evolutionary sequence (because extant organisms and their secondary metabolites are evolutionarily selected), and molecular detection of the direction of biological evolution via nucleic acid and proteins given direct chemical correlations between extant organisms and precursory fossils (Figure 1.18).

At this point it was broadly understood by petroleum geologists and chemists that petroleum was generated through progressive degradation, produced by heating organic sediments finely distributed across strata. The organic molecules most similar to the structures of hydrocarbons in petroleum are the lipid fraction of organisms (Eglinton and Calvin, 1967). Eglinton also outlined the degradation pathways of various prominent hydrocarbons, alcohols, esters, and fatty acids, including the identifiable characteristics of their products using retrosynthesis. For example, the number of carbon atoms in their chains is indicative of their reaction pathways, with odd-numbered carbon chains having undergone de-carboxylation (Eglinton and Calvin, 1967). In 1978, in the book *Petroleum Formation and Occurrence*, authors and professors of organic geochemistry, Bernard Tissot (1931-present) and Dietrich Welte (1935-present) developed Eglinton's previous concepts in the context of the petroleum industry. The evolutionary stage and classification of organisms acting as source material for petroleum determine the type and quantity of petroleum in specific source rocks. This makes it crucial to investigate the development of the biosphere relative to petroleum formation, which is enabled by biomarkers. Chemical fossils indicate the type of contributing organisms in sediments, and thus characterize, correlate, and reconstruct depositional environments (Tissot and Welte, 1978).

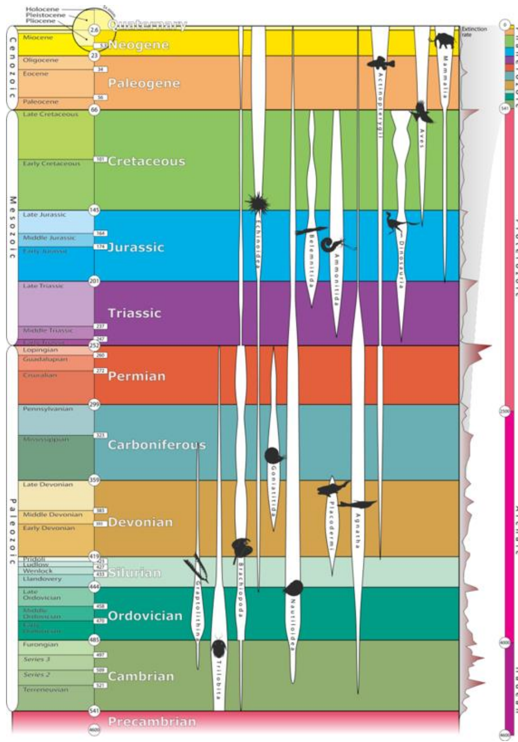


Figure 1.18: Geological timescale outlining major animal taxa and their estimated extinction rates over eras, periods, and epochs.

The prevailing and proposed uses of chemical fossils also included: providing correlation parameters for oil-oil and oil-source rocks, detecting contaminants, finding optimal oil traits, and characterizing facies. To determine the presence of a source bed, the type, composition, and maturity of organic matter must be found, which can be mediated through bioindicators which have established precursors (Tissot and Welte, 1978). Correlating different oils to one another (oil-oil) can determine whether they were expelled from the same source facies. Correlating oils to source rocks can determine which source facies produced the oil (oil-rock). This informs geologists of different fault zones to differentiate between petroleum reservoirs (Figure 1.19). By finding similarities and differences between chemical fossil types and their respective rocks based on biomarker distribution and concentrations, correlations can be made. Moreover, after oil types are separated following extraction, chemical fossils can identify their source rocks, which is crucial to identifying ideal petroleum reservoirs. This solidified biomarkers as imperative to defining exploration targets. Different organic molecules vary in their hydrocarbon potential (predicted oil generation and expulsion) due to their chemical structure; they must be distinguished to appraise source rocks (Tissot and Welte, 1978). The authors proposed this can be enabled by presenting three relevant types of biomass evidenced through biomarkers: Type I represents marine organic matter with phytoplankton and zooplankton being primary contributors in marine sediment; Type II represents continental organic matter mostly composed of plant debris in land-derived sediment; Type III represents microbial organic matter in lacustrine or deltaic sediments (Tissot and Welte, 1978). The quality and viability of source rocks vary extensively in composition depending on the type of organism and depositional environments (i.e., aquatic or subaerial) from which they arise. For example, Type I source beds present higher petroleum potentials compared to Type II and produce paraffin or naphthenic oils. Generally, Type I and III source beds are optimal (Tissot and Welte, 1978).

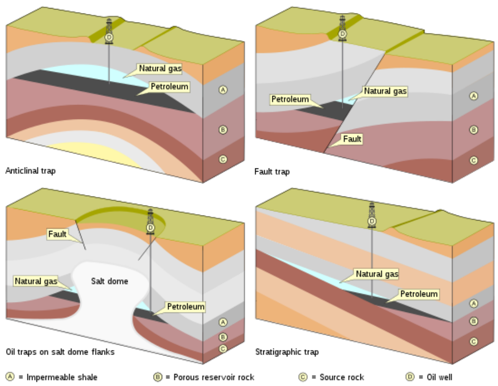


Figure 1.19: Cross-section diagram of different hydrocarbon traps found in anticlines, faults, salt dome flanks.

These pivotal developments in biological markers and chemical fossils guided the comparison of structurally analogous sedimentary organic compounds and crude oils to their proposed precursors of living organisms (Brocks & Grice, 2011). With a majority of this data and research mediated through oil conglomerates such as Exxon, this culminated in many important applications to the oil industry. Concurrently, as the discipline evolved, biomarkers became of increasing interest to other scientific fields.

Migrating from Oil: *Signs of Early Life*

The development of the biomarker concept through petroleum research generated new questions regarding the movement of organic matter through biogeochemical cycles. This was built off of historical work by Russian scientist Vladimir Vernadsky (1863-1945) who introduced the terms "biosphere" and "carbon cycle" in his 1924 book *La Géochimie* (Vernadsky, 1924*)*. Ahead of his time, he based his theories on an understanding of petroleum formation that was integrated into broader processes of biogeochemical cycling (Ghilarov, 1995). The focus of the field extended past the search for petroleum and set out to understand the original questions posed by the founders of the field.

Use of GC-MS to quantify isotopic signatures was used to understand life forms with no fossil record. Philip Abelson (1913-2004) was the first to detect biogenic molecules in pre-Cambrian rock in 1957 (Woodring, 1954). A variety of organic biomarkers were found, including the discovery of pre-Cambrian porphyrins in 1964 by American geologist Warren Meinschein (1920-1997), providing elementary evidence for the existence of photosynthetic activity, and thus oxygenation (Meinschein, Barghoorn and Schopf, 1964). Soon, concerns surrounding contamination from anthropogenic petroleum products and drilling sites discouraged the use of organic molecular structures for analysis (Smith, Schopf and Kaplan, 1970).

Instead, the use of isotopic signatures proved especially reliable for the study of pre-Cambrian microbial life (Hinrichs, et al., 1999). The role of archaebacteria in biogeochemical cycling was observed through changes in C and S isotope ratios, providing an age estimate for the evolution of biogenic carbon and sulfur cycling (Offre, Spang and Schleper, 2013). Dating of the Great Oxygenation Event was based on the time of disappearance of sulfur cycling in the isotopic record, which built on Meinschein's discovery of pre-Cambrian porphyrins (Wiechert, 2002).

Isotopic signatures were valuable for determining the presence of a general group of life forms with high sensitivity and accuracy but were unable to provide the specificity indicated by organic structures, which aid in the study of more specific taxa (Brocks and Grice, 2011).

To eliminate the possibility of contamination, evidence from organic structural analysis were later expected to meet the standard of being *syngenetic*, where the markers present in the bitumen sampled matches what is found in the surrounding source rock (Smith, Schopf and Kaplan, 1970). Applying a combination of organic structural and isotopic analysis is also a best practice in research.

As the placement of the biomarker concept into a broader context allowed researchers to discover increasing linkages between abiotic and biotic processes, the complex interdependencies at play in the evolution of early life and the natural world became increasingly recognized.

In response to the 1998 oil industry crash, most biomarker laboratories in petroleum companies closed down, and the field moved increasingly towards universities to conduct research (Brocks and Grice, 2011). The increasing availability of GC-MS allowed geologists in a diversity of subfields to apply biomarkers to their research, which expanded applications to studying specific regions in time in paleoenvironmental applications and to specific taxa in geomicrobiology (Brassell, et al., 1986; Summons and Powell, 1987). Together, these applications contribute to a more complete reconstruction of palaeontological dynamics and environments.

The Search for Martian Life with Biomarkers

Research into geological biomarkers has helped answer influential questions about the origin and evolution of life on Earth. Similarly, the search for life on Mars is one of the most important unsolved problems in scientific inquiry. Due to its similarity to early Earth conditions, it is of great interest for the study of the origins of life (van Zuilen, 2008).

The first speculations about life on Mars were in the 1700s and 1800s when astronomists began drawing similarities between Earth and Mars conditions: a similar diurnal timescale, and a similar axial tilt resulting in seasonally growing and shrinking polar ice caps (Savu, 2006). Current research proposes the use of chemical biomarkers within Martian samples, using both structural analysis of organic molecules and isotopic signatures to identify biosignatures as evidence of current or past life (van Zuilen, 2008). Mass spectrometry and isotope fractionation are two key approaches that were first used by researchers of Earth's biogeochemical cycles in the 20th century. Known extremophilic organisms on Earth, typically early Archaean archaebacteria, are the typical models for Martian biomarkers (Moelling and Broecker, 2019). An organism found on Mars is likely to undergo anaerobic respiration with a chemotrophic diet, an oxidizer of chemical compounds to obtain energy (Westall, et al., 2015).

It is theorized that Mars once possessed a liquid water layer of 100 to 1500 meters deep (Scheller, et al., 2021). Of this water, 30 to 99% is likely to have retreated into the crust (Scheller, et al., 2021). This water would form brines in the subsurface of Mars, which are proposed as habitable due to habitable pH and temperature ranges, and shielding from UV radiation at their depth (Chevrier and Rivera-Valentin, 2012).

Sampling Mars

Recuring Slope Lineae (RSL) are a Martian geological feature resembling flowing water (Figure 1.20) (Ojha, et al., 2015). The leading theory based on rover and satellite data proposes they are surface-level brines from seepage of the subsurface brines (Ojha, et al., 2015).

The Mars Organic Molecule Analyzer (MOMA), onboard the ExoMars rover, was launched in 2020 (Siljeström, et al., 2021). The MOMA is equipped laser desorption mass spectrometry, often used in laboratories but never in space (Siljeström, et al., 2021). It is a soft molecular ionization technique better suited for mid-high molecular weight analysis. Through sampling of the brines and surrounding sediment, the MOMA provides a unique opportunity to test for organic bioindicators of life on Mars (Arevalo, et al., 2017).

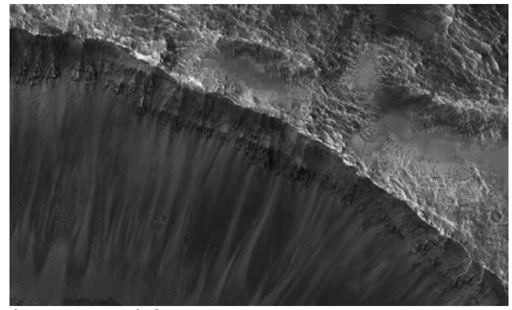


Figure 1.20: RSLs are geologically active slopes that protrude on a seasonal, annual basis. An image displaying a 5km section of an RSL on Mars.

Lipid Degradation

Aliphatic hydrocarbons such as phospholipids are preserved for extended periods of time, relative to most biomolecules (Brocks and Grice, 2011). Over a timescale of 10,000 to 1 million years, the functional groups on a lipid, such as double bonds, carboxyl, hydroxyl, and amino groups are degraded in a process called defunctionalisation (Eigenbrode, 2011). A stable hydrocarbon skeleton remains, which is relatively unaltered from the original carbon structure. Phospholipids typically produce straight-chained compounds 16 to 18 carbons long (Eigenbrode, 2011). The use of lipid biomarkers is common in the study of sulfate-reducing archaea on Earth, and is proposed to serve as a model for Martian life forms (Zhang, et al., 2002).

Isotope Fractionation

An integrated approach collecting multiple lines of evidence is increasingly common with geochemists studying pre-Cambrian life (Zhang, et al., 2002). Similarly, measuring the isotope ratios present in samples close to RSLs relative to other areas can determine if there is a significant difference in isotope abundance in likely environments of Martian life forms.

Study of Life

The study of biomarkers through mass spectrometry has supported the study of early life on Earth and is the starting point for the search for life on Mars. Research into both areas is meant to inform the other.

When thinking of the future, people tend to look to the stars, but rather, we should look to the ground beneath our feet for answers as within its many beds is a reservoir of equally important truths to our existence.

Chapter 1 References

Abotalib, A.Z. and Heggy, E., 2019. A deep groundwater origin for recurring slope lineae on Mars. *Nature Geoscience*, 12(4), pp.235–241.

Agricola, G., 1546. Georgii Agricolae De ortu & causis subterraneorum, lib. V. 5. Basel, Switzerland: Hieronymus Froben.

Al-Areeq, N.M., 2018. Petroleum Source Rocks Characterization and Hydrocarbon Generation. In: M. Zoveidavianpoor, ed. *Recent Insights in Petroleum Science and Engineering*. InTech.

Allmon, W.D., 2016. Darwin and palaeontology: a re-evaluation of his interpretation of the fossil record. *Historical Biology*, 28(5), pp.680–706. https://doi.org/10.1080/08912963.2015.1011397.

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

Alvarez, W., 2009. The historical record in the Scaglia limestone at Gubbio: magnetic reversals and the Cretaceous-Tertiary mass extinction. *Sedimentology*, 56(1), pp.137–148.

Alvarez, W., Arthur, M.A., Fischer, A.G., Lowrie, W., Napoleone, G., Silva, I.P. and Roggenthen, W.M., 1977. Upper Cretaceous–Paleocene magnetic stratigraphy at Gubbio, Italy. *Geological Society of America Bulletin*, 88(3), p.383.

Andreas, L., 1597. *Alchemia*. 5. Rothenburg, Germany: Hachette Livre-BNF.

Archibald, J.D., 2017. *Origins of Darwin's Evolution: Solving the Species Puzzle Through Time and Place*. 1st ed. New York Chichester, West Sussex: Columbia University Press.

Arevalo, R.D., Jr., Grubisic, A., van Amerom, F.H.W., Danell, R., Li, X., Kaplan, D., Pinnick, V.T., Brinckerhoff, W.B., Getty, S. and Goesmann, F., 2017. In situ characterization of martian materials and detection of organic compounds with the MOMA investigation onboard the ExoMars rover. 2017, pp.P42B-06.

Axelrod, D.I. and Bailey, H.P., 1968. Cretaceous Dinosaur Extinction. *Evolution*, 22(3), pp.595–611.

Ayala, F.J. and Fitch, W.M., 1997. Genetics and the origin of species: An introduction. *Proceedings of the National Academy of Sciences*, 94(15), pp.7691–7697. https://doi.org/10.1073/pnas.94.15.7691.

Bacon, F.R. and Brewer, J.S., 1859. Opus tertium. In: *Opera quædam hactenus inedita*, Rerum Britannicarum medii aevi scriptores, 2nd ed. London, England: Longman, Green, Longman and Roberts.

Bajema, C.J., 1988. Charles Darwin on man in the first edition of the Origin of Species. *Journal of the History of Biology*, 21(3), pp.403–410. https://doi.org/10.1007/BF00144088.

Bartholomew, M., 1975. Huxley's defence of Darwin. *Annals of Science*, 32(6), pp.525–535. https://doi.org/10.1080/00033797500200451.

Becker, G.F., 1909. Relations Between Local Magnetic Disturbances and the Genesis of Petroleum. 401. USA: U.S. Government Printing Office.

de Beer, G., 1954. Archaeopteryx lithographica. A Study Based Upon the British Museum Specimen. *Order of the Trustees of the British Museum*, 224.

Benton, M.J., 1990. Scientific methodologies in collision: the history of the study of the extinction of the dinosaurs. *Evolutionary Biology*, 24(37), pp.371–400.

Bergmann, U., Morton, R.W., Manning, P.L., Sellers, W.I., Farrar, S., Huntley, K.G., Wogelius, R.A. and Larson, P., 2010. Archaeopteryx feathers and bone chemistry fully revealed via synchrotron imaging. *Proceedings of the National Academy of Sciences*, 107(20), pp.9060–9065.

Berthelot, M., 1866a. *Annales de chimie et de physique*. 4. Paris: Chez Crochard.

Berthelot, M., 1866b. *Sur l'origine des carbures et des combustibles minéraux*. 4th ed. 9. Paris, France: Ann. de Chimie et des Physiques.

Bianchi, T.S., 2021. The evolution of biogeochemistry: revisited. *Biogeochemistry*, 154(2), pp.141–181.

Black, B.A. and Manga, M., 2017. Volatiles and the tempo of flood basalt magmatism. *Earth and Planetary Science Letters*, 458, pp.130–140.

Boero, F., 2015. From Darwin's Origin of Species toward a theory of natural history. *F1000Prime Reports*, 7, p.49. https://doi.org/10.12703/P7-49.

Brassell, S.C., Eglinton, G., Marlowe, I.T., Pflaumann, U. and Sarnthein, M., 1986. Molecular stratigraphy: a new tool for climatic assessment. *Nature*, 320, pp.129–133.

Brocks, J.J. and Grice, K., 2011. Biomarkers (Molecular Fossils). In: J. Reitner and V. Thiel, eds. *Encyclopedia of Geobiology*, Encyclopedia of Earth Sciences Series. Dordrecht: Springer Netherlands. pp.147–167.

Browne, M.W., 1985. Dinosaur Experts Resist Meteor Extinction Idea. *The New York Times*. [online] 29 Oct. Available at: <https://www.nytimes.com/1985/10/29/science/dinosaur-experts-resist-meteor-extinction-idea.html> [Accessed 25 November 2022].

Brusatte, S.L., Butler, R.J., Barrett, P.M., Carrano, M.T., Evans, D.C., Lloyd, G.T., Mannion, P.D., Norell, M.A., Peppe, D.J., Upchurch, P. and Williamson, T.E., 2015. The extinction of the dinosaurs. *Biological Reviews*, 90(2), pp.628–642.

Buckland, W., 1824. Reliquiæ diluvianæ; or Observations on the organic remains contained in caves, fissures, and diluvial gravel, and on other geological phenomena, attesting the action of an universal deluge. London: John Murray.

Buckland, W., 1823. *Reliquiae diluvianae*. London: Thomas Davison.

Caldeira, K. and Rampino, M.R., 1990. Carbon dioxide emissions from Deccan Volcanism and a K/T boundary Greenhouse Effect. *Geophysical Research Letters*, 17(9), pp.1299–1302.

Chevrier, V.F. and Rivera-Valentin, E.G., 2012. Formation of recurring slope lineae by liquid brines on present-day Mars. *Geophysical Research Letters*, 39(21).

Condamine, F.L., Guinot, G., Benton, M.J. and Currie, P.J., 2021. Dinosaur biodiversity declined well before the asteroid impact, influenced by ecological and environmental pressures. *Nature Communications*, 12(1), p.3833.

Coulter, I., Snider, P. and Neil, A., 2019. Vitalism-A Worldview Revisited: A Critique Of Vitalism And

Its Implications For Integrative Medicine. *Integrative Medicine (Encinitas, Calif.)*, 18(3), pp.60–73.

Cuvier, G., 1799. Mémoire sur les espèces d'éléphans vivantes et fossiles. *Mémoires de la Classe des Sciences, Mathématiques, et Physiques*, 2, pp.1–22.

Cuvier, G., 1798. *Tableau élémentaire de l'histoire naturelle des animaux*. Paris: Baudouin.

Cuvier, G., 1799. *Mémoire sur les espèces d'éléphans vivantes et fossiles*. Translated by M.J.S. Rudwick., 1997. Chicago: The University of Chicago Press.

Cuvier, G., 1817. *Le règne animal*. Translated by H. McMurtrie., 1834. London: Orr & Smith.

Cuvier, G. and Brongniart, M.A., 1835. *Description géologique des environs de Paris*. 3rd edition. Paris: Edmond D'Ocagne.

Cuvier, G., 1825. *Discours sur les révolutions de la surface du globe, et sur les changemens qu'alles ont produit dans le régne animal*. Translated by I. Johnston., 2009. Arlington: Richer Resources.

Coleman, W., 2013. *Georges Cuvier, zoologist: a study in the history of evolution theory.* Cambridge: Harvard University Press.

Darwin, C., 1859a. *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life*. 1st ed. London, UK: John Murray.

Darwin, C., 1859b. *To Charles Lyell*.

Darwin, C., 1863a. *To Hugh Falconer*.

Darwin, C., 1863b. *To James Dwight Dana*.

Darwin, C., 1872. *The origin of species by means of natural selection, or the preservation of favoured races in the struggle for life*. 6th ed. London, UK: John Murray.

Darwin, C., 2010. *The Origin of Species: A Variorum Text*. University of Pennsylvania Press.

Dauphas, N. and Schauble, E.A., 2016. Mass Fractionation Laws, Mass-Independent Effects, and Isotopic Anomalies. *Annual Review of Earth and Planetary Sciences*, 44(1), pp.709–783.

Desmond, A., 1984. *Archetypes and Ancestors: Palaeontology in Victorian London, 1850-1875*. 1st ed. Chicago: University of Chicago Press.

Edwards, N.P., Barden, H.E., van Dongen, B.E., Manning, P.L., Larson, P.L., Bergmann, U., Sellers, W.I. and Wogelius, R.A., 2011. Infrared mapping resolves soft tissue preservation in 50 million year-old reptile skin. *Proceedings of the Royal Society B: Biological Sciences*, 278(1722), pp.3209–3218.

Edwards, N.P., Wogelius, R.A., Bergmann, U., Larson, P., Sellers, W.I. and Manning, P.L., 2013. Mapping prehistoric ghosts in the synchrotron. *Applied Physics A*, 111(1), pp.147–155.

Edwards, N.P., Webb, S.M., Krest, C.M., van Campen, D., Manning, P.L., Wogelius, R.A. and Bergmann, U., 2018. A new synchrotron rapid-scanning X-ray fluorescence (SRS-XRF) imaging station at SSRL beamline 6-2. *Journal of Synchrotron Radiation*, 25(5), pp.1565–1573.

Eglinton, G. and Calvin, M., 1967. Chemical Fossils. *Scientific American*, 216(1), pp.32–43.

Eglinton, G., Scott, P.M., Belsky, T., Burlingame, A.L. and Calvin, M., 1964. Hydrocarbons of Biological Origin from a One-Billion-Year-Old Sediment. *Science*, 145(3629), pp.263–264.

Eigenbrode, J., 2011. Molecular Fossils. In: M. Gargaud, R. Amils, J.C. Quintanilla, H.J. Cleaves, W.M. Irvine, D.L. Pinti and M. Viso, eds. *Encyclopedia of Astrobiology*. Berlin, Heidelberg: Springer. pp.1070–1076.

Eigen, E.A., 1997. Overcoming first impressions: Georges Cuvier's types. *Journal of the History of Biology*, 30(2), pp.179-209.

England, R., 2017. Censoring Huxley and Wilberforce: A new source for the meeting that the Athenaeum 'wisely softened down'. *Notes and Records: the Royal Society Journal of the History of Science*, 71(4), pp.371–384. https://doi.org/10.1098/rsnr.2016.0058.

Falconer, H., 1863. *To Charles Darwin*.

Fenton, C.L., 1933. *The world of fossils*. New York: D. Appleton & Company.

Foth, C. and Rauhut, O.W.M., 2020. The Origin of Birds: Current Consensus, Controversy, and the Occurrence of Feathers. In: *The Evolution of Feathers*, Fascinating Life Sciences. [online] Cham: Springer International Publishing. pp.27–45. https://doi.org/10.1007/978-3-030-27223-4_3.

Frey, E. and Tischlinger, H., 2012. The Late Jurassic Pterosaur Rhamphorhynchus, a Frequent Victim of the Ganoid Fish Aspidorhynchus? *PLOS ONE*, 7(3), p.e31945. https://doi.org/10.1371/journal.pone.0031945.

Friedman, W.E., 2009. The meaning of Darwin's "abominable mystery". *American Journal of Botany*, 96(1), pp.5–21. https://doi.org/10.3732/ajb.0800150.

Fürsich, F., Mäuser, M., Schneider, S. and Werner, W., 2007. The Wattendorf Plattenkalk (Upper Kimmeridgian) – a new conservation lagerstätte from the northern Franconian Alb, southern Germany. *Neues Jahrbuch Fur Geologie Und Palaontologie-abhandlungen - NEUES JAHRB GEOL PALAONTOL-AB*, 245, pp.45–58. https://doi.org/10.1127/0077-7749/2007/0245-0045.

Galera, A., 2017. The Impact of Lamarck's Theory of Evolution Before Darwin's Theory. *Journal of the History of Biology*, 50(1), pp.53–70. https://doi.org/10.1007/s10739-015-9432-5.

Gawne, R., 2015. Fossil Evidence in the Origin of Species. *BioScience*, 65(11), pp.1077–1083. https://doi.org/10.1093/biosci/biv124.

Ghilarov, A.M., 1995. Vernadsky's Biosphere Concept: An Historical Perspective. *The Quarterly Review of Biology*, 70(2), pp.193–203.

Glen, W. ed., 1994. *The Mass-extinction debates: how science works in a crisis*. Stanford, Calif: Stanford University Press.

Greco, M., 2005. On the Vitality of Vitalism. *Theory, Culture & Society*, 22(1), pp.15–27.

Guerlac, H., 1955. Some aspects of science during the French Revolution. *The Scientific Monthly*, 80(2), pp.93–101.

Hartman, S., Mortimer, M., Wahl, W.R., Lomax, D.R., Lippincott, J. and Lovelace, D.M., 2019. A new paravian dinosaur from the Late Jurassic of North America supports a late acquisition of avian flight. *PeerJ*, 7, p.e7247. https://doi.org/10.7717/peerj.7247.

Hayes, J.M., Wedeking, K.W. and Kaplan, I.R., 1983. Precambrian organic geochemistry - Preservation of the record.

Herbert, S., 2005. *Charles Darwin, geologist*. Ithaca: Cornell University Press.

Hinrichs, K.-U., Hayes, J.M., Sylva, S.P., Brewer, P.G. and DeLong, E.F., 1999. Methane-consuming archaebacteria in marine sediments. *Nature*, 398(6730), pp.802–805.

Hooykaas, R., 1970. *Catastrophism in geology: its scientific character in relation to actualism and uniformitarianism*. Amsterdam: North-Holland Publishing Company.

Hunt, J.M., 1961. Distribution of hydrocarbons in sedimentary rocks. *Geochimica et Cosmochimica Acta*, 22(1), pp.37–49.

Hunt, T.S., 1863. *Geological Survey of Canada*. On the Geology and Mineralogy of Laurentian Limestones; Geology of Petroleum and Salt; the Porosity of Rocks; and on Peat and its applications. [Survey] Quebec, Canada: Government

Huxley, T., 1868a. I. Remarks upon *Archæopteryx lithographica*. *Proceedings of the Royal Society of London*, 16, pp.243–248. https://doi.org/10.1098/rspl.1867.0046.

Huxley, T.H., 1868b. On the animals which are most nearly intermediate between birds and reptiles. *Geological Magazine*.

Huxley, T.H., 1870. Further Evidence of the Affinity between the Dinosaurian Reptiles and Birds. *Quarterly Journal of the Geological Society*, 26(1–2), pp.12–31. https://doi.org/10.1144/GSL.JGS.1870.026.01-02.08.

Huxley, T.H., 1894. *Collected Essays: Darwiniana*. New York: Appleton.

Jorgensen, B.S., 1965. More on Berzelius and the vital force. *Journal of Chemical Education*, 42(7), p.394.

Justus Liebig, W.G., 1842. Animal Chemistry, or Organic Chemistry in Its Application to Physiology and Pathology. *The North American Review*, 55(117), pp.462–500.

Printing Beureau. pp.54–56. Available at: <https://publications.gc.ca/collections/collection_2017/rncan-nrcan/M40-2-1906-eng.pdf> [Accessed 28 November 2022].

Kampourakis, K. and Gripiotis, C., 2015. Darwinism in Context: An interdisciplinary, highly contextualized course on nature of science. *Perspectives in Science*, 5, pp.25–35. https://doi.org/10.1016/j.pisc.2015.05.002.

Kaplan, M., 2011. Archaeopteryx no longer first bird. *Nature*. [online] https://doi.org/10.1038/news.2011.443.

Karlsson, E.S., Charkin, A., Dudarev, O., Semiletov, I., Vonk, J.E., Sánchez-García, L., Andersson, A. and Gustafsson, Ö., 2011. Carbon isotopes and lipid biomarker investigation of sources, transport and degradation of terrestrial organic matter in the Buor-Khaya Bay, SE Laptev Sea. *Biogeosciences*, 8(7), pp.1865–1879.

Kaye, T.G., Pittman, M., Mayr, G., Schwarz, D. and Xu, X., 2019. Detection of lost calamus challenges identity of isolated Archaeopteryx feather. *Scientific Reports*, 9(1), p.1182. https://doi.org/10.1038/s41598-018-37343-7.

Keller, G., 1988. Extinction, survivorship and evolution of planktic foraminifera across the Cretaceous/Tertiary boundary at El Kef, Tunisia. *Marine Micropaleontology*, 13(3), pp.239–263.

Keller, G., Adatte, T., Gardin, S., Bartolini, A. and Bajpai, S., 2008. Main Deccan volcanism phase ends near the K–T boundary: Evidence from the Krishna–Godavari Basin, SE India. *Earth and Planetary Science Letters*, 268(3–4), pp.293–311.

Kenney, J.F., 1996. Impending shortages of petroleum re-evaluated. *Energy World. Institute of Fuel*, 2(240), pp.16–18.

Kritsky, G., 1992. Darwin's *Archaeopteryx* prophecy. *Archives of Natural History*, 19(3), pp.407–410. https://doi.org/10.3366/anh.1992.19.3.407.

Kurzer, F. and Sanderson, P.M., 1956. Urea in the history of organic chemistry: Isolation from natural sources. *Journal of Chemical Education*, 33(9), p.452.

Lack, D., 2013. *Evolutionary Theory and Christian Belief*. 1st ed. London: Routledge. https://doi.org/10.4324/9780203706305.

Lavoisier, A.L., 1789. *Traité élémentaire de chimie*. 1st ed. Paris, France: Chez Cuchet.

Lee, R., 1833. *Memoirs of Baron Cuvier*. New York: J & J Harper.

Lesquereux, L., Worthen, A.H., and Western Engraving Co., 1870. *Report on the fossil plants of Illinois*. Springfield, Ill.: Geological Survey of Illinois.

Londry, K.L., Jahnke, L.L. and Des Marais, D.J., 2004. Stable Carbon Isotope Ratios of Lipid Biomarkers of Sulfate-Reducing Bacteria. *Applied and Environmental Microbiology*, 70(2), pp.745–751.

Luterbacher, H.P. and Premoli Silva, I., 1962. Note preliminaire sur une revision du profil de Gubbio, Italie. 1. Observations stratigraphiques. 2. Sur quelques foraminiferes planctoniques du Cretace. *Rivista Italiana di Paleontologia*, 68, pp.253–288.

Lyell, C., 1830. Principles of geology : being an attempt to explain the former changes of the earth's surface, by reference to causes now in operation. London : John Murray

MacLeod, N., 2014. The geological extinction record: History, data, biases, and testing. In: *Volcanism, Impacts, and Mass Extinctions: Causes and Effects*. Geological Society of America.

Mayr, E., 1972. The Nature of the Darwinian Revolution: Acceptance of evolution by natural selection required the rejection of many previously held concepts. *Science*, 176(4038), pp.981–989. https://doi.org/10.1126/science.176.4038.981.

Meinschein, W.G., Barghoorn, E.S. and Schopf, J.W., 1964. Biological Remnants in a Precambrian Sediment. *Science*, 145(3629), pp.262–263.

Mendeleev, D., 1877. L'Origine du pétrole. *Revue Scientifique*, 8.

Moelling, K. and Broecker, F., 2019. Viroids-First—A Model for Life on Earth, Mars and Exoplanets. *Geosciences*, 9(5), p.241.

Mumma, M.J., 2012. The Search for Life on Mars. [online] Origin of Life Gordon Research Conference. Galveston, TX. Available at: <https://ntrs.nasa.gov/citations/20120003707> [Accessed 12 December 2022].

Newberry, J., 1873. *Report of the Geological Survey of Ohio: Geology and Palaeology*. [Survey] Ohio, USA: Legislature of Ohio. p.359.

Nudds, J. and Selden, P., 2008. Fossil–Lagerstätten. *Geology Today*, 24(4), pp.153–158. https://doi.org/10.1111/j.1365-2451.2008.00679.x.

McGrew, T.J., Alspector-Kelly, M. and Allhoff, F., 2009. *Philosophy of science: an historical anthology*. Blackwell philosophy anthologies. Chichester: Wiley-Blackwell.

Officer, C.B., 1996. The great dinosaur extinction controversy. Helix books. The great dinosaur extinction controversy.

Offre, P., Spang, A. and Schleper, C., 2013. Archaea in biogeochemical cycles. *Annual Review of Microbiology*, 67, pp.437–457.

Ojha, L., Wilhelm, M.B., Murchie, S.L., McEwen, A.S., Wray, J.J., Hanley, J., Massé, M. and Chojnacki, M., 2015. Spectral evidence for hydrated salts in recurring slope lineae on Mars. *Nature Geoscience*, 8(11), pp.829–832.

Oldham, R.D., 1914. The Constitution of the Interior of the Earth as Revealed by Earthquakes. *Nature*, 92(2312), pp.684–685.

Owen, F.R.S., 1863. III. On the archeopteryx of von Meyer, with a description of the fossil remains of a long-tailed species, from the lithographic stone of Solenhofen. *Philosophical Transactions of the Royal Society of London*, 153, pp.33–47. https://doi.org/10.1098/rstl.1863.0003.

Owen, R., 1860. Darwin, On the Origin of Species. *The Edinburgh Review*, 111, pp.487–532.

Pakhnevich, A., Kurkin, A., Lavrov, A., Tarasenko, K., Kovalenko, E., Kaloyan, A. and Podurets, K., 2018. Synchrotron and neutron tomography of paleontological objects on the facilities of the Kurchatov Institute. *Journal of Imaging*, 4(8), p.103.

Palmer, T., 2003. *Perilous planet Earth: catastrophes and catastrophism through the ages*. Cambridge: Cambridge University Press.

Patton, L., 2014. *Philosophy, science, and history*. New York: Routledge.

Pietsch, T.W., 2012. *Cuvier's history of the natural sciences: twenty-four lessons from antiquity to the renaissance*. Paris: Muséum National d'Histoire Naturelle.

Rauhut, O.W.M., Foth, C. and Tischlinger, H., 2018. The oldest Archaeopteryx (Theropoda: Avialiae): a new specimen from the Kimmeridgian/Tithonian boundary of Schamhaupten, Bavaria. *PeerJ*, 6, p.e4191. https://doi.org/10.7717/peerj.4191.

de Ricqlès, A., 2010. On Darwin's palaeontology in The Origin of Species. *Comptes Rendus Biologies*, 333(2), pp.87–94. https://doi.org/10.1016/j.crvi.2009.11.007.

Rossini, F.D., 1960. Hydrocarbons in petroleum. *Journal of Chemical Education*, 37(11), p.554.

Rudwick, M.J.S., 1985. The Meaning of Fossils: Episodes in the History of Palaeontology. University of Chicago Press.

Rudwick, M.J.S., 1976. *The meaning of fossils*. 2nd ed. New York: The University of Chicago Press.

Rudwick, M.J.S., 1997. *Georges Cuvier, fossil bones, and geological catastrophes*. Chicago: The University of Chicago Press.

Russell, D. and Tucker, W., 1971. Supernovae and the Extinction of the Dinosaurs. *Nature*, 229(5286), pp.553–554.

Ruse, M., 1975. The Relationship between Science and Religion in Britain, 1830–1870. *Church History*, 44(4), pp.505–522. https://doi.org/10.2307/3163829.

Savu, G., 2006. Earth–Mars similarity criteria for exploring martian vehicles. *Acta Astronautica*, 59(8), pp.734–741.

Scheller, E.L., Ehlmann, B.L., Hu, R., Adams, D.J. and Yung, Y.L., 2021. Long-term drying of Mars by sequestration of ocean-scale volumes of water in the crust. *Science*, 372(6537), pp.56–62.

Schoene, B., Samperton, K.M., Eddy, M.P., Keller, G., Adatte, T., Bowring, S.A., Khadri, S.F.R. and Gertsch, B., 2015. U-Pb geochronology of the Deccan Traps and relation to the end-Cretaceous mass extinction. *Science*, 347(6218), pp.182–184.

Schwartz, J.S., 1990. Darwin, Wallace, and Huxley, and Vestiges of the Natural History of Creation. *Journal of the History of Biology*, 23(1), pp.127–153. https://doi.org/10.1007/BF00158157.

Sen, G., 2001. Generation of Deccan Trap magmas. *Journal of Earth System Science*, 110(4), pp.409–431.

Senter, P. and Robins, J.H., 2003. Taxonomic status of the specimens of *Archaeopteryx*. *Journal of Vertebrate Paleontology*, 23(4), pp.961–965. https://doi.org/10.1671/22.

Siljeström, S., Li, X., Brinckerhoff, W., van Amerom, F. and Cady, S.L., 2021. ExoMars Mars Organic Molecule Analyzer (MOMA) Laser Desorption/Ionization Mass Spectrometry (LDI-MS) Analysis of Phototrophic Communities from a Silica-Depositing Hot Spring in Yellowstone National Park, USA. *Astrobiology*, 21(12), pp.1515–1525.

Simpson, G.G., 1983. *Fossils and the history of life*. New York: Scientific American Books.

Skedros, J.G. and Brand, R.A., 2011. Biographical Sketch: Georg Hermann von Meyer (1815-1892). *Clinical Orthopaedics and Related Research*®, 469(11), pp.3072–3076. https://doi.org/10.1007/s11999-011-2040-6.

Smith, J.W., Schopf, J.W. and Kaplan, I.R., 1970. Extractable organic matter in Precambrian cherts. *Geochimica et Cosmochimica Acta*, 34(6), pp.659–675.

Summons, R.E. and Powell, T.G., 1987. Identification of aryl isoprenoids in source rocks and crude oils: Biological markers for the green sulphur bacteria. *Geochimica et Cosmochimica Acta*, 51(3), pp.557–566.

Switek, B., 2010. Thomas Henry Huxley and the reptile to bird transition. *Geological Society, London, Special Publications*, 343(1), pp.251–263. https://doi.org/10.1144/SP343.15.

Tanghe, K.B., 2019. On The Origin of Species: The story of Darwin's title. *Notes and Records: the Royal Society Journal of the History of Science*, 73(1), pp.83–100. https://doi.org/10.1098/rsnr.2018.0015.

Taquet, P., 2009. Cuvier's attitude toward creation and the biblical flood. In: M. Kölbl-Ebert, ed. 2009. *Geology and religion: a history of harmony and hostility*. Bath: The Geological Society Publishing House. pp.127-134.

Thanukos, A., 2009. Darwin's "Extreme" Imperfection? *Evolution: Education and Outreach*, 2(1), pp.84–89. https://doi.org/10.1007/s12052-008-0105-0.

The Bible: contemporary English version, 1991. Cambridge University Press.

Tissot, B.P., 1969. Premieres donnees sur les mecanismes et la cinetique de la formation du petrole dans les sediments: simulation d'une schema reactionnel sur ordinateur. *Revue de L'Institut Francais du Petrole*, 24, pp.470–501.

Tissot, B.P. and Welte, D.H., 1978. *Petroleum Formation and Occurrence*. Berlin, Heidelberg: Springer Berlin Heidelberg.

Trask, P.D., 1942. Source Beds of Petroleum. *Nature*, 150(3798), pp.194–195.

Treibs, A., 1936. Chlorophyll- und Häminderivate in organischen Mineralstoffen. *Angewandte Chemie*, 49(38), pp.682–686.

van der Meer, J.M., 2008. Georges Cuvier and the use of scripture in geology. In: S. Mandelbrote andJ. van der Meer, eds. 2008. *Nature and scripture in the Abrahamic religions: 1700-present*. Leiden: Brill Publishers. Ch.4.

van Reybrouck, D., 2012. *From primitives to primates a history of ethnographic and primatological analogies in the study of prehistory*. Leiden: Sidestone Press.

Vernadsky, V., 1924. *La Géochimie*. Paris, France: Librairie Félix Alcan.

Wagner, A., 1862. XXVIII.—On a new fossil reptile supposed to be furnished with feathers. *Annals and Magazine of Natural History*, 9(52), pp.261–267. https://doi.org/10.1080/00222936208681227.

Walker, F.M., Dunhill, A.M. and Benton, M.J., 2020. Variable preservation potential and richness in the fossil record of vertebrates. *Palaeontology*, 63(2), pp.313–329. https://doi.org/10.1111/pala.12458.

Walters, C.C., 2006. The Origin of Petroleum. In: C.S. Hsu and P.R. Robinson, eds. *Practical Advances in Petroleum Processing*. New York, NY: Springer New York. pp.79–101.

Wang, S.C. and Dodson, P., 2006. Estimating the diversity of dinosaurs. *Proceedings of the National Academy of Sciences*, 103(37), pp.13601–13605.

Wellnhofer, P., 2010. A short history of research on *Archaeopteryx* and its relationship with dinosaurs. *Geological Society, London, Special Publications*, 343(1), pp.237–250. https://doi.org/10.1144/SP343.14.

Whybrow, P.J., 1985. A history of fossil collecting and preparation techniques. *Curator The Museum Journal*, 28(1), pp.5–26.

Wieland, G.R., 1925. Dinosaur Extinction. *The American Naturalist*, 59(665), pp.557–565.

Williams, J.D., 2009. Belief *versus* acceptance: Why do people not believe in evolution? *BioEssays*, 31(11), pp.1255–1262.

Wiechert, U.H., 2002. Earth's Early Atmosphere. *Science*, 298(5602), pp.2341–2342.

Woodring, W.P., 1954. Conference on biochemistry, paleoecology, and evolution. *Proceedings of the National Academy of Sciences*, 40(3), pp.219–224.

Xu, X. and Pol, D., 2014. Archaeopteryx, paravian phylogenetic analyses, and the use of probability-based methods for palaeontological datasets. *Journal of Systematic Palaeontology*, 12(3), pp.323–334. https://doi.org/10.1080/14772019.2013.764357.

Zhang, C.L., Li, Y., Wall, J.D., Larsen, L., Sassen, R., Huang, Y., Wang, Y., Peacock, A., White, D.C., Horita, J. and Cole, D.R., 2002. Lipid and carbon isotopic evidence of methane-oxidizing and sulfate-reducing bacteria in association with gas hydrates from the Gulf of Mexico. *Geology*, 30(3), pp.239–242.

van Zuilen, M., 2008. Stable Isotope Ratios as a Biomarker on Mars. In: O. Botta, J.L. Bada, J. Gomez-Elvira, E. Javaux, F. Selsis and R. Summons, eds. *Strategies of Life Detection*, Space Sciences Series of ISSI. [online] Boston, MA: Springer US. pp.221–232.

Chapter 1 Image References

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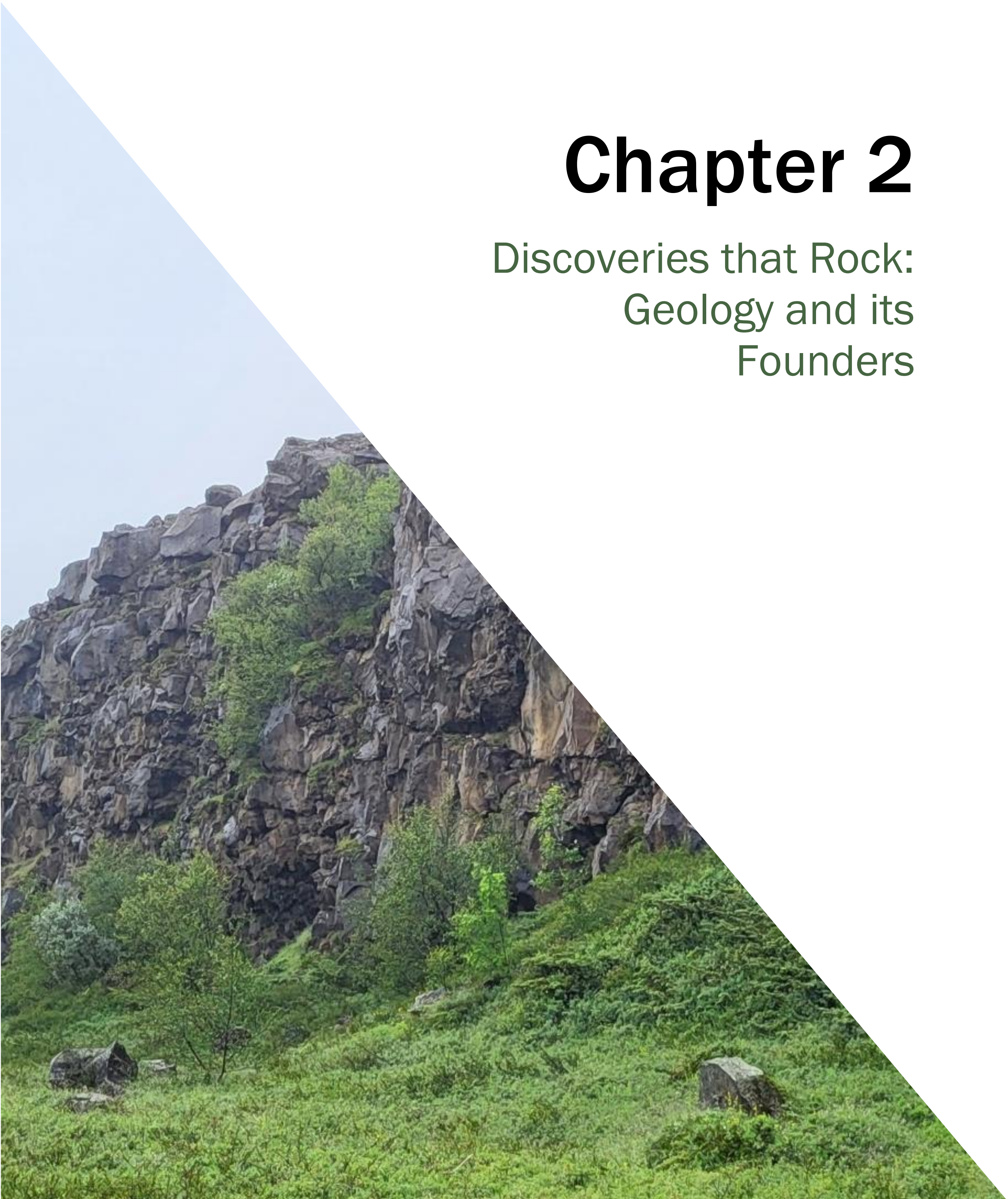
Chapter 2

Discoveries that Rock: Geology and its Founders



Introduction

Behind every new discovery is an idea. It is these ideas that form the basis of scientific understanding. Sometimes, these ideas may come in the form of a novel methodology. Other times, they may manifest in a new interpretation of data or observations, or a new concept entirely. In some rare cases, though, these ideas can spawn entirely new fields, branching science off into uncharted territory.

The progress of geology is no different. With investigations dating as far back as the early Middle Ages, the development of geology over the past 1000 years from its early state to where it is today was undoubtedly a product of revolutionary thinkers and ideas. Early ideas and investigations from scholars such as Ibn Sina and Shen Kuo formed the basis of geological thought. These pillars were later expanded upon by geologists centuries down the line, resulting in the inception of subfields of geology and the spread of geological thought around the world. For example, contributions from geologists such as Giovanni Arduino and D.N Wadia resulted in the inception of geological study in their native countries of Italy and India, respectively. Investigations by other geologists such as Victor Moritz Goldschmidt birthed new subfields of geology, such as Goldschmidt's modern geochemistry. These ideas were further developed and expanded upon by geologists centuries down the line, ultimately resulting in the modern field of geology.

In this chapter, our investigation into the history of the Earth concentrates on some of the most significant geologists throughout the field's history. Spanning from the earliest contributions to the field a millennium ago to the inception of subfields of geology within the past few centuries, this chapter's investigation will delve into their discoveries and impacts on geology as a whole.

D.N. Wadia: The Pioneer of Indian Geology

A dramatic shift in power from the Mughal Empire to the British Empire in 1858 shook the very foundation of the Indian subcontinent (Roopnarine, 2019). It marked the beginning of a period in constitutional history known as the Crown Rule. While Indian scholars were actively contributing to the field of science, British colonizers delegitimized their methods to establish hegemony (Kumar, 1996). British methodologies were presented in a form that appeared much superior, where science was envisioned as an instrument of economic policy seeking to enrich the Empire. The British introduced novel inventions such as the telegraph and railways, establishing technological and scientific prowess. The expansion of roadways and communication also allowed for increased access to the country, prompting premier geological research.

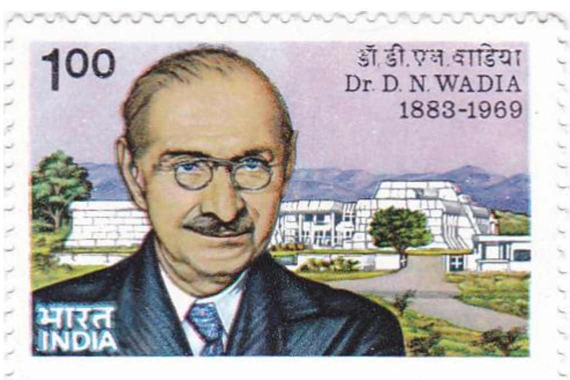


Figure 2.1: 100 p. stamp released by India Post in 1984, with Wadia's portrait. A building of the Wadia Institute of Himalayan Geology in Dehradun, India is in the background.

Searching The Himalayas for the Right or Wrong Reasons

The first half of the 19th century saw European scientists mainly work in the Nilgiri Valley of South India and the Raniganj region of East India in search of coal (Acharjee, 2016). Their investigations were motivated by a colonial interest in coal necessary for the transportation of boats and vessels. At that time, a sense of otherworldliness and awe surrounded the Himalayas. Epic tales of guardian deities protecting Himayat, a spiritual personification of the range, had been spun since the creation of written scripture in 1500 BCE. The foothills of the vast mountain range became areas of pilgrimage, with its secluded and ethereal nature at the heart of Hinduism. The British did not share the same sacred notions, failing to consider the deep religious ties between Indian citizens and their terrain. The intrigue of the mountain range for the British was instead tied to the prospect of monumental coal reserves and further economic development.

Himalayan geology, as a systematic field of science, did not emerge until the 1850s when formal explorations began (Sorkhabi, 1997). The *Geological Survey of Coal in India* was established during this time, with its purpose purely rooted in economic gain from coal. The institution, directed by Thomas Oldham, initiated the first formal exploration overseeing a map of coal bearing strata (Stubblefield, 1970). Charles Stewart Middlemiss was the pioneer *British* geologist of the Himalayas in the late 19th century working under Oldham (Fisher, 1878; Fermor, 1945). He was a driving force for the institution, promoting exploration motivated by geological curiosity rather than pure economic basis. The *Geological Survey of Coal in India* was soon renamed the *Geological Survey of India (GSI)*, signifying a change in the foundational beliefs of the institution, where geologic exploration was expanded from mere coal inspections.

Darashaw Nosherwan Wadia would soon enter the scene as the *Indian* geologist responsible for revolutionizing the field. He was a trailblazer who laid the foundation for further geological investigations in the Himalayas, a region that sparked his immense curiosity since childhood. The lack of foundational knowledge in Himalayan stratigraphy motivated not only Wadia's field explorations, but his desire to disseminate such discoveries to the general population, particularly students.

Early Life

D.N. Wadia (Figure 2.1) was born on October 25, 1883, in the Surat village of Gujrati-speaking India (Stubblefield, 1970). The Wadias were a well-known and respected Parsi family of high social status. D.N. Wadia attended a private Gujrati school then the Sir J. J. English School. In search of the best educational facility, his family moved to Baroda in 1894. Being the fourth of nine children, Wadia acknowledges his early love for science to stem from his older brother Munchershaw N., a distinguished educationalist. Living at the Himalayan foothills also sparked his curiosity of the region and its unknown origins. As a bright student, D.N. Wadia attended Baroda High School at the age of eleven and started his higher education at Baroda College when he was 16. Wadia soon received a BSc in Botany and Zoology in 1903 and another BSc in Botany and Geology in 1905. He also received an MA in Biology and

Geologyin 1905, eventually becoming an undergraduate professor. With geology being a new discipline taught only in universities at Calcutta, Wadia discerned knowledge mainly via self-study and fieldwork. In particular, he loved to explore the geological collections in the Museum of Arts and Sciences at Baroda. Wadia was determined to become not only a great geologist, but a great *Indian* geologist, a task significantly more difficult to gain recognition and credibility for under Crown Rule.

Wadia's Textbook

Wadia spent his early days as a professor and field researcher at The Prince of Wales College in Jammu. He always placed students at the forefront of his mind, finding a particular delight in the knowledge that could be gained from field work. Proximity to the Kashmir and Jammu regions of the Himalayas allowed Wadia to expand the fossil collection he used for teaching. While in the foothills of the Himalayas in 1907, he uncovered an astonishing three-meter-long tusk and its associated skull fragments. Its elephant-like tusks gave rise to its name, *Stegodon Ganesa,* after Lord Ganesh, a sacred Hindu God with an elephant head. This wondrous discovery became his most prized possession and provided students with physical evidence of the geological wonders in India.

Throughout his years as a professor, Wadia noted a gap in relevant geological information from when the *Manual of the Geology of India* was released by the GSI in 1893. Decades had passed, with the repository of geologic knowledge on India growing at a rapid rate. Wadia adressed this void in literature, noting how he had "constantly experienced great difficulty in the teaching of the geology of India, because of the absence of any adequate modern book on the subject." (Wadia, 1919, p.vii)

With support from the principles of the university and C.S. Middlemiss, Wadia published his textbook in 1919, titled *Geology of India* (Wadia, 1919; Stubblefield, 1970). His textbook detailed the stratigraphy and physiography of India's various regions. Previous works of Middlemiss were explained in detail, with Wadia's own maps included. The textbook was an instant hit, revolutionizing how geology was taught across instutions in India. The textbook was followed by six more editions, all of which played a pivotal role in shaping how students understood Indian geology from that time onward.

Extending Middlemiss' Work

The GSI was viewed as a prestigious organization led by wealthy European scientists. Talks of a man hired by the GSI who had not received an education in Europe began to spread in 1921. This was completely unheard of under Crown Rule. It was only those of European decent and with degrees from European institutions who were given such an opportunity. However, Wadia defied socio-political standards and opened a pathway for others like him to follow. As an *Indian* geoscientist, Wadia's perspective was different from his European colleagues, who were often more concerned with acquiring resources to build Britain's wealth (Toloman, 2016). Any interest that the Europeans had in developing India was closely tied to helping Britain as well. Exploitation was lain at the heart of environmental exploration. Instead, Wadia's research was geared towards making India self-sufficient and competitive globally. For his first project as a member of the GSI, he was entailed with surveying the state of Poonch within Kashmir. The region was poorly understood and had great allure to Wadia as a result. He also found inspiration in continuing investigations

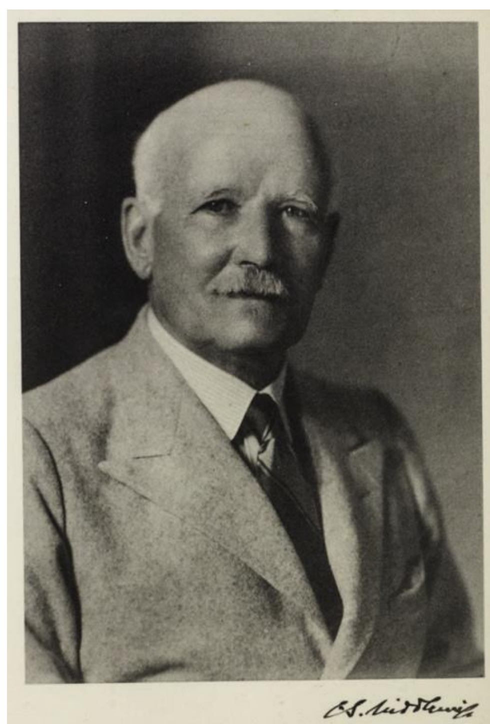


Figure 2.2: A photograph of Charles Stewart Middlemiss who is credited with many discoveries regarding the sequencing and dating of Himalayan stratigraphy.

Middlemiss (Figure 2.2) had pursued.

A few years prior, Middlemiss relocated his field work to the state of Kashmir after the discovery of the Gondwana-based plant Gangamopteris by Eduard Suess, an Austrian geologist. Middlemiss spent the summers of 1908 and 1909 exploring this area, serching for additional indicators of sediment age and succession. He eventually identified exposed layers with the same Gangamopteris and Glossoperis fossils as identified by Suess. These fossils allowed Middlemiss to begin dating and reorganizing the lowest beds of Gondwana across the southwestern region of Kashmir state.

Wadia extended his field research beyond Middlemess and into the northwest regions of Kashmir state. He was impelled by the encouragement that Middlemiss provided, producing a comprehensive map spanning Kashmir and the surrounding northern and southern regions, Indus Valley, and Punjab respectively (Figure 2.3). Theories at the time suggested the Himalayas rose from the sea, where Earth consisted of a solid crust floating above a liquid core (Sorkhabi, 1997; Dutt, 2006). It was only in 1922 following Alfred Wegner's Theory of Continental Drift that Emile Argand, a Swiss geologist, proposed the Tectonique de l'Asie Hypothesis (Sorkhabi, 1997). Argan argued that the Himalayas were created from the continental drift of the Indo-African plate and subsequent continental collision with Eurasia, leading to under thrusting and plastic deformation.

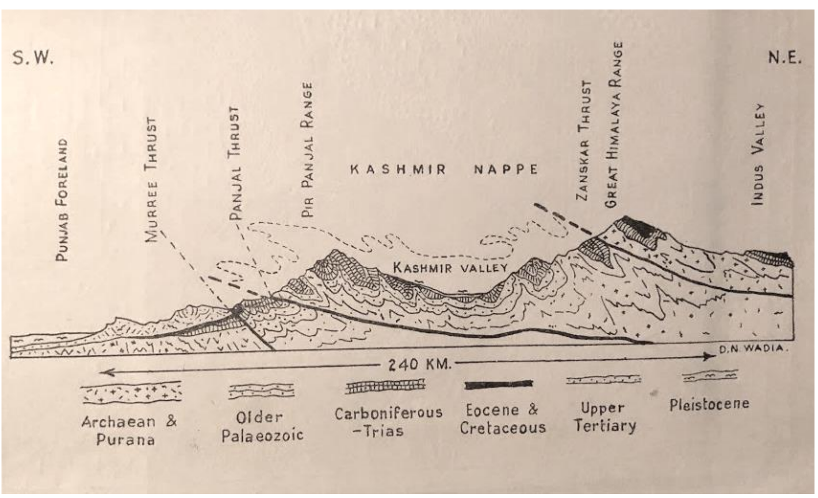


Figure 2.3: A printed map by Wadia during his investigation of the Kashmir Nappes zone. This map is featured in his book, co-authored by W.D. West, titled Structure of the Himalayas.

Kashmir state became a place of particular interest in an attempt to uncover this geological event. While Middlemiss had previously developed an eloquently labelled map identifying the sequence of events, Wadia's rigorous fieldwork brought to light a discontinuity in the stratigraphy previously described as being consistent throughout Kashmir state (Thakur, 2003). This discontinuity entailed a break in marine sediment deposition from 415-310 mya. Alternatively, land deposited sediments were identified containing Indian and other continent land-based fossil, such as the Glossopteris.

These findings provide clarity on the succession of events, shedding light on the validity of Wegner and Argand's theories, which were not well accepted in this time. In subsequent years, Wadia contributed more detailed records on the mechanism behind the creation of the Himalayas, postulating that the arcuate trend-line of the mountains formed from Northward pressures directed from the Gondwana shield against the floor of the Tethyan geosyncline (Fermor, 1945). The research conducted by Wadia in Kashmir was some of the last, with subsequent political and territorial disputes restricting access to the area (Searle and Treloar, 2019).

The Infamous Syntaxial Bend

As an active member of the GSI, Wadia continued investigating the northwestern region of the Himalayas, seeking clarity on key features whose formations puzzled many. A particularly interesting feature was the western syntaxial bend in the Hazara-Kashmir region of the Himalayas. Suess, credited for the discovery Gangamopteris, had also previously drawn conclusions about the history of this region. He theorized it formed during conflict between two different orogenic events, the Himalayas and Hindu Kush Mountain ranges. These opposing forces induced a slight bending of the region, forming the syntaxis as the mountain regions collided (Wadia and West, 1964; Thakur, 2003). Based upon Suess' theory, Wadia should have identified differences in the stratigraphy of the two mountain ranges. However, during his field work in the four years prior to 1931, Wadia uncovered a very different story. Unexpectedly, he observed a continuity between Kashmir and Hindu Kush stratigraphy, refuting Suess' proposed idea (Wadia, 1919). Experience in the field allowed Wadia to conclude there was a single orogenic event, the formation of the Himalayas. Thus, the syntax formed from the bending of the Himalayan mountains around a central mass composed of Pruna and Carboniferous-Eocene rock groups (Wadia and West, 1964). Wadia described this central mass as a tongue-like projection of the Archean Shield in the Peninsular of India. His explanation of the knee bend was then published in his 1931 paper *The syntaxis of the North-West Himalaya,* earning him the 1934 Back Award from the Royal Geographical Society (Wadia, 1931). Wadia's observations and conclusions were confirmed by other geologists, proving vital to understanding the Himalayan orogeny.

First Indian Soil Maps

Wadia was also a pioneer of soil science in India, an area of study previously neglected. In 1935, upon request from the International Association of Soil Sciences, Wadia and other GSI members were selected to complete a soil map of India and Asia (Thakur, 2003). Earlier soil maps created by Voelcker and Leather categorized Indian soil types into four groups: Indo-Gangetic alluvium, black cotton soil, red soil, and laterite soil (Kumar, 2020).

The increased presence of chemists in the field of geology enhanced the caliber of soil sampling and analysis techniques (Tolamn, 2016). This allowed for a rapid production of soil maps as soil samples could be tested in India now, rather than being sent to Britain.

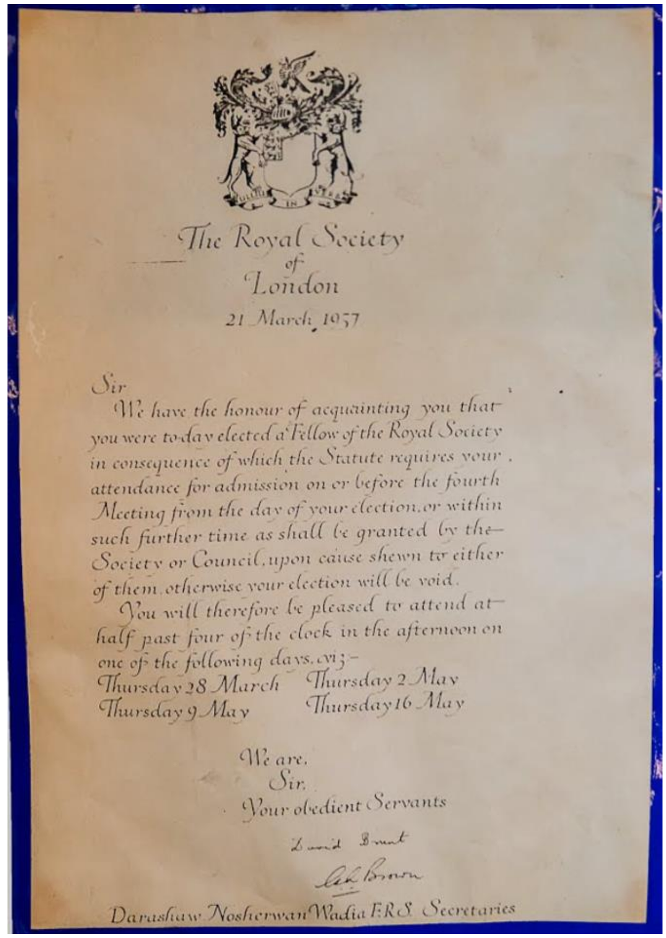
These improved conditions are what allowed Wadia and his collegues to expand upon previous maps, developing new ones that emphasized the connections between soil type and geological features. Their mapping system categorized soils as red, black, laterite and lateritic soils of Peninsular India and the Indo-Gangetic Plains (Kumar, 2020). Wadia's new fixation on soil mapping organizations encouraged others to use increasingly comprehensive methods, approaching this discipline from a similar perspective.

His work influenced the development of the first climate zone-based soil map, created by Vishwanath and Ukil (Bhattacharyya, et al., 2013). They integrated climate conditions with other factors, such as vegetation, to develop a meticulous soil map with 17 soil categories (Kumar, 2020). They also included colour and texture as new classification characteristics to develop a reenvisioned map.

Wadia's forward-thinking was revolutionary, evidently fast-tracking the development of a vital field that proved invaluable for agricultural workers in India. The development of soil mapping is closely tied to Wadia, his critical thinking central to pedology, enriching its economical applications.

Wadia as a Respectable Figure in Indian Society

Wadia possessed many titles throughout his prosperous career, including that of researcher, author, professor, mineralogist, and geological adviser (Stubblefield, 1970; Thakur, 2003; Mudga, 2022). His discovery of fossils, work on the syntaxial bend of the North-West Himalayas, comprehensive soil maps, and textbook has dubbed him the *Father of Indian Geology* (Stubblefield, 1970). He became the first Indian geologist to become a Fellow of the Royal Society, a prestegious award granted by judges at the Royal Society of London (Figure 2.4). Many described Wadia's work to have "a profound influence on a generation of students in geology, attracting them where others might have repelled, and stimulating them to take a keen interest in the subject" (Thakur, 2003).


The Royal Society
of
London
21 March 1957

Sir
We have the honour of acquainting you that you were to-day elected a Fellow of the Royal Society in consequence of which the Statute requires your attendance for admission on or before the fourth Meeting from the day of your election, or within such further time as shall be granted by the Society or Council, upon cause shewn to either of them, otherwise your election will be void.
You will therefore be pleased to attend at half past four of the clock in the afternoon on one of the following days, viz:-
Thursday 28 March Thursday 2 May
Thursday 9 May Thursday 16 May

We are,
Sir,
Your obedient Servants

Darashaw Nosherwan Wadia F.R.S. Secretaries

Figure 2.4: Letter dated March 21, 1957, from the Royal Society England informing Wadia of his selection as a Fellow. He was the second Indian to be selected as a Fellow.

Wadia's efforts in the dissemination of geological knowledge to students, government officials, and everyday citizens is also commendable. He delivered a series of talks on the Minerals Share in War to Congress in 1943 (Tolman, 2016). Wadia pleaded for an international mineral policy that would preserve peace and mitigate tension as talks of a civil war on resources were emerging.

The end of Crown Rule in 1947 demolished India's pre-existing economic, political, and societal structures, leaving the country in disarray (Khan, 2007). The simultaneous partitioning of India caused strife between India and Pakistan over mineral and resource shares. India suffered a great loss of resources, mainly salt and gypsum, when areas such as Jammu, Lahore, and Northwestern Kashmir became a territory of Pakistan. Under these circumstances, the quality and reserves of minerals, alongisde other resources such as coal, were brought to the forefront of the Indian government and citizens. Wadia was made Director of the Bureau of Mines in 1948 to address the issues of mineral conservation and beneficiation post-Independence (Collins, 1966). His wisdom guided India on a path towards self-sufficiency, where he took a nationalistic perspective tempered by international outlook. Wadia's tireless work earned him countless medals including the *Lyell Medal* and the *Joyakishan Medal* from the Indian Association for the Advancement of Science. To further honour Wadia's contributions to society, the Department of Geology at the University of Delhi renamed their institute *The Wadia Institute of Himalayan Geology* in 1976, following his death on June 15, 1969.

Soil Organic Carbon as a Proxy for Climate Change

Modern soil mapping has been an accumulation and refinement of techniques since 1914 (McKeague and Stobbe, 1978). While soil mapping was originally intended to aid in agricultural land planning and infrastructure development, modern applications have broadend its uses to include climate change mitigation.

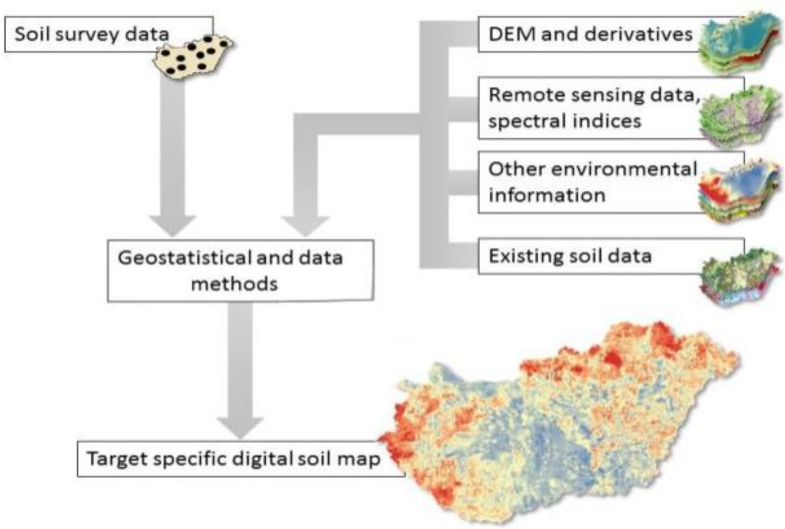


Figure 2.5: A depiction of the Digital Soil Mapping process. Selected covariates and required geospatial data, such as soil samples from previous maps, are inputted into a model. Specifications are applied to produce a 3-D map.

Digital Soil Mapping

Soil mapping is often approached from two perspectives by pedologists: top-down and bottom-up. The top-down approach is most commonly used, dividing soil regions into mutually exclusive subsections based on pre-existing soil properties or means of classification (Ma, et al., 2019). However, this method does not consider the fact that soil regions often overlap, a key property that could drastically influence the planning and implementation of agricultural practices. The opposite is true when using the bottom-up method, where individual soil type subgroups are identified and similarities between these groups allow for them to be grouped together into larger collections (Ma, et al., 2019). While this method results in a more objective and continuous classification system, it requires a significant amount of time and resources to take individual soil samples and compile this data. The top-down strategy is preferred and widely used because of the pressures on time and resources.

Soil quality is also highly influenced by environmental and geological conditions. The modern implementation of covariates into soil mapping allows for more accurate and complex map models to be developed (Figure 2.5). This is vital for implementation of soil maps to monitor climate change progression. Covariates can include factors such as climate, terrain, or geology (Ma, et al., 2019). For pedologists, choosing the covariate that will be most useful for the area of interest poses difficulty due to the plethora available (McBratney, Mendonça Santos and Minasny, 2003). Pedologists use their wide array of knowledge and expertise to adequately decide which covariate(s) work best in the region of interest. However, a level of subjectivity in their decision-making process remains (Ma, et al., 2019; McBratney, Mendonça Santos and Minasny, 2003). *Scorpan* factors are a standardized selection of covariates developed by McBratney, et al. (2003) as an expansion on Hans Jenny's State-Factor model. Jenny's State-Factor model considers climate, organism influence, parent material, relief (topographic factors), and time in soil type categorization. The *Scorpan* factors consider two additional parameters: age and spatial location. This is where the implementation of recursive feature elimination aids in improving the objectivity of selection, resulting in more accurate prediction data (Lorenzetti, et al., 2015). Covariate-based mapping acts as the basis for digital soil mapping

(DSM). DSM mitigates subjectivity present in traditional techniques by relying on mathematical models and qualifiable data to create soil maps (Ma, et al., 2019). This enables the complex calculations required to integrate soil type data with the local and regional environmental data to be performed.

DSM requires pre-existing soil map data and a mathematical model to integrate inputted data with environmental covariates and produce a meaningful soil map (Figure 2.5) (Minasny and McBratney, 2016). *Scorpan* factors can be used with various mathematical or statistical models depending on the context. One example is using covariates in conjunction with a spatial soil prediction function with autocorrelated error.

Soil Organic Carbon

Soil organic matter (SOM) plays a pivotal role in the biological, chemical, and physical functions of the soil ecosystem (Ayala Izurieta, et al., 2021). These functions entail nutrient cycling, soil structure, and water retention. Soils with high amounts of SOM act as carbon sinks, capturing carbon dioxide from the atmosphere and housing it in organic matter. The pool of carbon stored in SOM can be referred to as soil organic carbon (SOC) (Schmidt, et al., 2011). SOM-rich soils also possess improved water retention, accumulating larger amounts of water and depositing them further down the watershed to feed and support ecosystems (Ayala Izurieta, et al., 2021).

Environmental and climatic conditions are key modulators of SOC deposition and accumulation, making them an effective marker for climate change (Sothe, et al., 2022). Warming temperatures have been found to increase the decomposition of SOC at a rate that cannot be adequately compensated by SOC production. The effects of SOC loss are magnified once they enter the atmosphere. It is theorized that a 10% loss in SOC is equivalent to 30 years worth of anthropogenically produced carbon dioxide (Ayala Izurieta, et al., 2021). This often leads to a cycle of increasing temperature, to increased decomposition of SOC, which further contributes to climate change and the greenhouse effect. While the risk of such a drastic increase in SOC decomposition is low, it remains a prevalent issue. Therefore, SOC presents as a vital proxy for climate change and is being implemented into soil map data to monitor the past and predict future climate and environmental changes.

Monitoring Climate Change

Canadian peatlands and permafrost regions contain the second-largest amount of SOC in the world (Sothe, et al., 2022). This makes Canada an excellent location for the implementation of SOC concentration mapping for climate change monitoring. In recent years, machine learning models have been implemented to map the non-linear relations more accurately between SOC concentrations in soils and covariate factors across larger regions (McBratney, Mendonça Santos and Minasny, 2003). Sothe, et al. (2022) investigated the use of machine learning with covariate factors and current SOC measurements to develop a SOC DSM across a wider study area in Canada than ever previously observed. Recursive feature elimination was used to limit their selection of 40 covariates to the most significant ones as determined by the model. Additionally, 20 years of field and satellite information on SOC distribution were implemented. Their model maps SOC concentration at one of six depths and overlays this information with their selected covariates to produce a 3D map (Figure 2.6).

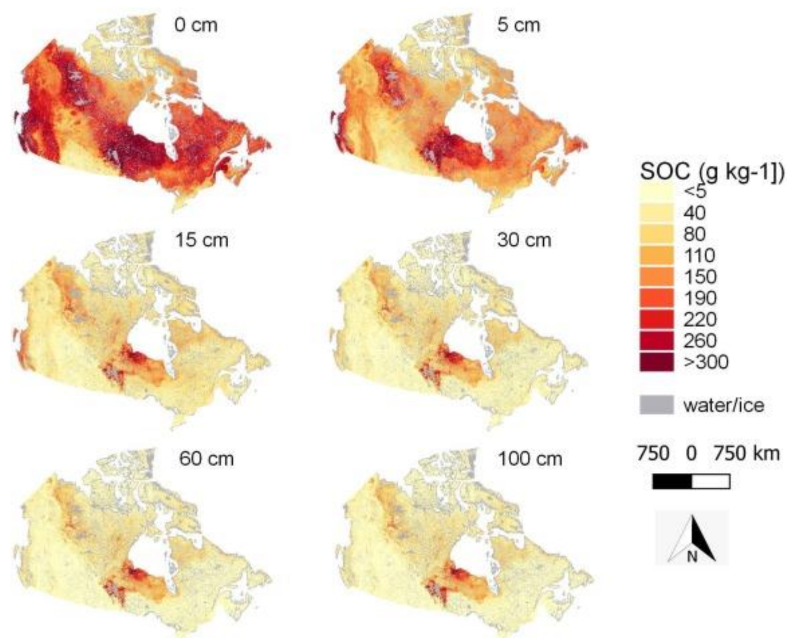


Figure 2.6: The final DSM produced by Sothe et al. in 2022. It features SOC data mapped at 6 varying depths based upon their chosen covariate model.

SOC map data can guide the government in pivotal decision-making processes with regards to climate change. Now, both overarching and location specific improvements can be applied with this technology (Sothe, et al., 2022). This highlights the importance of Wadia's work in India, signifying the advances in soil mapping technology after his passing.

Giovanni Arduino: The Father of Italian Geology

The scientific method turned over a new leaf in the 18th century as society transitioned from the 17th century Scientific Revolution and was propelled into the Age of Enlightenment. During this time, the pursuit of knowledge was at a peak as a shift began. Ideas were formulated based on reason and evidence rather than previous notions of religious dogma. Since science was only beginning to plant its roots, particular branches of science had not yet been differentiated. So, for the Earth sciences, there was no specific geological curriculum to adhere to. Rather, the 18th century fad was to collect minerals and fossils, particularly among the rich and elite (Gibbard, 2019).

Figure 2.7: An early 19th century painting depicting the Deluge by Joseph Turner.

Most of these wealthy fossil collectors paid no heed to the origin stories of such geological products of time and regarded fossil collecting as a hobby. Temporal relationships were also hardly ever considered when investigating the seafloor and other geological structures. The composition of strata was primarily attributed to the Noachian Flood as described in the Bible. The Noachian Flood, also known as the Great Flood and the Deluge (Figure 2.7), stems from the Biblical story of Noah and his ark (Brosseau and Silberstein, 2015). The story describes a global flood sent by God to cleanse the world of sin and begin anew. Through the eyes of early geologists, the Flood was to be credited with catalysing the singular process of sedimentation and stratification on Earth (Vaccari, 2006). This theory of Creationism– that everything natural was formed at the hands of supernatural forces and beings, was largely present well into the 18th century, which is when it began to dissolve (Brossea and Silberstein, 2015). Religious perspectives played a large role in society's beliefs as the ability to communicate science publicly was sparse, as the Industrial Revolution only began in the late years of the Age of Enlightenment.

The spread of the Protestant religion in the 18th century also called for the finding of a lingua franca. A lingua franca, or the language of wider communication, is a language developed to communicate between parties who do not share a mother tongue (Berns and Matsuda, 2020). The lingua franca in Europe until the 1800s was Latin. However, it has been noted that the pronunciation of the language differed so vastly between the English and Italians that it was essentially unintelligible to the other. Thus, Italian was rarely ever seen as a language necessary to learn by the highly influential British (Salmon, 1985). This consequently allowed a greater light to be shone on many English scholars and their publications.

A key character in early geology was Niels Stenson, with Latin alias Nicholas Steno, a Dutch geologist of the late 17th century (Kardel and Maquet, 2012a). Steno began as a pupil of science under the celebrated Thomas Bartholin, the man who discovered the lymphatic system at the University of Copenhagen. Steno's preliminary works revolved around biology; however, a shark dissection motivated him to look into fossilised shark teeth and as a result, turned to the field of geology. Steno spent his scientific career in several European countries, primarily Denmark, but he also studied in France and Italy (Kardel and Maquet, 2012a). In Italy, he published his four most famous stratigraphical discoveries in his 1669 paper, *Dissertatonis prodromus*. This publication was possible because of Steno's ability to read and write in Latin. Steno established the law of superposition, the principle of original horizontality, lateral continuity, and cross-cutting relationships. Of all four principles, the most impressionable was the law of superposition. This law describes that the bottom layer of rock in a sequence is the oldest, with each superposed bed being relatively younger than the rock below it in ascending order (Kardel and Masquet, 2012b). With this, Steno laid the groundwork for future geologists and aided in the rejection of Creationism and the progression of the scientific method.

Introducing Giovanni Arduino

A prominent geologist who helped transition society towards evidence-based discoveries was Giovanni Arduino (1714-1795). Arduino (Figure 2.8) was an Italian geologist credited with the discovery of the three orders which categorise geologic time (Gibbard, 2019). Here, he defined the terms Primary, Secondary, and Tertiary. Arduino was a jack of all trades, he was a mining engineer, mineralogist, and surveyor, with experience in chemistry. Above all, his work as a mining engineer served as a large benefactor to early geology. This mining experience supplied Arduino with insurmountable practical skills and knowledge. For instance, he had hands-on experience with multifarious terrain, each of which held its own intrinsic properties. Arduino was also distinguished among his Italian peers for his aptitude for the discernment of strata arrangement and their respective terrestrial processes. He was also very well known and noted to be in constant demand at foundries, quarries, and mines ranging over northern and central Italy (Ell, 2011a). Through letters designated to Antonio Vallisnieri Junior (1708-1777), Arduino provided a concrete solution to the millennium-long search of categorising a timeline of Earth's rocks and strata (Gibbard, 2019).

Figure 2.8: A medallion of Giovanni Arduino that is preserved in the Venetian Institute of Science.

Predecessors and Contemporaries

Biblical interpretations of mountain origins held steadfast in Italy during the early 18th century. Common interpretations of mountain formation involved God during the Creation or the aftermath of the Deluge (Rappaport). Antonio Vallisnieri Senior (1661-1730), a distinguished medical practitioner and naturalist, was one of the first to propose alternative theories for the origins of mountains (Vaccari). In 1721, Vallisnieri Sr. published his letter *De' corpi marini che su' monti si trovano* or 'On Marine Petrification's found in Mountains', which put forward an explanation for the origins of petrified marine organisms found in the Northern Apennines. In his letter, Vallisnieri Sr. rejected the idea that the Deluge caused the global dissolution and creation of mountains, instead positing that the Biblical flood was a local event made to eradicate humanity and not change the surface of the Earth. Though this was the case, Vallisnieri Sr. and many scientists at the time were still influenced by religious views, as Vallisnieri Sr. also reaffirmed the belief that God made primitive mountains unchanged since the dawn of all things. Regardless, Vallisnieri Sr. played a large role in influencing Giovanni Arduino through his study of the anatomy of mountains or *la anatomia de' monti* (Gibbard, 2019).

While Vallisnieri Sr. was a predecessor to Arduino, Anton Lazzaro Moro (1687-1764) and Giovanni Targioni-Tozzetti (1712-1783) were more akin to contemporaries. Moro strongly opposed the idea that the Deluge was the cause of all present mountains, a belief referred to as Diluvialism (Gibbard). Unlike Vallisnieri Sr. before him, Moro received strong opposition from Italian diluvianists who discredited his work (Vaccari, 2006). Moro was the first to distinctly classify mountains into two categories: *montes primarii* (or *primary* mountains) formed through plutonic activity, and *monticulos secundarios* (or *secondary* mountains), which formed from fragmented materials. Building upon the methods and field-based approach of Moro, Targioni-Tozzetti investigated the regional geology of the Tuscan mountains and attempted to classify them into two units: "primitive" formed from the oldest rocks and "primary" derived from the debris of ancient mountains (Vaccari, 2006). As Targioni-Tozzetti elaborated on his classifications of mountains and wrote his reports in the 1950s, Arduino began to make his seminal discoveries.

Process of Discovery

As a multi-talented scientist with interests in palaeontology, stratigraphy, lithology, and metallurgy, Arduino was always professionally focussed on lithology, mineralogy, and uncovering the mystery of Earth's processes. As such, he earned several diverse job titles and achievements in his lifetime. This success can be attributed to his academic background. He began his education in what we now know as Earth science in Verona but abandoned these studies at the age of eighteen to pursue an apprenticeship in northern Italy as an iron-ore technician (Ell, 2011a and Gibbard, 2019). Through his training, he travelled to many places in northern Italy, most notably Vicenza. In this province, he gained eight years of mineralogical experience which would come to serve him much later in life. Subsequent to the conclusion of his training, he was appointed as an expert and later as an engineer at the Municipal Property Magistrate. His work as a mining and civil engineer resulted in the culmination of his two famous letters where he inscribed the four orders of geological time (Gibbard, 2019).

It is important to note that Arduino's story is often left in its abridged version because his original observations are in Italian, which limited its accessibility. With many European scientists being concentrated in Britain, it was an arduous endeavour to find a community of like-minded individuals of the same school of thought. As such, Arduino kept in constant communication with Antonio Vallisnieri Junior, who was responsible for the publication of his letters (Vaccari, 2007). Antonio Vallisnieri Junior was the son of the famous Antonio Vallisnieri Senior who published *De' corpi marini che su'monti si trovano* in 1721. As mentioned previously, he postulated that fossils were accumulated along the seafloor over time and as such, are the product of several processes temporally rather than the result of one catastrophic event. After the death of his father, Vallisnieri Junior donated his father's entire library to the University of Padua where he was offered a personal chair and designation as curator of the collection (Ell, 2011a).

Arduino and Vallisnieri were interdependent on one another, from Arduino's perspective, he relied on Vallisnieri as a distinguished curator to discuss his findings. Conversely, Vallisnieri relied on Arduino to observe and collect samples of minerals he encountered. This partnership birthed the publications which named Arduino the Father of Italian geology. These letters hold observations built upon theories from Arduino's predecessors like Steno and his law of superposition and Giovani Targioni-Tozzetti, who proposed that the landscape in Tuscany was separated into three primary strata: mountains, hills, and plains (Ell, 2011a). These two figures were highly influential to Arduino and what he wrote in his time surveying the mountains of Tuscany. Mountains were the central subject of study in

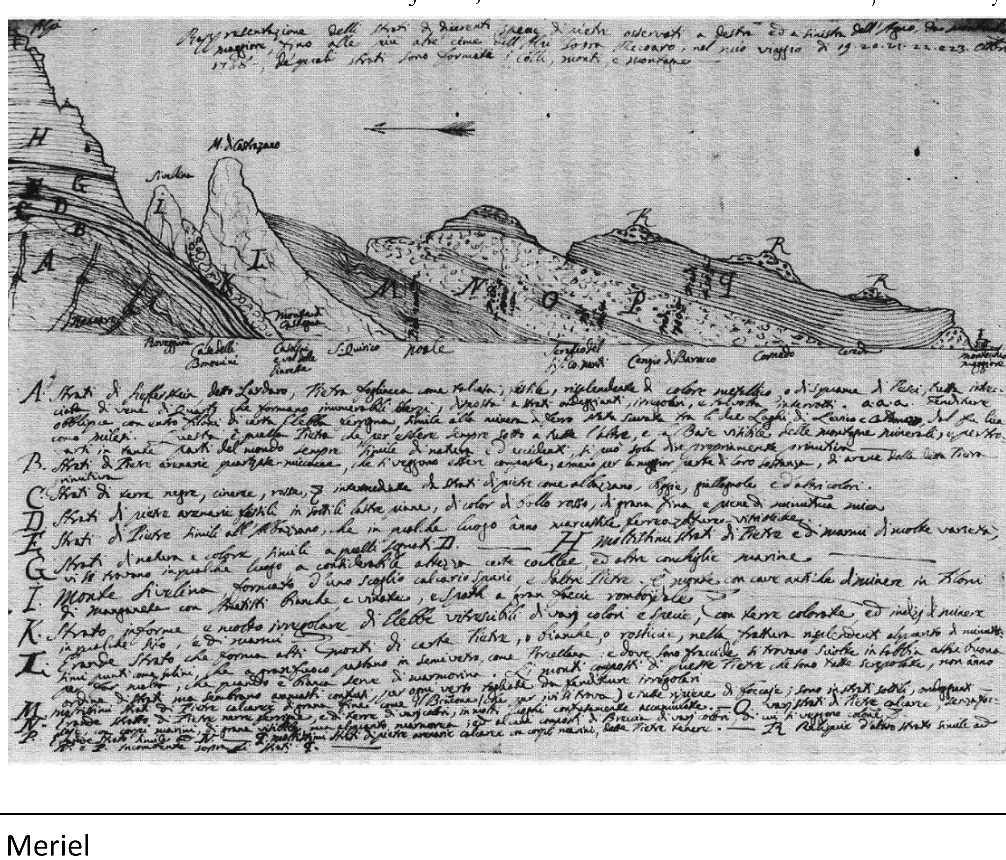


Figure 2.9: A cross section of Agno Valley, Vicenza, Italy. Label A identifies the first observation of the Primary rock.

chronostratigraphy, especially in mountainous countries like Italy. Due to this, Targioni-Tozzetti and Arduino both surveyed the famous mountain ranges in northern Italy: The Alps and the Appeninnes. In Arduino's famous 1760 publication *Due Lettre,* Arduino described the four *ordini* (orders) of rock: *primari*, *secondari,* and *terziari,* which described different parts of mountain. The *quatro* (fourth) unit he discovered, described the terrain of the alluvial plain (Arduino, 1760).

In his second letter, Arduino goes into greater depth on these findings (Ell, 2011b). The primary layer was originally described as a fissile rock and contained metallic flecks which resembled fish scales. Sometimes interbedded within this iron-containing rock were veins of white flint. We have presently come to know that this rock is schist which contains mica and quartz. Arduino also notes that this primary, or primitive layer of rock was consistently the base rock of all the mountains he surveyed. Arduino split this First Order into two subcategories: Primitive and Primary (O'Hara, 2018). Primitive rock contained many metal ore deposits, whereas Primary rock was superimposed and contained sandstones, conglomerates, and granite. The Secondary order was highly fossiliferous and contained limestone deposited from the great Mesozoan marine sedimentation. The Tertiary order contained limestones, sandstones, clays, conglomerates, more recent fossils, and dust which originated from the decay of the Primary and Secondary layers (O'Hara, 2018). The fourth order, which was given the name Quaternary by Arduino's geological successors, includes all the plains and the associated deposited minerals from water movement (Ell, 2011b). However, these descriptions of the beginning three orders were merely replications of past findings. Arduino was truly novel in just one aspect of his cross-section of the Agno Valley in Vicenza, northern Italy (Figure 2.9). He correctly identified the oldest visible strata, as a regional base layer of the Italian mountains (Ell, 2011b).

However influential Arduino's letters were, issues still arose from their publication. Vallisnieri published them in their original prose, and not as a treatise (Ell, 2011a). A treatise is a formal discourse on a particular subject, so the only account of Arduino's original observations was delivered informally. Often, if another scholar wished to read the publication, they would be tediously tasked to manually extract the important pieces of information to understand its contents. Alongside this, there contained many sporadic breaks in thoughts which were left incomplete. Other than this evident language barrier, the largest impediment to Arduino's lack of continental popularity is due to his original work being obscured. This was at the hands of Swedish mineralogist Jakob Ferber (1743-1790), who was responsible for both the dissemination of Arduino's findings and the detachment of Arduino from his original work (Ell, 2011a). Ferber reproduced Arduino's letters and recognized Arduino but left the idea that he was the primary contributor as an afterthought. Ferber's version was translated into German, French, and English which increased the accessibility of this information. However, Arduino had intentions of later reproducing his work as a treatise, but Ferber robbed him of this opportunity (Vaccari, 2006). Instead, Arduino's observations and ideations were told without their original context, a crime of reporting science without its historical context. This obstruction of the original letters omitted other of Arduino's findings and failed to make Arduino a household name.

Arduino's Legacy

Giovanni Arduino was most noteworthy for his predisposition to recognizing and understanding key differences in the Earth's strata. His steadfast devotion to the field of geology acquired him many esteemed titles, like land surveyor of Vicenza in 1750, engineer of the Municipal Property Magistrate, and agricultural superintendent of the Republic of Venice from 1769 to his death (Gibbard, 2019). Just like scholars Steno and Targioni-Tozzetti paved the way for Arduino, he paved the way for Jules Desnoyers (1800-1887) and Charles Lyell (1797-1875). Desnoyers properly proposed Quaternary order by studying sediment in the Seine valley Arduino's establishment of the Primary, Secondary, Tertiary, and an unnamed fourth order, facilitated a seamless integration of Desnoyers' Quaternary.

Arguably one of Arduino's most famous geological successors was Charles Lyell of England. Arduino passed away two years prior to the birth of Charles Lyell, a Scottish geologist of the late 18th century. Arduino's Tertiary order played a central role in Lyell's scientific career. Lyell most famously divided the Tertiary order into the Pliocene, Miocene, and Eocene epochs, having used Arduino as his foundation (Berggren, 1998 and Virgili, 2007). This next generation of geologists proved to be evidence of Arduino's contributions to the growing branch of stratigraphy. What is most bittersweet about this success was that Italian geology did not produce any prominent figures until the next century following Arduino's death. Though *Due Lettre* is a celebration of Italian scientific discovery and innovation, Arduino's full narrative of his discoveries may never reach a broader audience. Though Arduino's letters have never been republished since his original 1760 work, by following his story, we can celebrate the beginning of the scientific narrative becoming diversified.

The Geologic Time Scale in the Modern Age

Our understanding of the geologic past and the techniques we use to establish a geologic history have changed drastically since the discoveries of Giovanni Arduino. The primary, secondary, and tertiary divisions that Arduino wrote of have been revised and expanded upon, and the usage of these terms to describe geologic periods has become inaccurate. The broad ideas of the geologic past in Arduino's time have been replaced with more specific categories, including aeons, eras, periods, and epochs.

The Geologic Time Scale

The geologic time scale (GTS) is a representation of time using the rock record; it is the fundamental method we use to comprehend the history of Earth (Gradstein, 2012a). The GTS and any alterations made to it are managed by the International Commission on Stratigraphy (ICS). The ICS is a formal international body that defines the precise global and stratigraphic units that make up the time scale (Shields, et al., 2021). The construction of the GTS involves the synthesis of a chronometric, or time-based, scale and a chronostratigraphic scale that relates rock strata to time (Gradstein, 2012a).

The chronometric scale does not allow for a formal definition of a geologic period on its own (Robb, et al., 2005). Periods that are defined solely chronometrically lack the geological context that would give them distinctive characteristics and are recognized only by their place in time. The boundaries for these periods that are defined using exclusively geochronology are designated as Global Standard Stratigraphic Ages (GSSAs) (Gradstein and Ogg, 2012). Conversely, chronostratigraphic boundaries that can be physically and chronometrically determined have a precise reference point known as a Global Boundary Stratotype Section and Point (GSSP) (Gradstein and Ogg, 2012). GSSPs represent the point in time when a specific stage of rock succession began. GSSPs are usually found in a primary location but must be globally correlative (Waters, et al., 2018). Additionally, GSSPs must be defined by some readily observable physical change in the boundary, such as chemical changes or differences in the fossil content of strata.

Modern Geochronological and Chronostratigraphic Methods

The creation of the GTS involves various methods that allow for the dating and correlation of ancient strata. Establishing the chronometric scale of the GTS relies on absolute geochronological techniques such as radiogenic isotope geology (Gradstein, 2012a). With this temporal framework, stable isotope chronostratigraphy and biochronology can more accurately correlate sediments (Gradstein, 2012a).

Radiogenic isotope geology, or radiometric dating, allows for absolute dating based on the naturally occurring radioactive isotopes found in rocks (Dickin, 2018). Radiometric dating compares the abundance of the parent isotope to its decay product which forms after a time indicated by specific decay constants (Dickin, 2018). Radiometric dating methods and their applications vary based on the identity of the isotopes. Uranium-lead (U-Pb) dating is one such dating scheme and is often referred to as the gold standard of geochronology because of its precision and accuracy (Schmitz, 2012). U-Pb dating involves the decay of the isotopes ^{238}U and ^{235}U into radiogenic lead isotopes ^{206}Pb and ^{207}Pb respectively (Dickin, 2018). The half-life of ^{238}U is comparable to the age of the Earth, while the half-life of ^{235}U is much shorter at 704 Ma (Dickin, 2018). U-Pb decay allows for the dating of meteorites and Zircon rocks that can be 4.4 billion years old (Figure 2.10). Zircon rocks are usually dated with U-Pb as they naturally incorporate Uranium during their formation and reject lead, making them a closed system where all Lead isotopes are radiogenic (Dickin, 2018).

Stable isotope stratigraphy compares the abundance of non-radiogenic fractionated isotopes of one element, which can indicate the relative age of a rock and allow for correlation based on the environment that formed it (Sharp, 2007). The advantage of this method is its potential to allow for further differentiation of geological periods and stages within the constraints set by radiometric dating (Shields, et al., 2021). Strontium isotope stratigraphy compares the ratios of $^{87}Sr/^{86}Sr$ in the world's oceans through biogenic marine minerals. Fluctuations in strontium ratios are caused by crustal processes, with high ratios indicating periods of supercontinent amalgamation and low ratios indicating supercontinent separation (Shields, et al., 2021). Strontium isotope ratios can be correlated to other marine strata or calibrated to standard curves to determine a numerical age and place in the GTS (McArthur, Howarth and Shields, 2012). This method relies on materials such as foraminiferal calcites for Neogene analysis and brachiopod shells and calcified trilobites for Mesozoic and Paleozoic analysis (McArthur, Howarth and Shields, 2012). Analysis of Precambrian $^{87}Sr/^{86}Sr$ ratios is limited by sufficiently preserved materials, but solutions have been found with the usage of early diagenetic marine cement (Kuznetsov, Semikhatov and Gorokhov, 2018).

Biochronology is another modern method used in time-scale construction and is a developing succession of biostratigraphy, which has seen use since the 18th century (Gradstein, 2012b). It is the organisation of geologic time according to observed evolution in the paleontological record. This method correlates fossil assemblages not tied to stratigraphic sections, where biostratigraphy requires stratigraphic comparison. With aims to accurately identify intervals of geologic time, biochronology utilizes the first appearance and last appearance of fossils found in a rock sequence. The full potential of this method is not yet achieved due to imperfections in the paleontological record, but with further advancement, biochronology can generate a network of fossil correlations that can improve the accuracy of the GTS (Gradstein, 2012b).

Improving the Precambrian Time Scale

The Precambrian, which encompasses the Hadean, Archean, and Proterozoic, is an area of the GTS that is heavily critiqued by geologists. Currently, the Archaean and Proterozoic time scales are subdivided into eras and periods based solely on chronometry, making them GSSAs that have not been formally defined (Robb, et al., 2005). The Ediacaran period is the only GSSP in the Precambrian due to its well-preserved fossil record in Australia and (Bleeker, 2005). The boundaries between the Archean and Proterozoic eras in the current iteration of the GTS cannot be located in the stratigraphic record, meaning absolute dating is the only method for determining numerical ages for the Precambrian. This reliance presents an issue due to the 5-10 Ma uncertainties that come with even the most theoretically accurate U-Pb dating (Bleeker, 2005). Achieving a consensus on Precambrian GSSPs is not achievable currently due to shortcomings in the fossil record and other complications (Shields, et al., 2021). However, recent literature has proposed templates that replace Precambrian GSSAs with more precise intermediate chronostratigraphic units using strontium and carbon isotope ratios. This template will retain the existing period names we see in the most recent GTS, but by replacing the GSSAs with rock-based subdivisions, future improvements to the Precambrian time scale will be assisted and encouraged (Shields, et al., 2021).

Figure 2.10: Zircon crystals nestled in a mass of quartz and biotite mica.

The geologic time scale is the culmination of many geologic methods and discoveries over centuries. However, there remains room for improvement and innovation in this monumental task which is the geological organisation of the history of the Earth.

Ibn Sina: A Pioneering Geologist

Though there is much debate on who is most deserving of the title "Father of Geology", some would say that it belongs to the Persian philosopher and scientist Ibn Sina (980 – 1037 CE) (Gutas, 2016). Ibn Sina's work built off Greek philosophy, adding an Islamic perspective through his study of the Quran to combine religion and science in his highly regarded theories. While his contributions to the field of geology are of particular interest, his studies spanned every facet of the theoretical sciences, including physics, mathematics, and metaphysics, as well as the practical sciences, covering ethics and politics (Gutas, 2016). Ibn Sina's intellectual advancements dominated Islamic literature for centuries after their publication, etching his influence permanently within their pages.

Early Life

Figure 2.11: Imaginary rendition of Ibn Sina, Persian philosopher and scientist considered by some to be the Father of Geology.

From the mountains of Hindu Kush to the Zagros range lies Iran, a land as beautiful as it is prosperous. Iran has had many empires rise and fall before it, yet every time the nation is left standing, growing in its knowledge and prosperity. As the Muslim conquest of Persia (633 - 656 CE) took place, Islam's influence sparked a hunger for knowledge spanning from philosophy to geology (Akram, 2018). Men and women alike began searching for the answers to the mysteries of the earth, dedicating their lives to the pursuit of knowledge. Of these scholars came Ibn Sina (Figure 2.11). Today, glimpses of his life are seen through the autobiographical sketch he handed to his disciple, Al-Juzjani (Goodman, 2013). However, like many Islamic scholars, Ibn Sina kept this sketch very brief and excluded specific details that to this day are left unknown. In the small Persian village Afshana, Ibn Sina was born to a father, Abdallah, who came from Balkh, and a mother, Sitarah, in 980 CE (McGinnis, 2010). At the time, the reign of Nuh ibn Mansur (976 - 977 CE) fell upon one of the great Persian empires, the Sumanid Dynasty, in its capital, Bukhara; like his father, Ibn Sina served under his rule. After his brother's birth, they moved to Bukhara where Ibn Sina first touched the Holy Quran and was assigned a teacher who taught him adab – Islamic etiquette. Due to his young exposure, by the age of ten, he had mastered such sophisticated literature (McGinnis, 2010). At a time when many sects within the Islamic nation were rising, one in particular, the Ismaili sect, was considered an outcast (Goodman, 2013). Ibn Sina's father was highly involved in the establishment and growth of the Ismaili mission, a role that required intellect and much debate. By overhearing his father's discussions on the Ismaili movement, Ibn Sina got his first exposure to the nature of the soul and the mind (Goodman, 2013).

Other topics of interest to the Ismaili movement such as, philosophy, geometry, and Indian arithmetic, also had a great deal of influence on the young scholar (Goodman, 2013). It wasn't until later in his life that Ibn Sina started to discover the depths of geology through the scripts of Aristotle. Though his interest in the field of geology was due to many factors, much of the credit was owed to his past teachers, who first inspired him to question the earth's processes from a young age (Goodman, 2013).

Islamic Civilization and Its Influence

"Are those equal, those who know and those who do not know? It is those who are endued with understanding that received admonition" (Qur'an: 39:9). This is one verse of the many within the Quran that changed the perception and understanding of science for Ibn Sina and his fellow scholars within the Islamic civilization. These verses and hadith – collected traditions of the Prophet Muhammad (PBUH) based on his sayings and actions – were used as an inspiration due to their emphasis on the value of knowledge (Renima, Tiliouine and Estes, 2016). Many Muslims started to question the mere existence of what was around them and with every new discovery, they believed themselves to be closer to Allah - God (Lapidus, 1992). In the long-debated battle between religion and science, the two coexisted during this era. The scholars of the Golden Age used the teachings of the Quran to inform their scientific pursuits, building theories around the word of their Lord (Lapidus, 1992).

As the sun struck the mountains of Baghdad in 750 CE, this marked the beginning of not only the Abbasid Caliphate (750 CE -1258 CE) but also of the Islamic Golden Age (Renima, Tiliouine and Estes, 2016). As Europe entered the Middle Ages (500 CE - 14th Century), the Islamic world started to apply the scientific method which would be used for centuries to come (Renima, Tiliouine and Estes, 2016). The Abbasid Caliphate ruled over the Arabian Peninsula, the Mediterranean, and North Africa with the capital of the caliphate being Baghdad (Kennedy, 2016). In Baghdad, the Caliph embraced inclusivity and started the House of Wisdom, where many Christians and Jewish scholars came to share information with their Muslim counterparts, translating their work into Arabic (Figure 2.12) (Kaviani, et al., 2012). Many Golden Age scholars including Ibn Sina had their work published within the four walls of this sanctuary (O'Connell, 2010). The drive for scholars like Ibn Sina was based on several factors including the guidelines of the Prophet (PBUH) and the Quran (Falagas, Zarkadoulia and Samonis, 2006). With the words of their Prophet a mantra in their hearts, these religious scholars made advancements in mathematics, philosophy, chemistry, astronomy, and medicine (Falagas, Zarkadoulia and Samonis, 2006). The aftershocks of the revolutionary work in this period are still felt today as their theories carried through every civilization and were built upon by the most illustrious scholars.

Figure 2.12: Thirteenth century painting of scholars in the library of the House of Wisdom in Baghdad.

Modern science was shaped by the names of this age, and at its forefront was Ibn Sina. This era allowed Ibn Sina to publish books including the Kitab al-Shifa (1023) – The Book of the Remedy (Tirmizi, 1982). This book includes the vast array of geological processes examined by the Golden Age philosopher and is considered to be a precursor to the concepts of uniformitarianism, catastrophism, and gradualism (Al-Rawi, 2002). As every great era comes to an end, the Islamic Golden Age buckled under pressures from surrounding civilizations. With the fall of Baghdad (1258), the once so flourishing House of Wisdom was burned down, a symbol of finality for the Golden Age (Mayer, 2017). As an affront to the most fundamental tenet of Islam, books filled with the writings of the greatest minds of the generation were thrown into the Euphrates River, turning its blue waters black with ink (Mayer, 2017). However, the beauty of knowledge is that it can never truly be erased, and the ideas of this time were passed around the globe for centuries.

Geology Before Ibn Sina

During Ibn Sina's lifetime, religion governed scientific thought, limiting the exploration of the natural world in the Middle Ages (Oldroyd, 1996). At this time, scientific discovery was only valid if it aligned with the teachings of the Church. St. Augustine (354 to 430 CE), a saint of the Catholic Church, proposed through his analysis of biblical scripture that there is a 6,000-year period for earth's history, rendering any theories of the natural world that extend beyond this timetable unthinkable (Oldroyd, 1996). As geography and geology were not matters of interest to the Fathers of the Church, they directed their attention toward the study of astronomy. While the Ancient Romans were at the forefront of the study of geography, the fall of the Roman Empire ended these advancements. This caused the neglect of all sciences, especially natural sciences, during this era, leading to a vacuum of scientific discovery many refer to as the Dark Ages (Oldroyd, 1996).

The only solace came from the Greek philosopher Aristotle (384-322 BC), as his work on natural philosophy was eventually incorporated into the teachings of Christianity by the twelfth century (Grant, 2004). The most recognized and debated ideas in earth science were derived from Aristotle's book Meterologica (350 BC) (Oldroyd, 1996). In this book, Aristotle discusses early ideas of the water cycle, rocks, natural disasters, and minerals. While the Church accepted his view of the Earth as the centre of the cosmos, they rejected many of his other theories as they clashed with the teachings of the Church. In the midst of this battle between science and religion, the Muslims became the heirs to Greek philosophy, with Ibn Sina at the forefront (Oldroyd, 1996). In response to a request by his disciple, Al-Juzjani, Ibn Sina commented on Aristotelian philosophy to clarify his theories and add his own (Adams, 1938). This manifested in his book *Kitab al-Shifa*, where he has a section on *The Causes of Mountains* that elaborates on his theories of the natural world. In this book, he shares ideas on rock formation, mineralogy, mountain building, and earthquakes, many of which form the basis of modern geologic theory (Adams, 1938).

Ibn Sina on Rock Formation and Mineralogy

While the Greeks did not concern themselves with the mechanisms by which rocks are created, simply viewing them as objects to mine for their own use, Ibn Sina took a chemist's stance by building proto-chemical theories on mineralogy and rock formation (Oldroyd, 1996). These advancements in the study of mineralogy came at an appropriate time, fulfilling the industrial requirements of the Arab and Persian empires. The Greeks made passive observations of rock properties, noting their lustre, colour, and form, but Ibn Sina sought to understand the reasons behind these external characteristics (Oldroyd, 1996). This desire stemmed from his philosophy on causality, where every event or entity must have certain agents which bring it into effect (Morewedge, 2015). In fulfilment of this philosophy, he brought insight into the cleavage, hardness and internal chemistry of rocks (Brown, 1964). Ibn Sina's affinity for mineralogy expanded Aristotle's theories on rocks, taking them from the abstract categorization of "stones" to their distinction into four categories: stones, sulphur minerals, metals, and salts (Brown, 1964).

Ibn Sina's interest in the study of the earth began with a river he encountered in his childhood, the river of Oxus (Mandeville and Holmyard, 1927). In *Kitab al-Shifa*, he reflected on the clay deposits he saw at a young age turning into a soft stone over the course of 23 years. This observation sparked his two theories on rock formation: conglutination and congelation. He termed his observation of hardening clay as conglutination, where clay dries first into an intermediate between soft clay and stone, which he calls soft stone, then into its final form as a stone (Mandeville and Holmyard, 1927).

His second theory on the formation of stones he called the congelation of waters, where he believed water can petrify into rock through two processes: one involving dripping water and the other running water (Adams, 1938). In the first, water immediately solidifies as it drips down and makes contact with the ground, resulting in the formation of various rocks and pebbles. Ibn Sina believed that it was a petrifying quality of the ground that allows this to happen, though he admitted the exact reasoning was still unclear to him. In the case of running water, Ibn Sina's philosophy was more accurate to modern earth science. His theory involved the deposition of sediment from running water onto the bed of the channel, where it then solidifies into rock. Once again, he attributed this phenomenon to the ground's ability to solidify rock, a theory just shy of the cementation process we know to be true today (Adams, 1938). He also mentioned heat is a factor in this process, drying the moisture in the earth to create rocks (Mandeville and Holmyard, 1927). Interestingly, he specifically stated that rocks cannot be formed from solid earth, as its dryness will result in the rock crumbling instead of solidifying into a singular structure. Analyzing his theories on rock formation, it is fascinating to note they have a common theme in the presence of water, stemming from his first observation in the banks of Oxus (Mandeville and Holmyard, 1927).

After establishing his theories on stones, Ibn Sina advanced to his more notable study of mineralogy, examining not only the process of mineralization, but also their potential for medical treatment (Darbandi and Taheri, 2018). His early work theorized that mineralization involved the petrification of plants and animals in certain stony regions or during earthquakes and the subduction of land (Adams, 1938). In his encyclopedia Canon of Medicine (1023), Ibn Sina delves into the medicinal properties of sulphur-bearing minerals (Darbandi and Taheri, 2018). He began his investigation of this theory through his classification of alum (hydrated sulphates of aluminum and an alkali cation), evaluating their solubility, hardness, and colour. Ibn Sina differentiated minerals into soluble salts and insoluble, oily sulphurs, as well as into malleable metals and non-malleable stones. Using these properties, Ibn Sina was able to differentiate varying hydrated sulphate minerals, as well as reveal their uses in treatment ahead of every scientist of his time (Darbandi and Taheri, 2018). He found that the mineral alunite is the most astringent, followed by jarosite then melanterite (Darbandi and Taheri, 2018). He prescribed alum for itching, lice, and as a natural deodorant. Today, just as Ibn Sina found, alum is used in deodorant, mouthwashes, and in treatment for stomatitis and pharyngitis for its astringency (Darbandi and Taheri, 2018). Ibn Sina revolutionized the field of mineralogy, proving his genius over his Greek and Roman counterparts by admonishing their attempts to turn base metals into gold (Mandeville and Holmyard, 1927).

Ibn Sina on Mountain Building

In his book Kitab al-Shifa, Ibn Sina shared his ideas on mountain building, a branch of natural philosophy not yet ventured into by any other scientist at the time (Al-Rawi, 2002, p.1). As a precursor to the current theories on mountain building, he attributed mountain formation to two causes, one essential and the other accidental (Adams, 1938). The essential cause involved earthquakes that he believed uplifted the ground and created mountains. In the accidental cause, the erosive forces of wind and floods cause valleys to form in the soft rock where the current flows through, creating a mountain at its edge (Adams, 1938). This reasoning aligns with French naturalist Georges Cuvier's theory of catastrophism (1826), in that violent, sudden events in the earth's history create the geological phenomena seen today (McGrew, Alspector-Kelly and Allhoff, 2009). Ibn Sina theorized that mountains themselves were formed through a process similar to rock formation, with the solidification of agglutinative clay that was exposed at shorelines after the retreat of the sea (Oldroyd, 1996). This reasoning was rooted in ideas analogous to that of James Hutton's principle of uniformitarianism (1785); by looking at the mountain ranges of Iran, he proposed that they formed from a process similar to the rock formation he had observed millions of years ago (Ghasemnezhad and Hosseinzadeh, 2014). This fact is evidenced by the presence of fossils found inland. Ibn Sina attributed this formation to both the heat deep beneath the sea and the properties of the clay creating favourable conditions for rock formation (Adams, 1938). The scientist even named the process of rock layers forming on top of each other a sedimentary process, referring to the repeated petrification of clay to form tall mountains (Figure 2.13) (Adams, 1938). The concept that continuous repetitive action results in mountainous landforms subscribes to the school of thought known as gradualism, later established by James Hutton in 1788 (Huggett, 1999). These early ideas also allude to the law of superposition of strata proposed by Nicolas Steno centuries later in the 17th century (Oldroyd, 1996). Along with this process, Ibn Sina used his observation of rock strata to theorize that there is a stage of disintegration of mountain strata by the action of floods running over the land or strong winds (Adams, 1938). This erosion would then create the sediment that formed the clay on sea floors. Maintaining his religious views, he wrote that the mountains were built and eroded down by the will of God instilling these processes. This view is a perfect example of the way Ibn Sina and other Golden Age Scholars combined Islam and science. They researched and theorized on scientific concepts, but believed they are in existence due to the will and power of God (Adams, 1938).

Figure 2.13: The Alborz Mountains of Iran; just one of the mountain ranges Ibn Sina observed as the basis of his mountain-building theories. The visible strata inspired his ideas on superposition centuries before its discovery by Nicolas Steno.

Ibn Sina on Earthquakes

Drawing from Aristotle's theories, Ibn Sina wrote of his own perspectives on earthquakes and their causes (Baffioni, Avicenna and Rāzī, 2011). In agreement with Aristotle's philosophies, Ibn Sina proposed that earthquakes were caused by the movement of wind within the earth known as a wind body (Mandeville and Holmyard, 1927). In turn, this wind would shift the components beneath the earth and create earthquakes. Also in line with Aristotelian philosophy, he discussed the possibility of a fire body causing the same effect. His inspiration from Aristotelian thought ends there. He expanded on this theory by proposing water bursts from the earth as an earthquake occurs, providing the water sources seen on the earth. Ibn Sina's second theory on the cause of earthquakes takes place above the earth; an idea which he attributed to the Greek philosopher Anaximenes (600 BCE). This theory involved mountains breaking into pieces that collide with the earth and create earthquakes. As a nod to the current ideas on earthquake magnitude, Ibn Sina recognizes that earthquakes vary in their strength and length due to persisting shocks (Baffioni, Avicenna and Rāzī, 2011).

Ibn Sina's Influence on the Christian West

As the knowledge of the Golden Age of Islam was spreading throughout the Muslim world, it also found its way to the Christian West. Around the year 1150, the Middle Ages reached its height and many of the scholars' work started to spread across the Western World (Aboussouan, 1969). Among these scholars was Ibn Sina, who contributed both his philosophical and scientific texts. This great Persian thinker provided a gateway for the people of the west to study science as his work introduced a complete, organized approach to the sciences (Nasr and Leaman, 2013).

As all 335 of his works reached western Europe, Ibn Sina was eventually known for more than just his philosophy, which had a great impact on the development of knowledge in the Western World (Aboussouan, 1969). His work was presented beautifully, as if it were a piece of Persian tapestry, with each thread opening a new avenue of thought. Ibn Sina was held in such high regard by Roger Bacon (1214-1294) and others of the Franciscan school that his work remained the standard textbook in all the universities of Europe for 600 years, up until the 18th century (Nogales, 1980). Among these many textbooks are those of geology, which allowed for European thought surrounding earth's processes to expand beyond simple observations toward questioning and reasoning. Ibn Sina is known for the restoration of interest in Greek culture and philosophy in Europe, eventually terminating the Middle Age (Brown, 1964). He was regarded as one of the main sources of geological knowledge for the Latin Middle Ages with the principal book of reference being the Kitab al-Shifa translated by Alfred of Sareshel into Latin (Otte, 1972).

The *Kitab al-Shifa* was used by many honourable scholars in the west. Notably known as the great encyclopaedists of the thirteenth century, Albertus Magnus and Vincent de Beauvais understood the basic principles of geology from Ibn Sina's work (Falagas, Zarkadoulia and Samonis, 2006). Their mention of the motions of the sea, erosion, and the origins of mountains are simply repetitions of Ibn Sina's doctrines (Falagas, Zarkadoulia and Samonis, 2006). To further expand on his influence, his contribution to the study of mineralogy alone was revolutionary for the study of geology. Ibn Sina's classification of minerals was adopted into the European study of mineralogy in the Middle Ages through the Renaissance, until the 19th century (Sadykov, 1980). As further evidence of his influence, the very first classification of minerals by chemical composition introduced by Torbern Olaf Bergman of Sweden in 1780 was an exact replica of Ibn Sina's work. Bergman had synonymously sub-divided all minerals into Sales – salts, Terrae – earth and stones, Bitumine – hydrocarbons, and Metalla – metals (Sadykov, 1980).

Though these are only some examples of his influence among many, they show just a fraction of the far-reaching effects Ibn Sina had on the pursuit of knowledge in the Renaissance and beyond, particularly in the Christian West.

Mountain Building: A Modern Approach

Through studying Ibn Sina's contributions to the world of geology, we can sequence his work as a series of ideas building up to his theories on mountain building. Geology is a subject that builds on past ideas, with each new theory a continuation of those that came before (Brown, 1964). Thus, Ibn Sina's work must not be disregarded as of the past; it served as a crucial precursor to our modern understanding of mountain formation (Brown, 1964). Modern thought on tectonic uplift and plate collision branched out from Ibn Sina's proposal for similar phenomena. Therefore, a thorough analysis of mountain building through a modern approach is necessary to appreciate how far our understanding has come.

Continental Drift

One widely accepted theory on mountain building is that of the German meteorologist, Alfred Wegener (1880-1930) (Greene, 1984). Wegener's continental drift theory was one that shocked the world, as it involved the very continents that make up the Earth actively moving beneath us. This theory states that around 300-200 Ma, the continents were all a part of a single supercontinent known as Pangea (Runcorn, 2013). His argument was supported by the shape of the countries which presented themselves as a jigsaw puzzle. More concrete proof was established later, taking into consideration comparative fossil evidence and climactic evidence across the globe (Chander, 1999). Comparative fossil evidence pertains to the fact that fossils of similar species of plants and animals are found in rocks of similar age on the shores of different continents (Hallam, 1972). This alludes to the fact that the continents were once conjoined and housed these plants and animals before drifting apart. Comparative climactic evidence traces glacial activity, where Wegener found evidence that the Permo-Carboniferous ice sheet once covered all the southern major plates through the analysis of its glacial till deposits (Yount, 2009). Though Wegener's theories are accepted today, it was not until the 1950s that paleomagnetism was introduced and provided further evidence that continental drift became more widely accepted (Rezanov, 1968). Continental drift forms the basis of our understanding of plate tectonics and the formation of mountains.

Plate Tectonics

Plate tectonics claims that the earth's crust and upper mantle, which make up the lithosphere, are broken into several rigid plates (Pichon, Francheteau and Bonnin, 2013). These plates slide along the asthenosphere, the upper layer of the mantle. The lithospheric plates are composed of continental plates, oceanic plates, or both (Pichon, Francheteau and Bonnin, 2013). While oceanic plates are thinner, less than 100 km thick, and denser, continental plates are 150-200 km thick (Romanowicz, 2009). Each plate is moving in different directions with rates of 1-10 cm every year (Morgan, 1972). The driving force for this movement is the convection currents in the mantle where the hot material in the earth's core rises and cold mantle rocks sink (Morgan, 1972). This is what has allowed the earth's surface to change over time, creating the landforms seen today.

Modern Discoveries in Mountain Building

Through studies of mountain belts across the globe, many scientists have been able to investigate the discovery of plate tectonics and their role in orogenesis (Hubbard, et al., 2021). Through this act of uplifting and erosion, both climate and global carbon cycles are impacted over millions of years (Hubbard, et al., 2021). Therefore, understanding the process of orogenesis allows scientists to peek into the past studies are the Himalayas, a long stretch of mountains ranging over 2400 km across Asia (Figure 2.14) (Roy and Purohit, 2018). This mountain range is a result of recurring orogenesis as both the Indian and Eurasian plate collide. This collision zone has been used to explain ancient mountain building, but many scientists are still not sure how representative this model is. A recent study conducted at the University of Cambridge gives insight into whether this model is accurate using information within metamorphic and igneous rock records (Weller, et al., 2021). This information allowed the scientists to build on the knowledge of temperature and pressure conditions as the Himalayas' formed and compared it with the exposed remains of four different ancient mountain belts. The results showed that there were both similarities and differences between modern and ancient mountain building processes (Weller, et al., 2021). Ancient mountain ranges had comparable rock strength to the foreland basins of the Himalayas (Hobley, Sinclair, and Cowie, 2010). The authors drew a conclusion that the strength of this region is evidence of the effectiveness of orogen comparisons, as foreland rock strength points to the crustal thickness of mountain belts, a primary factor in mountain conditions (Weller, et al., 2021). Through controlling pressure and temperature conditions, crustal thickness also defines mountain rock records. Though they noted differences between the modern and ancient orogenic rock record, they ruled out the possibility of contrasting tectonic processes as their cause. They instead attributed these discrepancies to differences in the level of exposed rocks at the core of the ancient mountain (Weller, et al., 2021). This study shows key findings which pave the way for future research into the reasons behind variation in orogenesis.

Figure 2.14: The Himalayas in Nepal, used for mountain building research. Modern studies into their internal composition gives insight into ancient mountain building processes.

Shen Kuo: The Grandfather of Geology

Living in the Western world, we are often exposed to immensely skewed narratives of history, those which are meticulously tailored to display European superiority and dominance in scientific progression. Whether intentional or a product of ignorance, scientific discoveries tend to be accredited to more accessible and digestible work from the modern perspective. What were once revolutionary discoveries in developing the foundation of our current scientific narrative are swept aside due to their historical distance from our current position, leading to great minds of the past getting lost in translation. The geological discoveries of Shen Kuo (Figure 2.15) dating back to around 1000 CE, encompass similar ideas surrounding sedimentation and depositional environments suggested by James Hutton 700 years later (Hutton, 1795; Shen, et al., 2008). Shen's work tends to be overshadowed, as most modern geological texts accredit the discovery of erosional processes and the principles of sub-aqueous sedimentary deposition to Hutton.

Figure 2.15: Portrait of Shen Kuo, drawn in the 18th century during the Qing dynasty.

Science In the Sung Dynasty

Considered one of the few golden ages of imperial China, the Sung dynasty (960-1279 CE) saw the rise of self-cultivation and self-expression in tandem with the flourishment of scientific thought and art (Ch'ien, 2019). The Sung dynasty was born from a period of high conflict known as the Five Dynasties. Aware of the looming presence of larger, neighbouring military powers, the empire focused many resources on societal progression which had been stagnant in the previous empires due to political unrest. The new empire evolved social construction by assigning roles based not only on birthright, but also on capability, shifting the autocratic government structure towards bureaucracy. The Sung dynasty placed emphasis on the Imperial Examinations, a series of three examinations sat by young men of the upper class, determining their posts when entering the workforce. The funding of scientific pursuit, and development of agricultural infrastructure saw a large population boom across the dynasty (Zuo, 2018). The rise of the printing block allowed for the mass distribution of literature, this included the dispersion of scientific texts for public ownership, distributed to rural populations heavily segregated from the state (Mun, 2013). The perception of science in the general population was heavily skewed as the types of texts accessible to the general population were censored by the government. Only topics deemed necessary were provided, such as medicinal, mathematical, and agricultural texts. Additionally, there were censorship laws in place regulating the types of texts and scientific instruments legal for private ownership (Zuo, 2018). For example, the private use of astronomical instruments and military texts were prohibited, in fear of creating radical uprisings that countered the foundations of society. To maintain power and a sense of elite knowledge, the capital owned the vastest collection of texts which were only available to persons of high rank, creating a class disparity in who had access to knowledge (Mun, 2013). Due to increasing knowledge held by the general population, the elite sought to distinguish themselves through co-opting technical knowledge into existing cultural frameworks. As knowledge became more accessible and the pursuit of knowledge and education became more normalized, the elite distinguished themselves by following literary trends. By consuming and cycling through new information quickly, they aimed to demonstrate intellectual superiority and disposable wealth (Zuo, 2018).

Shen Kuo's Professional Career

Shen Kuo was born in 1031 to elite status (Holzman, 1958). As a bright and well-travelled child who accompanied his father all over the state for work, Shen Kuo was intrigued by the natural world he saw around him. Despite his fascination and knowledge of the natural world, as a Neo-Confucianist Shen Kuo prioritised his role as a civil servant. Throughout his professional career, he explored the realm of science, yet opted to privately journal his findings without pushing for publication. It was only after his retirement that he collected his observations in a series of essays entitled *The Dream Pool Essays*.

Shen entered official service at only 23 years of age (Holzman, 1958). His early years in administration were formative in developing his observational skills of the natural world. After joining the registrar in the subprefecture of Shu-yang, his first administrative tasks were to advance agricultural productivity. The nature of these tasks forced him to acknowledge and experiment with geological processes. Here, he reclaimed over 100,000 acres of prime farmland by draining and canalizing two prominent rivers in the area. For the next couple years, Shen worked under similar posts where his detailed understanding of hydrology allowed him to prove his competence. This immense early success earned Shen rapid promotions to secondary political roles, one of which was held at the Imperial Library. While working as a collator, he was able to dedicate much of his time to exploring his scientific interests and continued to immerse himself in challenging literature. Although removed from the field, Shen continued to travel and observe the world around him (Holzman, 1958).

In 1070 he first recorded his understanding of erosional processes through his observations of the cliffs in the Yen-Tang Mountains (Needham, 1984). After visiting the Yen-Tang Mountains (Figure 2.16), Shen noted that a large valley within the mountain range was a floodplain surrounded by cliff-like structures (Shen, et al., 2008). Periodically this area would flood with high velocity currents due to changing tides and large precipitation events. After watching the region flood, Shen suggested that the cliffs resulted from erosion of rock by high energy water over time creating a steep slope, instead of a gradual slope seen in other structures. He writes, *"Now I myself have noticed that Yen-Tang Shan is different from other mountains. All its lofty peaks are precipitous, abrupt, sharp, and strange; its huge cliffs, a thousand feet high, are different from what one finds in other places… Considering the reasons for these shapes, I think that (for centuries) the mountain torrents have rushed down, carrying away all sand and earth, thus leaving the hard rocks standing alone"* (Needham, 1984, p.603). He also suggested that all surrounding cliffs were of the same height. From this observation he suggested that at some point the cliffs made up a single plane, and that continuous high-velocity flooding resulted in the steep cliffs seen today.

The year 1071 marked his entrance into central

Figure 2.16: Sketch of the cliffs and torrents of the Yen-Tang Mountains.

politics, where he held important roles in administration, often still in scholarly archives and libraries for about a decade (Holzman, 1958). He was reintroduced to field work while at these posts, again being tasked with the restoration of lost land and repair of waterworks. On these missions Shen applied his knack for geologic observation to create the first topographic representation in recorded history. He gained valuable cartographic experience, developing one of the first terrain maps using sawdust and melted wax to produce elevation differences. Even without explicit instruction to do so, Shen engaged with the natural world he observed around him, constructing meticulous maps of the landscapes along his travels up until the last years of his administrative career (Holzman, 1958).

In 1074, while conducting inspection tours in regions near the Yellow River, Shen was surprised to discover the presence of fossilised clams and snails within layers of sediment on mountains far from the coast (Needham, 1984). The Taihang Mountain, near the town where Shen was stationed, was positioned a few kilometres inland. However, according to folk legend, the mountain should be positioned just along the Eastern Coast, much further seaward than its current location (Shen, et al., 2008). While inspecting the banks of the river, Shen Kuo also noted that the water itself contained mud and sand. From this observation he suggested that geological structures are the result of accumulated sediment transported by waters, and states in his *Dream Pool Essays, "Thus what we call the 'continent' must have been made of mud and sediment which was once below the water… In the west of Shensi and Shansi the waters run through gorges as deep as a hundred feet. Naturally mud and silt will be carried eastwards by these streams year after year, and in this way the substance of the whole continent must have been laid down"* (Needham, 1984, p.604). Shen suggested that the landforms he saw were the product of a gradual accumulation of sediments

Figure 2.17: Sketch of bamboo shoots and rock structures during the late Sung dynasty.

transported seaward by rivers and deposited sub-aqueously. He understood that high energy water eroded rock structures creating sediment, moving them to areas of low energy for deposition. To substantiate his theory of sediment deposition, Shen suggested that for marine fossils to be present in the mountain it must have previously been underwater.

Around the year 1080, a landslide on the bank of a large river in the Yung-Ning caused a collapse of the land, revealing several dozen feet of underground petrified forest containing hundreds of bamboo shoots (Needham, 1984). Stone forests, or fossils, had been noted before in several other areas, however, they were of little scientific interest as they consisted of native species found in the region. This sample, on the other hand, was the first region to contain non-native plants that could not grow in its present climate. Bamboos (Figure 2.17), which were present in the fossil, did not grow in the Yanzhou area, as the current climate was far too hot and arid, disagreeing with bamboo which thrives in a wetter, tropical climate with deep watering and good drainage. He wrote in the *Dream Pool Essays*, *"Probably in the distant past this place was a low-lying area with a humid climate fit for the growth of bamboo. In Mount Jinhua in Wuzhou there are stone pinecones, stone peach pits, stone reed rhizomes, stone fishes, stone crabs, and so on. As they are all native to this place, their existence does not cause a stir. But these stone bamboo shoots usually do not appear under the ground. What is more, they are not the traditional local products of Yanzhou"* (Shen, et al., 2008, p.661). Shen concluded that in some ancient time, the climate of Yenzhou must have been humid enough to promote the growth of such a bamboo forest. Over time, however, it had evolved to the present climate which no longer allowed for the growth of bamboo in the region. While he does not provide a mechanism or process for this change, this conclusion marks one of the first recorded examples of paleoclimatology in history, as Shen could see a distinct change in the environment of the area.

These passages from his *Dream Pool Essays* suggest that Shen understood as previously determined, that climates and environments change overtime, allowing for the deposition of fossils and life forms within sediment that could not presently survive in the region (Needham, 1984). While never truly synthesising his geological ideas, Shen demonstrates an understanding of many important concepts of the sedimentary cycle, such as erosion and subaqueous sediment transportation and deposition, that gradually over time, surmount in the construction of large geological structures.

Publication and Impact

After the turbulent demise of his career, Shen Kuo retired in immense wealth to the countryside where he was able to dedicate his time to interests outside of his civil service. It was during this time that he began to write and transcribe a series of essays outlining his life's work entitled the *Dream Pool Essays*. The essays covered a series of topics including technological inventions, religious commentary, scientific discoveries, and observations of the natural world. Shen writes of the many geological structures he happened upon while travelling making many attempts to explain their origin (Zuo, 2018). Through observations, Shen offers many hypotheses explaining the adaptation of the natural world. He provides distinct examples that when set to a geological time frame, can be used to explain the world around him.

The geological processes proposed by Shen Kuo were easily digestible during the Sung dynasty as Buddhism declined and Neo-Confucianism blossomed (Kuhn, 2011). Despite his advanced scientific discoveries of the time, Shen Kuo was in many ways a traditionalist, adhering closely to Ancient Chinese philosophical concepts such as Yin-Yang theory and five elements theory (Shen, et al., 2008). His strong belief of these concepts and their integration in much of his writings meant he could document his scientific observations freely without challenge. Regardless of his theories on the world, he held true to the foundations with which the Sung dynasty was built upon. Classical Confucianism promotes the belief that all humans are inherently good and that the human is a civil servant, obligated to fulfil their destined role to achieve universal balance (Simionato, 2020). Neo-Confucianism adopts these traditional beliefs to develop societal order and structure. Neo-Confucianists believe that the universe must maintain harmony and that relationships between humans, creatures, and the universe are transformative and dynamic, making Shen's proposed mechanisms of geological transformation innocuous. As a Neo-Confucianist, Shen Kuo prioritised his appointed role, delaying the formal publication of his scientific pursuits.

Shen's epistemology greatly stemmed from his participation in the literati, a higher society in the Sung dynasty (Zuo, 2018). Learning, according to the Sung literati, encompassed philosophical articulateness, classical literacy, and competence in statecraft. This model gave rise to the "Age of Systems", wherein systems, both in government and the natural world, were viewed as a unified front, deterring individualism in their interpretation. Shen challenged the system model in the political sphere, opting for a 'non-system' philosophy in which he narrowed his approach to solve one isolated issue at a time, instead of constantly holding the broad system in mind. This gave him a unique opportunity to rise rapidly in the Sung dynasty. He felt that a complete understanding of a system at its whole was not attainable if individual aspects were disregarded (Zuo, 2018). Shen's non-system was built on reliability and accuracy rather than pursuing unity through theoretical means. This translates in his scientific work, which prioritizes discovery through observation. Despite countering widely held structural beliefs, Shen generally adhered with most major schools of thought. He was a hard-working politician with an impressive record to show, who by following closely to Neo-Confucianist ideals, was left to explore his theories on the natural world without many barriers (Zuo, 2018).

Similar Works

Despite proposing similar theories for geological processes, Shen is hardly discussed in the Western education system, overshadowed by figures like James Hutton, the late 18th-century geoscientist given the title of the Father of Modern Geology. One of Hutton's most prominent discoveries was the suggestion that the world was developed from the natural processes of the sea (Hutton and Playfair, 1970).

Hutton performed the "traditional" scientific process to a tee. He spent close to 20 years making geological observations and formalizing theories through evidence-based work. He assembled his work into a comprehensive and chronological piece of writing and presented it to other academics of his time. Hutton developed theories, found evidence to support them, and refined where necessary, repeating this process cyclically. In 1788, Hutton presented his fully developed theory in front of the Royal Society of Edinburgh; he postulated that the world was formed not by the Biblical cosmos, but rather through a constant cycle of erosion and tectonic uplift (Hutton and Playfair, 1970). A few years later Hutton formally published his observations in a book entitled Theory of the Earth; or an Investigation of the Laws Observable in the Composition, Dissolution, and Restoration of the Land Upon the Globe. While this caused immense uproar, it also brought notable attention to his work, a privilege not afforded to Shen. Following extreme criticism, Hutton was able to publish a second follow up, containing his initial work overlaid with more detailed pieces of evidence and analysis (Hutton, 1795).

Shen Kuo wanted to find explanations for what he saw in the world around him, whereas James Hutton had an established belief system to disprove. Shen never dwelled for a considerable time on one observation, using analogous systems which he understood to explain unknown phenomena. His geologic discoveries in *Dream Pool Essays* reserve about a paragraph of writing each, detailing his observation of the phenomenon, and his theory on its origin, before swiftly moving on to the next essay (Shen, et al., 2008). Despite this, Shen Kuo's observations from more than 700 years prior echo a remarkably similar conclusion to Hutton's. Both propose that the earth is shaped by continuous processes occurring over large timeframes incomparable to human perception (Hutton and Playfair, 1970; Shen, et al., 2008). Shen and Hutton both used observational analysis rather than direct experimentation to test their hypotheses, eventually concluding similar mechanisms of erosion and sedimentation, with Hutton's proposed principles including additional mechanisms. In their work, both suggest that modern geological structures were laid sub-aqueously as sediment. Both propose that high velocity waters erode rock into finer grain, transporting it from areas of high energy to areas of low energy for deposition (Hutton and Playfair, 1970; Shen, et al., 2008). However, while Shen carefully adhered to Neo-Confucian ideals through his proposal, Hutton's work directly challenged his religious beliefs. In doing so, James Hutton's work is seen as revolutionary and foundational because there was an established system of belief for him to challenge. The Sung dynasty did not hold strong beliefs on the origin of the world, so Shen was not challenging the status quo (Zuo, 2018). This demonstrates how the societal implications of scientific discoveries impacts its perceived importance in modern contexts.

Paleoclimate Indicators

Shen Kuo's observations of climate evolution laid the foundation for modern paleoclimatology. This field of Earth science studies climate change overtime using different indicators found in sediments to predict past climates and their mechanisms of change (Fairbridge, 2009). The study of paleoclimates allows scientists to predict future climates and assist in resource exploration. Shen Kuo's work is considered to be the first attempt at paleoclimatology, as he used fossil indicators of specific flora and fauna species found in strata to predict past climates (Needham, 1984). Much like Shen Kuo's work, modern paleoclimatology is heavily observational. Scientists assess many different indicators found in strata to predict past average temperatures, precipitation rates, and temperature ranges (Elias, 2021). One particular indicator of interest is bioindicators. Variations in angiosperms can be used to predict past climates and their contributing factors (Parrish, 2019). For example, proportions of deciduous smooth leaves to toothed leaves can be used to predict temperatures, and the density and composition of stomata can be used to determine atmospheric composition and CO_2 concentration at the time. Additionally, the thickness of a leaf's cuticle is depictive of the amount of available water, as thicker leaf cuticles are indicative of larger water supplies. Experimentally, scientists are able to determine atmospheric and oceanic composition and circulation, both from the physiological structures of flora species, as well as the chemical composition of carbonates and sediments (Elias, 2021). When pieced together, scientists create computer generated models simulating past climates, in which they can manipulate variables to predict the impact of specific geological events. These events include mountain building activity, plate tectonic movement, and changes in Earth's orbit (Parrish, 2019).

Isotopic Dating of Bioindicators

The introduction of dating methods based on the uranium decay series and its radioactive disequilibrium have furthered the field of paleoclimatology immensely by building on the process of fossil observation and adding an experimental component. These techniques can be applied to minerals which incorporate uranium but not thorium into their product, as ^{230}Th is the daughter product of ^{234}U (Frank and Hemsing, 2021). This can apply, for example, to ancient corals, which form calcareous and aragonitic skeletons while they are under the seawater (Figure 2.18). Seawater contains dissolved uranium but very little thorium, as it is insoluble, meaning the age of a coral can be measured by the amount of ^{230}Th in the sample. (Frank and Hemsing, 2021).

In the 21st century, scientists have discovered that the mineral system of corals is not entirely isolated, but rather that uranium and thorium

Figure 2.18: Image of a fossilised coral used for isotopic dating.

exchanges with sedimentary environments can occur (Frank and Hemsing, 2021). Higher $^{234}U/^{238}U$ ratios than expected presented a huge problem in U-series dating of corals, making the $^{230}Th/^{234}U$ dating method less precise than initial analyses might indicate. Scholz, Mangini, and Felis (2004) suggested a modified open system corrective model to account for the influence of these disturbances. In this model, a coral can be cut into several smaller components to be measured as independent samples to which open system corrections may be applied. Scholz and colleagues looked to correct two pre-existing open system models. The first, proposed by Villemant and Feuillet (2003), attempted to consider initial ^{230}Th excess, and suggested that the continuous redistribution of radioactive materials was controlled by the nuclear recoil effect. This effect causes a nucleus to be displaced from its expected position in the lattice over time, which may result in the atoms of the daughter product being more susceptible to dissolution. The second, presented by Thompson, et al. (2003), suggested that the positive correlation seen between measures of $^{230}Th/^{238}U$ and $^{234}U/^{238}U$ activity ratios could be explained by the addition of ^{230}Th and ^{234}Th.

While these models were able to reproduce the isotopic trends found at some corral terraces, Scholz noted that in general, data from a given corral terrace are not all co-linear (Scholz, Mangini and Felis, 2004). Co-linearity would be necessary for open system correction using these previous models. Scholz and colleagues developed a new model which combined the uptake and loss of uranium to produce characteristic isochrons, denoting mineral samples formed at the same time. They found that the intersection of the isochron and seawater evolution curve could reveal the true age of their highly altered coral samples and extrapolated that corals which had been less diagenetically altered may use the same approach (Scholz, Mangini and Felis, 2004).

Determining historical changes in sea level is largely based on the relationship between the height and age of shallow water coral reefs (Frank and Hemsing, 2021). By knowing precise changes in sea level during climate cycles, researchers can reconstruct more exact timelines of climate changes and relate them to other factors such as paleotemperatures determined from polar ice cores. Connecting the location and age of corals to sea level requires choosing corals whose habitat characteristics are well established, as factors such as the depths at which they have grown, is an important factor which must be accounted for. To minimize the impacts of uplift or subsidence rates, samples should ideally be collected from the most tectonically stable areas (Frank and Hemsing, 2021). Establishing a chronological framework using this method can help researchers understand relationships between different components of the climate system, allowing us to study variation on continental surfaces and their erosion during climate cycles.

Techniques such as coral dating allow researchers to determine climate factors of the past. Paleoclimatology has assisted in the development of computer-based models which can be used to predict how Earth's climate may transform in the future. However, continued research in paleoclimatology is still required to improve model accuracy. Using the lens of the past, these models can help guide the development of environmental policy and action, leading to a more sustainable society.

The Founding Father of Modern Geochemistry

It is evident that the intersection between the physical, chemical, and geological sciences constitutes the foundational basis on which geochemistry as we know it today, stands. Modern geochemistry studies the geologic processes which dictate the abundance, distribution, and circulation of chemical elements, compounds, and isotopes across geologic environments (Dembicki, 2017; Goldschmidt, 1954). Although the vast majority of recent geochemical discussions focus primarily on modern geochemistry and its applications, it is crucial to acknowledge that geochemistry is not a new field of study. As such, its dynamic evolution must be observed in order to not only grasp the breadth of knowledge in the field, but to also fully appreciate the overlap between the scientific disciplines of which it is composed.

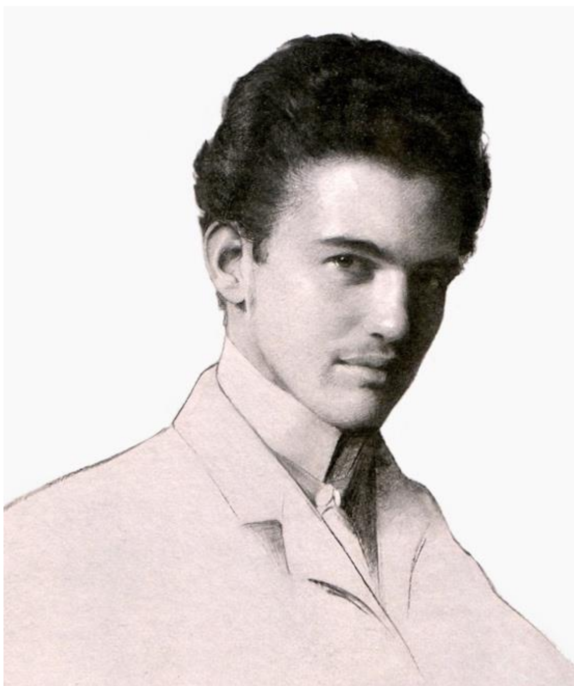


Figure 2.19: Drawing from 1909 depicting a 21-year-old Victor Goldschmidt, the founding father of geochemistry.

One scientist who contributed heavily to the establishment of modern geochemistry is Victor Moritz Goldschmidt (1888-1947) (Figure 2.19), better known as the 'father of geochemistry' (Tilley, 1988; Grossman, 1993). Goldschmidt's contributions to the field of geochemistry spanned across crystallography, mineralogy, metallurgy, geothermobarometry, and chemistry. Nevertheless, his most notable contributions include his work in elemental classification by geologic significance and his doctoral thesis on contact metamorphisms in the Oslo region of Norway. These research interests led to the creation of Goldschmidt's rules, and particularly, Goldschmidt's Mineralogical Phase Rule, which is a version of Gibbs' Phase Rule that is amended to account for the parameters which can be seen in rock-formation in geologic settings (Speidel, 1983; Rosbaud, 1988; Tilley, 1988). There has been some controversy surrounding the practical application of the mineralogical phase rule in particular, although this has not marred Goldschmidt's reputation. Goldschmidt's contributions were crucial in substantiating the validity of modern geochemistry as a standalone field, establishing his role as the father of geochemistry (Weill and Fyfe, 1967; Speidel, 1983).

Early Life

Victor Moritz Goldschmidt was born in Zürich, Switzerland on January 27, 1888, and was the only son of Amelie Köhne, and Dr. Heinrich Jacob Goldschmidt (Rosbaud, 1988; Tilley, 1988; Kauffman, 1997). Goldschmidt's first exposure to the chemical and physical sciences was undoubtedly through his father, who was a distinguished professor of physical chemistry at various prestigious academic institutions across Europe. As a young child, Goldschmidt received much of his early education in Heidelberg, Germany, as his father was teaching at the University of Heidelberg, although the family followed his move to Oslo when Goldschmidt was in secondary school (Kauffman, 1997). This exposure to the chemical and physical sciences from childhood shaped his research interests, as his academic pursuits focused on combining knowledge from both of these sciences, with his passion for geology and mineralogy. In 1905, Goldschmidt graduated from high school and entered the University of Oslo's prestigious school of the Earth Sciences, where he was exposed to the work of Waldemar Christopher Brøgger, a renowned petrologist whose mentorship served as an immense influence in Goldschmidt's path of study (Rosbaud, 1988). Brøgger aided Goldschmidt in his first publication at the age of 18 titled, *Die Pyrolumineszenz des Quarzes* (i.e., "The Pyroluminescence of Quartz", in English) in 1906, which focused on the strong pyroluminescence exhibited by quartz crystals in the Gudbrandsdalen region of Norway

(Kauffman, 1997). In the spring of 1907, while still a student, Goldschmidt began his most widely known work by investigating the contact metamorphisms of the Oslo region by assisting in field mapping for the Norway Geographical Survey and studying mineralogy in the meantime. In December of 1909, following the 1908-1909 winter where he intensely studied optical mineralogical techniques in Austria, Goldschmidt was given a university fellowship in mineralogy and petrology, and by May of 1911, he was able to earn his doctorate for his work studying contact metamorphisms in the Oslo region (Rosbaud, 1988; Tilley, 1988; Kauffman, 1997). Goldschmidt continued to gain academic favour as he lectured and taught between Munich and Oslo, and by age 26, in 1914, he was the Professor and Director of the university's Mineralogical Institute (Rosbaud, 1988; Kauffman, 1997).

Figure 2.20: Photograph of banded Hornfels (black). Poor grading can be seen in the small white intrusion within the metamorphic rock.

Contact Metamorphism

As mentioned above, Goldschmidt's 1911 doctoral thesis titled *Die Kontaktmetamorphose im Kristianiagebiet* (i.e., "The Contact Metamorphisms in the Christiania Region" in English; n.b., The Christiania region of Norway is now referred to as the Oslo region) addressed his focus on the contact metamorphisms in the Oslo area, with an emphasis on the aureoles of metamorphism around major igneous intrusions (Tilley, 1988). In this thesis, Goldschmidt focussed primarily on the geology of southern Norway, and the mineral associations which are found in aureoles of contact metamorphic rock that is created as a result of magmatic intrusions.

Contact metamorphism, also referred to as thermal metamorphism, is the process by which magmatic intrusions heat up surrounding rock. Based on the pressure, cooling rate and permeability of the sedimentary rock which comes into contact with the magmatic intrusion, new compositions of metamorphic rocks can be seen in a layer (≥50m thick) which surrounds the igneous intrusion (i.e., a metamorphic aureole) (Brooks Hanson, 1995). Contact metamorphism, as opposed to regional metamorphisms, rely primarily on the physical contact between igneous intrusions and sedimentary rock face, extremely high temperatures, and the concentration of volatiles (e.g., H2O, CO2) in an igneous intrusion for metamorphosis (Kerrick, 1991). Goldschmidt examined hornfels (Figure 2.20) in particular, which are the non-foliated, fine-grained, low-grade metamorphic rocks that are usually produced as a result of contact metamorphism between Paleozoic sediments (e.g., shale) and Permian plutonic igneous intrusions (Bowen, 1925; Kauffman, 1997).

In contemplating the conditions under which the contact metamorphisms that he observed were produced, Goldschmidt was able to modify Gibbs' Phase Rule, so that it accounted for a boundary in which pressure and temperature are externally fixed. This yielded Goldschmidt's Mineralogical Phase Rule. Gibbs' Phase Rule states that $P + F = C + 2$, where P represents the number of phases in the system. It should be noted that a phase is any physically separable compound (i.e., magma, immiscible liquids, vapours), and as such, it is possible to have multiple phases which are in the same state of matter. F represents the variance of the system (i.e., the degrees of freedom). In a geological application of the Phase Rule, such as that which was taken by Goldschmidt, the variance can be represented by the number of variables which can be altered individually while keeping the number of phases and their compositions constant (e.g., temperature and pressure). C represents the minimum number of chemical species that are required to constitute all the phases in the system, although components can be combined such that a ratio between them is addressed instead of individual species (Bowen, 1925; Weill and Fyfe, 1967). Goldschmidt's mineralogical phase rule is somewhat more general, although it is more so a reflection of contact metamorphisms, as it considers the contact between solid phases and their saturated solutions during contact metamorphism. As such, his mineralogical phase rule states that 'The maximum number of solid minerals that can co-exist in stable equilibrium is equal to the number of individual components that are contained in the minerals if the singular temperatures of transition points are excluded' (Goldschmidt, 1954; Bowen, 1925). There have been many other scientists who have come to criticize Goldschmidt's mineralogical phase rule, as they view his idea as intuitive, and even perhaps confusing, once a firm understanding of Gibbs' Phase Rule is established (Weill and Fyfe, 1967; Speidel, 1983). Despite this however, Goldschmidt's mineralogical phase rule is still recognized as a valuable, and foundational contribution in the field of geochemistry.

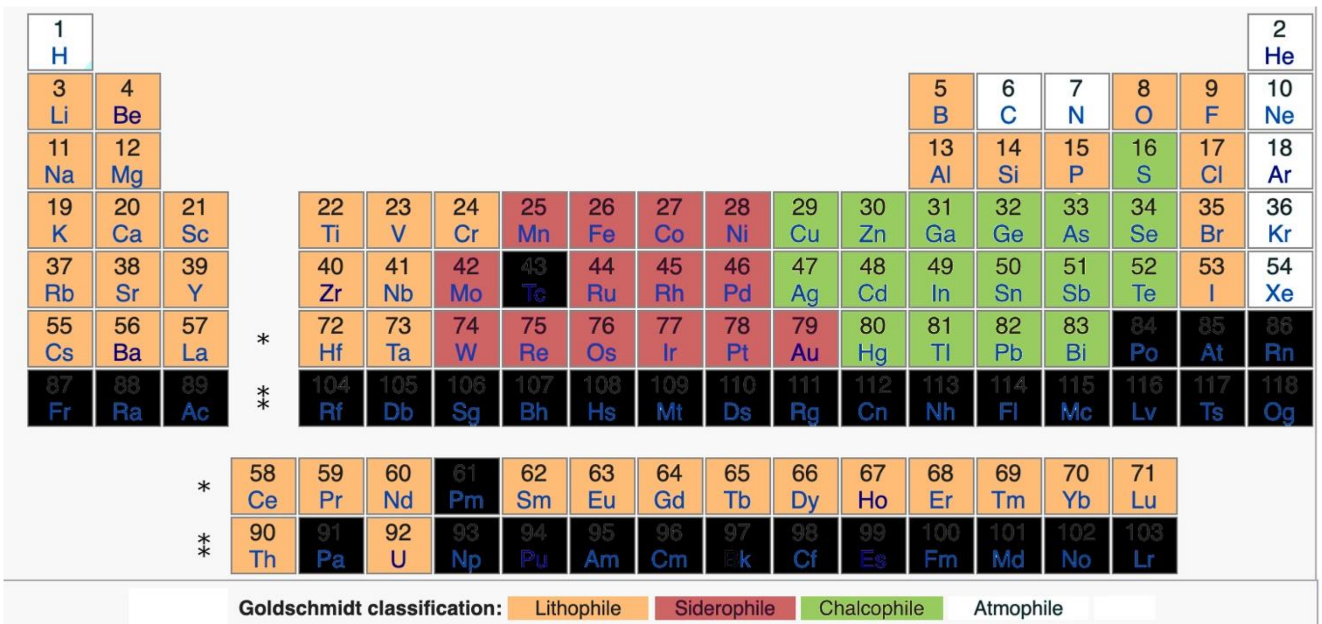


Figure 2.21: Goldschmidt Classifications of the elements of the periodic table showing atmophiles (white), lithophiles (orange), chalcophiles (green), siderophiles (red). It should be noted that under certain conditions, some elements can exhibit behaviours typical of multiple categories.

Exploration of Mineral Resources

Due to the onset of the First World War, the effects of halting international trade echoed across European countries as the distribution of traditionally imported resources became increasingly scarce. The effects of resource scarcity led many nations, including Norway, to turn inwards and investigate their own natural resources. The Norwegian government's efforts to gain insight into native mineralogical resources was spearheaded by Goldschmidt, who was commissioned from 1917 through 1922 to direct the country's efforts into resource exploration at the State Raw Materials Laboratory (Kauffman, 1997). The shift towards laboratory work was also beneficial to Goldschmidt, as his deteriorating health made field work increasingly difficult. The onslaught of WWI can thus be historically viewed as a time-period in which many countries were forced to explore native resources. In the life of Goldschmidt, it can be seen as a catalyst towards the second phase of his career, in which he focuses on crystal chemistry and the creation of the rules by which he was able to classify various elements by their geological presence and abundance (Kauffman, 1997; Rosebaud, 1988).

Classifications of Elements

Many scientists in the 18th and 19th century sought to understand the distribution of elements across Earth as a means of assessing resource-allocation and locating areas enriched with high-value elements (e.g., gold and platinum). Also during this time, meteorites became an area of interest, as their composition was hypothesised to be analogous to bulk Earth compositions. As such, they were seen as a potential source of aid in estimating elemental composition and the terrestrial distribution of elements (Brownlow, 1979). This analogy was ultimately strengthened in 1850, as 18 elements that were also seen on Earth (Carbon, Oxygen, Sodium, etc.), were identified as main meteoric constituents (Palme and O'Neill, 2014). Despite this hypothesis being presented in 1850, it was not until 1922 that Goldschmidt expanded on it, suggesting that the three main phases of meteoric composition (i.e., native iron, sulphide, and silicate) could represent major zones within the Earth. His suggestions implied that the major zones of Earth can be seen as the crust, mantle, and a ferrous core. Further expanding on these suggestions, Goldschmidt also predicted that the distribution of the elements would also align between the meteoritic phase-distribution and the major zones of Earth. Although the accepted truth at the time was that elements such as gold and platinum were located within the iron phase of some meteorites, Goldschmidt believed that all phases of meteorites would house some amounts of these metals (Brownlow, 1979). In attempts to verify this hypothesis, Goldschmidt and his colleagues were able to combine existing analytical techniques, such as chemical analysis by X-ray spectra, with novel methodologies like quantitative spectroscopy to further investigate minerals (Kauffman, 1997). The novel techniques in particular were used for chemical analyses of meteoric phases, which allowed for the discovery that high-value metals were highly concentrated within the iron phase of meteorites, suggesting the enrichment of these elements within the Earth's core. In combining a wide range physico-chemical analytical techniques, Goldschmidt and his colleagues characterised the crystal structures of 200 compounds, containing 75 elements.

Ultimately, Goldschmidt and his associate Lars Thomassen were able to use X-ray spectroscopy to deduce the laws which govern the terrestrial distribution of chemical elements. These laws allowed for the explanation of the relationship between elemental distribution of individual elements and their atomic numbers. It was suspected that the size of the atom would also play a role in its distribution, so when Finish scientist J. A. Wasastjerna used molecular refraction data to determine the ionic radii of fluoride and oxide ions, Goldschmidt adopted this method and published the first table of ionic radii in 1926, revolutionising modern crystal chemistry (Kauffman, 1997). Goldschmidt continued to investigate the behaviours of various elements, and elemental species in order to further develop the trends associated with the periodic table. In turn, this investigation led to his classification of elements based on their geologic significance (Brownlow, 1979).

Goldschmidt classified the elements as lithophiles, siderophiles, chalcophiles, and/or atmophiles, although an element, its ions, or isotopes, may demonstrate more than one characteristic in geologic settings. As such, an element may be identified under multiple of these classifications, which is particularly true in terms of the siderophilic and chalcophilic elements (Goldschmidt, 1954). The classification scheme was designed such that classifications were assigned to elements which displayed higher affinities for binding with certain entities, such as lithophiles for instance. Lithophiles are elements that appear to have a higher affinity for silicates and would bind readily to oxygen. As such, Goldschmidt hypothesised that they would make up the bulk of the Earth's crust and mantle rocks. Siderophiles consist of elements which prefer the metal phase, resulting in their solubility in ferrous solutions such as Earth's core, where they are most likely to be found. Chalcophiles are able to readily bond with sulphide, so they demonstrate a lesser affinity for binding with oxygen. Thus, it is hypothesised that chalcophiles would be enriched in the continental crust. Additionally, atmophiles are those elements that mainly occur within the atmosphere and consist of gases such as the noble gases, as well as hydrogen and nitrogen (Figure 2.21) (Hollabaugh, 2007; Palme and O'Neill, 2014). Through the combination of varying physico-chemical methodologies, Goldschmidt was able to revolutionise the field of crystal chemistry, while discovering and classifying chemical elements according to their geological prevalence. These discoveries ultimately aided in forming the hypotheses on the primary fractionation of Earth, setting the foundational basis for geochemistry as a field by connecting chemical elements with their behaviours in geological settings (Brownlow, 1979).

WWII and Later Life

By the 1920s, Goldschmidt had established himself as a reputable scientist with a phenomenal reputation in both research and education, although this is not to say that his life was exempt from hardship. As a Jewish man in Europe during both world wars, antisemitism was a significant, and constant sociocultural struggle which Goldschmidt encountered throughout his life, but especially in the advent of the Second World War. It is evident that antisemitism influenced his personal life, but like many Jewish scientists of his time, antisemitism also ran rampant in the academic circles of Europe, bleeding into Goldschmidt's professional life as well. For instance, faculty at the University of Munich denied Goldschmidt an appointment as Professor of Mineralogy for which he was specifically recommended by the outgoing predecessor. The reasoning for this was stated in a letter addressed to Goldschmidt, saying that they, "did not want a scholar of presumably Jewish descent (or probably partly Jewish)", and they, "already have one Jew at the Faculty" (Kauffman, 1997; Rosebaud, 1988). He was also talked out of many opportunities and positions in Germany by his mentor W. C. Brøgger, and other elite-class Norwegians (e.g., Gunnar Knudsen, former Norwegian prime minister), due to concerns for both his safety and academic reputation. Despite the concerns of Germany's rising antisemitism, and the rise of Nazism in areas such as Munich, Goldschmidt decided to accept a position at the University of Göttingham in 1929. Goldschmidt himself described his years in Göttingham as his happiest, although the joy of being in a community of thriving academics was soon overshadowed by the glaring threat posed by the ascent of Nazi Germany in 1933. Following his resignation in August of 1935, Goldschmidt promptly received a letter of dismissal signed by Adolf Hitler and Hermann Göring, after which he and his ageing father fled Germany, returning to Norway once more.

In Norway, Goldschmidt resumed his prior works in Norwegian resource exploration, where he pioneered techniques for Olivine use in refractories (Figure 2.22); processes which are still used, as Olivine is a primary mineral export of Norway (Kauffman, 1997). He also focused on geochemistry in terms of the agricultural development of fertilisers and low-grade phosphate for use as cost-efficient fertilisation, which was research that prevented his deportation into the ghettos or concentration camps of Poland (Rosbaud, 1988).

Figure 2.22 An image of unprocessed Olivine (left) and a processed Olivine crystal (right).

Following the German occupation of Norway in 1940, the Nazi-controlled government demanded information on the ethnic history of all employees. Goldschmidt, who declared that he was fully Jewish, was arrested in 1942 and along with the other 2000 Jews of Norway, his property was confiscated, and he was imprisoned in the Berg concentration camp. Despite his imprisonment, he managed to escape into Sweden with the help of Norwegian police and the Norwegian resistance (Kauffman, 1997).

In an attempt to be useful to the allies during WWII, Goldschmidt moved from Sweden to England, where he was assisted by the British Agricultural Research Council in seeking employment in Scotland. Here, he worked to identify trace elements in soil geochemistry, and to prevent silicosis and skin cancer in foundry workers (Kauffman, 1997) Following a severe heart attack, and a subsequent hospitalisation of a year and a half, Goldschmidt finally decided to return to the freshly liberated Norway in 1945. There, he attempted to compile his life's work into a publishable book, although he died of a sudden cerebral haemorrhage in 1947, and was unable to complete it. Nevertheless, Alex Muir, in collaboration with Goldschmidt's peers, were able to compile his works into his 1954 publication entitled *Geochemistry* (Kauffman, 1997; Goldschmidt, 1954; Rosbaud, 1988).

Continuance of Goldschmidt's Work

V.M. Goldschmidt's work set the stage for modern geochemistry and allowed for a wide range of applications to arise from his hypotheses and the methodologies which he pioneered. Specifically, Goldschmidt believed that a primary objective within geochemistry was "to find the laws of distribution of the elements" (Ahrens, 1953). This work, and its continuance by his successors, set the precedent for modern day developments in geochemistry such as economic assessments of mineral concentrations and predictions of petroleum basin migration patterns. With economic geology being a great interest in modern day geochemistry, the methods coined by Goldschmidt are still widely used. His chemical classification of the elements, with their subsequent groupings in particular, continues to allow for scientists to predict where elements are more likely to be found based on geologic conditions and chemical properties at the time of their formation.

Overall, if it were not for the work of Goldschmidt in establishing geochemistry as a field of valuable interest, industrial applications of geochemistry such as resource exploration and mining would be at a great loss. Not only did Goldschmidt establish techniques which are continuously used to date in these fields, but he also pioneered the foundational knowledge in the prediction of terrestrial chemical resource-allocation.

Modern Applications of Geochemistry

Evidently, there have been major developments in instrumental analytical techniques since Goldschmidt's time, which allow modern-day geochemists to accurately deduce elemental and isotopic abundances in geological materials. The introduction of novel methodologies has allowed for a more comprehensive overview of ground composition which, in turn, has led to a better understanding of hydrocarbon-distribution. As hydrocarbons are highly sought after due to rapid industrial consumption, a deeper understanding of their terrestrial distribution is of great interest in the 21st century.

Some of these novel techniques include atomic absorption spectrometry (AAS), microwave plasma-atomic emission spectroscopy (MP-AES), and inductively coupled plasma atomic emission spectrometry (ICP-AES) (Balaram, 2020). Additionally, the use of inductively coupled plasma mass spectrometry (ICP-MS), as an analytical technique has become increasingly popular amongst geochemists over the last decade (Figure 2.23). Its widespread favour can be attributed both to its capacity for measuring elements at trace levels in organic materials, and its ability to test multiple elements concurrently (Wilschefski and Baxter, 2019).

This specific technique was used in a 2011 study where researchers quantified iodine concentrations in sample fields from west-central India in an attempt to determine the validity of using threshold iodine-concentrations as indicators of hydrocarbon-presence and hydrocarbon microseepage (Mani, et al., 2011). In using ICP-MS, they were able to determine that the distribution pattern of iodine within the sample areas aligned with other geochemical indicators of hydrocarbons, suggesting the potential of iodine-detection in the geochemical exploration of hydrocarbons (Mani, et al., 2011). Along with assessing the distribution and abundance of elements, geochemists must evaluate deposit composition of minerals to determine whether the pursuit of certain deposits are economically and laboriously viable. Since this evaluation is invaluable to mining companies, it has resulted in the birth of economic geology as its own field. Given the high demand of specific minerals, such as hydrocarbons, advancements in mining technology, such as developments in hydrometallurgy, have also been made to develop fiscally sustainable methods of recovering otherwise impossible deposits (Scott, 2014).

The evolution of inorganic geochemistry has been revolutionary for petroleum geologists. Given the unsustainably rapid use of natural materials such as oil and gas, geochemical techniques have been employed for petroleum exploration. In particular, the prediction of stages and locations of oil basins, as well as the migration of oil that has previously been produced is of great interest (Tedesco, 2012). In comprehending all of the constituents of sediments, along with their hydrological interactions in sedimentary basins, it is possible to accurately estimate where to find oil and gas, as well as the process of their development (Robinson, 2009). Through the use of analytical techniques along with developments in previously used methods, such as X-ray diffraction, petrography, and fluorescence microscopy, geochemists have a better understanding of subsurface processes, and are able to perform basin modelling in order to detail where oil basins may be formed (Tedesco, 2012). Inorganic geochemistry allows for the compilation of data from sedimentary records, relative ages of mineral growth and regression, as well as presence of fluids, including that of water and petroleum. Temperature data allows for information around which pressures and temperatures minerals are likely to dissolve or accrue, as well as which fluids were present within the varying deposits. These records also provide information on the chemical composition of these environments, leading to details on the history of fluids, as well as their interactions with different deposits. All of this is crucial in tracking phases in the development of oil basins and oil migration patterns, and therefore is important in the field of petroleum exploration (Robinson, 2009).

Figure 2.23: Image of the ICP-MS machine used in laboratories to determine sample compositions.

Chapter 2 References

Aboussouan, C., 1969. Avicenna. UNESCO, XXII (8/9), p.38.

Acharjee, A., 2016. Development of Indigenous ModernScience and Technology in Colonial India. Journal of People's History and Culture, 2(2), pp.58–65.

Adams, F.D., 1938. The Birth and Development of the Geological Sciences. William & Wilkins Company.

Ahrens, L.H., 1953. A Fundamental Law of Geochemistry. Nature, 172(4390), pp.1148–1148.

Akram, A.I., 2009. The Muslim Conquest Of Persia. Maktabah Booksellers and Publishers.

Al-Rawi, M.M., 2002. The Contribution of Ibn Sina (Avicenna) to the development of Earth Sciences. Foundation for Science Technology and Civilisation.

Arduino, G., 1760. Due lettere […] sopra varie sue osservazioni naturali: Al Chiaris. Sig. Cavalier Antonio Vallisnieri professore di Storia Naturale nell'Università di Padova: Lettera Prima […] Sopra varie sue Osservazioni Naturali (Vicenza, 30 gennaio 1759): Lettera Seconda […] Sopra varie sue Osservazioni fatte in diverse parti del Territorio di Vicenza, ed altrove, appartenenti alla Teoria Terrestre, ed alla Mineralogia (Vicenza, 30 marzo 1759), In: Nuova Raccolta di Opuscoli Scientifici e Filologici, Venezia (1760), pp. 99-180.

Ayala Izurieta, J.E., Márquez, C.O., García, V.J., Jara Santillán, C.A., Sisti, J.M., Pasqualotto, N., Van Wittenberghe, S. and Delegido, J., 2021. Multi-predictor mapping of soil organic carbon in the alpine tundra: a case study for the central Ecuadorian páramo. Carbon Balance and Management, 16(1), p.32.

Baffioni, C., Avicenna, I.S./ and Rāzī, F. al-Dīn al-, 2011. The causes and features of earthquakes in Avicenna and Fakhr al-Dīn al-Rāzī. European Review, 19(3), pp.355–366.

Balaram, V., 2020. Current and emerging analytical techniques for geochemical and geochronological studies. Geological Journal, 56.

Berggren, W.A, 1998. The Cenozoic Era: Lyellian (chrono)stratigraphy and nomenclatural reform at the millennium. In: Blundell, D.J. and Scott, A.C., eds. 1998. Lyell: the Past is the Key to the Present. The Geological Society pp. 111-132.

Berns, M. and Matsuda, A., 2020. Lingua Franca and Language of Wider Communication. The Encyclopedia of Applied Linguistics [e-journal] https://doi.org/10.1002/9781405198431.wbeal0708.pub2.

Bhattacharyya, T., Pal, D., Mandal, C., Chandran, P., Ray, S., Sarkar, D., Velmourougane, K., Srivastava, A., Sidhu, S., Singh, S., Sahoo, A., Dutta, D., Nair, K.M., Srivastava, R., Tiwary, P., Nagar, A.P. and Nimkhedkar, S.S., 2013. Soils of India: Historical perspective, classification and recent advances. Current Science, 104, pp.1308–1323.

Bleeker, W., 2005. Toward a "natural" Precambrian time scale. In: F.M. Gradstein, J.G. Ogg and A.G.E. Smith, eds. 2005. A Geologic Time Scale 2004. Cambridge University Press. pp.141–146.

Bowen, N.L., 1925. The mineralogical phase rule. Journal of the Washington Academy of Sciences, 15(13), pp.280–284.

Brooks Hanson, R., 1995. The hydrodynamics of contact metamorphism. GSA Bulletin, 107(5), pp.595–611.

Brosseau, O. and Silberstein, M., 2015. Evolutionism(s) and Creationism(s). In: T. Heams, P. Huneman, G. Lecointre, and M. Silberstein, eds. 2015. Handbook of Evolutionary Thinking in the Sciences. SpringerLink pp. 811 - 896.

Brown, B.W., 1964. The Influence of Avicenna and Geology on Philosophy. Southern Quarterly, 2(3), pp.179–189.

Brownlow, A.H., 1979. Geochemistry. Englewood Cliffs: Prentice-Hall.

Bruner, R.F. and Miller, S.C., 2020. The Great Industrial Revolution in Europe: 1760-1860. Darden Business Publishing pp. 1-18.

Ch'ien, M., 2019. The Song Dynasty. Berlin: Springer International Publishing, pp.59-80.

Chander, R., 1999. Wegener and his Theory of Continental Drift. Resonance, 4(7), pp.24–41.

Cohen, B.I., 1976. The Eighteenth-Century Origins of the Concept of Scientific Revolution. Journal of the History of Ideas 37(2) pp. 257-288.

Collins, B.W., 1966. Honouring a great Indian geologist. New Zealand Journal of Geology and Geophysics, 9(3), pp.362–364.

Darbandi, M.P. and Taheri, J., 2018. Using sulfur - Containing minerals in medicine: Iranian traditional documents and modern pharmaceutical terminology. Earth Sciences History, 37(1), pp.25–34.

Dickin, A.P., 2018. Radiogenic isotope geology. Third edition. Radiogenic isotope geology. Cambridge: Cambridge University Press.

Dutt, S., 2006. India in a globalized world. 1st ed. Manchester: Manchester University Press.

Elias, S.A., 2021. Introduction to Paleoclimates. In: D. Alderton and S.A. Elias, eds. Encyclopedia of Geology (Second Edition). Oxford: Academic Press, pp.288-298.

Ell, T., 2011a. Two Letters of Signor Giovanni Arduino, Concerning His Natural Observations: First Full English Translation Part 1. Earth Science History. History of Earth Sciences Society pp. 267-286.

Ell, T., 2011b. Two Letters of Signor Giovanni Arduino, Concerning His Natural Observations: First Full English Translation Part 2. Earth Science History. History of Earth Sciences Society pp. 168-192.

Fairbridge, R.W., 2009. History of Paleoclimatology. In: V. Gornitz, ed. Encyclopedia of Paleoclimatology and Ancient Environments, Encyclopedia of Earth Sciences Series. Dordrecht: Springer Netherlands, pp.414-428.

Falagas, M.E., Zarkadoulia, E.A. and Samonis, G., 2006. Arab science in the golden age (750-1258 C.E.) and today. FASEB journal: official publication of the Federation of American Societies for Experimental Biology, 20(10), pp.1581–1586.

Fisher, O., 1878. On the Possibility of Changes in the Latitudes of Places on the Earth's Surface; being an Appeal to Physicists. Geological Magazine, 5(7), pp.291–297.

Frank, N., Hemsing, F., 2021. Dating of Corals and Other Geological Samples via the Radioactive Disequilibrium of Uranium and Thorium Isotopes. In: Ramstein, G., Landais, A., Bouttes, N., Sepulchre, P., Govin, A. (eds) Paleoclimatology. Frontiers in Earth Sciences. Cham: Springer

International Publishing, pp.89-100

Ghasemnezhad, M. and Hosseinzadeh, S.R., 2014. Ibn Sina and uniformitarianism. Geography and Environmental Planning, 25(3), pp.43–62.

Gibbard, P.L., 2019. Giovanni Arduino - the man who invented the Quaternary. Quaternary International, 500, pp. 11-19.

Goldschmidt, V., 1954. Geochemistry. UK.

Goodman, L.E., 2013. Avicenna. London: Routledge.

Gradstein, F.M. and Ogg, J.G., 2012. Chapter 2 - The Chronostratigraphic Scale. In: F.M. Gradstein, J.G. Ogg, M.D. Smith, and G.M. Ogg, eds. 2012. The Geologic Time Scale 2012. Elsevier B.V. pp.31–42.

Gradstein, F.M., 2012a. Chapter 1 - Introduction. In: F.M. Gradstein, J.G. Ogg, M.D. Smith, and G.M. Ogg, eds. 2012. The Geologic Time Scale 2012. Elsevier B.V. pp.1–29.

Gradstein, F.M., 2012b. Chapter 3 - Biochronology. In: F.M. Gradstein, J.G. Ogg, M.D. Smith, and G.M. Ogg, eds. 2012. The Geologic Time Scale 2012. Elsevier B.V. pp.43–61.

Grant, E., 2004. Science and Religion, 400 B.C. to A.D. 1550: From Aristotle to Copernicus. Greenwood Publishing Group.

Greene, M.T., 1984. Alfred Wegener. Social Research, 51(3), pp.739–761.

Grossman, L.K., 1993. Victor Moritz Goldschmidt: Father of Modern Geochemistry. Science, 261(5117), pp.114–116.

Gutas, D., 2016. Ibn Sina [Avicenna]. In: E.N. Zalta, ed. The Stanford Encyclopedia of Philosophy, Fall 2016. Metaphysics Research Lab, Stanford University. Available at: <https://plato.stanford.edu/archives/fall2016/entries/ibn-sina/> [Accessed 11 December 2022].

Hallam, A., 1972. Continental Drift and the Fossil Record. Scientific American, 227(5), pp.56–69.

Hobley, D.E.J., Sinclair, H.D. and Cowie, P.A., 2010. Processes, rates, and time scales of fluvial response in an ancient postglacial landscape of the northwest Indian Himalaya. GSA Bulletin, 122(9–10), pp.1569–1584.

Hollabaugh, C.L., 2007. Chapter 2 Modification of Goldschmidt's geochemical classification of the elements to include arsenic, mercury, and lead as biophile elements. In: D. Sarkar, R. Datta and R. Hannigan, eds. Developments in Environmental Science, Concepts and Applications in Environmental Geochemistry. Elsevier. pp.9–31.

Holzman, D., 1958. Shen Kua and His Meng-ch'i pi-t'an. T'oung Pao, 46(3), pp.260-292.

Hubbard, M., Mukul, M., Gajurel, A.P., Ghosh, A., Srivastava, V., Giri, B., Seifert, N. and Mendoza, M.M., 2021. Orogenic Segmentation and Its Role in Himalayan Mountain Building. Frontiers in Earth Science, 9.

Huggett, R., 1999. Gradualism. In: Environmental Geology, Encyclopedia of Earth Science. Dordrecht: Springer Netherlands. pp.298–299.

Hutton, J., 1795. Theory of the Earth: with Proofs and Illustrations, Volume 1 (of 4). Reprint of Theory of the Earth by James Hutton, 2018, Wyoming: Creative Media Partners.

Hutton, J., Playfair, J,. 1805. System of the Earth, 1785: Theory of the Earth, 1788, Observations on Granite, 1994. Together with Playfair's Biography of Hutton. Reprint of the works of James Hutton, 1970, introduced by Victor A. Eyles. United States: Hafner Publishing Company.

Kardel, T. and Maquet P., 2012a. Steno's Scientific Life in a Nutshell (1638–1677). In: T. Kardel, and P. Maquet, eds. 2012. Nicolaus Steno Biography and Original Papers of a 17th Century Scientist. SpringerLink pp. 1-2.

Kardel, T. and Maquet, P., 2013. Steno's Scientific Life in a Nutshell (1638–1677). In: T. Kardel and P. Maquet, eds. Nicolaus Steno: Biography and Original Papers of a 17th Century Scientist. Berlin, Heidelberg: Springer Berlin Heidelberg. pp.1–2.

Kauffman, G.B., 1997. Victor Moritz Goldschmidt (1888-1947): A Tribute to the Founder of Modern Geochemistry on the Fiftieth Anniversary of His Death. The Chemical Educator, 2(5), pp.1–26.

Kaviani, R., Salehi, N., Ibrahim, A.Z.B., Mohd Nor, M.R., abdul hamid, A., Hamzah, N.H. and Yusof, A., 2012. The significance of the Bayt al-Hikma (House of Wisdom) in early abbasid caliphate (132A.H-218A.H). 11, pp.1272–1277.

Kennedy, H., 2016. The Early Abbasid Caliphate: A Political History. London: Routledge.

Kerrick, D. ed., 1991. Contact Metamorphism. Boston, MA: De Gruyter.

Khan, Y., 2007. The great Partition: the making of India and Pakistan. London: Yale University Press.

Kuhn, D., 2011. The Age of Confucian Rule: The Song Transformation of China. Cambridge, MA: Harvard University Press.

Kumar, D., 1996. The 'Culture' of Science and Colonial Culture, India 1820-1920. 29(2), pp.195–209.

Kumar, K.S.A., Lalitha, M., Shivanand, Sujatha, K., Nair, K.M., Hegde, R., Singh, S.K. and Mishra, B.B., 2020. The Soils of India. World Soils Book Series. Springer Cham International Publishing.

Kuo, S., 1088. Mengxi bi tan. Translated by D. Hu, L. Jin, X. Hu, H. Wang, Z. Zhao., 2008. Chendu Shi: Sichuan Literature & Art Publishing House.

Kuznetsov, A.B., Semikhatov, M.A. and Gorokhov, I.M., 2018. Strontium Isotope Stratigraphy: Principles and State of the Art. Stratigraphy and Geological Correlation, 26(4), pp.367–386.

Lapidus, I.M., 1992. The Golden Age: The Political Concepts of Islam. The ANNALS of the American Academy of Political and Social Science, 524(1), pp.13–25.

Lorenzetti, R., Barbetti, R., Fantappiè, M., L'Abate, G. and Costantini, E.A.C., 2015. Comparing data mining and deterministic pedology to assess the frequency of WRB reference soil groups in the legend of small scale maps. Geoderma, 237–238, pp.237–245.

Ma, Y., Minasny, B., Malone, B.P. and Mcbratney, A.B., 2019. Pedology and digital soil mapping (DSM). European Journal of Soil Science, 70(2), pp.216–235.

Mandeville, and D.C. and Holmyard, E.J., 1927. Avicennae de congelatione et conglutinatione lapidium. Paris: Librairie Orientaliste.

Mani, D., Kumar, T.S., Rasheed, M.A., Patil, D.J., Dayal, A.M., Rao, T.G. and Balaram, V., 2011. Soil Iodine Determination in Deccan Syneclise, India: Implications for Near Surface Geochemical Hydrocarbon Prospecting. Natural Resources Research, 20(1), pp.75–88.

Mayer, W., 2017. History of geoscience: celebrating 50 years of INHIGEO. Geological Society special publication; no. 442. London: The Geological Society.

McArthur, J.M., Howarth, R.J. and Shields, G.A., 2012. Chapter 7 - Strontium Isotope Stratigraphy. In: F.M. Gradstein, J.G. Ogg, M.D. Smith, and G.M. Ogg, eds. 2012. The Geologic Time Scale 2012. Elsevier B.V. pp.127–144.

McBratney, A.B., Mendonça Santos, M.L. and Minasny, B., 2003. On digital soil mapping. Geoderma, 117(1), pp.3–52.

McGinnis, J., 2010. Avicenna's Intellectual and Historical Milieu. In: J. McGinnis, ed. Avicenna. New York: Oxford University Press.

McGrew, T., Alspector-Kelly, M. and Allhoff, F., 2009. Philosophy of Science: An Historical Anthology. Chichester: John Wiley & Sons.

McKeague, J.A. and Stobbe, P.C., 1978. History of Soil Survey Canada 1914-1975. Historical Series Canada Department of Agriculture Research Branch. Canada Department of Agriculture Research Branch.

Minasny, B. and McBratney, Alex.B., 2016. Digital soil mapping: A brief history and some lessons. Geoderma, 264, pp.301–311.

Morewedge, P., 2015. The 'Metaphysica' of Avicenna (ibn Sīnā): A critical translation-commentary and analysis of the fundamental arguments in Avicenna's 'Metaphysica' in the 'Dānish Nāma-i 'alā'ī' (The Book of Scientific Knowledge). London: Routledge.

Morgan, W.J., 1972. Plate Motions and Deep Mantle Convection. In: R. Shagam, R.B. Hargraves, W.J. Morgan, F.B. Van Houten, C.A. Burk, H.D. Holland and L.C. Hollister, eds. Studies in Earth and Space Sciences. Boulder: Geological Society of America.

Mun, S.H., 2013. Printing Press Without Copyright: A Historical Analysis of Printing and Publishing in Song, China. Chinese Journal of Communication. 6(1), pp.1-23.

Nasr, S.H. and Leaman, O., 2013. History of Islamic Philosophy. London: Routledge.

Needham, J., 1984. Science and Civilisation in China. Cambridge, UK: University Press.

Nogales, S.G., 1980. How Ibn Sina became Avicenna: Transmitted to Europe, his writings sparked off an intellectual revival. UNESCO, XXXIII (10), pp.32–39.

O'Connell, S., 2010. The House of Wisdom will rise again. New Scientist, 205(2743), pp.24–25.

O'Hara, K., 2018. Toward a Geologic Time Scale. In: K. O'Hara, ed. 2018. The History of Geology. Cambridge University Press pp. 28-51.

Oldroyd, D.R., 1996. Thinking about the Earth: History of Ideas in Geology. Cambridge: Athlone Press.

Otte, J.K., 1972. The Life and Writings of Alfredus Anglicus. Viator, 3, pp.275–292.

Palme, H. and O'Neill, H.St.C., 2014. Cosmochemical Estimates of Mantle Composition. In: Treatise on Geochemistry pp.1–39.

Parrish., J.T., 2019. Paleoclimatology. In: AssessScience. McGraw Hill. doi: 10.1036/1097-8542.48 3500

Pichon, X.L., Francheteau, J. and Bonnin, J., 2013. Plate Tectonics. Amsterdam: Elsevier.

Qur'an. 39:9. Translated by Abdullah Yusuf Ali (2013). Ware, Hertfordshire: Wordsworth Editions Limited.

Rappaport, R., 2011. Dangerous Words: Diluvialism, Neptunism, Catastrophism. In: R., Rappaport, ed. 2011. Studies on Eighteenth-Century Geology. Cornell University Library and The New York Public Library pp. 102-131.

Renima, A., Tiliouine, H. and Estes, R.J., 2016. The Islamic Golden Age: A Story of the Triumph of the Islamic Civilization. In: H. Tiliouine and R.J. Estes, eds. The State of Social Progress of Islamic Societies: Social, Economic, Political, and Ideological Challenges, International Handbooks of Quality-of-Life. Cham: Springer International Publishing. pp.25–52.

Rezanov, I.A., 1968. Paleomagnetism and continental drift. International Geology Review, 10(7), pp.765–776.

Robb, L.J., Knoll, A.H., Plumb, K.A., Shields, G.A., Strauss, H. and Veizer, J., 2005. The Precambrian: the Archean and Proterozoic Eons. In: F.M. Gradstein, J.G. Ogg and A.G.E. Smith, eds. 2004. A Geologic Time Scale 2004. Cambridge University Press. pp.129–140.

Robinson, A.G., 2009. Inorganic Geochemistry: Applications to Petroleum Geology. John Wiley & Sons.

Romanowicz, B., 2009. The Thickness of Tectonic Plates. Science, 324(5926), pp.474–476.

Roopnarine, L., 2019. The British in India: A Social History of the Raj By David Gilmour. The Historian, 81(4), pp.718–719.

Rosbaud, P., 1988. Victor Moritz Goldschmidt (1888–1947). Applied Geochemistry, 3(4), pp.361–369.

Roy, A.B. and Purohit, R., 2018. Chapter 17 - The Himalayas: Evolution Through Collision. In: A.B. Roy and R. Purohit, eds. Indian Shield. Cambridge: Elsevier. pp.311–327.

Runcorn, S.K., 2013. Continental Drift. New York & London: Elsevier.

Sadykov, A.S., 1980. A forerunner of modern science. XXXIII (10), pp.41–44.

Salmon, V., 1985. The study of foreign languages in 17th-century England. 24th ed. Histoire Épistémologie Langage.

Schmidt, M.W.I., Torn, M.S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I.A., Kleber, M., Kögel-Knabner, I., Lehmann, J., Manning, D.A.C., Nannipieri, P., Rasse, D.P., Weiner, S. and Trumbore, S.E., 2011. Persistence of soil organic matter as an ecosystem property. Nature, 478(7367), pp.49–56.

Schmitz, M.D., 2012. Chapter 6 - Radiogenic Isotope Geochronology. In: F.M. Gradstein, J.G. Ogg, M.D. Smith, and G.M. Ogg, eds. 2012. The Geologic Time Scale 2012. Elsevier B.V. pp.115–126.

Scholz, D., Mangini, A., Felis, T., 2004. U-Series Dating of Diagenetically Altered Fossil Reef Corals. Earth and Planetary Science Letters. 218(1), pp.163-178.

Scott, S.D., 2014. Volume Editor's Introduction. In: H.D. Holland and K.K. Turekian, eds. Treatise on Geochemistry (Second Edition). Oxford: Elsevier. pp.xxiii–xxv.

Searle, M.P. and Treloar, P.J., 2019. Introduction to Himalayan tectonics: a modern synthesis. Geological Society, London, Special Publications, 483(1), pp.1–17.

Sharp, Zachary., 2007. Principles of stable isotope geochemistry. Principles of stable isotope geochemistry. Upper Saddle River, N.J: Pearson/Prentice Hall.

Shields, G.A., Strachan, R.A., Porter, S.M., Halverson, G.P., Macdonald, F.A., Plumb, K.A., de Alvarenga, C.J., Banerjee, D.M., Bekker, A., Bleeker, W., Brasier, A., Chakraborty, P.P., Collins, A.S., Condie, K., Das, K., Evans, D.A.D., Ernst, R., Fallick, A.E., Frimmel, H., Fuck, R., Hoffman, P.F., Kamber, B.S., Kuznetsov, A.B., Mitchell, R.N., Poiré, D.G., Poulton, S.W., Riding, R., Sharma, M., Storey, C., Stueeken, E., Tostevin, R., Turner, E., Xiao, S., Zhang, S., Zhou, Y. and Zhu, M., 2021. A template for an improved rock-based subdivision of the pre-Cryogenian timescale. Journal of the Geological Society, 179(1), pp. 2020-222.

Simionato, A., 2020. "Harmony" (HE 和) and "Coherence" (LI 理) in Neo-Confucianism. Journal of East-West Thought. 2(10), pp.103-118.

Sorkhabi, R.B., 1997. Historical Development of Himalayan Geology. Geological Society of India, 49(1), pp.89–108.

Sothe, C., Gonsamo, A., Arabian, J. and Snider, J., 2022. Large scale mapping of soil organic carbon concentration with 3D machine learning and satellite observations. Geoderma, 405, p.1-14.

Speidel, D.H., 1983. Mineralogic phase rule. In: Mineralogy, Encyclopedia of Earth Science. Boston, MA: Springer US. pp.276–276.

Stubblefield, C.J., 1970. Darashaw Nosherwan Wadia, 1883-1969. Biographical Memoirs of Fellows of the Royal Society, 16, pp.543–562.

Tedesco, S.A., 2012. Surface Geochemistry in Petroleum Exploration. Springer Science & Business Media.

Thakur, V., 2003. Research contributions of D N Wadia. Resonance, 8, pp.65–75.

Thompson, W.G., Spiegelman, M.W., Goldstein, S.L., Speed, R.C., 2003. An Open-System Model for U-Series Age Determinations of Fossil Corals. Earth and Planetary Science Letters, 210 (1-2), pp.365-381.

Tilley, C.E., 1988. Victor Moritz Goldschmidt (1888–1947). Applied Geochemistry, 3(4), pp.371–378.

Tirmizi, S.M.A., 1982. Ibn Sina as a Scientiest. Islamic Quarterly, 26(4), pp.211–215.

Tolman, A.B., 2016. Geologists and the British Raj, 1870-1910. [online] https://doi.org/10.26076/9A0D5B0A.

Vaccari, E., 2006. The "classification" of mountains in eighteenth century Italy and the lithostratigraphic theory of Giovanni Arduino (1714–1795). In: G.B. Vai and W.G.E Cladwell, eds. 2006. The Origins of Geology in Italy. The Geological Society of America pp. 157-177.

Vaccari, E., 2007. Linnaeus and Giovanni Arduino Some Notes on a Difficult Reception in Mineralogy and Geology. In: M. Beretta, M. and A. Tosi, eds. 2007. Linnaeus in Italy The Spread of a Revolution in Science. Science History Publications/USA pp. 189-198.

Villemant, B., Feuillent N., 2003. Dating Open Systems by the 238 U- 234 U- 230 Th Method: Application to Quaternary Reef Terraces. Earth and Planetary Science Letters, 210 (1-2), 105-118.

Virgili, C., 2007. Charles Lyell and scientific thinking in geology. Comptus Rendes Geoscience 339(8) pp. 572 – 584.

Wadia, D.N. and West, W.D., 1964. Structure of the Himalayas. New Delhi: The Temple Press

Wadia, D.N., 1919. Geology of India, for students. London: Macmillan and co., limited.

Wadia, D.N., 1931. The Syntaxis of the North-West Himalaya; Its Rocks, Tectonics, and Orogeny. Records of the Geological Survey of India, LXV, Part 2, pp.190–220.

Waters, C.N., Zalasiewicz, J., Summerhayes, C., Fairchild, I.J., Rose, N.L., Loader, N.J., Shotyk, W., Cearreta, A., Head, M.J., Syvitski, J.P.M., Williams, M., Wagreich, M., Barnosky, A.D., An, Z., Leinfelder, R., Jeandel, C., Gałuszka, A., Ivar do Sul, J.A., Gradstein, F., Steffen, W., McNeill, J.R., Wing, S., Poirier, C. and Edgeworth, M., 2018. Global Boundary Stratotype Section and Point (GSSP) for the Anthropocene Series: Where and how to look for potential candidates. Earth-Science Reviews, 178, pp.379–429.

Weill, D.F. and Fyfe, W.S., 1967. On equilibrium thermodynamics of open systems and the phase rule (A reply to D. S. Korzhinskii). Geochimica et Cosmochimica Acta, 31(7), pp.1167–1176

Weller, O.M., Mottram, C.M., St-Onge, M.R., Möller, C., Strachan, R., Rivers, T. and Copley, A., 2021. The metamorphic and magmatic record of collisional orogens. Nature Reviews Earth & Environment, 2(11), pp.781–799.

Wilschefski, S.C. and Baxter, M.R., 2019. Inductively Coupled Plasma Mass Spectrometry: Introduction to Analytical Aspects. The Clinical Biochemist Reviews, 40(3), pp.115–133.

Yount, L., 2009. Alfred Wegener: Creator of the Continental Drift Theory. New York: Infobase Publishing.

Zuo, Y., 2018. Shen Gua's Empiricism. Cambridge, MA.: Harvard University Asia Centre.

Chapter 2 Image References

Figure 2.1: 100 p. stamp released by India Post. India Post, 1984. Approval obtained by Department of Posts.

Figure 2.2: A photograph of Charles Stewart Middlemiss. Fermor, L.L., 1945. Public Domain (fifty years post death).

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Figure 2.5: Target-specific digital soil mapping supporting spatial planning in Hungary (Image modified by removing figure title, removing an image included in the figure, eliminating the word “mining”, and cropping the image to fit the page). Takàcs, K., 2016. CC Attribution 3.0 Licence.

Figure 2.6: The final DSM produced. Sothe, C., Gonsamo, A., Arabian, J. and Snider, J., 2022. https://doi.org/10.1016/j.pec.2007.03.024 CC BY-NC-ND 4.0 Licence.

Figure 2.7: Painting depicting the Deluge. London Tate Museum Collection, Turner, JMW, 1805.

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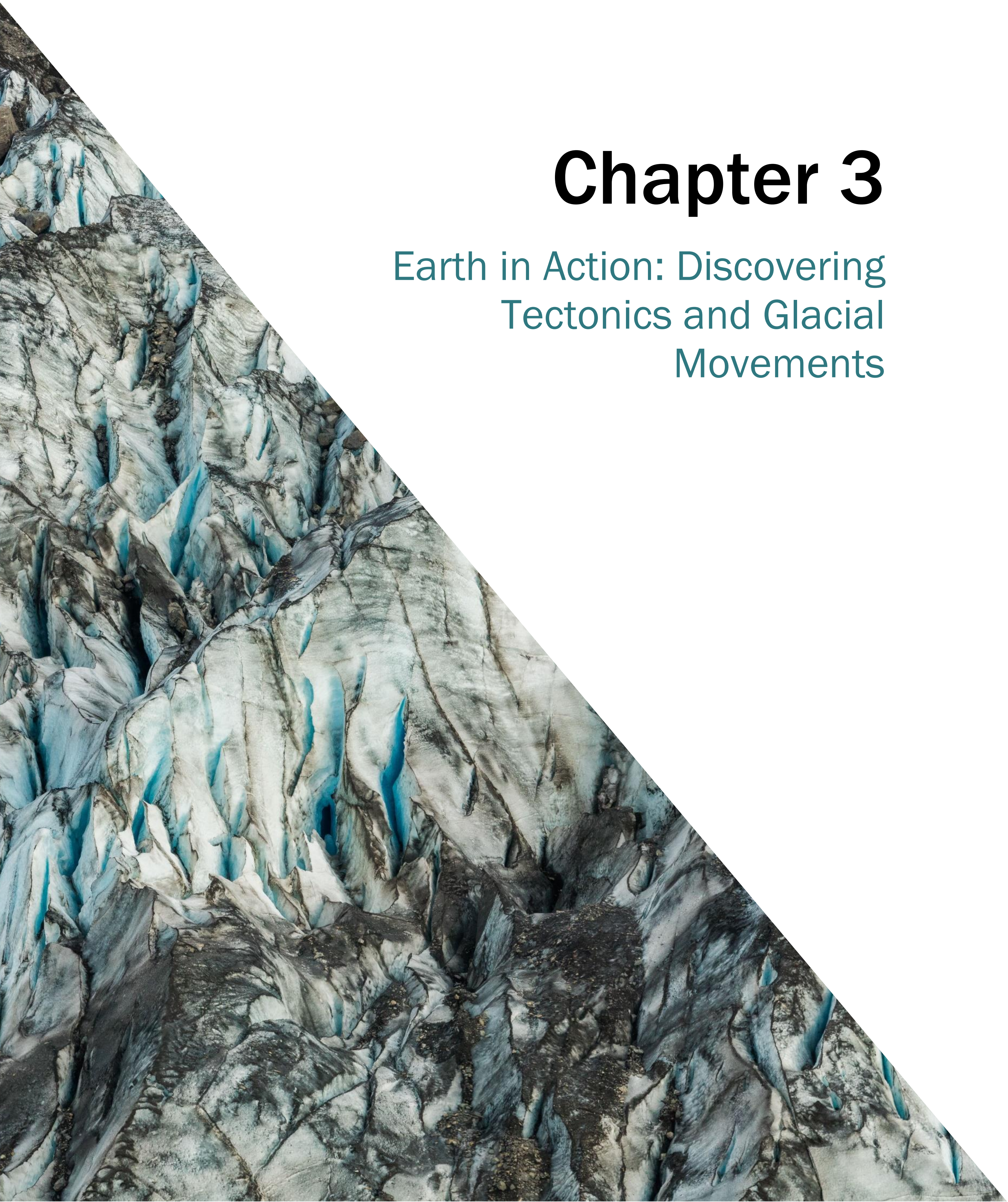
Chapter 3

Earth in Action: Discovering Tectonics and Glacial Movements



Introduction

There are processes on the Earth so powerful and vast that their effects Can be observed throughout nearly every aspect of Earth's history. The oceans, tectonic plates, and glaciers all hold rich histories which have been the focus of extensive scientific inquiry throughout human history. Today, the tremendous powers of the tectonic plates which move Earth's crust in an ever-shifting jigsaw puzzle, and the glaciers which carve upon the surface of that crust, are well studied. Many secrets of the Earth's oceans have been revealed, while many more remain hidden with the promise of future discovery. However, for most of human history, the forces that produced the complexities of our world were only speculated upon.

While humans had numerous potential explanations for the shape of the land and oceans, there were missing details that presented a compelling and unattainable mystery for past scientists. From an unusually shaped boulder in an open field to fossil deposits found in critical locations, there were many clues discovered by keen thinkers who began to develop theories to explain these happenings. These clever observations led to insightful analyses and innovative experiments, allowing explanations for Earth's critical processes to be developed. It was not always easy to overcome long held beliefs about what forces governed the Earth, or how the lands came to be, but eventually, much of the scientific community could agree on ideas backed by evidence.

The scientific tools and techniques developed by generations of scientists working before us provided the basis for modern research of Earth's processes. Now, we can use these tools to turn our questioning towards the future - what will Earth look like when the present becomes history? Join us in Chapter 3 as we dive into the rich history of glacial processes, tectonics, and oceanography.

Alfred Wegener and The Discovery of Pangea

Before the surface of Earth looked that way it does now, the landmasses on top of the Earth were once a large-scale amalgamation of continents and microcontinents (Stampfli, et al., 2013). This amalgamation resulted in the formation of a supercontinent called Pangea (Wu, et al., 2020). In the scientific community, it is widely accepted that Pangea was formed in the late Paleozoic (299 – 252 Mya) from the closing of the Iapetus and Rheic oceans that were bounded by Laurentia (North America and Greenland), Baltica, and northern Gondwana (Wu, et al., 2020). There have been various reconstructions of Pangea such as Pangea A (Figure 3.1), Pangea B, and Pangea C which propose slightly different geographic configurations for Pangea influenced by different geologic factors that occurred over long periods of time (Wu, et al., 2020). Pangea A remains the predominantly used reconstruction (Wu, et al., 2020). Although other historical figures have suggested the concept of Pangea, Alfred Wegener (Figure 3.2) was considered to have put forth the first defensible argument for the supercontinent (Domeier, Van der Voo and Torsvik, 2012).

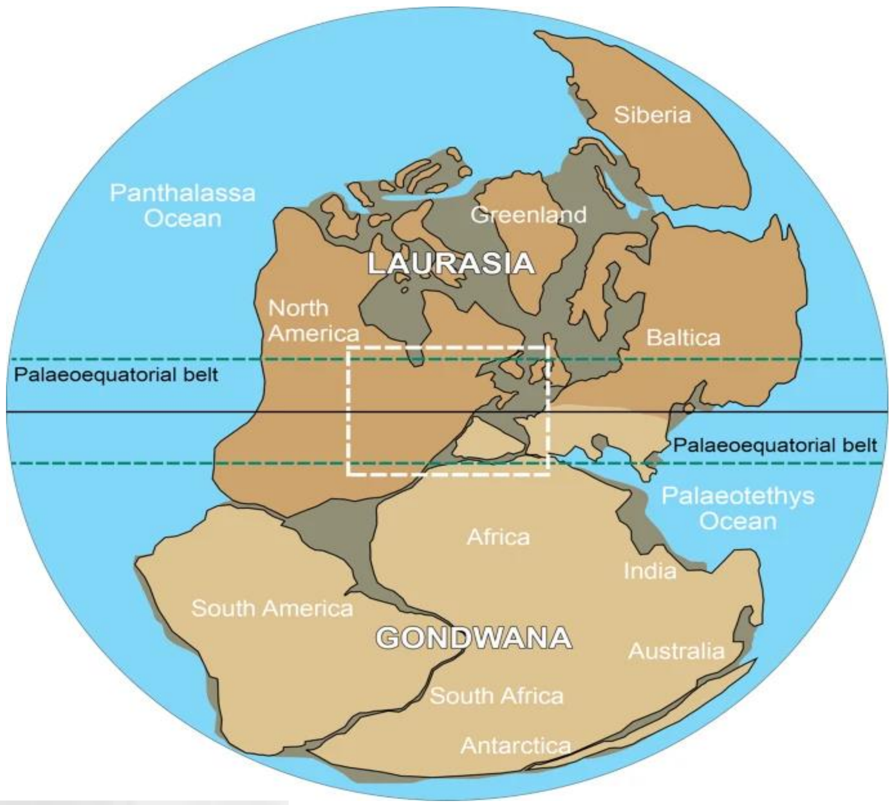


Figure 3.1: Configuration of Pangaea-A ("Wegenerian") based on the continental connection between eastern Laurentia (Laurasia) and Iberia (northwestern Gondwana) in the late Paleozoic. Colour legend for the figure: blue represents oceans; light brown represents Gondwana; dark brown represents Laurasia; and grey represents shallow seas and coastal flooded areas.

Figure 3.2: Photograph of Alfred Wegener, a German meteorologist and geophysicist who formulated the first complete statement of the continental drift hypothesis and Pangea.

The Idea of Pangea

As a concept, Pangea is attributed to the 16th century geographer Abraham Ortelius (Romm, 1994). He noted the congruence of peri-Atlantic coasts of America, Europe, and Africa in his book *Thesaurus Geographicus* in 1596 (Ortelius, 1596). This was followed by Snider-Pellegrini's draft of the first paleogeographic map of what would later be recognized as Pangea in 1858 (Domeier, Van der Voo and Torsvik, 2012). Only until the 20th century was Pangea introduced into mainstream science by Alfred Wegener as a tenable paleogeographic model (Domeier, Van der Voo and Torsvik, 2012). Wegener's late Paleozoic to early Mesozoic paleogeographic model of Pangea is widely used in modern society (Domeier, Van der Voo and Torsvik, 2012). However, minor modifications due to continental distortions in his reconstruction have been made (Domeier, Van der Voo and Torsvik, 2012).

Theory of Continental Drift

Looking at maps of the world in the early twentieth century, Wegener realized that the coastlines of certain continents fit remarkably similarly to the coastlines of others like a jigsaw puzzle (Wegener, 1915). This realization allowed Wegener to conclude that at one point there existed masses of land known as supercontinents, and over time, these supercontinents split to form the geography of Earth today (Wegener, 1915). With these realizations, Wegener predicted that roughly 300 million years ago (Mya), there existed a major supercontinent made up of connected continental plates which we now know today as Pangea. It was suggested by Wegener that the breakup of Pangea was caused by the Eötvös effect (Wegener, 1915). The Eötvös effect describes a change in Earth's gravity due to the change in centrifugal acceleration. A change in centrifugal acceleration is caused by either eastbound or westbound acceleration (Gasperid and Chierici, 1996). Wegener predicted the Eötvös effect to have moved the continents towards the equator during the start of Pangea's separation. Furthermore, the tidal attraction of the sun and moon was thought to have had effects on the breakup of Pangea, dragging different parts of Earth's crust in various directions simultaneously (Wegener, 1915). Wegener also proposed centripetal force from Earth's rotation pushing the supercontinent fragments apart. From these observations and postulations, Wegener named his theory "continental drift" (Wegener, 1915). In Wegener's fourth edition of *Die Entstehung der Kontinente und Ozeane*, which translates to "The Origin of Continents and Oceans", he published a proposed map of Pangea as well as maps showcasing the separation of Pangea (Figure 3.3). The maps showcase the postulated topological arrangements of the continents during the late Carboniferous period (300 – 299 Mya), when Pangea is thought to have first been fully formed (Golonka and Ford, 2000), as well as the Eocene era and older quaternary era (Batchelor, et al., 2019; Licht, et al., 2014). The Eocene era is a period between the late carboniferous era and the older quaternary era approximately 34-55 Mya (Licht, et al., 2014).

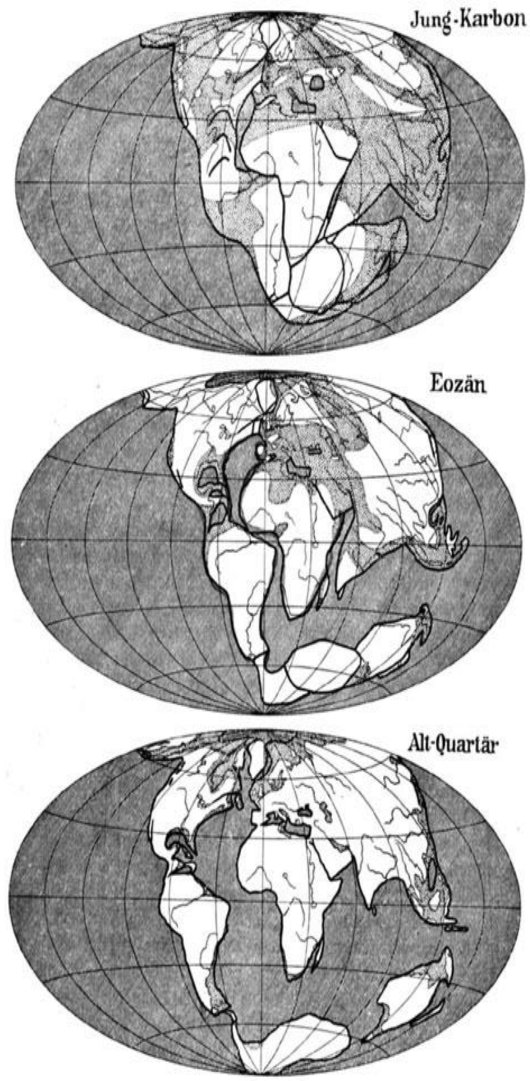


Figure 3.3: Maps of the world published in Alfred Wegener's fourth edition of "Die Entstehung der Kontinente und Ozeane". The three maps represent different time periods and showcase the separation of continents over time. The labels on the maps are in German and translate to "Late-Carboniferous", "Eocene", and "Old-Quaternary" from top to bottom respectively. Going from top to bottom, the maps illustrate Pangea in the Late-Carboniferous period splitting during the Eocene and then transitioning to the geological structure of the Old-Quaternary period.

The older quaternary period is the current period humans live in which began 2.6 Mya (Batchelor, et al., 2019). Wegener's maps were incredibly revolutionary as at the time, the thought of continents changing shape was new (Wegener, 1929). Not only did Wegener predict one of the previous possible arrangements of Earth's continents, but he also predicted a transitional step in the creation of Earth's current continental structure (Wegener, 1929). Wegener's maps established a foundation for future geologists to make predictions of Earth's past. Furthermore, Wegener's findings provided great insight into the Earth's structural past and the mechanisms between the movements of continents.

Resistance and Acceptance

When Wegener first presented his theory 1912, it was rejected by the scientific community (Domeier, Van der Voo and Torsvik, 2012). Later historians note that Wegener had remarkable intuition and was able to develop the correct theory without much evidence; however, his intuition alone was not enough to convince fellow scientists (Domeier, Van der Voo and Torsvik, 2012). At the time, his main opponents were American geologists such as Bailey Willis and Charles Schubert (Newman, 1995). American geologists explained Earth's history through observed physical evidence such as geological features and phenomena, while Europeans did so through physics and chemistry laws (Greene, 2016; Oreskes, 1999). Greene (2016) suggested that the disagreement from American Geologists was due to the difference in the two approaches: Wegener gave importance to the plausibility of a theory, while for the Americans, it was necessary to demonstrate existence beyond its plausibility. This conflict ultimately concluded in the 1960s with paleomagnetism supporting Wegener's theory on Pangea (Carey, 1959). Carey (1959) improved on the schematic reconstructions from Wegener, which was achieved through the use of a semi-quantitative "orocline analysis". "Orocline analysis" involved the closing of ocean basins through continental rotations that straightened curved mountain belts (Domeier, Van der Voo and Torsvik, 2012). Through these initial tests, Carey (1959) verified the congruence of the South American-African continental margin through spherical tracing on a globe. Furthermore, veracity of Laurasia's shape and orientation for the late Paleozoic and early Mesozoic was also achieved. Carey (1958) interpreted this as an indication that reconstruction was appropriate only for later periods. To reach the true paleogeography of the late Paleozoic, additional (late Paleozoic) strain would need to be reversed (Domeier, Van der Voo and Torsvik, 2012).

Adaptations of Wegener's Findings

Although Alfred Wegener paved the way for the understanding of plate tectonics, his postulations of how continents moved were flawed. Wegener was correct in discovering that continental drift occurs; however, his theory of the Eötvös effect causing this movement was incorrect as a new mechanism was proposed in which made the Eötvös effect postulation seem like a miniscule possibility. The current understanding of continental drift is that Earth's crusts move through the process of what we know as convection currents (Holmes, 1928). This understanding was discovered by Arthur Holmes who strengthened Wegener's continental drift theory and corrected the mechanisms behind continental drift. Holmes defined convection currents as currents of heat and thermal expansion that occur in the mantle of the Earth. As well as continental separation, convection currents also explained mountain range and ocean floor formations. Ocean floors would form via plate separation and mountain ranges would form when plates collided due to the immense force of the collisions (Holmes, 1928). Although Wegener's mechanisms of plate tectonics were flawed, they paved the way for convection currents to be discovered, outlining how continental plates move and how ocean floors and mountain ranges form.

Another improvement made on Alfred Wegener's discoveries was the discovery of Laurasia and Gondwana. It was proposed by Alexander du Toit in 1937 that after Pangea split up, two smaller supercontinents known as Laurasia and Gondwana were formed about 180 Mya (du Toit, 1937). The formation of Laurasia and Gondwana was never mapped out by Wegener as he most likely was not aware of the exact geological structure of Earth as Pangea completely separated. These findings by Alexander du Toit strengthened Wegener's continental drift theory as they supported the idea of the transition of continental forms from the time Pangea split until the Old-Quaternary period. A map was illustrated by du Toit outlining the form of Earth's continents after the separation of the continental plates that made up Pangea (Figure 3.4).

du Toit's map not only depicted the changes in the geological structure of continental crusts from the separation of Pangea, but also how waterways were created and destroyed. This is evident as the separation of Pangea resulted in the formation of a major body of water known as the Tethys Ocean. This map supported previous views held by both Wegener and Holmes on ocean floors being formed from the separation of the continental crust. These discoveries from du Toit also inspired the idea of yet even more possible supercontinents and geological arrangements of Earth having occurred before Laurasia, Gondwana, and Pangea. This is as Laurasia, Gondwana, and Pangea only being hundreds of millions of years old are relatively young compared to Earth's timeline. At the time of du Toit's discoveries it was already proposed that the Earth was at least three billion years old due to the elements present and the approximate ages of meteorites that had landed on Earth (Kovarik, 1931). With the potential age of the Earth, there was no doubt that there had been many other variations of Earth's geological formation. The real challenge was determining what geological structures were present and when they approximately existed.

To further improve the accuracy of Pangea reconstructions, quantitative reconstruction methods were used. The first quantitative reconstruction of Atlantic-bordering continents was produced by Bullard, Everett and Smith (1965) and was performed through least-squares-fitting of 500 fathom bathymetric contours of continental margins on a computer, which is a method used to find the best fitting curves by minimizing the residuals. The results from this reconstruction revealed the congruence of Atlantic coastlines, with a very high accuracy (Domeier, Van der Voo and Torsvik, 2012). This technique also allowed refinements of work from du Toit (1937) by Smith & Hallam (1970). The work from Bullard, Everett and Smith (1965) and Smith & Hallam (1970) culminated in the Pangea A-1 reconstruction. A second modified quantitative reconstruction of Pangea A-1 known as Pangea A-2 was also proposed by Le Pichon & Fox (1977) and Walper & Rowett (1972), suggesting improvements on the alignment of late Paleozoic orogenic belts and paleogeographic setting for the Florida peninsula (Domeier, Van der Voo and Torsvik, 2012).

Historical Context Conclusions

The discovery of Pangea by Alfred IWegener is one of the great geological discoveries of all time. Based on previous findings by geologists such as Ortelius and Snider-Pellegrini, Wegener's discoveries on continental drift their puzzle-piece connections worked towards unravelling the mechanisms behind Earth's structural changes. With the remarkable findings of Wegener, previous supercontinents were discovered, and mechanisms were proposed that caused transitions between these supercontinents. This led the way to a much more in-depth search back in time to discover previous physical forms of Earth. After Wegener's findings, both Holmes and du Toit modified their findings and proposed new theories surrounding plate tectonics and supercontinent discovery. In addition, further work performed through quantitative reconstructions by Bullard, Everett and Smith (1965), Smith & Hallam (1970), Le Pinchon & Fox (1977) and Walpher & Rowett (1972) have resulted in improved reconstructions of Pangea. Overall, historical knowledge on supercontinents and continental drift discovered

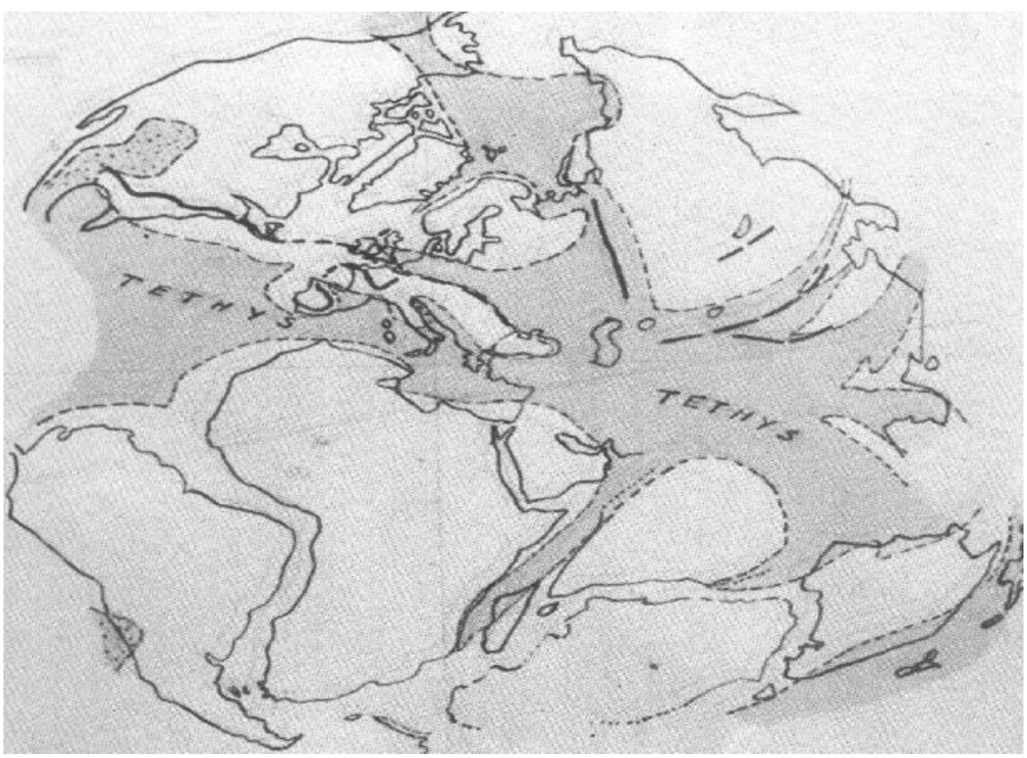


Figure 3.4: Map created by Alexander du Toit of Gondwana at the South of the Tethys Ocean and Laurasia at the north of the Tethys Ocean. These two supercontinents resulted from the split of Pangea. Convection currents caused Laurasia and Gondwana to further separate over time. The formation of Laurasia and Gondwana was part of the transition of Pangea to the current formation of the continents in the Old-Quaternary period.

by Wegener and others created a strong backbone for modern discoveries to be made surrounding the topic.

Modern Reconstructions and Understanding of Geologic Events

Research into the reconstruction of Pangea and the events surround it is still ongoing. Issues remain with reconstructions and theories of Pangea, resulting in ongoing debates. Areas of debate include the apparent polar wander (APW) paths of the continents in forming Pangea and reconstructions of the East Asian Block. Novel discoveries regarding events during the period in which Pangea was amalgamated include the catastrophic slab loss event.

Apparent Polar Pathways

There remains debate on the processes responsible for mid-to-late Paleozoic amalgamation events of Pangea. This debate stems from the widely differing compilations of paleopoles using different quality-filter criteria and approaches for their construction of apparent polar wander (APW) paths (Wu, et al., 2020). APW paths record the apparent motion of the rotation axis relative to a continent, depending on whether the movement is plotted using the north or south pole (Torsvik, 2005). In a study performed by Wu, et al. (2020), an updated compilation of high-quality paleopoles of the mid-to-late Paleozoic from Gondwana, Laurentia, and Baltica was produced using the Van der Voo selection criteria. They infer that the formation of Pangea was likely initiated 400 Mya during the collision between Laurasia and a ribbon-like Gondwanan promontory that was formed through a scissor-like opening of the Paleo Tethys Ocean. They further suggest that this amalgamation culminated in the mostly orthogonal convergence between Gondwana and Laurasia (Wu, et al., 2020). The study presents radically revised reconstructions of the formation of Pangea during the mid-to-late Paleozoic, offering new insights into the history of Pangea.

East Asian Block Reconstructions

The geological reconstructions of the East Asian blocks in Pangea remain a source of controversy (Zhao, et al., 2018). In particular, controversy surrounds the fact of whether or not the East Asian blocks were assembled to join before the breakup of Pangea (Zhao, et al., 2018). A study performed by Zhao, et al. (2018) carried out a geological and paleomagnetic investigation into the East Asian blocks and their history in relation to Pangea. The East Asian blocks in Pangea include North China, South China (Yangtze and Cathaysia), Tarim, Qaidam, Central Qilian, North Qinling, South Qinling, North Qiangtang, South Qiangtang-Lhasa, Indochina (Annamia), and Sibumasu (Zhao, et al., 2018). Numerous models have been proposed for the reconstruction of the East Asian blocks associated with Pangea by authors such as Zhao and Coe (1987) and Zheng, Xiao and Zhao (2013). In many of these models, the East Asian blocks are isolated micro-continental blocks that surrounded the Paleo-Tethys Ocean during the existence of Pangea. Recent geological data, especially for collisional mountain belts between continental blocks in East Asia, have not been fully incorporated; this suggests that previous models are inaccurate. Zhao, et al. (2018) used more recent field-based structural, metamorphic, geochemical, geochronological, paleomagnetic and paleontological investigations on the Early Paleozoic orogenic belts, Central Asian Orogenic Belt, Central China Orogenic System and Paleo-Tethys Belt.

Zhao, et al. (2018) indicates that about 750 Mya, Rodinia's separation opened numerous oceans such as the Proto-Tethys and Paleo-Asian oceans in East Asia. The closing of the Proto-Tethys Ocean in the early Paleozoic (500–420 Mya) led to the East Asian blocks colliding at the northern margin of Gondwana. Paleo-Asian Ocean subduction formed the Central Asian Orogenic Belt, and its closure led the Tarim, Alex, and North China blocks to join Eastern Europe-Siberia as parts of Pangea. They further suggest that in the early Devonian (420–380 Mya), the East Paleo-Tethys Ocean opened with two branches known as the Mianlue Ocean and the East Paleo-Tethys Ocean (stricto sensu). During the Triassic time period, the East Paleo-Tethys Ocean (stricto sensu) closed along the Longmu Co – Shuanghu – Changning –

Menglian – Inthanon belt, which ultimately led to the inclusion of a coherent East Asian continent in Pangea 220 Mya (Zhao, et al., 2018). Overall Zhao, et al. (2018) offers a high degree of insight into the possible formation of the East Asian Blocks and Pangea.

Catastrophic Slab Loss

Recent research performed by Gianni and Navarrete (2022) observed catastrophic slab loss in southwestern Pangea that has been preserved in the mantle and igneous rocks. The lithospheric slab is the frontmost portion of the subduction plate that descends into the upper mantle at convergent margins (Levin, et al., 2002). This descent can lead to tearing, detachment, and sinking of the slab material, accompanied by uplift, extension, and magma with distinctive properties (Levin, et al., 2002). The Choiyoi Magmatic Province in southwestern Pangea represented a major episode of silicic magmatism during the mid-Permian-Triassic, which has a highly debated origin (Gianni and Navarrete (2022) (Figure 3.5). Using lower mantle slab records and plate-kinematic reconstructions between southwestern Pangea, geochemical data analysis, and geochronological information, Gianni and Navarrete (2022) propose that large-scale slab loss occurred. These findings make the Choiyoi Magmatic province the oldest example of a geophysically constrained slab loss event allowing greater avenues to assess geodynamic settings of silicic large igneous provinces back to the late Paleozoic (Gianni and Navarrete, 2022).

Modern Concluding Remarks

The discovery of supercontinents such as Pangea was heavily influenced by the discoveries made by Alfred Wegener. Over time, Wegener's theory has been revised and improved on, leading to a better understanding of the formation of Pangea. Today there is still some debate over processes involved in Pangea's formation and separation and the time frame in which Pangea split. Areas of debate include the apparent polar pathways surrounding the amalgamation of Pangea and the reconstruction of the East Asian Block. Novel research has also provided further insight into geological events during Pangea. One such example includes new findings by Gianni and Navarrette (2022) that suggest catastrophic slab loss in southwestern Pangea. These new discoveries and research in these areas enhance our understanding of Pangea, ultimately providing a more informed understanding of the history of the Earth.

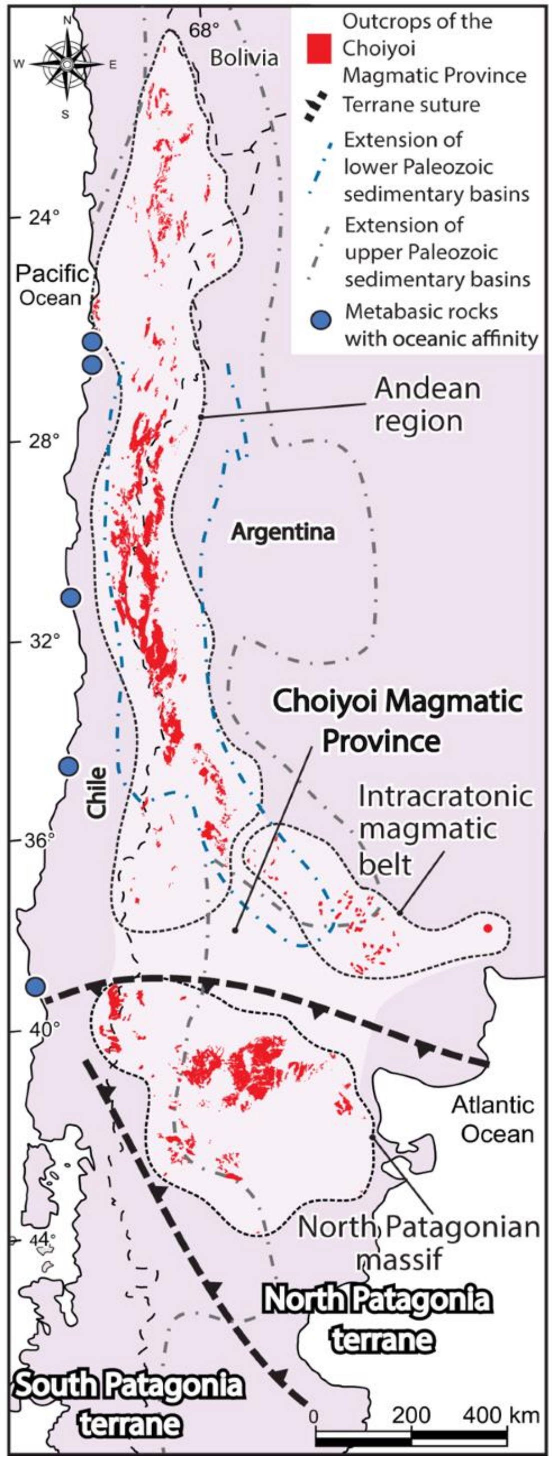


Figure 3.5: Schematic map in present day coordinates of the mid-Permian-Lower Triassic Choiyoi Magmatic Province. The red spots represent the distribution of the Choiyoi Province, and the dashed black lines represent the late Paleozoic terrane suture zones from the North Patagonia and Southern Patagonia terranes. Metabasic outcrops and ocean affinities in the western continental margins are also indicated.

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Discovering the Internal Structure of the Earth

The internal structure of the Earth, whether it be solid, liquid, or gaseous, was a heavily debated topic amongst scientists, spanning the 19th and 20th centuries. Physicists and mathematicians often supported the solidist arguments, while geologists supported the fluidist arguments. This debate exemplified how social power and personal biases interfere with and prolong the scientific process. It is for which Richard Feynman famously quotes in his *Seeking New Laws* speech, "If it disagrees with experiment, it's wrong… It doesn't make any difference how beautiful your guess is, it doesn't make any difference how smart you are, who made the guess, or what his name is. If it disagrees with experiment, it's wrong" (Brush, 1979). Throughout the debate, this principle of science had been heavily disobeyed, as numerous theories were hypothesized and speculated using preferential evidence to defend scientists' personal viewpoints. Additionally, the answer of what lies below the Earth's surface could not be measured with certainty due to the limitations of the technology and the availability of information at the time. It wasn't until the study of seismology was introduced to the debate that the true answer could be confirmed. This section highlights the most influential hypotheses given by predominantly European mathematicians and geologists, who commonly possessed elite status and regard in the scientific community.

Origins and Contributors to The Debate

The debate surrounding the internal structure of the Earth began with French mineralogist and geologist Louis Cordier (1777-1861). In 1827, he published studies that outlined the increasing internal temperatures of the Earth. Prior to his discovery, it was believed that any heat possessed by the Earth was due to extraterrestrial bodies such as the sun (Brush, 1979). Cordier directly challenged this theory by proving that heat efflux is an inherent property of the Earth that is generated from the core. He discovered that the average temperature increased with depth at an approximate rate of one degree every 30 to 40 meters (Cordier, 1827). This led to the emergence of new ideas such as the debate between a solid and liquid center of the Earth. Before Cordier's research emerged, many scientists were satisfied with the belief that the Earth was solid, however, the logic of Cordier's discoveries evoked novel thinking by mathematicians, physicists, and geologists (Cordier, 1827).

This discourse would last for a century, with many distinguished scientists adding research and theories that contributed to both a solid and a fluid internal Earth. The most notable solidists leading the debate included William Hopkins and William Thomson. In opposition, the most influential supporters of the fluidist theories were Henri-Édouard Tresca, Osmond Fisher, and Siegmund Günther. Over time, the prevailing theories of the discourse transitioned from solidist viewpoints to predominantly fluidist beliefs. The debate concluded with the fundamental seismological discoveries of scientists Andrija Mohorovicic, Beno Gutenberg, and Inge Lehmann.

General Models Introduction

William Hopkins (1793-1866) was a leading researcher in discovering the unknown internal structure of the Earth, acting as a catalyst for this debate. Hopkins was well known as a professor of mathematics at the University of Cambridge and for his background in geologic research (Smith, 2007). His first theory, proposed in 1838, used elements of varying melting points to state that there was no absolute way to understand the fluidity of the Earth unless the mineral and chemical compositions were known and analyzed (Hopkins, 1839). Using theoretical geology and his knowledge of

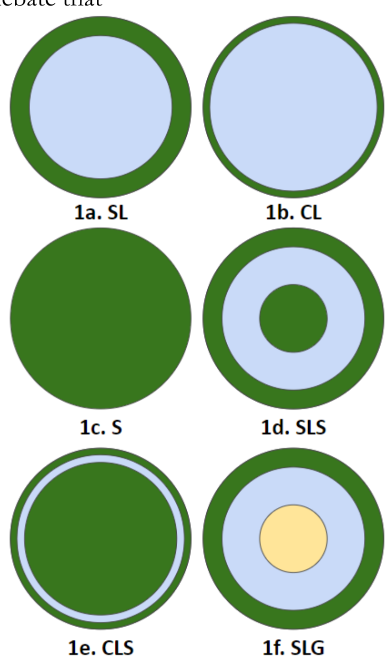


Figure 3.6: Diagrams of the five models of the internal structure of the Earth as described by Hopkins, with green representing solid, blue representing liquid, and yellow representing gas. 1a. SL model: shows a 100-800 mile thick solid crust and a liquid interior, 1b. CL model: shows a 10-30 mile thick solid crust and a liquid interior, 1c. S model: shows a fully solid Earth, 1d. SLS model: shows a thick solid crust, a liquid layer, and a solid nucleus, 1e. CLS model: shows a thin solid crust, a thin liquid layer, and a large solid nucleus, 1f. SLG model: shows a thick solid crust, a liquid layer, and a gaseous nucleus.

physics and mathematics, Hopkins stated three overarching models (Figure 3.6) representing the internal composition of the Earth in his paper *Researches in Physical Geology – Third Series* (1842).

The first model stated in his paper suggests that due to the rapid increase in temperature towards the center of the Earth, the melting points of the compositional materials would be surpassed; thus, the Earth would transition from a solid crust to a liquid interior with increasing depth (Figures 3.6a and 3.6b). Alternatively, the second model proposes that the increase in pressure when travelling towards the core is so rapid that the innermost layer is solid. Hopkins states in this scenario that much of the interior would still be liquid, however the crust and core would be solid (Figures 3.6d and 3.6e). His third prediction suggests that the Earth is solid beginning from the nucleus and continues to be solid all the way through. This theory operates on the idea that if liquid was under the Earth's crust, said crust would break apart and sink (Figure 3.6c) (Hopkins, 1842). From these three scenarios proposed by Hopkins, five models for the internal structure of the Earth were born. These models would be the basis of the debate for centuries to come, where mathematicians and geologists would attempt to prove their personal theories and viewpoints.

Beginnings of Solidist Theories

Hopkins set out to prove his models in 1840 using principles of astronomy such as precession: the movement of the axis of rotation of the Earth, and nutation: the periodic variation in the incline of the Earth's axis (Hopkins, 1839; 1840). In his models, he found that the Earth would either have to be completely solid or have a thick solid crust that gradually transitioned into a liquid interior, conforming to the S or SL models (Figures 3.6c and 3.6a) respectively. From his studies, he determined that the Earth was solid with cavities that fluids could travel through to create different regions of various pressures, resulting in visible geologic features (Hopkins, 1840).

As a highly accredited scholar with both a prominent academic and social status, Hopkins influenced arguments both supporting and opposing his various models. For example, Henry Hennessey (1826-1901) stated in 1846 that it would not matter if the inside of the Earth was liquid, as it would rotate together with the solid crust due to frictional forces between the two layers (Hennessy, 1846). This argument would completely invalidate Hopkins' theories, however Hennessey's arguments were not recognized by the scientific community. Hopkins was an overall more influential scientist and his research was perceived to be more credible. Therefore, the solidist viewpoint remained a strong contender in the debate for the next 40 years.

Thomson's Solidist Influence

William Thomson (1824–1907), also known as Lord Kelvin, was a renowned mathematician, engineer, and mathematical physicist. As a student of Hopkins, he became a public supporter of the S model (Figure 3.6c). He amplified Hopkins' arguments against a thin crust and a liquid mantle (CL model) and supported his calculations of precession and nutation, to ultimately support solid Earth theories. Upon replicating Hopkins' experiments in 1862, Thomson stated that the hypotheses would be stronger if a fluid interior was ignored, and a completely solid Earth was considered instead (Thomson, 1863). Due to his work as an influential scientist, he was knighted and later granted Lordship by Queen Victoria. These awards caused him to become a distinguished member of society who was respected and honoured both socially and academically. This was effectively what made it possible for Thomson to popularize his theories, as well as Hopkins' work.

Thomson also believed that if the Earth had a liquid interior, there would be no possibility of a solid crust resting on top. In his 1862 paper, *On the Secular Cooling of the Earth*, he suggests that since the Earth was solid at the crust, it had to solidify from the inside out for the crust to remain intact (Thomson, 1862). Additionally, in 1867, he postulated that the Earth must be made from substances so hard that they would not get disfigured from the tidal forces imposed by the sun and moon. Thomson's theory states that if there was liquid below the Earth's crust, it would be affected by these celestial objects, similarly to ocean tides (Thomson, 1876). As Thomson developed the S model, he became less inclined to consider alternate ideas on the internal composition of the Earth, especially those supporting fluidist models. Since Thomson was so influential in many scientific and social circles, scientists followed his solidist beliefs despite the lack of supporting evidence, which became a predominant reason that the solidist movement prevailed for so long.

Bridging Solidist and Fluidist Theories

Many theories corresponding to a solid Earth, which were presented by physicists, lacked prevailing evidence on the Earth's surface and known processes. This discrepancy stemmed from the theoretical reasoning many physicists used in the 19th century versus the applied reasoning geologists employed (Frank, 1952). Due to the limited geological knowledge obtained by mathematicians and physicists, their theories were often derived from abstract mathematical equations that made numerous assumptions about the Earth. For example, Thomson attempted to disprove liquidist arguments utilising evidence from gravitational, centrifugal, and tidal forces while neglecting the physical properties of the crust, such as vulcanism, mountain formation, and structural deformations, which were used to support liquidist theories (Mallet, 1872). A double standard was commonly seen in the scientific community, as geological facts would have to be reinforced by theoretical physics, although the inverse was not deemed necessary (Brush, 1979). As a result, gaining credibility for a fluidist model became challenging for geologists, as many were able to provide substantial physical geological evidence, however they often lacked the mathematical reasoning to prove their theories.

The transitional thinking from a solid to fluid composition was majorly influenced by Henri-Édouard Tresca's (1814-1885) criterion of maximum shearing stress, tested from 1864 to 1870. The French civil and mechanical engineer developed his hypothesis as a professor of applied mathematics in Paris at the *Conservatoire des arts et métiers*. Among many of his other world-renowned achievements, he is known to be the father of the field of plasticity and has been recognized by being one of the 72 names carved into the Eiffel tower (Salencon, 2021). Throughout his career, he was able to build academic acclamation and pivot the perspective of many solidist mathematicians. His work, in agreement with other theories of plastic deformation, was specific to ductile and isotropic solids, which mimicked the potential plasticity of the material below the Earth's crust. Tresca grouped the tensile and compressional stresses of ductile solids into three different categories: perfect elasticity, imperfect elasticity, and fluidity (Salencon, 2021). Tresca's work can be summarized by the equation:

$$\sigma_0 = \sigma_{\mathrm{I}} - \sigma_{\mathrm{III}}$$

where $\sigma_{\mathrm{I}} - \sigma_{\mathrm{III}}$ are respectively the minimum and maximum tensile or compressional strengths and σ_0 is the flow stress, also referred to as the yield strength in tension, that is required to continue the plastic deformation of the solid (Wright, 2011). This mathematical modelling, although lacking geological context, was used by geologists as a theoretical backing to their fluidity models. They reasoned that if the Earth was under immense tensile, compressional, and shear stressors and had increasingly high temperatures proportional to depth, as explained by Cordier, then the material within the Earth must be in a state of constant plastic deformation, thus insinuating a liquid interior.

Solidist's Comeback

Despite Thomson's persisting solidist views, there were still many opposers to his work, with the number of fluidists growing over time. Charles-Eugene Delaunay (1816-1872) had been arguing against the solidist viewpoint since Hennessy's work was published, agreeing with the other scientists' findings (Delaunay, 1868). However, none of his papers gained any traction until 1871, when his work became more widespread in the scientific community due to his increasing academic and social status (Brush, 1979). Delaunay, like Hennessey, proved that the precession and nutation evidence for a solid Earth was not sound, and eventually, in 1876, Thomson conceded. He agreed that nothing could be proven absolute while using this research as supporting evidence (Thomson, 1876).

Since the primary arguments for a solid Earth had been disproven, many scientists were rethinking the solidist theories of tidal forces, Thomson included. He began looking for new ideas to substantiate his tidal force theories and was influenced by the research of George Howard Darwin (1845-1912), son of Charles Darwin. In 1878, Darwin began testing models to calculate the bodily tides of sphere-like shapes to simulate a model of the Earth. Through this experimentation, he concluded that the Earth had to be solid, as none of the models that he tested was consistent with a fluid-filled Earth (Darwin, 1879). Despite this new research, the scientific consensus slowly began to transition to recognise fluidist theories.

Emergence of Fluidist Theories

Other passionate geologists, largely Osmond Fisher (1817-1914), were reluctant to conform to the plastic or solid hypotheses appointed at the time. Rather, he believed in a convection model liquid interior. In 1863, Fisher entered Jesus College in Cambridge to study mathematics, although he was always motivated by his interests in geology (Johnston-Lavis, 1914). Throughout his career as a mathematical geologist, he authored numerous papers that were published in the Philosophical and Geological Magazine in the Cambridge University Press. In particular, he published his life's work of 30 years, *The Physics of the Earth's Crust*, in 1881 along with the second edition in 1889. These addressed his fluidist views, where he utilised both mathematical theories and geological properties (Fisher, 1889). The text exemplified his views by not only creating supporting arguments for his liquid interior hypothesis primarily through vulcanism and observable crust disturbances, but also devoted entire chapters to critiquing and rejecting solidist theories (Hill, 1882).

To identify the internal structure of the Earth, Fisher's specific arguments pertain to tidal forces and the cooling of the molten globe. Both arguments were highly contradictable as his mathematical modelling depended on the imprecise values of the thickness of the crust and age of the Earth. Fisher suggested that the effects of temperature and pressure on the viscours internal fluid would restrict the tidal movement created by celestial objects, causing a minimal effect at the surface (Fisher, 1889). The visibility of the internal tidal forces would be dependent on the thickness of the crust, proposed in the SL and CL models (Figure 3.6a, 1b). Fisher also hypothesized that the current state of the Earth was dependent on the stage of cooling from the initial molten stage. Thus, mathematical calculations would be dependent on the highly variable age of the Earth approximated by mathematicians (Fisher, 1889). These variables demonstrate how a scientist's personal viewpoints may alter evidence, as certain mathematical models for the thickness and age of the Earth could be manipulated to prove their reasoning for either a solid or liquid interior.

Although Fisher's previous work that elaborated on liquidity models were accredited by physical geologists worldwide, he was not recognized by the body of mathematicians and physicists who opposed his views (Davison, 1914). Despite this, his theories still aided in the transition from a predominantly solidist to a more fluidist dominated debate.

Push for A Gas Nucleus

Given the arguments most commonly used to support a liquid interior, where temperature and pressure increase with depth towards the Earth's nucleus, some geologists believed there could be another change in state. A body of scientists had hypothesized the nucleus of the Earth was in a gaseous state since the 18th century. However, it wasn't until work published by August Ritter (1811-1885) in 1878 and heavily publicised by Seigmund Günther (1848-1923) in 1884 that the gaseous core theory (Figure 3.6f) became acknowledged by mathematicians and geologists.

Ritter, a practicing civil engineer and theorist, suggested in the *Annalen der Physik* German journal that the Earth's internal temperature surpasses the critical temperature of magma at a certain depth, resulting in a gaseous material (Ritter, 1878). Given the theoretically computed compressional forces at the center of the Earth, the immense temperature and pressure would not allow matter to be in any other state than a gaseous one. Through looking at the lack of references to his work and personal biographies, it can be noted that Ritter was not an influential figure to geologists or mathematicians at the time. Thus, his hypothesis held minimal social or academic influence. In opposition, the social power Günther accumulated as an active politician in the National Liberal Party in Germany from 1878 to 1884 and as a professor at *Technische Hochshule* teaching geology with a background in mathematics and physics allowed him and most of the hypotheses he supported to have a great deal of credibility (Dörflinger, 2016). Expanding on Ritter's hypothesis, Günther constructed a seven-layer model of the Earth (Figure 3.7), for which each layer had differing temperatures and

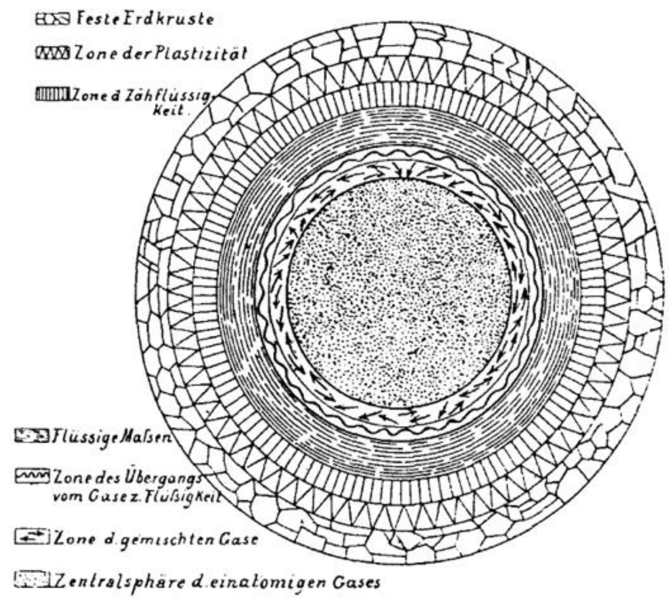


Figure 3.7: Seigmund Gunther's illustration of the seven layered Earth in German. Translated to English, the layers are: solid crust, zoned plastic, zoned viscousness, liquid malt, zoned transition from gas-liquid, zone mixed gases, and central sphere of gases.

pressures. Subsequently, each of the states: solid, liquid, and gas, were represented in the model, with varying plasticity, viscosity, and critical temperatures.

Resolving the Debate

The resolution of this centuries-long debate between solidists and fluidists ended with the development of seismology. Seismological research emerged through the analysis of earthquakes and other seismic activity that could be measured through seismographs, seismometers, or seismoscopes. These instruments measured body waves: a type of seismic wave, classified as either primary or secondary, that travels through the interior of the Earth. Through analysis of the speed and angles of the different waves, seismologists were able to understand characteristics of the Earth's subsurface (Milne, 1908). Using these techniques, Andrija Mohorovicic (1857-1936), Beno Gutenberg (1889-1960), and Inge Lehmann (1888-1993) performed pivotal research that aided in proving that the Earth contains both solid and liquid layers.

In 1909, Mohorovicic discovered that the layer directly under the Earth's crust was semi-solid. He found this discontinuity, termed the Moho discontinuity, through the analysis of various primary and secondary seismic waves (Mohorovicic, 1992). Gutenberg, in 1912, discovered that there were both liquid and solid parts of the Earth. He observed through his seismology research that at a certain distance below the Earth's surface, primary waves slowed down and secondary waves stopped travelling altogether (Benioff, 1958). These patterns in the waves can be attributed to the presence of a solid layer sitting above a liquid layer. He concluded that there was a discontinuity, now coined the Gutenberg discontinuity, that separates the more solid mantle from the liquid outer core, and that it was approximately 2900 km below the Earth's surface (Gutenberg, 1959).

In addition to these ground-breaking discoveries by Mohorovicic and Gutenberg, Lehmann was able to prove through her analysis of seismic waves that underneath the liquid outer core, Earth had a solid inner core (Lehmann, 1936). This boundary between the inner and outer core was an incredible discovery, however, it wasn't until the 1950s that Lehmann was properly recognized for her work. This delay in acknowledgement stemmed from the social structure of the 20th century, for which female scientist were often not recognized for their research findings and accomplishments. Her findings were eventually supported by other well-known seismologists, including Gutenberg and Charles Richter, allowing the solid inner core discovery to be more widely accepted (Lehmann, 1936).

Through with the progression of technology during the 20th century, theories proposed had to be substantiated with tangible evidence to become widely accepted within scientific communities. Thus, the findings of Mohorovicic, Gutenberg, and Lehmann finally concluded the debate on the internal structure of the Earth by providing factual evidence that solely relied on scientific data and not social status and theoretical ideology.

Seismic Tomography

The field of seismic tomography has been largely developed during the 21st century to determine and illustrate the Earth's geodynamics and composition (Zhao, 2008). The field, pioneered in the 1970s by Keith Aki, has provided essential insight into the individual layers and tectonic boundaries of the Earth, expanding the fields of seismotectonics, magmatism, and mantle dynamics (Zhao, 2019). Furthermore, given these discoveries, seismologists can interpret where tectonic plates lie, track movement, planes of weakness, and potential seismic and volcanic activity to proactively protect the technosphere (Perkins, 2019).

By definition, the phrase 'seismic tomography' can be broken down into its Ancient Greek origins, for which seismic means earthquakes and vibrations, while the term tomography refers to slices. Therefore, the computational imaging software for seismic tomography translates signal data from internal vibrations to 2D images, which are then stacked to produce high-definition 3D images of the Earth's interior. The imaging technique utilises the velocity and attenuation of the natural and artificial waves produced by either earthquakes or explosions to create geophysical modelling on a local, regional, and global scale (Thurber and Ritsema, 2015). Differing waves, including body and surface waves, are contrasted to provide data on the heterogenous composition of Earth's interior (Iyer, 1989).

Primary and Secondary Waves

Global tomography elaborates on the concepts of S- and P- waves used by seismologists who discovered the internal structure of the Earth in order to analyse first arrival timelines. First arrival timeline tomography is vital as it provides information about near-surface velocities, up to 100 km depth, given by seismic waves (Rawlinson, Pozgay and Fishwick, 2010). Near-surface velocities are comprised of two components, compressional and shear, that change depending on parameters such as temperature, crack density, and chemical composition (Rizvi, et al., 2020). It acts as a diagnostic characteristic of differing rock types, thus can be used to analyse and determine the composition of the mantle. This data collected from P- and S- waves is inputted through a first-arrival tomographic inversion method, which can give insight to the velocity fluctuations recorded (Zaroli, et al., 2014; Young, et al., 2013). Correspondingly, these velocity fluctuations determine the geologic composition of different parts of the mantle, outputting a tomographic image (Figure 3.8) (Zhu, et al., 2000).

P- and S- waves can also indicate the convectional movement of magma throughout the mantle. For example, P-waves indicate that at a depth of 150 km beneath the surface, wave velocities increase under continental shields and ocean basins whilst decreasing below mid-ocean ridges (Zhao, 2008). In regard to S-waves, anisotropic convection of magma can be recorded within the mantle. Respectively, magma flows horizontally with the corresponding plate's movement, upwards below mid-ocean ridges, and in the opposing direction underneath older static ocean plates (Iyer, 1989). This illustrates the movement of plate tectonics seen at the surface, which can be used to model the presence of hot spots within the mantle. The information collected can be utilised when proposing infrastructure development on potentially hazardous hotspot regions around the world (Zhao, 2008).

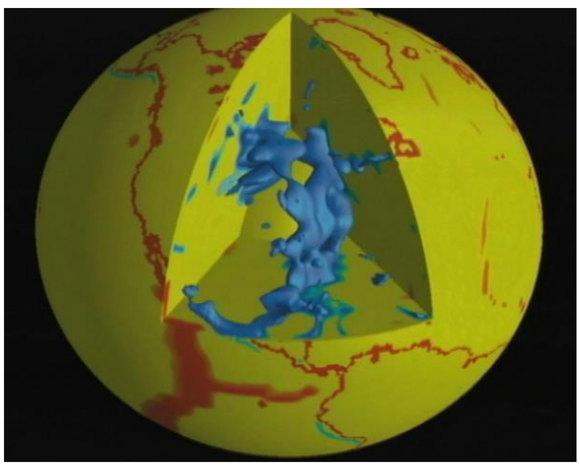


Figure 3.8: Imaging of ancient Farallon Plate (oceanic) subducted below North American Plate. Seismic tomography computational software, more specifically TERRA mantle software, highlight in blue the remanence of the melted plate within the mantle, in yellow the surrounding material in the mantle, core and asthenosphere, and red outlining the current visible land masses.

Sustainable Resource Exploration

As the demand for oil, gas, and mineral resources in the 21st century grows, a subsection of seismic tomography called ambient noise surface wave tomography (ANSWT) is increasingly employed. This non-invasive, low-cost, and sustainable resource exploration technology is a viable method to maintain the ecological integrity of mining sites prior to excavation (Martakis, Tselentis and Paraskevopoulos, 2011). Surface wave velocities producing ambient seismic noise are accompanied by reflection tomography to produce 3D imaging of the Earth's subsurface at designated mining locations (Lynch, et al., 2019). The application uses both P- and S- waves produced from microearthquakes, ocean waves, and anthropogenic activity to determine the presence of liquid and gas substrates (Lynch, et al., 2019). In particular, primary waves are used to detect petroleum presence and the ratio between primary and secondary waves can detect natural gases (Palupi, Raharjo and Yulianto, 2020). Other seismic interpretation algorithm models, such as High Order Singular Value Decomposition, can detect structural traps, including salt domes and faults (Amin, et al., 2019). The greatest advantage of this prospering technological advancement is its ability to produce accurate 3D imaging of fold and thrust structures where natural resources are found in abundance (Martakis, Tselentis and Paraskevopoulos, 2011). In comparison, normal seismic tomography cannot accurately illustrate the regions of interest due to the low signal-to-noise ratio within the subsurface (Vestrum and Cameron, 2022). Thus, the advantages of ANSWT not only provide an economically productive mining technique, but also decrease the negative ecological impacts exploratory mining provokes.

History of Oceanography and Plate Tectonics

The ocean's depths were a great mystery until the 19th century. Before that, it was viewed as vacant and featureless. It was seen as a vessel for travel and economic purposes such as fishing, but curiosity about the topic was limited. Fishermen and sailors tended to follow well-traversed routes without exploration into the structure of the ocean. A long-held, common view of the ocean was that its depths would not be greater than the heights of the tallest mountains (Jewell, 1878). Beginning in the 19th century, there was increased curiosity about the surrounding world, the Arctic, jungles, mountains, subsurface, and the ocean's depths (Rozwadowski, 2005). The mid to late 1800s was also a time of great exploration in astronomy, which brought forth the question of, if we are learning so much about the stars and sky above us, outside of our planet, how is it that we do not understand the ocean below us? This led to the idea that instrumentation could be developed that would allow for the observation of both the vastness of space and the depths of the ocean (Maury, 1856). The 19th century was also a great time of immigration to America from Europe, travelling, and whaling, which meant more individuals were out at sea, increasing curiosity about what loomed below (Rozwadowski, 2005).

Early Sounding Technology

Throughout the 1800s, the technology used to record the depth of the ocean rapidly developed. Initially, a form of the sounding line made of silk threads, spun hemp yard, or common line was used by officers of the English, Dutch, and French Navies (Maury, 1856). The assumption behind using these lines was that the bottom of the sea had been reached once they felt a shock in the line. However, the known horizontal movement of ocean currents and that the line more weakly propagated the signal at greater depths was not considered. Many other unsuccessful methods were attempted as curiosity remained high. One of these mechanisms involved detonating heavy charges of powder in the deep sea when there were low wind and sound conditions in hopes of hearing the echo of the explosion. The thought was that the depth could be calculated using the speed at which sound propagated through water, but no sound was ever observed. A similar idea was proposed in which torpedoes, used in whaling, could detonate on the seafloor (Maury, 1856). Following this detonation, the depth could be calculated using the time interval of the rate of torpedo descent and sound/gas ascension. A mechanician in New York, Mr. Baur, developed a lead which contained a screw propeller that would rotate every 100 fathoms and keep track of the distance travelled (Maury, 1856). The fathom was the preferred unit of measure for ocean depth at the time and corresponds to approximately 1.83 m. Another idea was to use a magnetic telegraph in which the circuit would be restored every 100 fathoms, sending a message up a wire within the sounding line. This was a promising technology; however, the machinery was too complex to practically operate. The mechanism that won amongst all these proposals was simply a thread line attached to a cannonball (Maury, 1856). Due to the simplicity and accessibility of this sounding equipment's components, a wide range of people could perform soundings, rather than the inventor alone (Maury, 1856).

First Soundings

By the mid-1800s, most American Naval ships had been provided with common twine that had every 100 fathoms marked. They were told to use excess cannonballs for the twine and cannonball-sounding mechanism as a part of the Navy's plan to map the ocean floor (Maury, 1856). In addition, the United States Congress provided three public vessels to be used solely for sounding research and subsequent expeditions (Maury, 1856). Sailors were then told to measure the depth whenever possible by throwing the cannonball attached to the twine and cutting the twine once the cannonball had reached the bottom. The depth could then be calculated by the amount of twine left on the reel, subtracted from the amount of twine at the beginning. The issue with this mechanism was that the twine was not strong enough and would not stop unravelling once the cannonball had reached the bottom (Maury, 1856). While this issue was somewhat resolved using specialized stronger twine, it remained suboptimal for deep-sea sounding. Cannonball soundings allowed for knowledge of the depth of the ocean, but people at the time questioned the usefulness of this data without knowing what was at the bottom (Maury, 1856). The first access to this knowledge came in 1854 with the apparatus developed by Passed Midshipman J.M. Brooke of the United States Navy. He proposed a sounding apparatus in which the sinker could detach, eliminating previous issues due to weight when bringing the apparatus back to the surface (Figure 3.9) (Jewell, 1878). Pierced through a cannonball sinker was a rod on which samples from the seafloor could be collected. Upon impact with the seafloor, the sinker would detach, and the line and rod would be reeled back to the surface, allowing for both depth measurements and specimen collection (Maury, 1856; Jewell, 1878). This method was termed The Brooke's Deep Sea Sounding Apparatus, and was used to record depths and collect specimens at over 4000 fathoms (Jewell, 1878).

Transatlantic Telegraph Cables

A major driving force towards the pursuit of knowledge of the seafloor stemmed from the aspiration to enhance communication between Britain and America. The thought was that a transatlantic telegraph cable would unite and maintain peace between the two nations while aiding trade (Field, 1868). This led telegraph companies and governments to push towards deep-sea sounding by providing ships and funding for mapping projects (Rozwadowski, 2005). The sounding data used to form the initial routes of transatlantic telegraph cables were sourced from exploratory missions unrelated to the telegraph cables. Then, to fill in necessary gaps, telegraph cable-specific expeditions were commissioned (Bright, 1903). There was much debate regarding the location of this cable, with two main routes proposed. The earliest proposed route, planned to be installed in 1852, was the North Atlantic telegraph which would span from Northern Scotland to the Faroe Islands, across Iceland, over to Greenland, ending in Labrador (Shaffner, 1860). Alternatively proposed, a cable would be laid across the 'telegraph plateau,' spanning from Valencia, Ireland to Heart's Content, Newfoundland, to be installed in 1858. The main point of debate in cable placement was the delay in electric current transmission through subaqueous conductors brought forth by Michael Faraday, which raised questions about whether the direct Ireland-Newfoundland cable would function. The cables for either of the routes would be roughly the same length but stretches of the North Atlantic route would be on land (Shaffner, 1860). The North Atlantic route needed the permission of the Danish, Swedish, and Norwegian governments to run the cable over their land, but this was agreed upon with the condition of allowing those governments to also utilize the cable (Shaffner, 1860; Shaffner, et al., 1860).

In the soundings documented by Maury, a steppe was observed between Cape Race, Newfoundland and Cape Clear, Ireland, which Maury dubbed the telegraph plateau (Maury, 1856). These soundings were primarily performed by the *U.S.N. Arctic* and *H.M.S. Cyclops* in the summer of 1856 (Bright, 1903). It was observed to be a region no deeper than approximately 3000-3700 m. This was within the range where the plateau was shallow enough for the cable to rest on, but also not too shallow to be concerned about the impact of currents and icebergs (Maury, 1856). The Atlantic telegraph cable from Ireland to Newfoundland was chosen over the North Atlantic telegraph due to the concerns surrounding the colder climate of the alternate route. There was the potential that the ice covering the coast of Greenland could cause damage to the cable without proper grounding, making hiring staff to work in these harsh conditions difficult (Bright, 1903). The cable was laid out from Valencia to Heart's Content in 1858, however, it broke within a month of use due to strain and issues with cable construction (Deane, 1865; Field, 1868).

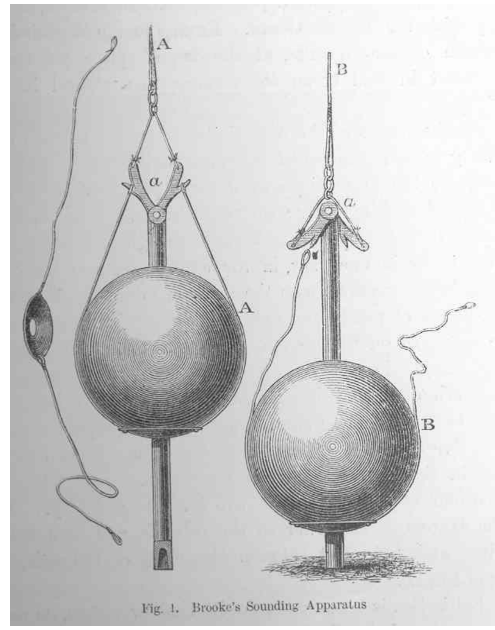


Figure 3.9: Brooke's Deep Sea Sounding Apparatus. On the left, this is the position in which the apparatus is lowered, with the cannonball sinker secured to the rod. As the apparatus strikes the seafloor, the cannonball continues to sink, snapping the cords securing it. This allows the sinker to remain on the seafloor while the rod, which would collect samples, could be pulled up by the line.

The idea of the North Atlantic telegraph cable grew in popularity following the failure of the 1858 transatlantic cable from Ireland to Newfoundland (Bright, 1903). Little was known about the ocean depth along the North Atlantic route, prompting the commission of the *H.M.S. Bulldog* to determine the practicability of the laid cable, which used a version of Brooke's sounding apparatus to measure depth and retrieve samples. Though seafloor depths were much greater, with dramatic changes at many points, this route was deemed suitable by Captain F. L. M'Clintock, a member of the British Royal Navy, of the *H.M.S. Bulldog*. It was too deep for there to be damage caused by the Arctic current or icebergs, and the seafloor was found to be made of soft clayey material that was thought to be deposited by ice and would bury the cable, protecting it from external forces (Shaffner, 1860; Shaffner, et al., 1860). Though

Brooke's sounding apparatus aided in some of this sample collection, Captain M'Clintock thought the samples received were not quantitatively substantial. Instead, he initially requested a conical cup that could scoop up mud and sand using a circular lid that would lower to trap sediments upon ascent (Shaffner, et al., 1860; Dr. Carpenter, Jeffreys and Thomson, 1869). Later, a new apparatus was developed, dubbed the 'Bulldog Sounding Machine,' created by assistant engineer Mr. Steil, which had a double-scoop mechanism allowing for samples to be collected by both the superficial layer (organic materials and mud) and lower layer (stones with a diameter of a few centimetres) (Shaffner, et al., 1860).

Though a practical cable location was found, the North Atlantic telegraph cable was still dismissed because of fear of cable damage due to ice (Bright, 1903). There was also substantial persistence and hope that a new version of the first Atlantic cable would succeed, which was the case in 1866 (Deane, 1865; Bright, 1903). This time, the cable end was placed in calmer areas contained by a bay, as opposed to the placement of the 1858 cable that experienced friction from the seas. In the placement of this cable, samples of the seafloor were brought up for analysis on every occasion at which the cable had to be brought up by grapnel for repair (Deane, 1865). Overall, the development and placement of transatlantic telegraph cables allowed for increased surveying and understanding of the depths and contents of the seafloor (Rozwadowski, 2005).

Figure 3.10: Map drawn by Wegener. The dark lines show continental margins proposed. Dashed lines show theorized past continental connections.

Seafloor Sampling

Brooke's apparatus was the first to bring samples of the seafloor of the telegraph plateau to the surface. When first observed by Lieutenant Berryman and the officers aboard the ship, they declared that the seafloor was composed of clay (Maury, 1856). These samples were then sent to two microscopists, one of which was Professor Bailey at West Point. Professor Bailey replied, explaining that the sample was not clay, nor did it contain sand or gravel, but rather microscopic shells (Maury, 1856). He found that they were mostly *Foraminifera* with some *Diatomaceae* present and believed the organisms had lived near the surface and settled on the seafloor after death. Their lack of fractures or rounding resulted in the conclusion that deep ocean environments were relatively calm. As such, the seafloor was also determined to be soft and loosely compacted. This led to the perception that the seafloor was a cemetery for living organisms and human wreckage (Maury, 1856). The observation of forams as the main component of the seafloor also led to ideas that the seafloor may also be an area for the recycling of material. The theorized mechanism was that upon earthquakes or upheaval, the seafloor material was brought to the surface to form mountains and other landforms (Maury, 1856).

Wegener's Theory of Continental Drift

Umbgrove, in his writing of *The Pulse of the Earth* (1908), shared the four most prominent opinions surrounding the existence of plate tectonics and their connection to the ocean floor at the time. These views included ideas that continents and oceans represented permanent features, ocean basins originated from land-mass submergence, continents drifted apart, and continental blocks stretched. The generation of these ideas started with Sir Francis Bacon, the first recorded individual to note the symmetry in coastlines (Schwarzbach, 1907). In 1620, Bacon proposed the parallelism of the opposing shores of the Atlantic Sea in his book *Novum Organum* (Carozzi, 1970). However, the idea that these two continents had been connected only arose when Alfred Wegener proposed Displacement Theory in 1915 (Figure 3.10), now called the theory of co, in his book *The Origins of Continents and Oceans.* During the same time, other researchers, such as Frank Bursley Taylor, believed that Africa and South America were joined at a point in the past but broke at a mid-Atlantic ridge (Alfred Wegener, 1915). Taylor was upset about how his paper *Bearing of the Tertiary Mountain Belt on the Origin of the Earth's Plan* took over two years to publish (Frankel, 2012). In a letter Taylor wrote to the *Popular Science Monthly,* he versed his anger, certain that Wegener's paper published in January 1911 was strongly influenced by his 1910 publication. Taylor firmly stated to *Popular Science Monthly*, "your positive statements about Wegener quoted at the beginning of this letter are absolutely wrong and untrue" (Frankel, 2012, p.71). Despite Taylor's negative attitude towards Wegener, the only evidence he had that Wegener based his work on the 1910 publication was a note received in 1911, which can no longer be found (Frankel, 2012). A similar race to develop a scientific theory first is found at an earlier point in history surrounding Darwin and Wallace's contribution to the theory of evolution. Darwin is recognized as the 'Father of Evolution' (Fields and Johnston, 2010). However, this is primarily since Lyell, recognized as the head of Victorian England's scientific aristocracy at the time, decided to present Darwin's paper first at the Royal Society. Wallace, a man with a seventh-grade education and limited connections, sent his draft to Darwin and Lyell to hasten the publishing process. Rather, this increased the rate at which Darwin conceived his paper, *On the Origin of Species* (Fields and Johnston, 2010). Similarly, Wegener gained the most popularity in his theory surrounding the theory of continental drift. However, not everyone at the time accepted these ideas (Mac Bride, 1939). Author Dr. Jeffrey wrote an article criticizing Wegener's proposition that Earth was composed of a viscous fluid. However, Mac Bride, a marine biologist writing to the Editor of the Times, rightfully pointed out that Wegener based his theory on a 2,414-kilometre-thick basaltic shell surrounding the interior viscous fluid of the Earth (Mac Bride, 1939). In short, the theory of continental drift, as best described by Wegener, allowed individuals at this time to make sense of geographical observations.

Paul Langevin: Sonar Technology Influenced by World War I

During the dark time of World War I (WWI), many new technologies were implemented to detect enemy ships and submarines from 1914 to 1918. In 1915, Paul Langevin began working with the French Navy on sonar technology. In 1917, he developed an early form of a piezoelectric ultrasound transducer (Duck and Thomas, 2022). At the time, German U-boats posed a significant threat to the Allies, prompting the development of a technology that could detect submarine obstacles. The pulse-echo transducer, which could both emit an ultrasonic pulse and receive an echo, was distributed to Allied laboratories in countries including Britain, Italy, and the USA. Langevin was open to readily sharing the technology with fellow Allies, considering the pressure felt by WWI.

Langevin felt the hardships of war when, in October of 1940, he was arrested and imprisoned, his daughter was deported, and his son-in-law was shot. Despite these events, Langevin returned to Paris after its liberation, motivated by working toward social justice and international solidarity (Duck and Thomas, 2022). He continued managing *École de Physique et Chimie* as chair at *Collège de France* (Joliot, 1951). Langevin was an esteemed professor at the Collège de France, working full-time since 1910. Langevin held a passion for teaching the next generation of scientists courses, including acoustic shock formation and transducer design, prompting his post-war return.

The conversion of electromagnetic vibrations into acoustic vibrations played a profound role, not only in both world wars, but also in the exploration of the seafloor. The outlook for whether underwater acoustics would continue to be used in oceanography post-WWI was poor (Zimmerman, 2002). Scientists moved on from the intensive efforts of war-time development back to peacetime industrial or academic careers. Many of these scientists, unlike Langevin, joined motivated by patriotism and the economic boost associated with being part of the war effort, as opposed to a lifelong dedication to sonar detection technology. The few remaining individuals working at the American Naval Research Laboratories focused on the detection of submarines, specifically expanding the detection range beyond 600 m and 1300 m (Zimmerman, 2002).

Victor Vacquier: Fluxgate Magnetometer in World War II

Victor Vacquier played an important role in extending the detection capabilities of ships used in oceanography by inventing the fluxgate magnetometer (Shor and Sclater, 2010). During World War II (WWII), the construction of a more effective magnetic antitank mine and magnetometer to detect submarines was needed to continue the Allies' war efforts. Working to combat German tanks became especially important as the 'Blitzkrieg' method, which translates to 'lightning fast,' was introduced at the beginning of WWII (Gukeisen, 2005). General Paul Armenguad of the French Army described this technique as a way to rapidly invade enemy territory through the use of dive-bombers and tanks. Vacquier's development of the magnetometer was motivated by the need to build better antitank mines to slow this effective military strategy. The development of magnetometers, later used in oceanography, was further driven by pressure to detect German U-boats (Kahan, 2014). From 1939 to 1941, only 66 U-boats were lost while sinking over 1000 Allied ships. The magnetometer, along with strategies of bombing oil refineries, launching more Allied ships, and improving the sonar detection methods lowered the negative impacts of German U-boats. Although the technology was used extensively at sea as a proton precession magnetometer, Vacquier saw the greatest potential use as a gyrocompass for dead reckoning navigation (detection of location based on the previous position) (Shor and Sclater, 2010).

Another version of this technology, a more sensitive one, was used to detect submerged submarines. Vacquier worked on the survey ship *Pioneer* for the U.S. Coast and Geodetic Survey to detect magnetic patterns using a version of his fluxgate magnetometer. Vacquier expressed his disappointment in the construction of the fluxgate magnetometer Bell Laboratories decided on, based on his design, due to the addition of a filter to remove the second harmonic (Vacquier, 1989). When the new nuclear hydrogen proton magnetometer was introduced by the Navy, Vacquier was driven to simplify the technology to better fit the *Pioneer* voyage. From Naval voyages, including the *Pioneer,* it was demonstrated that magnetic patterns were repeated at intervals of ~256 km, implying a large displacement of the ocean floor (Shor and Sclater, 2010). The fact that there was an offset in geologically similar material, without continuous relative motion, was indicative of the theory of plate tectonics, as proposed in 1965 by Wilson (Shor and Sclater, 2010).

Harry Hammond Hess: Seafloor Spreading and Mid-Ocean Ridges

Harry Hammond Hess built a framework now known as seafloor spreading, focusing on the existence of mid-ocean ridges (MORs) (Hess, 1962). MORs have raised limbs due to mantle convection cells built up by high heat flow and low seismic activity. The increasing thermal expansion used to cover the trans-Pacific ridge, formed along the Marians Islands towards Chile, for example. Hess's *History of Ocean Basins* (1962) describes the concept of seafloor spreading, which impressed many at Princeton's Geology Department Meeting, including geologists willing to accept the theory upon learning about the geological evidence (Merritt, 1966). Hess did not buy into the theory of continental drift as proposed by Wegener and colleagues at the school of South African and Australian geologists, since it could not be reconciled with physical laws. Hess' involvement in the Navy Reserve allowed much data to be collected to support his theory. After the attack on Pearl Harbor, Hess did not hesitate to volunteer for military service. Throughout his military journeys, 402,336 kilometres of the Pacific bottom were observed using a fathometer (using echolocation) onboard Navy ships to determine the location of flat-topped seamounts called guyots (Figure 3.11). Finding the presence of guyots was motivated by an interest in understanding the unique depth data collected from Naval ships during WWII. There were approximately 160 guyots located using a fathometer. Hess's colleague said he had "the whole U.S. Navy working for him as a data-collecting agency" (Merritt, 1966, p.277). This proved especially useful because Hess' theory was not well established before his 1962 paper, making securing research funding an arduous process. The validity of Hess' theory was further received by the publication *Magnetic Anomalies over a Young Oceanic Ridge off Vancouver Island* in 1965 where Frederick Vine presented magnetic evidence for MORs (Vine and Wilson, 1965). In this paper, Vine describes the process of collecting data about the Earth's magnetic field and its reversals influencing the discovery of magnetization parallel of MORs (Raymo, 1989). Society at this time saw Hess' contribution as revolutionary in understanding the movement of plate tectonics and the development of the

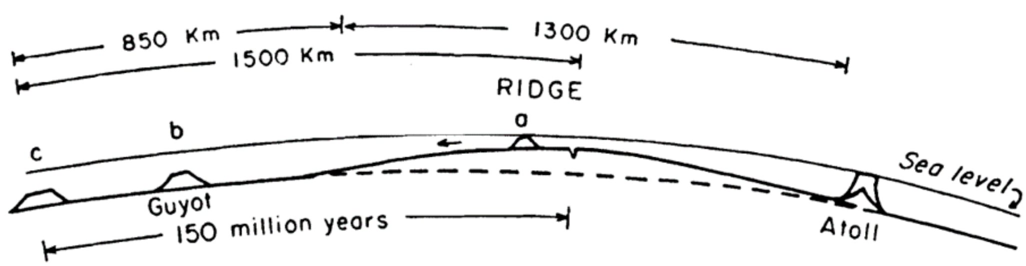


Figure 3.11: Movement of the guyots away from MORs, show a tendency to increase in age as they move away from the newly formed ridge crust.

ocean floor (Raymo, 1989).

JOIDES' Deep Sea Drilling Project

In 1964, the Joint Oceanographic Institutions Deep Earth Sample (JOIDES) was established to investigate the ocean floor by collecting core samples (JOIDES, 1967). A preliminary map (Figure 3.12) showed the different sites to be sampled, considering depth, economic cost, and location. The initial research into boreholes, and thus the selection of drilling sites, was driven primarily by Pan American Petroleum and Transport Company (PAT). This company owned a mobile oil drilling rig, *Caldrill,* that they planned to move from California to the Grand Banks of Newfoundland. The moving costs of the one-month drilling program that would last from April to May of 1965 were covered by PAT. The Blake Plateau Project, funded by PAT in 1965, allowed for the successful collection of six boreholes drilled into the seafloor from 120 to 320 m. Of the holes collected, only 36% resulted in recovered data. The boreholes that resulted in the highest core recovery rates were found in soft formations, including silt or clay, and the lowest were collected in hard layers such as chert or dolomite. The panel aimed to select drilling sites that could test the oldest sediments, the influence of MORs in the development of ocean basins, and sample sediment from locations known to be undisturbed. The Atlantic Advisory Panel was motivated to determine the origin of the Atlantic Ocean to settle the debate between continental drift theory and seafloor spreading (JOIDES, 1967). Until the 1940s, the continental drift theory was most prominent, using arguments from palaeontologic correlations, similar rock types, and coastlines across the Atlantic Ocean (National Science Foundation, 1974). The idea was re-popularized during the 1950s when paleomagnetic evidence showed the change in the position of continents concerning their magnetic poles. The theory of continental drift failed to explain a mechanism for the movement of continents, which the theory of seafloor spreading attempted to explain through MORs. These predictions were consistent with the fact that drilling completed on the *Glomar Challenger* established that ocean basins were ~200 Ma. The deep drilling project confirmed this explanation by taking samples from Rockall Bank, found in the North Atlantic, which has been sinking gradually over time. This supported the idea of MORs, where the floor of the ocean moves away from the spreading centre as it gets older (National Science Foundation, 1974).

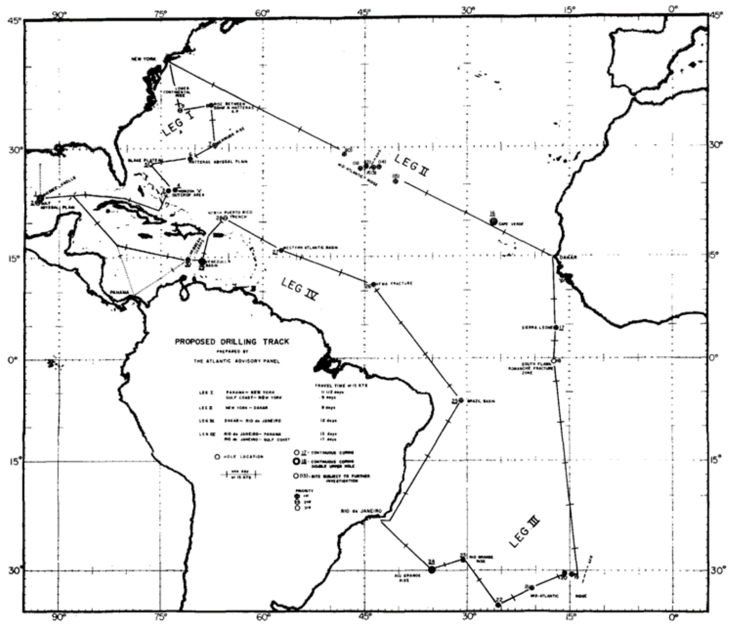


Figure 3.12: Selection of Atlantic Drilling Sites, beginning in the Gulf of Mexico Sigsbee Knolls (JOIDES, 1967). The four legs of the planned trip recorded coordinates, depth (m), sedimentary thickness (m), purpose, and priority ranking from I to III for all borehole samples.

Scientists were seeking the most well-rounded answer to support the mechanism for seafloor spreading, which led them to examine linear magnetic anomalies found along the seafloor. Sample cores, collected as part of the Deep Sea Drilling Project, provided physical evidence of such bands of alternating magnetic polarity. These 'abnormalities' were reassuring to researchers since they were symmetrical on either side of the central rift valley, running parallel to the ridge system (National Science Foundation, 1974). Collecting further evidence of seafloor spreading was crucial in understanding the mechanism behind how continents move. Erich Bloch, the director of the National Science Foundation (National Science Foundation, 1974), saw the project as a success since it further understood the development of ocean basins and provided strong evidence for the theory of seafloor spreading (Mayer, et al., 1985). He coined this as the 'second *Challenger* expedition' referring to the important *H.M.S. Challenger* which discovered the Marianas trench, the deepest known location in the ocean (Mayer, et al., 1985). Overall, the JOIDES Deep Sea Drilling Project proved crucial in persuading society at the time of the concept of seafloor spreading. At the time the *Glomar Challenger* left Lisbon, the project sparked controversy over the location of drilling over the Canadian continental margin, causing a revision in the drilling location (Sanger, 1970). Despite this, the geological drilling cores and their implications on geologic knowledge were publicized in the *Globe and Mail* to the public in a positive light (Sanger, 1970).

Modern Bathymetry and Ocean Geology

Many see the modern theory of plate tectonics as the single unifying idea of geology due to its ability to explain a wide range of phenomena. With the well-established plate tectonic theory, and therefore a good understanding of seafloor movement, current research turns its focus back toward mapping the ocean floor. This can be done using Multibeam Echosounding (MBES) and satellite-derived bathymetry (SBD) (Ashphaq, Srivastava and Mitra, 2021), and is documented by the General Bathymetric Chart of the Oceans (GEBCO) Seabed 2030 Project (Mayer, et al., 2018).

Plate Tectonics

Oreskes (1999) describes plate tectonics theory as the geological equivalent of the Bohr model of the atom, with its simplicity, elegance, and ability to explain a wide range of observations. There are very limited updates to the theory of plate tectonics beyond 1969, with the theory primarily based on Hess' *History of Ocean Basins* (1962) (Oreskes, 2003). In 1977, Marie Tharp and Bruce Heezen built upon Hess' work to publish the first complete map of the world's ocean floor, creating a physiographic map over a bathymetric map (Doel, Levin and Marker, 2006). Their findings explained earthquakes, volcanoes, and the formation of new seafloor through the movement of plate tectonics. The map accomplished this through a detailed outline of the Rift Valley of MORs, a discovery of Tharp. Until Forsyth and Uyeda proposed 'slab pull' in 1975, convection currents were thought to cause the movement of these large plates (Forsyth and Uyeda, 1975). Slab pull refers to the higher force felt by the colder, denser subducting plate compared to the surrounding mantle (Forsyth and Uyeda, 1975). This follows the fundamental understanding of plate tectonics, including that the oceanic crust at collisional margins is denser than the asthenosphere. This greater density causes the oceanic crust to sink into the mantle at subduction zones, pulling the lithosphere apart at divergent boundaries, such as MORs, resulting in seafloor spreading (Figure 3.13). Forsyth and Uyeda (1975) proposed another force contributing to seafloor spreading known as 'ridge push.' This occurs due to the thermal expansion of the hot mantle entering a crack between diverging plates, resulting in an elevated ridge. The lithospheric crust on the slope of the ridge has more potential energy which is converted into kinetic energy, moving to a lower energy state. This phenomenon, generated by ridge push, results in the gravitational sliding of the lithospheric crust outward along the asthenosphere. In short, the theory of plate tectonics has remained relatively stable; however, modern advances in the publication of ocean floor maps and mechanisms have helped revise the theory.

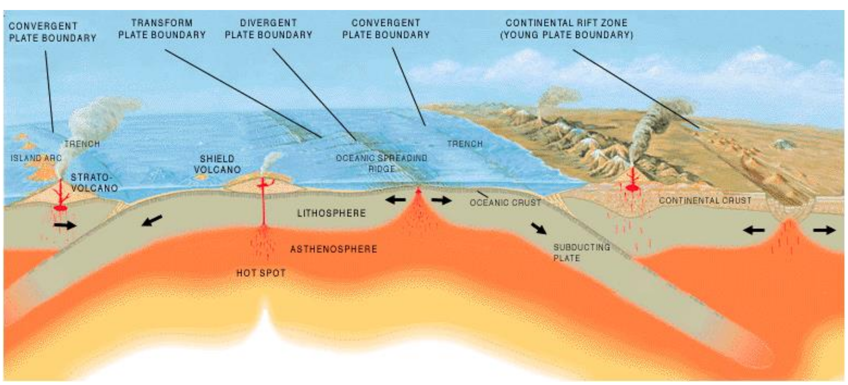


Figure 3.13: Various processes caused by the movement of plate tectonics, surrounding plate boundaries. Volcanic activity, earthquakes, and the transfer of magma from the Earth's mantle to the crust are all phenomena associated with these plate boundaries.

Multibeam Echosounding

MBES is a modern measurement technique that uses multiple sonar beams spread out in a fan pattern attached to the underside of a ship (Calder and Mayer, 2003). Depth is calculated by comparing the time the sound beams take to contact the ocean floor and return to the receiver. This technology can precisely map the bathymetry of large ocean regions, forming a morphological description of the seafloor (National Oceanic and Atmospheric Administration, 2022). MBES can also be used to map various processes caused by the movement of plate tectonics, such as seafloor spreading and abyssal plains (Picard, et al., 2017). Furthermore, MBES can produce backscatter data, measuring the intensity of sound echoed back to a source (Roberts, et al., 2005; National Oceanic and Atmospheric Administration, 2022). This can characterize attributes of the seafloor, including hardness, texture, and fabric, based on the intensity values of the backscatter. This technology is often associated with large volumes of data that can be difficult to process (National Oceanic and Atmospheric Administration, 2022). Computer algorithms, such as Combined Uncertainty and Bathymetry Estimator can be used to create statistically similar outcomes to hand-generated results for these large datasets (Calder and Mayer, 2003). In short, MBES is useful in detecting objects along the seafloor due to local attachment to ships allowing for the mapping of tectonic movement.

Satellite-Derived Bathymetry

Using bathymetry to measure coastlines remains relevant because of their high susceptibility to erosion, sea-level changes, and coastal navigation (Ashphaq, Srivastava and Mitra, 2021). Since MBES cannot be used in areas too shallow for ships to navigate across, another method is required (USGS, 2019). Optical green laser LiDAR sensors stand as an alternative, however, this method is costly and inaccurate in areas of high turbidity (Sagawa, et al., 2019). Instead, SDB can be used to estimate coastal bathymetry elevation values. This uses multi-spectral sensors and satellite imaging to estimate the depth of the ocean near coastlines (Ashphaq, Srivastava and Mitra, 2021). Data recorded by multi-spectral sensors use satellite images with resolutions greater than 30 m, which often use machine learning techniques (e.g., Random Forest) to build models based on water depth (Sagawa, et al., 2019). Overall, SDB provides crucial bathymetry data from areas difficult to access by ships.

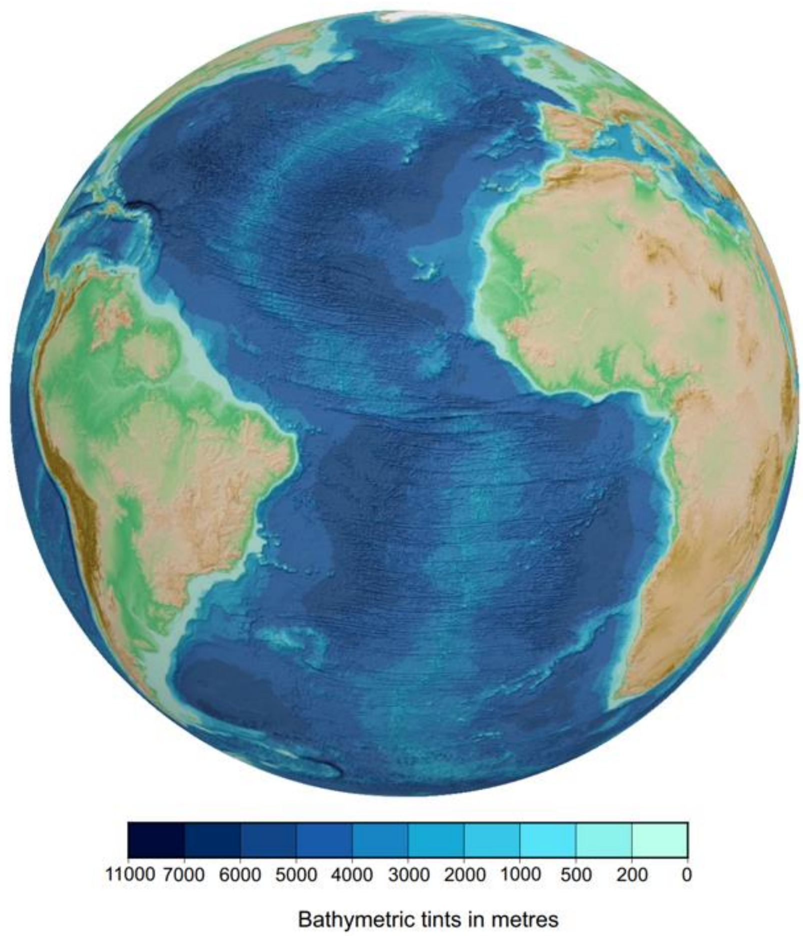
Measuring Seafloor Dynamics

Satellites can aid in determining the depth of the seafloor, however, they are limited in measuring crustal dynamics due to the frequency-dependent attenuation of electromagnetic waves in salt water. Instead, GPS-acoustic (GPS-A), first developed in the 1980s, uses GPS signalling between satellites and a ship, combined with acoustic ranging between the ship and an array of transponders on the seafloor (Petersen, et al., 2019). The distance from the ship's transducer to the transponders is determined by the time it takes for an acoustic signal to travel to the transponder and back to the ship (Honsho and Kido, 2017). To track seafloor movement, the speed of the sound waves between transponders and the ship can be measured at the microsecond level, corresponding to millimetres of movement between the ship and transponder (Speiss, et al., 1998). The movement of the centre of the transponder array can also be tracked by monitoring its position using the GPS. Overall, this technique allows for the measurement of horizontal seafloor movements that are difficult to detect using satellite imagery (Petersen, et al., 2019).

GEBCO Seabed 2030 Project

The GEBCO Seabed 2030 Project is currently the largest ocean floor mapping project in development (Mayer, et al., 2018). It aims to have 100% of the 350 million square kilometres (The Nippon Foundation, 2022) of the ocean floor mapped by 2030 and release the bathymetry data publicly (Figure 3.14) (Harris, et al., 2014). This project uses MBES for most of the mapping and SBD for localized coastal regions. Such data can track the effects of climate change, which causes rising sea levels and increased ocean acidity. Ocean acidification, due to high CO2 levels, can make it difficult for sensitive areas like coral reefs to sustain healthy ecosystems (US Department of Commerce, 2022). Furthermore, MBES can be used to establish the location and activity of volcanoes, helping to predict future natural disasters (Casalbore, et al., 2022) and detect oil and gas seeps (Decker, et al., 2021). In short, an international collection of bathymetry data is useful for the political division of continental shelves, military, defense operations, and addressing climate change concerns (Mayer, et al., 2018)

Figure 3.14: Bathymetric data of the Atlantic Ocean, produced by GEBCO. Data was collected using MBES as well as SDB to map the depths of the ocean. There is a noticeable decrease in ocean depth in the centre of the Atlantic, where the MOR lies.



The Richter Magnitude Scale

The early 20th century was a revolutionary era for seismological discoveries in America. Frequent occurrences of earthquakes in southern California prompted the Seismological laboratory (Seismo Lab) at The California Institute of Technology (Caltech) to develop a device that could record the seismic waves of such events (Figure 3.15): the Wood-Anderson seismometer (Perkins, 2022). However, a method to classify these readings in terms of their impact was not available. Not long after joining the team at Caltech, American geophysicist Charles Richter (1900-1985), alongside German- American seismologist Beno Gutenberg developed the Richter magnitude scale, commonly referred to as the Richter scale. Prior to this discovery, only intensity scales were available to classify earthquakes, which were solely based on observable earthquake damage rather than scientific readings. As a result, these scales were regarded "unscientific" by many. (Hough, 2007). Seismographs were also used to determine the energy output of earthquakes. However, using the total energy output in context to the real world was unachievable, as the total energy output was not always representative of the impact an Earthquake has. As a result, Charles Richter took inspiration from both ideas, ultimately creating his magnum opus. The Richter scale left a lasting impact on the seismological community, as it was the first mathematical device to rate the magnitude of an earthquake. (Richter, 1935).

Figure 3.15: The stars of the Seismological Laboratory at Caltech University: Frank Press, Geno Gutenberg, Hugo Benioff, Charles Richter (pictured from left to right).

Intensity Scales

Prior to the Richter scale, only intensity scales were available, therefore there was no quantifiable way to measure the impact of earthquake activity (Hough, 2007). Intensity scales were anthropogenic, categorizing how much damage they did to civilization rather than quantifying the amount of energy they expelled. The first intensity scale was created by Michele Stefano Conte de Rossi and François-Alphonse Forel and adopted in the late 19th century (Astronomical Society of the Pacific, 1895). This scale was the first of its kind to categorize the effect an earthquake has on its surrounding environment (Natural Resources Canada, 2021). The scale ranges from 1-10, where an earthquake with a value of 1 is inconsequential and may be recorded with a single seismograph, and an earthquake with a value of 10 is detrimental, causing fissures in the ground and major destruction (Natural Resources Canada, 2021). Two decades later, the Rossi-Forel scale was expanded to twelve steps with the Mercalli Intensity Scale (MS). MS was further revised to account for specific building types, this was the Modified Mercalli scale (MMS) (Richter, 1935). Using a scale ranging from I-X, the MMIS was more anthropogenic than the Rossi-Forel scale. These scales were useful to interpret earthquakes in terms of society, but they were not beneficial for scientific purposes as the distribution of earthquakes became skewed based on the size of the affected city, and the distance between the city to a fault (USGS, 1905; Pacific Northwest Seismic Network (PNSN), n.d.).

Seismometers and Seismographs

Devices for measuring earthquakes existed as early as 132 A.D. However, it wasn't until the year 1855, that Luigi Palmieri created the first mercury seismograph (USGS, n.d.). Although seismographs existed to record earthquake activity, they were quite difficult to interpret without a way to quantify these readings. Seismographs record how much a needle moves over time in a seismometer, due to the shaking caused by seismic waves released from an earthquake (PNSN, n.d.). This needle is marked in order to record the amplitude of the shakes on paper, which is then analyzed to determine how severe the seismic waves may be. Seismic waves are differentiated by the medium they are able to pass through and the speed at which they travel. At the time, the Wood-Anderson seismometer was considered the gold standard. The Wood-Anderson seismometer was an earthquake-measuring device created in 1921 by Henry Wood and John Anderson. It operated as an oscillator, detecting sound and motion waves underground as the earthquake passes through the area the seismograph is recording. In fact, it was so effective that there are still hundreds of Wood-Anderson seismographs in use today. Most importantly, the Wood-Anderson seismograph also allowed scientists to visually represent varying types of seismic waves, such as primary (P) and secondary (S) waves. The P-wave is a compressional wave which represents the vibrations of rock caused by the collision of plates, whereas the S-wave is an oscillating lateral wave, making it extremely destructive in comparison to P-waves (USGS, n.d.). P-waves also travel much faster than S-waves in multiple mediums, reaching speeds of 6,000 metres per second through sedimentary rock, compared to just 3,300 metres per second through sedimentary rock an S-wave can reach (University of Hawaii, n.d.). P-waves also have the unique ability to propagate through liquids, which allows seismologists to theoretically record them globally depending on their strength, apart from a shadow zone (Figure 3.16) (Panchuk, 2019). Overall, the geological composition of the ground, speed differences between P and S waves, and the propagation mediums of P and S waves decrease the accuracy of accessing the impact of any given earthquake. The culmination of factors made it impossible to predict or determine the strength with which an earthquake would strike (Panchuk, 2019). However, Richter would later use this to his advantage in his creation of the Richter Scale.

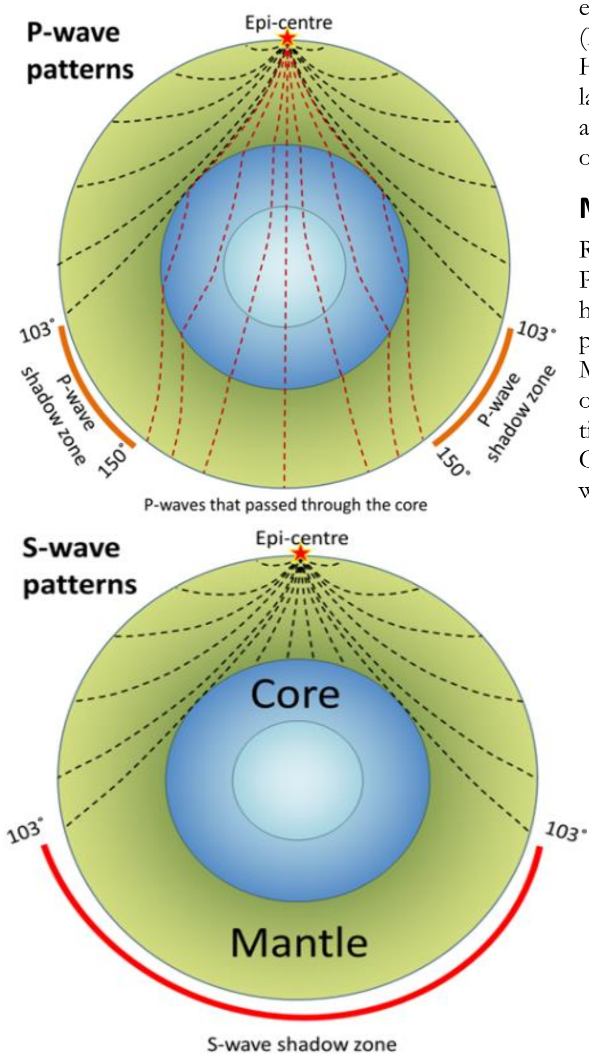


Figure 3.16: Representation of how primary (P) *and* secondary (S) waves *propagate through the Earth. As seen, P-waves can propagate through the core of the Earth, however, are reflected, and therefore cannot be recorded from 103° to 150° with respect to the epicentre. This range is known as the "shadow zone". S-waves cannot propagate through the liquid, and therefore have a significantly larger shadow zone.*

Magnitude scale

Richter completed his Ph.D. at Caltech where he met Nobel-winning physicist Robert Andrew Millikan. Millikan offered Richter a part-time research position at Caltech's Seismo Lab where he gained exposure to the geophysics of earthquakes. (Hough, 2007).

Richter's interest in seismology peaked when he encountered seismologist Kiyoo Wadati's studies on deep earthquakes (Richter, 1935). Wadati, a Japanese seismologist, was the first in his field to propose the idea of deep earthquakes in a publication called "Shallow and Deep Earthquakes" (1928), published in Geophys. Magazine. He inferred that differential motion from an oceanic plate subducting causes many rapid earthquakes, with foci hundreds of kilometres in depth (Kukowski, 2014). Wadati then used the fact that Japan falls on a continental barrier to test his theory. After confirmation, this zone was deemed the 'Wadati Zone', later changed to the 'Wadati-Benioff Zone' after Hugo Benioff developed a way to identify the boundary at which an earthquake was generated (Kukowski, 2014).

This publication fascinated Richter since he lived near a continental barrier and fault line in Los Angeles. Ultimately, Wadati's original paper inspired Charles Richter to create the Richter Scale to quantify earthquakes (Hough, 2007, Richter, 1935).

Richter could not accomplish this task alone. With the aid of Beno Gutenberg, Richter was able to create a device capable of roughly estimating the magnitude of an earthquake. Beno Gutenberg is most well-known for determining the speeds and travel times of S-waves and P-waves through the Earth's interior (Hough, 2007). This information would be vital to determining the calculations necessary to derive a Richter magnitude.

Calculations and Derivations

The timing of P and S wave arrival at any one of the Wood-Anderson seismometers stationed around southern California was critical in locating seismic events. The team at Seismo Lab extracted this data by analyzing the horizontal motion of these seismic waves that were graphed onto seismographs (Boore, 1989).

Triangulation was used to find the epicentre of the earthquakes by measuring the time differences between the P-waves and S-waves on three or more seismometers. The epicentre range specific to the scale was less than 600 km (373 miles); the closer the amplitude was taken to the epicentre, the more accurate the reading was. Triangulation is a process similar to measuring the lag time between thunder and lightning in different regions to figure out the exact location of a lightning bolt. Using the speed difference between P-waves and S-waves, calculated by Gutenberg and Richter, the exact latitude and longitude of the earthquake could be found with ease (Boore, 1989; Richter, 1935). The distance from the epicentre and peak amplitudes were extracted, and plotted against each other to compare earthquake sizes, an idea which Richter credits Wadati's 1931 paper for (Boore, 1989). Now the issue was, the range was too large between small and large earthquake sizes. Gutenberg suggested plotting the amplitudes logarithmically to account for this. A rough sketch of the procedure for estimating magnitudes where Log WA indicated the log values of peak amplitudes of earthquakes picked up on Wood-Anderson (WA) seismometers and Log D represents distance (Figure 3.17). The clouds labelled with M values are representative of the recorded peak amplitudes and are pointing to a dashed line denoting a reference curve of the average attenuation of seismic waves. Each M defines the earthquake magnitude, based on the offset factor required for the data points in each cloud to be brought to the reference curve, in the same x-axis value (Boore, 1989). This distance was defined by the following formula:

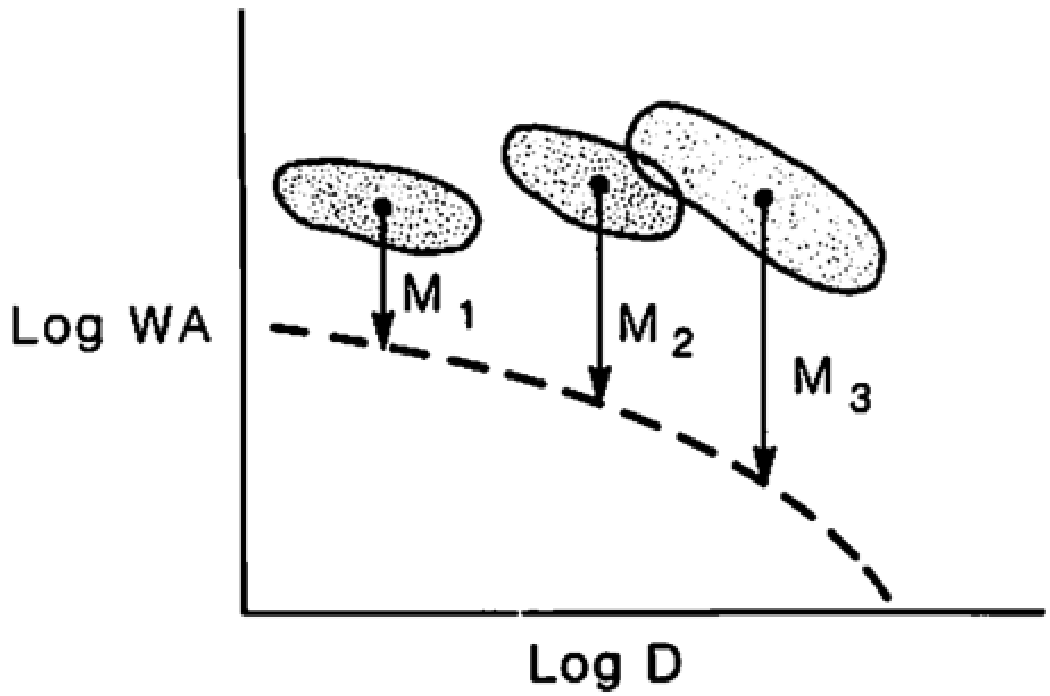


Figure 3.17: Rough sketch of the method used to determine magnitude (M) based on the peak amplitudes of earthquakes.

$$M = log\ WA - log\ WA_o \quad (1)$$

Where WA is as defined earlier, and $log\, WA_o$ is the point on the reference curve (Boore, 1989). As a result, each order of magnitude on the scale corresponds to a ten-fold increase in peak amplitude for an earthquake. Many misunderstood that magnitude values corresponded to a 10 times greater energy release from an earthquake with each successive scale.

Nine years after the Richter scale (Figure 3.18) was published, using data on southern California's earthquake activity, Richter and Gutenberg derived a law to estimate the frequency of occurrence of varying earthquake magnitudes. This is known as the Gutenberg-Richter law, and is presented with the following equation:

$$log_{10}N(M) = a - bM \quad (2)$$

Where N is the number of earthquakes per year of magnitude M or larger, a represents total seismicity rate of a region and b is a scaling parameter constant. Typically, the b value is one, but can vary depending on the region (i.e., 1 for tectonic earthquakes, 2 for volcanic earthquakes) (Fiedler, et al., 2018).

Although the Richter scale did not actually account for total energy release, an empirical formula known as the "Gutenberg-Richter energy-magnitude relationship" was derived from both of their findings and published in a variety of literature. This formula is:

$$log_{10}E = 1.5M_s + 11.8 \quad (3)$$

Where E represents energy in ergs. This equation, in its exact form, is reportedly not found in any of Richter or Gutenberg's papers or published pieces. However, it can be derived by combining two equations proposed by Gutenberg (Gutenberg, 1956):

$$m = 0.63M_s + 2.5 \quad (4)$$

$$log_{10}E = 2.4m + 5.8 \quad (5)$$

In Equation 1, Gutenberg proposed a relationship between what he called unified magnitude m, and the surface wave magnitude Ms. He developed the concept of surface wave magnitudes as an extension to the Richter scale to accommodate lower frequency seismic waves of specific amplitudes. Equation 2 shows the relationship between unified magnitude and energy release (in ergs) (Equation 2). It is important to note that neither slope values (2.4 or 6.3) have a physical justification.

The closest mention of the equation

$$log_{10}E = 1.5M_s + 11.8 \quad (6)$$

is in the introduction of Gutenberg and Richter's book 'Seismicity of the Earth and associated phenomena' (1954) where they share

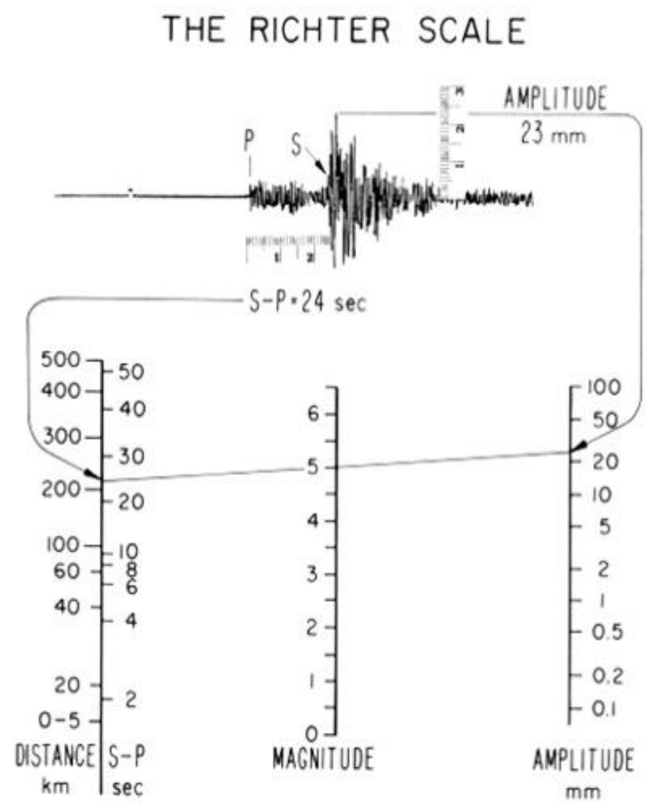


Figure 3.18: Original Richter Scale chart from Caltech archives that was used to determine magnitude of an earthquake. After measuring the difference in time between S-waves and P-waves and the amplitude of the greatest wave, straight edge lines for these points on their respective scales connect to the middle scale to determine magnitude.

the following:

"In this book, we have assumed for radiated energy the partly empirical equation:

$log_{10}E = 12 + 1.8M.$

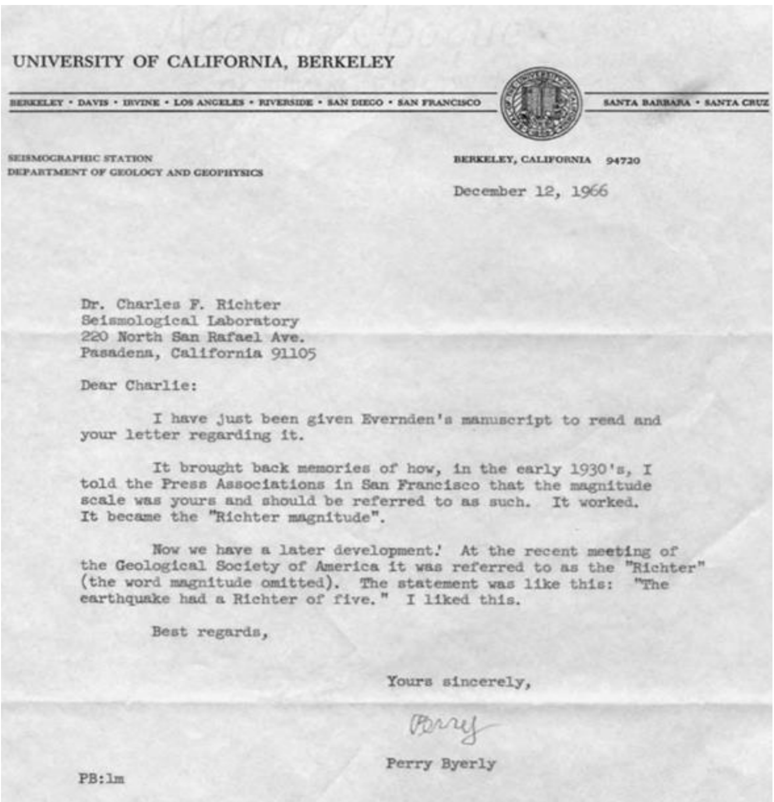
This seems to give too great energy. At present (1953), the following form is preferred:

$log_{10}E = 11 + 1.6M$ "

However, neither the book nor any other formal documentation from either scientist clearly justified their preferred form of the empirical equation (Okal, 2018). Another mystery lies in where the slope of 1.5 came from in the established "Gutenberg-Richter energy-magnitude relationship". Many experts conducted mathematical derivations to figure this out, using a variety of materials available from Richter and Gutenberg's research Although, that is beyond the scope of this piece. The relevance of the Greenberg-Richter energy-magnitude relationship will be revisited later on in this article (Gutenberg, 1956).

What about Gutenberg?

The Richter scale was received well amongst scientists, especially after being published in the first 31 pages of the January 1935 issue of the Bulletin of the seismological society (Hough, 2007). Richter was seen by the public and media as the leading expert on southern Californian earthquakes. However, questions arose as to why Gutenberg did not receive the same recognition, and whether Richter tried to dissuade the public from associating solely his name with the scale. This was addressed by



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SEISMOGRAPHIC STATION
DEPARTMENT OF GEOLOGY AND GEOPHYSICS

BERKELEY, CALIFORNIA 94720

December 12, 1966

Dr. Charles F. Richter
Seismological Laboratory
220 North San Rafael Ave.
Pasadena, California 91105

Dear Charlie:

I have just been given Evernden's manuscript to read and your letter regarding it.

It brought back memories of how, in the early 1930's, I told the Press Associations in San Francisco that the magnitude scale was yours and should be referred to as such. It worked. It became the "Richter magnitude".

Now we have a later development. At the recent meeting of the Geological Society of America it was referred to as the "Richter" (the word magnitude omitted). The statement was like this: "The earthquake had a Richter of five." I liked this.

Best regards,

Yours sincerely,

Perry

Perry Byerly

PB:lm

Figure 3.19: Letter from Perry Byerly to Charles Richter in 1966 recalling the first time this scale was called The Richter Scale.

Richter in a 1979 interview where he remarks he originally called it the "magnitude scale," and "refrained from attaching [his] personal name to it for a number of years." (Hough, 2007). He then mentions University of Berkeley seismologist Byerly whom he attributes with being the first to refer in public to the "Richter scale". A 1966 letter from Byerly (Figure 3.19) read: "It brought back memories of how, in the early 1930s, I told the Press Associations that the magnitude scale was yours and should be referred to as such. It worked. It became the 'Richter magnitude'. Now we have a later development. At [a] recent meeting of the Geological Society of America, it was referred to as the 'Richter' (the word magnitude omitted). The statement was like this: 'The earthquake had a Richter of five.' I liked this." (Hough, 2007).

In Richter's obituary in the Los Angeles Times, a long-term Caltech colleague of his and Gutenberg's states that "[Charles] did very little to emphasize Beno's role. If you wanted to think it has all been Richter's doing, that was OK with Charlie" (L.A. Times Archives, 1985). This exemplifies the frequent pattern in the scientific community, where credit is not always given to members with significant roles behind a discovery. Without Gutenberg's contributions and expertise, it is possible that the Richter scale would not have been as successful as it was at the time.

Limitations

Around the 1970s, seismologists began noticing limitations with the Richter scale. Although the scale theoretically did not have an upper or lower limit, it was saturated, meaning it underestimated the magnitude of larger earthquakes. The different frequency tones of seismic waves impact the severity of the earthquake as intensity increases and frequency emitted decreases, relative to the distance from the epicentre. Since the Richter scale omitted the impact of vertical movement, it did not accurately capture the entire energy output measured by the seismometer. (PNSN, n.d.; Boore, 1989). This led to discrepancies, where larger-scale earthquakes seemed less significant than they actually were, according to the destruction they had caused. Since the Richter scale was originally developed to measure magnitudes of moderately sized earthquakes that occurred in southern California, typically of magnitude 3 to 6.5, this scale was not accurate globally (Bormann and Saul, 2009). The scale is centred around a specific geographic region, along with its dependence on only one particular type of seismograph made it unreliable.

Both the Richter scale and Wood-Anderson seismometer needed revision. This instrument was rather inaccurate in detecting earthquakes of lower frequencies. Scientists realized the importance of this parameter, and that the detection of shaking severity, especially low-tone frequencies given off by big earthquakes, was the optimal feature of a high-quality seismometer. These discoveries prompted repeated fine-tuning and design improvement leading to the development of more sophisticated and reliable seismological instruments to precisely record the full range of motion during an earthquake event (Hough, 2007).

The Moment Magnitude Scale

The absence of a more accurate, universally applicable magnitude scale gave rise to the development of the moment-magnitude (Mw) scale (Figure 3.20). Since its discovery in 1979 by Thomas Hanks and Hiroo Kanamori, seismologists still prefer to use the Mw scale even to this day. Unlike the Richter scale, the Mw scale reflects the overall seismic energy released, providing a more accurate representation of earthquake activity from a wider range of sizes. This refrains the Mw scale from saturating. Furthermore, the Mw scale is not limited to a particular type of seismometer and derives magnitudes from a variety of seismic stations (Mereu, 2016). Despite these differences, the fundamental principles of the Richter magnitude scale were the stepping stones that helped derive the Mw scale.

Calculating Mw

The term moment signifies the parameter used to measure the angular leverage on the faults, causing them to move during an earthquake (Mereu, 2016). The discovery of the Mw scale was revolutionary since it was the first time an absolute term could be applied to an earthquake rather than using a relative measure to compare the sizes of earthquakes. Seismic moment (M_o) is directly related to the size of the rupture and is calculated using the following equation:

$M_o = \mu DA$ (7)

where μ represents rock rigidity; the rock's resistance to shear strain and bending, providing the force needed to generate seismic waves. D represents slip (i.e. the distance the fault moved). A represents the area of the fault that slipped. Moment tells us that stronger rock material, larger area, and/or more movement in faults will result in a larger earthquake (Bormann and Di Giacomo, 2011). The equation so far shows us the relevance of seismic moment, but the question of determining the magnitude remains. Referring back to the Gutenberg-Richter energy magnitude relationship, by relating M_0 to this formula, Kanamori defined the moment magnitude as (Kanamori, 1979):

$$M_w = 23 log M_0 - 10.7 \quad (8)$$

Converting magnitude scales in Eastern Canada

For the last decade, the moment magnitude scale has been a critical tool used by Canadian seismologists to routinely assess earthquakes that occur over various regions in the country.

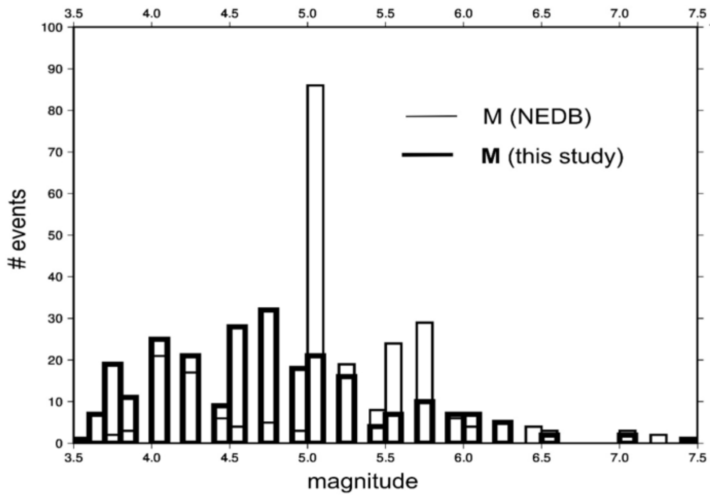

Figure 3.20: Data distribution according to magnitude and number of earthquake events for the Geological Survey of Canada study (this study) represented by the thicker bars, and recorded magnitudes in the dataset extracted from the (Canadian) National Earthquake Database (NEDB), represented by the thinner bars. Moment magnitude is recorded in this study, whereas the NEDB dataset includes primarily Richter magnitudes, but also moment magnitudes.

Prior to the early 2000s, earthquake magnitudes were calculated using the Richter scale in Eastern Canada, since typically the nature of earthquake activity was smaller and of higher frequency. Nonetheless, records of these earthquakes are essential for hazard assessment and public safety, as well as observing trends in seismic activity across various regions in Canada (Bent, 2022).

In a 2022 revised moment magnitude catalogue of Eastern Canadian earthquakes, the Geological Survey of Canada decided to convert previously recorded Richter scale magnitudes to Mw using a variety of published literature. Mw values that were already available in their dataset were also revised to derive appropriate conversion scales. The purpose of this was to classify earthquakes with a consistent magnitude scale for more accurate comparison and risk assessment (Bent, 2022).

Due to the association of the Mw scale with larger earthquakes, smaller regional events were examined and revised more thoroughly when converting between the two scales. The catalogue mentions that it should not be regarded as a static product and that revisions are bound to happen in the future (Bent, 2022). This shows that the geology and classification of seismic events is not a linear, concrete process. Just as the earth is continuously evolving, so will the instruments we use to study it as we proceed to the future.

Theory of an Icy Past

In 1837, Louis Agassiz (1807-1873) delivered a shock to the scientific community when, instead of giving his expected talk about fossil fishes, he presented a novel glacial theory (Figure 3.21) (Agassiz, 1840, p. xvii). In the publication *Discourse of Neuchâtel* (1837), Agassiz addressed the Swiss Society of Natural Sciences and proclaimed that the surface of the Earth was once covered by a vast sheet of ice from the North Pole to the Mediterranean and Caspian seas. While this talk received vehement opposition from most scientific figures at the time, including Agassiz's closest mentors, he continued to study glaciers and build evidence to support his speculations. In 1838, he presented his theory of ice ages to a broad audience. In the following year he completed several more field trips with colleagues to build evidence of a vast glacial past. Agassiz published his major work in the field of glaciers, *Studies on Glaciers*, in 1840, which is full of anecdotes, experiments, and sketches from his fieldwork to support his theory (Agassiz, 1840). His background, personality, and academic connections contributed towards the eventual acceptance of the theory of ice ages.

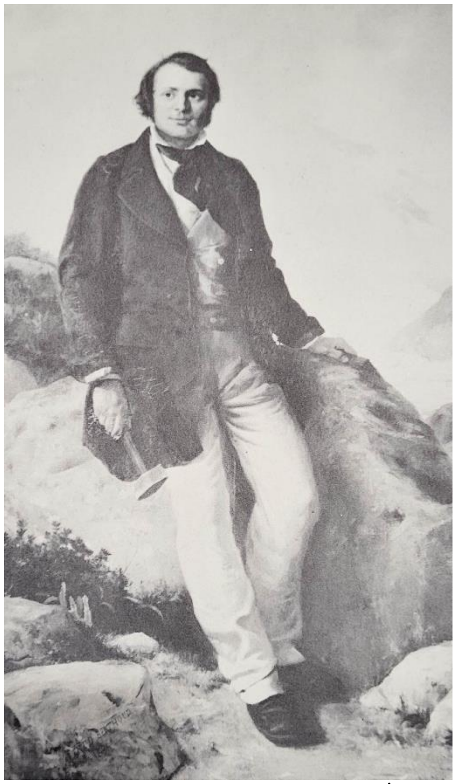

Figure 3.21: Oil painting of Louis Agassiz at the Unteraar Glacier.

An Unmatched Passion for Learning

As a child, young man, and eventually a renowned scientist, Agassiz demonstrated a passion for teaching and a love for exploring and learning (Gould, 1908). His father, a talented teacher, was likely a source of his inspiration. Agassiz's father became a pastor in the city of Orbe at the foot of the Jura mountains. Spending time in this city provided Agassiz with ample opportunities to sustain his innate love of the science of nature as he later discovered marks indicating the presence of glaciers in this city at the Jura mountains (Guyot, 1883). As students, Agassiz and his brother were known to copy treatises on natural history by hand as they could not afford to buy the books; however, he regarded this as a blessing in disguise, as he gained an appreciation for studying natural processes himself rather than relying on written accounts.

Agassiz's parents encouraged the study of medicine, which was the profession of his mother's family. Funded by his uncle, Agassiz attended the universities of Heidelberg and Munich, studying medicine and natural history (Mazur, 2022). Agassiz's time at Heidelberg allowed him to develop scientific friendships. These formative years were packed with time spent developing scientific ideas and inquiries with his friends Karl Schimper and Alexander Braun (Gould, 1908). At the university in Munich, he edited and published his first scientific work at the age of 21, which was passed to him by two professors. This publication, *Brazilian Fishes*, gained him undeniable recognition in the scientific community, and helped Agassiz prove to his parents that natural history was a suitable profession for a self-sustaining young man. He obtained his Doctor of Philosophy in 1829 alongside the publication of *Brazilian Fishes*, and obtained a Doctor of Medicine in 1830. Agassiz had a passion for gathering data to make conclusions. He did not want to merely accept the ideas of previous scientists, but instead he sought to generate hypotheses and substantiate them with evidence. This approach to studying science set Agassiz apart from other scientists at the time as no other scientist set out to study nature in the way Agassiz did. It was during his two-year period studying medicine where Agassiz was encouraged to pursue this methodological approach by his professor, Heinrich Rudolf Schinz. (Guyot, 1883).

Agassiz Rolling Onto the Scene

In his early career, Agassiz made numerous lasting friendships and connections to prominent figures in geology and natural sciences. This began as early as his high school years, when Agassiz first met Jean de Charpentier (1786-1855), an influential figure in shaping his career as a naturalist and who would become a significant mentor and colleague in his future work. In his university years, he continued his work in natural science with fossils, and after obtaining his degree, spent a year in Paris (Gould, 1908). There, he befriended the influential scientist Alexander von Humboldt (1769-1859) and the French zoologist Georges Cuvier (1769-1832), the latter of whom recognized the remarkable ambition displayed by Agassiz and his shared passion for paleontology.

Agassiz's connection to Cuvier (Figure 3.22) was significant due to Cuvier's contributions and experience in the field. Cuvier published over 300 papers throughout his career and was highly valued within the scientific community and beyond (Soloviev, 2010). Cuvier's passion for science began when he went to Normandy to begin a job as a tutor. In this role, he taught himself the anatomy of marine invertebrates and made various geological observations. In 1795, he moved to Paris, publishing over 10 papers in this year alone. During the year 1799, he began to teach as a professor at a college in France and became a leading expert in zoology. In the year 1800, Cuvier was appointed a secretary of the Institute of France within the Department of Physical and Mathematical Sciences, which later became a permanent position. Cuvier continued to study paleontology and make significant contributions to the scientific world. For instance, in 1812 he published a study that stated each organism has relationships between its organs, and with this knowledge he was able to reconstruct the appearance of an entire organism with just one bone. This discovery was monumental as it allowed him to reconstruct the appearance of extinct animals. Cuvier was highly regarded by the French people and well known for his scientific contributions. His work also reached beyond France with the translation of his most famous work into Russian (Soloviev, 2010). Cuvier gave Agassiz access to his entire collection so Agassiz could finish the work Cuvier began (Guyot, 1883). Cuvier passed away shortly after handing his work over to Agassiz.

Following the death of Cuvier, Agassiz struggled financially for months before he could secure publication funds from von Humboldt (Warren, 1928). Although Agassiz's funding to support himself and continue his research was limited, he always found a way to pursue his passions with the help of his connections (Gould, 1908). His determination to study science and share his findings with the world was so strong that Agassiz paved his own path. He accepted professorship as the chair of natural history at Neuchâtel in 1832, a position designed specifically for him, and founded his own lithographing and printing establishment to improve the plates for his work. The influence of Agassiz's colleague von Humboldt as a minister to the King of Prussia allowed Agassiz to obtain support and funding several times from the King of Prussia.

Figure 3.22: Portrait of Georges Cuvier, an influential zoologist and paleontologist who boosted Agassiz's career by passing on his work for Agassiz to finish.

In 1833, de Charpentier invited Agassiz to Bex to study fossils, folding, and igneous action (Agassiz, 1840, pp. xv-xvi). In 1836, he once again visited Bex in the company of de Charpentier, this time to study glaciers for five months (Agassiz, 1840, p.7). His connection to the early developer of glacial theories provided the opportunity for this trip, during which his perspective on glacial theory was fundamentally changed, providing the basis for his later speculations.

An Extensive Debate: The Rise of Ice Age Theory

While Agassiz's predecessors in the study of glaciers made many observations and even theories pertaining to ancient periods of glaciation, it was Agassiz who captured the world's attention and brought about wider acceptance of ice age theory. The passion with which Agassiz conducted and presented science, in addition to his connections to renowned scientists provided him the necessary leverage to argue the validity of his theories. Before Agassiz's work, it had been proposed that the Alpine glaciers once extended farther than their present location, by both Marie Deville and Jean-Pierre Perraudin around 1815, but these ideas were largely overlooked (Agassiz, 1840, p. xiii). The main reason for speculation about the history of glaciers was due to the presence of erratics, which were large boulders found on plains without any apparent explanation for how they had been transported there (Mazur, 2022). Historically, locals observing these features believed that the devil had brought them on his way to deposit them on top of a church on Sunday (Krüger, 2013, p.23). Other features commonly seen in alpine regions were scratches and structures in polished rocks, which locals called *laves*, believing they were signs of ancient cart tracks that had been smoothed by water. By the mid-18th century, scholars took greater interest in these geological features and sought scientific explanations.

The mountaineer Perraudin proposed to de Charpentier around 1815 that the erratics in Alpine valleys had been deposited by glaciers (Marcou, 2011). This was followed by several observations by the engineer Ignaz Venetz, who described moraines found outside the range of modern glaciers in 1821, suggesting the existence of some past epoch of cold (Agassiz, 1840, p. 6). Ancient moraines and polished rocks were previously noted by Horace Bénédict de Saussure, but he believed water currents had created the polished rocks, and overlooked the role of the ancient moraines. Danish-Norwegian professor Jens Esmark (1763-1839) thought that transport by glaciers was a more suitable explanation for the phenomenon of erratics than transport by water. He observed a variety of grain sizes in the nearby deposits, which differs from the expected well-sorted grains of a fluvial deposit. (Krüger, 2013, p.92). Franz Joseph Hugi (1791–1855) studied the glaciers of the Swiss Alps, observing rounded rocks in the vicinity of glaciers, but did not believe they were moved by ice (Agassiz, 1840, p. 6). During his frequent trips to the Alpine glaciers, Hugi constructed a hut at the foot of the *Im Abschwung* rock on the margin between two glaciers in 1827. The hut would later be discovered by Agassiz in 1839 at a great distance from its original location, having moved 1300 metres since its construction (Figure 3.23) (Agassiz, 1840, p. 84-85). Venetz also expressed a belief that glaciers were responsible for the transport of erratics, convincing de Charpentier of this theory as well (Marcou, 2011). The hesitance to accept the theory of glacial transport was likely due to the understanding held by two influential figures: von Humboldt, and the uniformitarian geologist Charles Lyell (1797-1875). Since prehistoric Europe had a warmer climate, evidenced by the fossil records, they applied a principle of gradualism to theorize that the Earth had experienced a gradual cooling rather than dramatic fluctuations in historical temperatures (Krüger, 2013, p.225; Mazur, 2022). Lyell proposed that angular boulders were transported on top of ice rafts carried by water currents (Agassiz, 1840, p.155).

Figure 3.23: The hut constructed by Hugi in 1827, discovered by Agassiz in 1839, over 1300 metres from its original location.

The first theory of periods of extensive glaciation that garnered significant attention was proposed by Venetz and de Charpentier (Agassiz, 1840, p. xv). In 1834, at a meeting of the Swiss Society of Natural Scientists at Lucerne, de Charpentier presented the theory that erratic boulders had been transported by glaciers, an idea which was met with immense opposition in the scientific community. Agassiz himself was initially an opponent, following Lyell's theory instead (Agassiz, 1840, p. xv; Marcou, 2011). However, his openness to new discoveries and quick reasoning allowed him to change his mindset upon studying the glaciers in Bex with de Charpentier in 1836 (Agassiz, 1840, p. xvi). During his time with de Charpentier, Agassiz witnessed evidence of boulder transportation as he studied a group of giant boulders in Monthey. After studying the boulders in Monthey, Agassiz accepted de Charpentier's glacial theory as he concluded that there was no other explanation for the transportation of these boulders. During the same year, Agassiz observed a polished and smooth plain between the Alps and the Jura mountains; he attributed this plain to the former presence of a glacier. Although this surface was covered with cities and fields during Agassiz's time, he suggested that this plain was once covered by an ice sheet over 700 metres thick. Agassiz took this idea one step further by suggesting that a universal glacier era resulted in a mass extinction at the end of the tertiary age (Guyot, 1883). This cold period also known as an ice age or a glacial epoch was revolutionary to the scientific community and caused great conflict.

Agassiz continued to develop and substantiate his glacial theory with a large body of evidence collected over six summers spent in the Alps from 1838 to 1843 (Gould, 1908). His viewpoint that science should be experienced and proved for oneself by witnessing natural phenomena was again showcased by his many expeditions on glaciers. He once had his companions lower him into a crevasse so that he could better observe the patterns and structure of the glacier. He performed field experiments such as producing boring holes, adding coloured liquids to the ice, taking samples of ice to view under a microscope, and setting rows of stakes across glaciers to track the locations of swiftest current (Agassiz, 1840, p. 34; Gould, 1908). In his studies, he substantiated why the previously suggested mechanisms of the smoothing of polished rocks could not be adequate explanations, stating that water polish is more dull and imperfect than that of ice (Agassiz, 1840, p. 106). He also observed striations in rocks of the Jura mountains and the bottoms of great Swiss valleys, cross-cutting the irregularities of rocks on the sides of beds. In Le Landeron, he observed distinct striations oriented nearly perpendicular to the mountain slope, indicating the past action of ice (Figure 3.24). This supported his theory that floating ice could not have produced these features (Agassiz, 1840, p.159).

The Battle for Acceptance

The glacial theory developed by Agassiz built upon the work of Venetz and de Charpentier, and took over 25 years to supersede the previous theory that large boulders had been transported by water currents (Agassiz, 1840, p. xii). One of the major setbacks in the adoption of Agassiz's theory was the extremity of the accompanying biological explanation he presented for the existence of ice ages. In his *Discourse of Neuchâtel*, he argued that an ice age marked the death of an era of animals, and the following rise in temperature corresponded to a new creation of life (Agassiz, 1840, pp. liii, lvii-lviii). This theory was developed with Karl Schimper, a friend of Agassiz whose somewhat eccentric influence seemed to fuel Agassiz's more unsubstantiated theories. It was in a humorous, half-scientific piece of poetry by Schimper where the term "ice age" first appeared in print (Agassiz, 1840, p. xvii). The predominant response to Agassiz's discourse was incredulity and ridicule, his major opponents including von Humboldt, Leopold von Buch, and Elie de Beaumont. Shockingly, even de Charpentier was not pleased with Agassiz's presentation, as Agassiz had used de Charpentier's ideas in his unverified new theory.

Despite initial opposition, Agassiz was passionate about convincing the world of the processes he could see. In 1838, Agassiz, de Charpentier, and a colleague Arnold Guyot presented evidence of Alpine ice reaching up to the Jura mountains at the meeting of the Geological Society in Porrentruy, allowing a broader audience to see the evidence of their theory (Krüger, 2013, p.225). William Buckland (1784-1856), considered one of the most famous British geologists at the time, reported in an 1840 letter to Agassiz that he had converted Lyell, although some of Lyell's future publications hint that he may have remained in quiet opposition (Krüger, 2013, pp.10, 246; Mazur, 2022). Before publishing his book, *Studies on Glaciers*, in 1840, Agassiz contacted one of his strongest opponents, de Beaumont, asking him to communicate his work to the Academy of Science, but this effort proved unsuccessful (Agassiz, 1840, p. xxiv).

Figure 3.24: Polished rocks in a lave *in Le Landeron, near Neuchâtel, observed by Agassiz. He observed striations perpendicular to the slope of the Jura, indicative of a glacier's movement.*

A factor that contributed to the general acceptance of ice age theory was a massive, 700-kilometre, unbroken wall of ice discovered by a British warship exploring the Antarctic from 1839 to 1843. This provided an extant example of the ice sheets Agassiz envisioned (Mazur, 2022). In 1844, Agassiz attended the meeting of the Geological Society of France, which marked a predominant acceptance of his glacial theory by all but a few dwindling opponents (Agassiz, 1840, pg xxxi). Additionally, the work and publications of Charles Frédéric Martins, whose work focused on moraines and their formation, helped affirm Agassiz's glacial theory and bring it further into public acceptance. Martins communicated observations to the Geological Society in 1842 which may have been the first to note the importance of fluvioglacial deposits (Krüger, 2013, pp.202–205). He also published three articles near the end of 1847 addressing objections to the ice age theory with evidence from several others' studies of glaciers (Krüger, 2013, p.225). The same year, he published a text targeted to the general public to promote the ice age theory, popularizing the theory in France (Krüger, 2013, p.235). Agassiz's theories quickly reached America, and were supported by Edward Hitchcock, a respected American scientist. Hitchcock reproduced some of the plates from *Studies on Glaciers* in an 1841 report, and these quickly entered the American education system to be published in an 1851 textbook by Samuel St. John (Agassiz, 1840, p. xxvi).

In 1846, Agassiz landed in Halifax to begin traveling through North America. During his travels, he observed indicators of past ice ages similar to those he had seen in the Alps. He began to develop a story outlining the history of North American glaciers over the next several years; however, this became his secondary focus as he concentrated most of his efforts on studying marine biology (Agassiz, 1840, p. xxxiii). In his time studying glaciers, Agassiz accomplished what few have done in history; he carried an idea from mere speculation to a well-substantiated theory which finally began to be accepted near the end of his career.

Glacier Modelling

Although Agassiz's work provided integral information on glacial theory, his experimental methods were time consuming and limited by the effort and expense of travel. Modern technology is much more efficient than techniques used during Agassiz's time as new technology allows geologists to study and monitor glaciers without being physically present. Remote sensing is a powerful tool which allows for the observation of large areas without making physical contact with the area (Gupta, 2018). Glacial reconstructions are also effective methods for the study of glaciers as they use observations to produce maps of glaciated regions (Pearce, et al., 2017). Glacial melt simulations generate useful modelling of the melt rate of both snow and ice on glaciers (Hock, 2005).

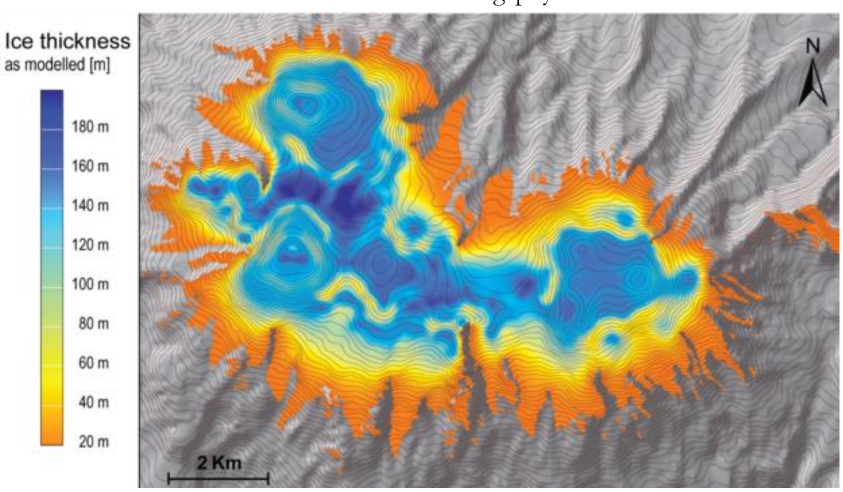

Figure 3.25: Model of ice thickness of the Coropuna Glacier in Peru, generated with GIS and statistical multiple regression techniques.

Out of this World: Glacial Remote Sensing

Remote sensing by satellite is the detection and monitoring of physical characteristics of a region through the measurement of electromagnetic radiation. It is based upon the concept that an object of interest reflects and emits different intensities of electromagnetic radiation based upon its characteristics (Gupta, 2018). The use of remote sensing in glacier monitoring provides information on various features of the glacier, such as equilibrium line altitude, albedo, terminus position, volume, accumulation area ratio, glacier area, surface elevation, and length. The information provided from remote sensing can be further enhanced when combined with another powerful technique, geographic information systems (GIS) (Kimothi, et al., 2022). This technology was used to assess water supply changes from climate change through a remote sensing analysis of the Coropuna glacier in Peru (Peduzzi, Herold and Silverio, 2010). Researchers collected data from satellite imagery and field measurements using digital elevation models, ground penetrating radar, and a ground positioning system (GPS). They modelled the data using GIS, applying statistical multiple regression techniques. This allowed them to generate a low-cost model of ice thickness (Figure 3.25). This model provided evidence supporting glacier area and volume changes, which informed the development of a climate change adaptation strategy to regulate and bring awareness to the impact of glacier shrinkage on local water supply.

The use of remote sensing technology in the monitoring of glaciers is fundamental as the rise of global temperatures promotes glacier loss and recession (Milner, et al., 2017). The melting of glaciers places tremendous stress on nearby streams as the glacial runoff is diverted into these streams, impacting the hydrological systems of the region. The loss and recession of glaciers poses a major risk to ecosystem and human health as glacier shrinkage impacts sediment transport, biodiversity, and access to water for agriculture (Milner, et al., 2017).

Glacial Reconstructions

Glacial reconstructions are often done for the purposes of paleoenvironmental analysis and the estimation of equilibrium line altitudes (ELAs). ELAs are altitudinal zones on a glacier where ablation and accumulation are balanced equally, and they respond to air temperature and precipitation (Pearce, et al., 2017). If the ELA can be determined based on a known paleotemperature, then the historical precipitation total can be calculated. Several methods of performing glacial reconstructions are available, but for most applications, the process begins with geomorphological mapping. This technique uses glacial, periglacial, and fluvial evidence from present observations of glacial landforms including moraines, terraces, fans, and deltas, to produce a map of glaciated regions. For the reconstruction of former ice sheets, a glacial inversion model can recreate the previous extent, configuration, dynamics, and retreat patterns of past ice sheets, and sedimentary structures can be analyzed to determine paleocurrent direction. For the reconstruction of former mountain glaciers, one potential process is to use geomorphology to define the two-dimensional extent of the glacier, then use a GIS program to reconstruct the three-dimensional form of the ice mass. Using GIS data of current watershed boundaries, features including the former locations of ice boundaries are identified on the three-dimensional reconstruction. Additionally, the positions of former ELAs are approximated. Modern, accessible geospatial data is easily manipulated in software such as GIS, which makes these modelling techniques prominent in current glacier studies (Pearce, et al., 2017).

Monitoring Ice Melt

The mass balance of a glacier, which is the balance of the mass lost and the mass gained by the glacier results from its constantly changing rates of melting and freezing (Kotlarski, et al., 2009). Glacial melt is influenced by the complex interactions between physical properties of the glacier and meteorological conditions (Hock, 2005). Energy-balance melt models allow melt rates of glaciers to be computed using a sum of energy fluxes to summarize interactions between the glacier and the surrounding environment. Another type of model is temperature-index melt models, one of the most widely used models to compute ice and snow melt. Since temperature tends to be an accessible and predictable variable, this technique is frequently used (Hock, 2005).

Several types of glacial melt simulations exist, such as general circulation models and regional climate models. While these models are useful, there are limitations due to environmental factors that are difficult to account for (Kotlarski, et al., 2009). One particular model developed in 2009, which is an extended regional climate model for glaciers ($REMO_{glacier}$), aims to generate a complete simulation of the interactions between glaciers and climates with the use of a tile system to define the region (Kotlarski, et al., 2009). The study area is divided into a grid and within each grid square, the area is subdivided into tiles which are assigned as non-glacierized land, water, glacier ice, or sea ice. This subdivision allows surface fluxes to be calculated separately for each tile to account for different properties of the surface. The $REMO_{glacier}$ model was tested to reproduce the glacial activity in the entire Alpine region in the second half of the 20th century and was relatively accurate at reproducing the year-to-year variability and general magnitude of glacier mass balance (Kotlarski, et al., 2009).

Another study applied data from climate projections and modelling to a glacial model accounting for numerous glacier mass balance and dynamics considerations to project the deglaciation of Western Canada from 2005 until the year 2100 (Clarke, et al., 2015). It used surface topography obtained from the 2000 Shuttle Radar Topography Mission (Figure 3.26) and glacier outlines in a regional glaciation model to generate a high-resolution model of glacier dynamics. The complex model used in this study was tuned using present glacial data to calibrate the model to actual observations. The model projected that by the year 2100, coastal glaciers would lose 70 ± 10% of the volume they occupied in 2005, and the glaciers in the regions defined as Interior and Rockies would lose over 90% of ice area. Access to this kind of projection is highly informative for making predictions about future environmental conditions which have enduring impacts on ecosystems, agriculture, and numerous resources and industries (Clarke, et al., 2015).

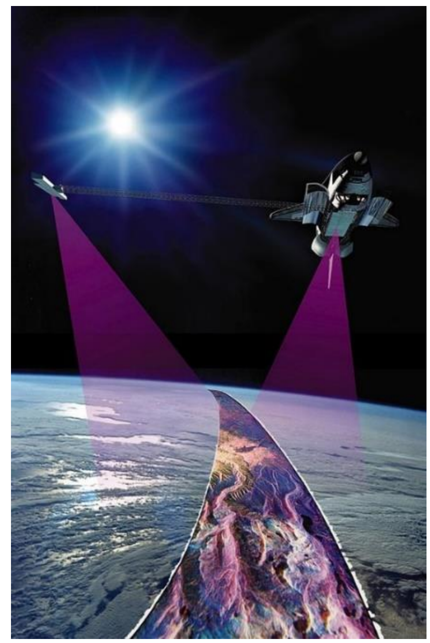

Figure 3.26: Illustration of the Shuttle Radar Topography Mission. Launched in 2000, this shuttle used two radar antennas to sweep the surface of the Earth in 10 days to obtain extensive, high-resolution data of the Earth's topography.

The advancement of scientific technology, such as remote sensing has greatly impacted the methods with which scientists study glaciers. The use of remote sensing technology for monitoring glaciers removes limitations that Agassiz faced, allowing for the collection of greater amounts of precise data. Modern approaches using advanced technology have led to a more comprehensive understanding of glacier movements and future activity.

Understanding Glacial Processes Through a Historical Lens

Since the first recorded existence of early civilizations, humans have attempted to understand the multitude of effects glaciers have on reconstructing landscapes and climates. Glacial activity was often a challenge to study accurately, likely due to the high-altitude, extreme temperature conditions that hindered the ability of individuals to voyage through and measure impacts and mechanisms (Hambrey and Alean, 2004). It was not until approximately 18 CE when Greek philosopher, historian, and geographer Strabo first developed an accurate assessment of glaciers and described horizontal layers of ice sheets that crystallize and accumulate (Acolat, 2007). Similar close encounters with glaciers helped develop an understanding of the substantial effect glaciers have on climate conditions, which would later contribute to the development of mapping techniques and measurement tools to accurately depict paleoclimate conditions. Throughout this section, there will be a focus on the exploration of historical changes in our understanding of glacier morphology and glacial activity, the development of knowledge on paleoclimates, such as the Ice Age, and the novel theories that contributed to current modelling techniques.

Figure 3.27: Painting of Ignaz Venetz, Swiss engineer, naturalist, and glaciologist who was one of the first to study the impact of glaciers on shaping climates.

Early Creationist Perspectives

From first recorded observations, the idea of glaciers was a terrifying yet intriguing thought to early travellers in northern climates. Although many feared being close to them, glacial regions were the subject of many mythological and creationist perspectives (Hambrey and Alean, 2004). In the late Middle Ages, many people believed that spirits roamed the high altitudes of these regions and occasionally sent out mass storms and flows of snow. Italian poet Dante Alighieri described the centre of these glaciers in his 1321 poem, *Divine Comedy,* as a large pool of freezing ice and a playground of demons that occasionally erupted (Clarke, 1987).

Until the end of the 18th century, early biblical schools of thought dominated scientific writing and research in Europe. Even when approaches to glacier research were being made, they were often criticized due to their promotion of "godlessness" (Silliman, 1994). The Bible describes the Genesis flood, which was interpreted to be the cause of large erratic boulders — likely a mechanism for glacier changes and the presence of unfamiliar sediment and rocks. This perspective throughout Europe caused hindrances in early geological research (Clarke, 1987).

It was clear that early hypotheses in regard to glaciation were those of speculation, likely attributed to the danger that came with exploration. This is why, for early civilizations, mythological and creationist thought dominated the knowledge of glacial activity and climates.

Early 19th Century Perspectives: The "Glacier-Monstre"

In the 19th century, the development of glaciology and geology brought forth several unique theories that argued the historical movement of glaciers and geomorphology. As Europe began to accept scientific thought away from the Bible, new theories were established in the scientific community by the end of the century.

In June 1818, disaster struck the town of Martigny in the Swiss Alps as there was sudden, rapid flooding from Lac de Mauvoisin, a glacial lake formed from the blockade of avalanching ice of the Gietroz Glacier. The eventual outburst of the Dranse river caused the death of 47 individuals (Lambiel, et al., 2020). This was just one of the events that signified early 19th century Europe was approaching the end of the so-called "Little Ice Age." Research was required to create solutions for mitigating glacier impacts on developed regions near the Alps (Painter, et al., 2013).

Swiss engineer Ignaz Venetz (Figure 3.27) was tasked to survey the land and analyse the impacts of glaciers on a regional level. He worked alongside Jean-Pierre Perraudin, who had previously discovered marks on rocks and ridges of moraines that were kilometres away from active glaciers. Perraudin theorised that these were indicators that much larger glaciers spanned the region beforehand, and have retreated over time (Woodward, 2014). Venetz furthered his theory and produced topographic maps of the terminal and lateral moraines located further down from the investigated glaciers. He was one of the first to recognize how glaciers modify landscapes, and the forms of evidence used to classify patterns of glacial movement (Clarke, 1987).

After Venetz presented his findings to the *Helvetic Society of Natural Sciences*, most were unconvinced due to affiliations with the *Geologic Society of London* (Woodward, 2014). However, Swiss-German geologist, Jean de Charpentier, shared similar observations that led him to believe Venetz's conclusions. Charpentier's work in 1841 on the Rhône Valley of Switzerland recognized depositional glacial erratics (Figure 3.28) and differences in the smoothing of surrounding bedrock (Lambiel, et al., 2020). Using these observations, Charpentier mapped the recorded erratics and noticed evidence of a previous, larger glacier than what was present in the valley (Woodward, 2014). The differences in the smoothing of the bedrock indicated the presence of a large glacier in one layer, in which he developed the term *Glacier-Monstre* (Grove, 2019). This was similar to a paper published by Jens Esmark a decade prior, the first professor of geology in Norway who conducted similar observations and published his findings (Woodward, 2014).

Esmark, Charpentier, Venetz, and other contributing researchers provided a foundation of glacier theory, supported by their observations of glacial erratics, moraine ridges, and bedrock geology. Not only was the presence of past glacial activity in European mountain ranges established, but geomorphological changes in landscapes were also understood.

The Drift Theory

Despite these well-established theories, it was no surprise that Charles Lyell dominated most mid-19th century scientific views on glaciation. As the president of *The Geological Society of London* from 1835-1837 and 1849-1851, his views on uniformitarianism challenged biblical thought and brought a new perspective on many geological theories (Silliman, 1994). In conjunction with Roderick Impey Murchison and his work on *The Silurian System*, the drift origin of glacial erratics was established.

Lyell promoted the idea that erratic boulders and finer sediment were transported through large ice masses such as glaciers. These masses of debris, which he termed diluvium, were deemed to be a result of warm climates present before the glaciers (Fairbridge, 1968). He theorised that erratic boulders were deposited as the glaciers melted and were carried by warm waters. One of the key elements explaining this was Lyell's idea, stating that Europe was once submerged in a marine environment, which dried up and left sediment runoff (Woodward, 2014).

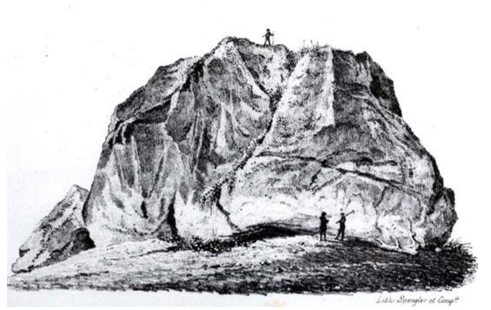

Figure 3.28: Illustration by Jean de Charpentier titled "Pierre es Marmettes," describing a large glacial erratic found near the Rhône glacier in Switzerland.

However, the strongest supporting case for the drift theory was not made by Lyell, as Murchison solidified many uniformitarianism theories that soon became extremely difficult to overpower. Murchison shifted towards avoiding the term diluvium due to its biblical relations and instead established the term "drift" (Glikson, 1981). The presence of shells and erratic gravels at high altitudes aided in solidifying this theory. This evidence included the fossils found by Joshua Trimmer in 1831, well preserved at Moel Tryfan 427 metres above sea level (Fairbridge, 1968). From this, Murchison noted that this was likely caused by deposits under marine waters that were relatively recent in geologic time. Similar to Esmark, he stated that the subaqueous drift theory likely also had glacial origins (Woodward, 2014).

Unlike Lyell, Murchison theorised that the drift was not a result of diluvial current since it would not have had the strength to deposit large sediments such as boulders. He proposed that instead, there were likely melting chunks of ice, which he deemed to be "ice floes," that were upon a surface of sand, gravels, and shell fragments (Fairbridge, 1968). However, he agreed with Lyell and various other 19th-century geologists in the sense that he deemed these indicators to be driven by a past force that was much larger in magnitude (Silliman, 1994).

Lyell and Murchison's view overpowered most glacial theories with the idea of drift and floating ice. As a result of Lyell's large influence and unchanged views, it required an entirely new basis of evidence to shape new perspectives on glaciers. (Woodward, 2014).

Louis Agassiz: Shifting 19th Century Perspectives

Undoubtedly, Jean Louis Rodolphe Agassiz heavily advanced the glacial theory in the late 19th century, bringing forth a new realm of thought into the world of geology. Agassiz is best known for his theory that an Ice Age once covered the Alps in massive ice sheets. He also established further implications of continental glaciation, thus modifying the general drift theory established at the time (Hansen, 2017).

It is believed that Agassiz was first convinced of this concept in 1836 when he ventured to the glaciers of the Chamonix and Diablerets area with Charpentier, who had already proposed ideas pertaining to Alpine glaciation (Gordon, 1995). The year after, Agassiz presented the theory of glaciation to the Helvetic Society of Natural Sciences (Hansen, 2017). Although Agassiz mentioned glacier enthusiasts that influenced his outlook on the Ice Age theory during his presentation, they were not properly credited as Agassiz wished to receive the majority of the praise (Irmscher, 2013). During this time, Agassiz was known to claim more credit than what was due to him. He then travelled to the Hasli valley and the Grimsel, where he continued to observe the same phenomena from multiple other sites (Carozzi, 1966). He noticed polished and striated rocks above and beyond the edges of glaciers, old, well-preserved moraines, and erratic bounders arranged in a manner unexplainable by water movement.

Succeeding his presentation of the Ice Age theory, Agassiz and his companions investigated the dilation theory in the 1840s (Clarke, 1987). The theory concluded that ice is relatively permeable to water and therefore meltwater can easily flow into the glacier interior (Clarke, 1987). The water would freeze, expanding within the glacier, thus resulting in the down-glacier movement of the ice. From this, Agassiz published his first book in 1840, *Étude sur les glaciers* (Gordon, 1995). He included a detailed atlas, several illustrations of the study site (Figure 3.29), and discussed glacier descriptions, the formation of massive ice sheets, and glacial movement observations at the time (Carozzi, 1966). Building upon Charpentier's theory describing that Alpine glaciation once extended towards the Aars and Rhône Rivers, Agassiz continued the idea that glaciers swept over all of southeastern Switzerland, reaching up to the Jura Mountains (Sidjak, 2010). The publication of this book was very influential, persuading Darwin and Lyell to shift their perspectives from their older theories (Hansen, 2017).

In 1840, Agassiz presented his Ice Age theory to the *British Association for the Advancement of Science* in Glasgow, Scotland (Irmscher, 2013). He explained that at a certain epoch, Northern Europe, America, and Asia were covered by a massive ice sheet, in which elephants and other mammalian fossils were preserved. At this conference, he met James D. Forbes, a physicist from Edinburgh, who stayed with Agassiz at the Hôtel in Unteraargletscher, setting out new flow markers (Clarke, 1987). Due to a falling out with Agassiz, Forbes published some of the findings and began his research on the Mer de Glace in France. He confirmed that the continuous motion of glaciers is variable in different parts, thus resulting in the formation of the viscous flow theory and affecting the central area most sensibly (Clarke, 1987).

The viscous flow theory motivated lab measurements for the deformational properties of ice and established a connection between glaciers and fluid mechanics, provoking glacier-flow measurements to estimate ice viscosity (Clarke, 1987). This led to further inquiry on whether the viscosity of glaciers was real or apparent, and if there is a presence of a property equivalent to viscosity. London physicist John Tyndall studied this predicament as he focused on the fundamental mechanisms of massive glaciers (Carozzi, 1966). One of Tyndall's well-known discoveries reported that the viscosity of ice is apparent, not real, and the property equivalent to it is "regulation"

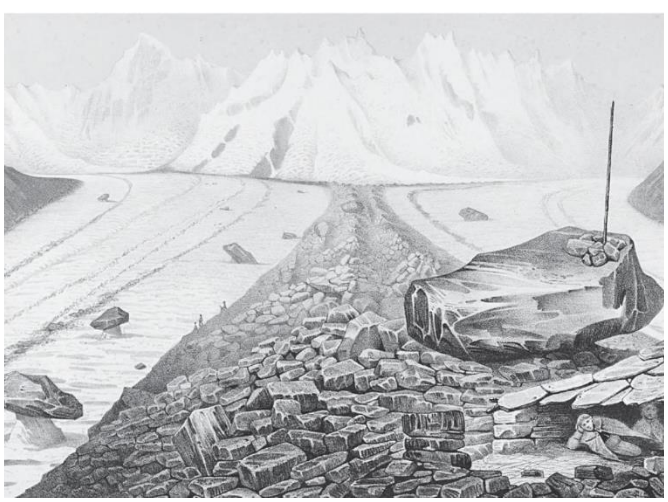

Figure 3.29: Moraine featuring glaciers on both sides, drawn and lithographed by Joseph Bettannier, in Agassiz's book Étude sur les glaciers. This illustration is significant as it displays the glaciers as well as the debris resulting from their movement.

(Clarke, 1987).

During the 1840s and 1850s, involved members in geologic research believed in the theories including icebergs rather than the theory of glaciers existing on what is now land (Hansen, 2017). However, by the 1870s and 1880s, the Ice Age theory started gaining popularity, and so it became recognised as the most accepted theory of the time (Hansen, 2017).

20th Century: Geophysical Research

The 20th century introduced an interdisciplinary approach to glaciology, inviting geology, physical geography, and physics into its realm of study. Incorporating these fields was essential in advancing methods of research and further applying the study of glaciers to paleoclimates. At this time, the technological progression of research on recent climate change was also attributed to anthropogenic activity (Clarke, 1987). Due to these factors, substantial changes to the field of glaciology were made.

Throughout the early 1900s, technology was advancing and could therefore be applied to research projects for more accurate and convenient data collection by the middle of the century. In the 1960s, glaciologists Peter Kasser and Hans Röethlisberger used aerial surveys to produce contour maps of the drainage basin of the Aletsch glacier (Kasser, 1963). The maps emphasized favourable glacier conditions, portrayed its extent, and recorded changes over time with repeated surveys (Kasser and Roethlisberger, 1996). At this time, aerial technology was considered quite advanced; however, there were many issues with capturing and analysing the data (Kasser, 1963). Maintaining accuracy was difficult since photogrammetric autographs could not locate pure white ice present on the edges of the glacier. To solve this issue, black control points were placed on the edges of the glacier to interpret images where the depth was difficult to perceive. Although there were issues with the aerial surveying process, the maps and data collected from this method helped understand the Aletsch glacier.

With implications of climate change emerging during this time, the melting of glaciers was discussed as a slow-moving indicator of global warming rates (Dyurgerov and Meier, 2000). It was found that as temperatures drop, the glacier meltwater flowed through tubular channels near the bed, producing frictional heat, enlarging the channel diameter and picking up sediment (Walder, 2010). Röthlisberger studied this system, specifically researching laws of watercourses within the glacier by applying physical theory in the 1960s (Röthlisberger, 1972). He proposed that the steady flow of water combined with the equilibrium of channel closure and melt rate produce the principles essential for calculating ice pressure within a channel. William Henry Mathews also investigated the drainage of ice-dammed channels and wrote a differential equation for water temperature as a function of distance, with the assumption that the water is warmed by friction and cooled by the loss of heat from the ice walls (Walder, 2010).

Physical Models on Glacier Flow

Although early 20th century models focused on ice as a highly viscous liquid, British physicist John Fredrick Nye's 1951 paper took an entirely different approach to its understanding. His experimentation showed that the properties of ice exhibited plasticity. This implied that glaciers and ice sheets would not move unless a stress was applied, thus altering the slope and how much the ice would shear (Nye, 1952). He also determined that this strain likely concentrated on the lower layers, which was useful in the context of temporal movement. From 1959-1963, he further advanced these theories, applying them to the impact of climate conditions on the flow of ice (Benn, Warren, and Mottram, 2007).

One of Nye's most prominent observations was his 1960 paper discussing seasonal and climatic changes modelled by glaciers (Oppenheimer, 1998). He noted that glaciers were a one-dimensional flow system, constantly advancing and retreating in response to climate conditions. Although it was established that glaciers were climate indicators, his work modelled the scaled spatial and temporal changes of glaciers (Nye, 1960). This also introduced new glacial measurement methods, including mapping details of the glacial layers and how they were situated using radio echoes sent from the bed. Since they would remain stagnant with the ice sheet moving over them, this was an important detail to map (Oppenheimer, 1998). Using mathematical modelling on flow and ice distribution, Nye made important advancements regarding the physical and geomorphological components of glaciers.

Historical perspectives on glacier research were pushed forward due to technological advances, techniques for measurement, and general interest. From its beginning as a subject of mythical thought, early scientists began to look into sedimentology and surrounding landscapes of glaciers to understand its processes. Theories on paleoclimates, such as those by Louis Agassiz, advanced glacier research into what we know today. The peak of research in the 19th century continued into 20th century thoughts, where technological models could advance mathematical, and geophysical mapping. Due to the conjunction of glacier and climate research, it was determined that glaciers affect monitoring climates, reconstructing landscapes, and impacting the deposition of sediments in glaciology.

Current Technology in Monitoring Glaciers

Based on our understanding of glaciers, it is easy to establish their importance as accurate indicators of paleoclimates, as they can provide evidence for the past conditions of landscapes and global climate. Recent scientific developments allow modelling of modern glaciers and a better understanding of processes that control their behaviour. In particular ice-dynamical modelling are satellite mapping techniques developing fields that have helped fill gaps of knowledge in glaciology, providing information on how glaciers evolve.

Ice-Dynamical Modelling

One of the most well-developed modelling approaches is Ice-Dynamical Glacier Evolution Studies (IDGES). These accurate models of the temporal evolution of glaciers account for the complex ice flow dynamics that were previously difficult to represent. Since ice flow is not a linear process, this creates the need for geometrically complex representations that can predict changes. Modelling with IDGES can be done on individual glaciers or on larger-scaled regions that measure changes over longer periods of time. IDGES can further be divided into flowline approaches or three-dimensional modelling technologies, which predict glacier trajectories of paleoclimates while providing an interpretation for the future of glacier research.

As a starting point for IDGES, flowline dynamics are essential for modelling glacial movement, giving information on the change in length of glaciers, the complex topography of glacier regions, or simple centreline modelling. One of the most essential inputs for current glacier models are glacier centrelines, where the flow dynamics can be interpreted. These are derived from taking the "least-cost route" which is derived from measurements of high and low elevation points on the glacier (Kienholz, et al., 2014). Flowline measurements also consider the mass balance of the glacier, which measures the relative accumulation and loss of ice on a spatial and temporal scale. This provides useful information on the mass transfer of glaciers, while giving insight into the physical processes that impact glacier movement and flow mechanics (Flowers, 2005). Using simplified approaches from the late 20th century, current mass balance measurements apply an understanding of energy balance and melting processes (Zekollari, et al., 2022). However, instead of only using linear measurements, flowline models have become integrated to include a multitude of different factors.

Three-dimensional modelling systems in IDGES account for stress balance in glaciers, along with higher-order ice-flow dynamics. This can be combined with flowline modelling to accurately represent changes on a temporal scale (Zekollari, et al., 2020). Three-dimensional modelling allows for small details to be represented, along with the measurement of debris cover changes and glacier calving. For example, the Open Global Glacier Model (OGGM) combines topographic datasets and glacier centerline identifications to accurately assess glacier dynamics (Maussion, et al., 2019). OGGM calculates glacier flow lines, which represent ice flow through a singular path. Additionally, taking measurements of ice thickness at the flow lines and the total calculated volume of the glacier can help model the estimated thickness of the entire glacier and predict changes over time (Zekollari, et al., 2020).

The usage of IDGES is restricted by two main factors: accessing extensive databases on a particular glacier or series of glaciers, and the large costs of computational modelling in research. Open databases provide information on bed topography and glacier flowlines, however, the measurement of some data required for the model may be difficult to access or collect in the field. As mentioned previously, the dynamic moment of glaciers does not occur in a linear model that is easily computed (Maussion, et al., 2019). Future studies in glacial research are likely to improve upon these methods to develop accurate estimations of aspects such as mass balance and ice thickness (Kienholz, et al., 2014).

Satellite-Based Technology

As climate change continues to be a topic of global concern, it is important to note that current modelling techniques focus on monitoring indicators of temperature change. Glacier movement and retreat are widely known to be related to climate change, which provides information on the future trajectories of sea level fluctuations, ice cover, and general landscapes on both a regional and global scale. This information can be assessed using satellite imaging, which provides crucial information in glacier research.

Currently, the satellite-based Interferometric Synthetic Aperture Radar (InSAR) technique is commonly used for imaging changes in surface movement over time (Simons and Rosen, 2007). InSAR images are created by computing the phase difference between two Synthetic Aperture Radar (SAR) images of the same area, and movement can therefore be evaluated by the phase changes (Pavelka, et al., 2019). SAR images are created by two or more satellites, emitting electromagnetic waves, and recording the returned energy to form an image (Osmanoğlu, et al., 2016). InSAR images are recognized for their large-scale coverage with unprecedented resolution, the ability to capture images during the night and during poor weather conditions, the ability to measure ground motion on Earth with an accuracy of less than a millimetre per year, and the many applications that it serves (Biggs and Wright, 2020). This technology has aided in understanding earthquake dynamics, anthropogenic influences on the environment, and glacier movement. For example, with InSAR images, scientists can monitor glacier movement (Figure 3.30), better predict how glaciers may change with global warming and how the water released from glaciers may contribute to sea level fluctuations (Gray, 2011).

InSAR imaging has aided in our understanding of periglacial environmental changes, glacier movement, and the effects of climate change on permafrost distribution (Zhang, et al., 2021). It has also altered previous understandings of glacier movement, as it can now be seen that the speed of glaciers of the polar ice sheets can change on a shorter time scale than previously anticipated (Gry, 2011). For example, rock glaciers have been extensively studied by Zhang, et al. (2021) using InSAR, as these structures influence the properties of runoff from mountain watersheds. These measurements have been used for mapping the permafrost zonation index and can be applied as indicators of periglacial environment changes. From the Zhang, et al. study, one of the main conclusions stated that InSAR data was determined to be significantly more efficient in comparison to field measurements for investigating active landslide deformation and glacier movement, due to the large spatial coverage, high resolution, and frequency of data acquisitions accomplished by this technique (Zhang, et al., 2021).

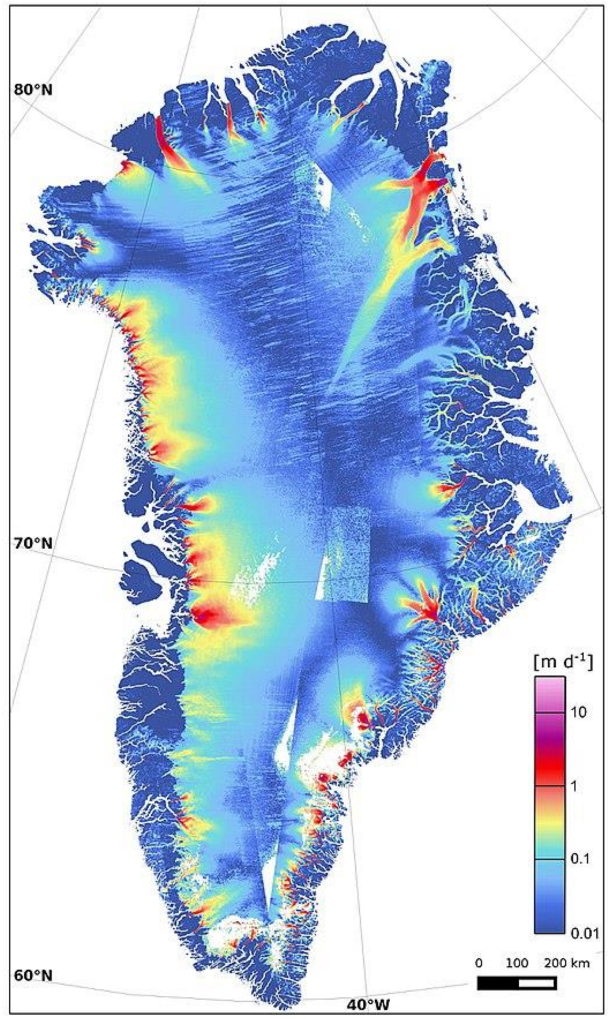

Figure 3.30: Map of Greenland ice sheet velocity over three months using Sentinel-1A SAR satellite images. The colour scale is in metres per day.

Technology plays a substantial role in understanding glacial processes and climate change. Glaciers continue to be an important factor in understanding past environments and how they have evolved over time. This makes the study of their processes a crucial part of fields in geology and glaciology. Modern technological methods such as InSAR and IDGES have advanced our understanding substantially through the ability to map complex ice mass changes and complex flow dynamics over a large spatial and temporal scale, which will continue to advance further as new models and techniques develop.

Chapter 3 References

Acolat, D., 2007. Comments on what the Romans knew about Alpine Landforms and Processes. Revue de géographie alpine, (95–3), pp.85–94.

Agassiz, L., 1840. Studies on Glaciers; preceded by the Discourse of Neuchâtel. Translated and introduced by Albert V. Carozzi, 1967. New York and London: Hafner.

Amin, A., Deriche, M., Qureshi, M.A. and Memon, K.H., 2019. New attributes for salt dome detection in 3D seismic data using higher order SVD. Journal of Applied Geophysics, 163, pp.108–116.

Ashphaq, M., Srivastava, P.K. and Mitra, D., 2021. Review of near-shore satellite derived bathymetry: Classification and account of five decades of coastal bathymetry research. Journal of Ocean Engineering and Science, 6(4), pp.340–359.

Batchelor, C.L., Margold, M., Krapp, M., Murton, D.K., Dalton, A.S., Gibbard, P.L., Stokes, C.R., Murton, J.B. and Manica, A., 2019. The configuration of Northern Hemisphere ice sheets through the Quaternary. Nature Communications, 10(1), p.3713.

Benioff, H. (1958) Contributions in geophysics in honor of Beno Gutenberg. London: Pergamon Press. Beno Gutenberg, 1959. Physics of the Earth's Interior.

Benn, D.I., Warren, C.R., and Mottram, R.H., 2007. Calving processes and the dynamics of calving glaciers. Earth-Science Reviews, 82(3–4), pp.143–179.

Bent, A.L. 2002. A revised moment magnitude catalog of Eastern Canada's largest earthquakes. [online] Available at: <https://publications.gc.ca/site/eng/9.915810/publication.html> [Accessed 1 December 2022].

Biggs, J. and Wright, T.J., 2020. How satellite InSAR has grown from opportunistic science to routine monitoring over the last decade. Nature Communications, 11(1), p.3863.

Boore, D.M., 1989. The Richter scale: its development and use for determining earthquake source parameters. Tectonophysics, 166(1), pp.1–14.

Bormann, P. and Di Giacomo, D., 2011. The moment magnitude Mw and the energy magnitude Me: common roots and differences. Journal of Seismology, 15(2), pp.411–427.

Bormann, P. and Saul, J., 2009. Earthquake Magnitude. In: R.A. Meyers, ed. Encyclopedia of Complexity and Systems Science. New York, NY: Springer. pp.2473–2496.

Bright, C., 1903. The story of the Atlantic cable. London: George Newnes Ltd.

Brush, S.G., 1979. Nineteenth-century debates about the inside of the Earth: Solid, liquid or gas? Annals of Science, 36(3), pp.225–254.

Bullard, E., Everett, J.E. and Gilbert Smith, A., 1965. The fit of the continents around the Atlantic. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 258(1088), pp.41–51.

Burchfield, J. (1990) Lord Kelvin and the Age of the Earth. Chicago and London: The University of Chicago Press.

Calder, B.R. and Mayer, L.A., 2003. Automatic processing of high-rate, high-density multibeam echosounder data. Geochemistry, Geophysics, Geosystems, 4(6), p.1048.

Carey, S.W., 1959. The Tectonic Approach to Continental Drift. Geology Department, University of Tasmania.

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

Carozzi, A.V., 1970. New historical data on the origin of the theory of continental drift. Geological Society of America bulletin, 81(1), pp.283–285.

Carpenter, D., Jeffreys, J.G. and Thomson, W., 1869. Preliminary Report of the Scientific Exploration of the Deep Sea in H.M.Surveying-Vessel 'Porcupine,' during the Summer of 1869. Proceedings of the Royal Society of London, 18, pp.397–492.

Casalbore, D., Di Traglia, F., Romagnoli, C., Favalli, M., Gracchi, T., Tacconi Stefanelli, C., Nolesini, T., Rossi, G., Del Soldato, M., Manzella, I., Cole, P., Casagli, N. and Chiocci, F.L., 2022. Integration of Remote Sensing and Offshore Geophysical Data for Monitoring the Short-Term Morphological Evolution of an Active Volcanic Flank: A Case Study from Stromboli Island. Remote Sensing, 14(18), p.4605.

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

Clarke, G.K.C., Jarosch, A.H., Anslow, F.S., Radić, V. and Menounos, B., 2015. Projected deglaciation of western Canada in the twenty-first century. Nature Geoscience, 8(5), pp.372–377.

Cordier, L., 1827. Essai sur la température de l'intérieur de la Terre. Paris: Annals des Mines.

Darwin, G.H., 1879. On the Bodily Tides of Viscous and Semi-Elastic Spheroids, and on the Ocean Tides upon a Yielding Nucleus. Philosophical Transactions of the Royal Society of London, 170, pp.1–35.

Davison, C. (1913) The Rev. Osmond Fisher. Nature (London), 93 (2334), 535–536.

Deane, J.C., 1865. Narrative of the Atlantic Telegraph expedition. Macmillan's magazine, 12.

Decker, J., Teas, P., Orange, D. and Bernard, B., 2021. Sea bottom characteristics and geochemistry of oil and gas seeps in the Gulf of Mexico. Interpretation, 10, pp.1–60.

deformation and strain-build up with acoustic direct-path ranging. Journal of Geodynamics, 124, pp.14–24.

Delaunay, C.-E., 1868. Notices of Memoirs: On the Internal Fluidity of the Earth. Geological Magazine, 5(53), pp.507–517.

Doel, R., Levin, T. and Marker, M., 2006. Extending modern cartography to the ocean depths: military patronage, Cold War priorities, and the Heezen–Tharp mapping project, 1952–1959. Journal of Historical Geography, 32, pp.605–626.

Domeier, M., Van der Voo, R. and Torsvik, T.H., 2012. Paleomagnetism and Pangea: The road to reconciliation. Tectonophysics, 514–517, pp.14–43.

Dörflinger, G., 2016. Günther, Siegmund. Heidelberg: Universitätsbibliothek Heidelberg.

du Toit, A., 1937. Our Wandering Continents: An Hypothesis of Continental Drifting. Edinburgh and

London: Oliver and Boyd.

Duck, F.A. and Thomas, A.M.K., 2022. Paul Langevin (1872-1946): The Father of Ultrasonics. Medical Physics International, 10(1).

Dyurgerov, M.B. and Meier, M.F., 2000. Twentieth century climate change: Evidence from small glaciers. Proceedings of the National Academy of Sciences, 97(4), pp.1406–1411.

Fairbridge, R.W., 1968. Drift, glacial; drift theory. In: Geomorphology, Encyclopedia of Earth Science. Dordrecht: Kluwer Academic Publishers. pp.291–292.

Fiedler, B., Hainzl, S., Zöller, G. and Holschneider, M., 2018. Detection of Gutenberg–Richter b-Value Changes in Earthquake Time Series. Bulletin of the Seismological Society of America, 108(5A), pp.2778–2787.

Field, C.W., 1868. Europe & America: reports of proceedings at an inauguration banquet. London, England, 10, March 1868. London: J. Causton.

Fields, S. and Johnston, M., 2010. The Law of Evolution: Darwin, Wallace, and the Survival of the Fittest. In: Genetic Twists of Fate. Cambridge, MA: MIT Press.

Fisher, O. (1889) Physics of the Earth's crust. 2nd ed. London: Macmillan and Co.

Flowers, G.E., 2005. Sensitivity of Vatnajökull ice cap hydrology and dynamics to climate warming over the next 2 centuries. Journal of Geophysical Research, 110(F2), p.F02011.

Forsyth, D. and Uyeda, S., 1975. On the Relative Importance of the Driving Forces of Plate Motion. Geophysical Journal International, 43(1), pp.163–200.

Frank, P., 1952. The Origin of the Separation between Science and Philosophy. Proceedings of the American Academy of Arts and Sciences, 80(2), pp.115–139.

Frankel, H.R. ed., 2012. Wegener and Taylor develop their theories of continental drift. In: The Continental Drift Controversy: Volume 1: Wegener and the Early Debate. Cambridge: Cambridge University Press. pp.38–80.

Gasperid, M. and Chierici, F., 1996. The Eotvos force revisited. Terra Nova, 8(4), pp.356–360.

geomorphology and seafloor processes in the remote southeast Indian Ocean. Marine Geology, 395, pp.301-319.

Gianni, G.M. and Navarrete, C.R., 2022. Catastrophic slab loss in southwestern Pangea preserved in the mantle and igneous record. Nature Communications, 13(1), p.698.

Glikson, A.Y., 1981. Uniformitarian Assumptions, Plate Tectonics, and the Precambrian Earth. In: Developments in Precambrian Geology. Elsevier. pp.91–104.

Golonka, J. and Ford, D., 2000. Pangean (Late Carboniferous–Middle Jurassic) paleoenvironment and lithofacies. Palaeogeography, Palaeoclimatology, Palaeoecology, 161(1), pp.1–34.

Gould, A.B., 1908. Louis Agassiz. Boston: Small, Maynard & Co.

Gray, L., 2011. Using multiple RADARSAT InSAR pairs to estimate a full three-dimensional solution for glacial ice movement. Geophysics Research Letters, 38(5).

Greene, M.T., 2016. Alfred Wegener: Science, Exploration, and the Theory of Continental Drift.

Arctic, Antarctic, and Alpine Research, 48(4), pp.767–769.

Grove, J.M., 2019. Little Ice Ages: Ancient and Modern. 2nd ed. Routledge. Milton Park, Abingdon Oxfordshire.

Gukeisen, T.B., 2005. The Operational Art of Blitzkrieg: Its Strengths and Weaknesses in Systems Perspective. Fort Belvoir, VA: Defense Technical Information Center.

Gupta, R.P., 2018. Introduction. In: R.P. Gupta, ed. Remote Sensing Geology. Berlin, Heidelberg: Springer. pp.1–11.

Gutenberg, B. (1959) Physics of the Earth's interior. New York: Academic Press.

Gutenberg, B., 1956. The energy of earthquakes. Quarterly Journal of the Geological Society, 112(1–4), pp.1–14.

Guyot, A., 1883. Memoir of Louis Agassiz, 1807-1873. C. S. Robinson &Company, Printers.

Guyot, A., 1883. Memoir of Louis Agassiz, 1807-1873. Princeton, N.J.: C. S. Robinson & Co., Printers.

Hambrey, M.J. and Alean, J., 2004. Glaciers. 2nd ed. New York, NY, USA: Cambridge University Press.

Hanks, T.C. and Kanamori, H., 1979. A moment magnitude scale. Journal of Geophysical Research: Solid Earth, 84(B5), pp.2348–2350.

Hansen, B., 2017. The Early History of Glacial Theory in British Geology. Journal of Glaciology, 9(55), pp.135–141.

Harris, P.T., Macmillan-Lawler, M., Rupp, J. and Baker, E.K., 2014. Geomorphology of the oceans. Marine Geology, 352, pp.4–24.

Hess, H.H., 1962. History of Ocean Basins. In: A.E.J. Engel, H.L. James and B.F. Leonard, eds. Petrologic Studies: A Volume to Honor A. F. Buddington. USA: Geological Society of America. pp.599–620.

Hey, R.N. and Wilson, D.S., 1982. Propagating rift explanation for the tectonic evolution of the northeast Pacific—the pseudomovie. Earth and Planetary Science Letters, 58(2), pp.167–184.

Hill, E., 1882. Fishers "Earth's Crust". Nature. 9 Mar. p.433-435.

Hock, R., 2005. Glacier melt: a review of processes and their modelling. Progress in Physical Geography: Earth and Environment, 29(3), pp.362–391.

Holmes, A., 1928. Theory of Continental Drift: a Symposium on the Origin and Movement of Land Masses, both Inter-Continental and Intra-Continental, as proposed by Alfred Wegener. Nature, 122(3073), pp.431–433.

Honsho, C. and Kido, M., 2017. Comprehensive Analysis of Traveltime Data Collected Through GPS-Acoustic Observation of Seafloor Crustal Movements. Journal of Geophysical Research: Solid Earth, 122(10), pp.8583–8599.

Hopkins, W., 1839. Researches in Physical Geology. Philosophical Transactions of the Royal Society of London, 129, pp.381–423.

Hopkins, W., 1840. Researches in Physical Geology—Second Series. Philosophical Transactions of the Royal Society of London, 130, pp.193–208.

Hopkins, W., 1842. Researches in Physical Geology—Third Series. Philosophical Transactions of the Royal Society of London, 132, pp.43–55.

Hough, S.E., 2007. Richter's Scale: Measure of an Earthquake, Measure of a Man. Princeton University Press.

Island. Science, 150(3695), pp.485–489.

Iyer, H.M., 1989. Seismic Tomography. Geophysics, Encyclopedia of Earth Science. Boston, MA: Springer US. pp.1133–1151.

Jewell, T.F., 1878. Deep Sea Sounding. The Papers and Proceedings of the U.S. Naval Institute. Annapolis, MA, June. Claremont, N.H.: The Claremont Manufacturing Company.

Johnston-Lavis, H.J., 1914. Obituary -Rev. Osmond Fisher. M.A., F.G.S. Vosges: Cambridge University Press.

JOIDES, 1967. Deep-Sea Drilling Project. The American Association of Petroleum Geologists Bulletin, 51(9), pp.1787-1802.

Joliot, F., 1951. Paul Langevin 1872-1946. Obituary Notices of Fellows of the Royal Society, 7, pp.405-419.

Kahan, W., 2014. How Blabber-Mouth German U-Boats got Themselves Sunk in World War II. University of California, Berkeley. Available through: <http://www.eecs.berkeley.edu/~wkahan/BlaUboat.pdf >

Kasser, P. and Roethlisberger, H., 1996. Some Problems of Glacier Mapping Experienced With the 1:10 000 Map of the Aletsch Glacier. Canadian Journal of Earth Sciences, 3(6), pp.799–809.

Kasser, P., 1963. Notes on the New Map of the Aletsch Glacier. International Association of Scientific Hydrology. Bulletin, 8(2), pp.113–114.

Kienholz, C., Rich, J.L., Arendt, A.A. and Hock, R., 2014. A new method for deriving glacier centerlines applied to glaciers in Alaska and northwest Canada. The Cryosphere, 8(2), pp.503–519.

Kimothi, S., Singh, R., Gehlot, A., Akram, S.V., Malik, P.K., Gupta, A. and Bilandi, N., 2022. Intelligent energy and ecosystem for real-time monitoring of glaciers. Computers and Electrical Engineering, 102, p.108163.

Kotlarski, S., Jacob, D., Podzun, R. and Paul, F., 2009. Representing glaciers in a regional climate model. Climate Dynamics, 34(1), p.27.

Kovarik, A.F., 1931. The Age of the Earth-Radioactivity Methods of its Determination. The Scientific Monthly, 32(4), pp.309–318.

Krüger, T., 2013. Discovering the Ice Ages: International Reception and Consequences for a Historical Understanding of Climate. Leiden: Brill.

Kukowski, N., 2014. Wadati-Benioff Zone. In: J. Harff, M. Meschede, S. Petersen and J. Thiede, eds. Encyclopedia of Marine Geosciences. Dordrecht: Springer Netherlands. pp.1–11.

L.A. Times Archives, 1985. Charles F. Richter Dies; Earthquake Scale Pioneer. [online] Los Angeles

Times. Available at: <https://www.latimes.com/archives/la-xpm-1985-10-01-mn-19126-story.html> [Accessed 1 December 2022].

Lambiel, C., Reynard, E., Corboz, P., Bardou, E., Payot, C. and Deslarzes, B., 2020. Reconstructing past flood events from geomorphological and historical data. The Giétro outburst flood in 1818. Journal of Maps, 16(2), pp.500–511.

Le Pichon, X., Sibuet, J.-C. and Francheteau, J., 1977. The fit of the continents around the North Atlantic Ocean. Tectonophysics, 38(3–4), pp.169–209.

Lehmann, I., 1936. Inge Lehmann's Paper: 'P" (1936). Classic Paper in the History of Geology, pp.82–114.

Levin, V., Shapiro, N., Park, J. and Ritzwoller, M., 2002. Seismic evidence for catastrophic slab loss beneath Kamchatka. Nature, 418(6899), pp.763–767.

Licht, A., van Cappelle, M., Abels, H.A., Ladant, J.-B., Trabucho-Alexandre, J., France-Lanord, C., Donnadieu, Y., Vandenberghe, J., Rigaudier, T., Lécuyer, C., Terry Jr, D., Adriaens, R., Boura, A., Guo, Z., Soe, A.N., Quade, J., Dupont-Nivet, G. and Jaeger, J.-J., 2014. Asian monsoons in a late Eocene greenhouse world. Nature, 513(7519), pp.501–506.

Lynch, R., Hollis, D., McBride, J., Arndt, N., Brenguier, F., Mordret, A., Boué, P., Beaupretre, S., Santaguida, F. and Chisolm, D., 2019. Passive Seismic Ambient Noise Surface Wave Tomography Applied to Two Exploration Targets in Ontario, Canada. ASEG Extended Abstracts, 2019(1), pp.1–3.

Mac Bride, E. W., 1939. The Wegener Theory. The Times, 10 Feb. p.10.

Macmillan-Lawler, M. and Sullivan, J., 2017. Malaysia Airlines flight MH370 search data reveal

Mallet, R., 1872. III. Volcanic energy: an attempt to develop its true origin and cosmical relations. p.84. London: Royal Society.

Marcou, J. ed., 2011. Life, Letters, and Works of Louis Agassiz. Cambridge: Cambridge University Press.

Martakis, N., Tselentis, A. and Paraskevopoulos, P., 2011. High Resolution Passive Seismic Tomography-a NEW Exploration Tool for Hydrocarbon Investigation, Recent Results from a Successful Case History in Albania. American Association of Petroleum Geologists.

Maury, M.F., 1856. In: The Physical Geography of the Sea, 1st ed. London: Sampson Low, Son, & Co. pp.240–265.

Maussion, F., Butenko, A., Champollion, N., Dusch, M., Eis, J., Fourteau, K., Gregor, P., Jarosch, A.H., Landmann, J., Oesterle, F., Recinos, B., Rothenpieler, T., Vlug, A., Wild, C.T. and Marzeion, B., 2019. The Open Global Glacier Model (OGGM) v1.1. Geoscientific Model Development, 12(3), pp.909–931.

Mayer, L., Jakobsson, M., Allen, G., Dorschel, B., Falconer, R., Ferrini, V., Lamarche, G., Snaith, H. and Weatherall, P., 2018. The Nippon Foundation—GEBCO Seabed 2030 Project: The Quest to See the World's Oceans Completely Mapped by 2030. Geosciences, 8(2), p.63.

Mayer, L.A., Theyer, F., Barron, J.A., Dunn, D.A., Handyside, T., Hills, S., Jarvis, I., Nagrini, C.A., Pisias, N.G., Pujos, A., Saito, T., Stout, P., Thomas, E., Weinreich, N. and Wilkens, R.H., 1985. Initial Reports of the Deep Sea Drilling Project, vol. 85. Washington: U.S. Government Printing Office. pp.1021.

Mazur, A., 2022. Ice Ages: Their Social and Natural History. Cambridge: Cambridge University Press.

Mereu, R.F., 2016. A Note on the Ratio of the Moment Magnitude Scale to Other Magnitude Scales: Theory and Applications. Seismological Research Letters, 88(1), pp.193–205.

Merritt, J.I., 1966. Hess's Geological Revolution. pp.273-77.

Milne, J., 1908. Seismology. 2nd ed. London: Kegan Paul, Trench, Trubner and Co.

Milner, A.M., Khamis, K., Battin, T.J., Brittain, J.E., Barrand, N.E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G.M., Jacobsen, D., Hannah, D.M., Hodson, A.J., Hood, E., Lencioni, V., Ólafsson, J.S., Robinson, C.T., Tranter, M. and Brown, L.E., 2017. Glacier shrinkage driving global changes in downstream systems. Proceedings of the National Academy of Sciences, 114(37), pp.9770–9778.

Mohorovicic, A., 1909. Earthquake of 8 October 1909. Translated from Croatian by D. Skoko., 1992. Zagreb: Andrika Mohorovicic Geophysical Institute.

NASA, 2022. Shuttle Radar Topography Mission. [online] Available at: <https://www2.jpl.nasa.gov/srtm/mission.htm> [Accessed 3 December 2022].

National Oceanic and Atmospheric Administration, 2022. Exploration Tools: Multibeam Sonar: NOAA Office of Ocean Exploration and Research. Available at: <https://oceanexplorer.noaa.gov/technology/sonar/multibeam.html>

Natural Resources Canada, 2021. 1883 Rossi-Forel Scale of Earthquake Intensity. [online] 1883 Rossi-Forel Scale of Earthquake Intensity. Available at: <https://earthquakescanada.nrcan.gc.ca/info-gen/scales-echelles/rossi-en.php> [Accessed 3 December 2022].

New York: Oxford University Press.

Newman, R.P., 1995. American Intransigence: The Rejection of Continental Drift in the Great Debates of the 1920's. Earth Sciences History, 14(1), pp.62–83.

Nye, J.F., 1952. The Mechanics of Glacier Flow. Journal of Glaciology, 2(12), pp.82–93.

Nye, J.F., 1960. The response of glaciers and icesheets to seasonal and climatic changes. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 256(1287), pp.559–584.

Okal, E.A., 2019. Energy and Magnitude: A Historical Perspective. Pure and Applied Geophysics, 176(9), pp.3815–3849.

Oppenheimer, M., 1998. Global warming and the stability of the West Antarctic Ice Sheet. Nature, 393(6683), pp.325–332.

Oreskes, N., 1999. The rejection of continental drift theory and method in American earth science.

Oreskes, N., 1999. The rejection of continental drift: theory and method in American earth science. New York: Oxford University Press.

Oreskes, N., 2003. Plate Tectonics: An Insider's History of the Modern Theory of the Earth. Boulder:

Ortelius, A., 1596. Thesaurus geographicus. Munich: (n.p.).

Osmanoğlu, B., Sunar, F., Wdowinski, S. and Cabral-Cano, E., 2016. Time series analysis of InSAR data: Methods and trends. ISPRS Journal of Photogrammetry and Remote Sensing, 115, pp.90–102.

P., C.D., 1895. The Rossi-Forel Scale of Earthquake Intensity. Publications of the Astronomical Society of the Pacific, 7(41), pp.123–125.

Pacific Northwest Seismic Network. 2022. Magnitude/Intensity. [online] Available at: <https://pnsn.org/outreach/about-earthquakes/magnitude-intensity> [Accessed 1 December 2022].

Painter, T.H., Flanner, M.G., Kaser, G., Marzeion, B., VanCuren, R.A. and Abdalati, W., 2013. End of the Little Ice Age in the Alps forced by industrial black carbon. Proceedings of the National Academy of Sciences, 110(38), pp.15216–15221.

Palupi, I.R., Raharjo, W. and Yulianto, G., 2020. Study of passive seismic tomography with various grid by using Matlab. Journal of Physics: Conference Series, 1568(1), p.012026.

Panchuk, K., 2019. Physical Geology, First University of Saskatchewan Edition. 1st ed. [online] University of Saskatchewan.

Pavelka, K., Šedina, J., Matoušková, E., Hlaváčová, I. and Korth, W., 2019. Examples of different techniques for glaciers motion monitoring using InSAR and RPAS. European Journal of Remote Sensing, 52(sup1), pp.219–232.

Pearce, D.M., Ely, J.C., Barr, I.D. and Boston, C.M., 2017. Glacier Reconstruction. In: Geomorphological Techniques. British Society for Geomorphology. pp.1–16.

Peduzzi, P., Herold, C. and Silverio, W., 2010. Assessing high altitude glacier thickness, volume and area changes using field, GIS and remote sensing techniques: the case of Nevado Coropuna (Peru). The Cryosphere, 4(3), pp.313–323.

Perkins, S., 2019. Seismic tomography uses earthquake waves to probe the inner Earth. Proceedings of the National Academy of Sciences, 116(33), pp.16159–16161.

Petersen, F., Kopp, H., Lange, D., Hannemann, K. and Urlaub, M., 2019. Measuring tectonic seafloor

Picard, K., Brooke, B., Harris, P., Siwabessy, P.J., Coffin, M., Tran, M., Spinoccia, M., Weales, J.,

Rawlinson, N., Pozgay, S. and Fishwick, S., 2010. Seismic tomography: A window into deep Earth. Physics of the Earth and Planetary Interiors, 178(3), pp.101–135.

Raymo, C., 1989. What is Science? The Boston Globe, 31 Jul., p.1.

Richter, C.F., 1935. An instrumental earthquake magnitude scale*. Bulletin of the Seismological Society of America, 25(1), pp.1–32.

Ritter, A., 1878. Untersuchungen über die Höhe der Atmosphäre und die Constitution gasförmiger Weltkörper. Annalen der Physik und Chemie, 241(12), pp.543–558.

Rizvi, Z.H., Akhtar, S.J., Haider, H., Follmann, J. and Wuttke, F., 2020. Estimation of seismic wave velocities of metamorphic rocks using artificial neural network. Materials Today: Proceedings, 26, pp.324–330.

Robert Perkins. 2022. Caltech's Seismo Lab Celebrates 100 Years at the Forefront of Earthquake Science. [online] California Institute of Technology. Available at: <https://www.Caltech.edu /about/news/Caltechs-seismo-lab-celebrates-100-years-at-the-forefront-of-earthquake-science> [Accessed 1 December 2022].

Roberts, J.M., Brown, C.J., Long, D. and Bates, C.R., 2005. Acoustic mapping using a multibeam echosounder reveals cold-water coral reefs and surrounding habitats. Coral Reefs, 24(4), pp.654–669.

Romm, J., 1994. A new forerunner for continental drift. Nature, 367(6462), pp.407–408.

Röthlisberger, H., 1972. Water Pressure in Intra- and Subglacial Channels. Journal of Glaciology, 11(62), pp.177–203.

Rozwadowski, H.M., 2005. Fathoming the Ocean: The Discovery and Exploration of the Deep Sea. Cambridge, MA: Harvard University Press.

Sagawa, T., Yamashita, Y., Okumura, T. and Yamanokuchi, T., 2019. Satellite Derived Bathymetry Using Machine Learning and Multi-Temporal Satellite Images. Remote Sensing, 11(10), p.1155.

Salencon, J., 2021. About Tresca's Memoirs on the Fluidity of Solids (1864-1870). Institut de France Académie des Sciences, 349(1), pp.1-7.

Sanger, C., 1970. Drilling in Atlantic produces evidence for revising Ice Age date. The Globe and Mail, 14 Aug. p.3.

Schwarzbach, M., 1907. Alfred Wegener: The Father of Continental Drift. Madison, WI: Science Tech

Shaffner, P.T., 1860. The North Atlantic Telegraph. Wiley Digital Archives: Royal Geographical Society (with IBG) - Part I, Journal Manuscripts.

Shaffner, P.T., McClintock, L.F., Young, A. and Tayler, W.J., 1860. The North Atlantic Telegraph Survey. Wiley Digital Archives: Royal Geographical Society (with IBG) - Part I, Journal Manuscripts.

Shor, E.N. and Sclater, J.G., 2010. Victor Vacquier (1907–2009). Eos, Transactions American Geophysical Union, 91(30), p.264.

Silliman, R., 1994. Agassiz Vs. Lyell: Authority in the Assessment of the Diluvium-Drift Problem by North American Geologists, with Particular Reference to Edward Hitchcock. Earth Sciences History, 13(2), pp.180–186.

Simons, M. and Rosen, P.A., 2007. Interferometric Synthetic Aperture Radar Geodesy. In: G. Schubert, ed. Treatise on Geophysics. Amsterdam: Elsevier. pp.391–446.

Smith, A.G. and Hallam, A., 1970. The Fit of the Southern Continents. Nature, 225(5228), pp.139–144.

Smith, C., 2007. Hopkins, William (1793–1866). Oxford Dictionary of National Biography.

Soloviev, Yu.Ya., 2010. 240th anniversary of the birth of Georges Cuvier (1769–1832). Paleontological Journal, 44(6), pp.708–712.

Speiss, F.N., Chadwell, C.D., Hildebrand, J.A., Young, L.E., Purcell Jr., G.H. and Dragert, H., 1998. Precise GPS/Acoustic positioning of seafloor reference points for tectonic studies. Physics of the Earth and Planetary Interiors, 108(2), pp.101–112.

Stampfli, G.M., Hochard, C., Vérard, C., Wilhem, C. and vonRaumer, J., 2013. The formation of Pangea. Tectonophysics, 593, pp.1–19.

Taylor & Francis Group.

The Nippon Foundation, 2022. The Nippon Foundation-GEBCO Seabed 2030 Project. The Nippon Foundation-GEBCO Seabed 2030 Project. Available at: <https://seabed2030.org/>

Thomson, W., 1862. On the Secular Cooling of the Earth. Transactions of the Royal Society of Edinburgh, 23(1), pp.157–169

Thomson, W., 1863. On the Rigidity of the Earth. London: Philosophical Transactions of the Royal Society of London.

Thomson, W., 1876. The Internal Condition of the Earth; as to Temperature, Fluidity, and Rigidity. Popular Lectures and Addresses: Cambridge Library Collection, pp.299–318.

Thurber, C. and Ritsema, J., 2015. 1.10 - Theory and Observations - Seismic Tomography and Inverse Methods. In: G. Schubert, ed. Treatise on Geophysics (Second Edition). Oxford: Elsevier. pp.307–337.

Torsvik, T.H., 2005. PALAEOMAGNETISM. In: R.C. Selley, L.R.M. Cocks and I.R. Plimer, eds. Encyclopedia of Geology. Oxford: Elsevier. pp.147–156.

Tselentis, A., Martakis, N., Paraskevopoulos, P. and Lois, A., 2011. High-resolution passive seismic tomography for 3D velocity, Poisson's ratio m, and P-wave quality QP in the Delvina hydrocarbon field, southern Albania.

Umbgrove, J. H. F., 1947. 2. The Pulse of the Earth. The Hauge: M. Mijhoff.

United States Geological Survey, 1905. The Modified Mercalli Intensity (MMI) Scale assigns intensities as: [online] Available at: <https://www.usgs.gov/media/images/modified-mercalli-intensity-mmi-scale-assigns-intensities> [Accessed 3 December 2022].

United States Geological Survey, n.d. Body waves inside the earth. [online] Available at: <https://earthquake.usgs.gov/earthquakes/events/1906calif/18april/earthwaves.php>.

University of Hawaii, n.d. Compare-Contrast-Connect: Seismic Waves and Determining Earth's Structure. [online] Available at: <https://manoa.hawaii.edu/exploringourfluidearth/node/1336#:~:text=P%20waves%20can%20travel%20through,resulting%20S%20and%20P%20waves.>.

US Department of Commerce, N.O. and A.A., 2022. Mapping the Gaps in Our Ocean Knowledge with Seabed 2030. Available at: <https://oceanservice.noaa.gov/news/jun22/seabed-2030.html>

USGS, 2019. Satellite-Derived Bathymetry | U.S. Geological Survey. Available at: <https://www.usgs.gov/special-topics/coastal-national-elevation-database-%28coned%29-applications-project/science/satellite>

Vacquier, Victor, 1989. Victor Vacquier - Section II. [Oral Interview], 24 January 1989 Available at: <https://www.aip.org/history-programs/niels-bohr-library/oral-histories/35305-2>.

Vestrum, R.W. and Cameron, G.H., 2022. Challenges in Seismic Imaging in Fold and Thrust Belts. In: GeoConvention, Calgary, Canada, 20-22 June 2022. Calgary: GeoConvention.

Vine, F.J. and Wilson, J.T., 1965. Magnetic Anomalies over a Young Oceanic Ridge off Vancouver

Walder, J.S., 2010. Röthlisberger channel theory: its origins and consequences. Journal of Glaciology, 56(200), pp.1079–1086.

Walper, J.L. and Rowett, C.L., 1972. Walper, J.L., Rowett, C.L., 1972 . Transactions of the Gulf Coast Association of Geological Societies 22, pp.105–116.

Wegener, A. 1915. The Origins of Continents and Oceans. New York: Dover Publications.

Wegener, A., 1915. Die Entstehung der Kontinente und Ozeane. 1st ed. Schweizerbart. Braunschweig: Vieweg & Sohn.

Wegener, A., 1929. Die Entstehung der Kontinente und Ozeane. Braunschweig: Vieweg & Sohn.

Woodward, J., 2014. The Ice Age: A Very Short Introduction. Oxford University Press. Oxford, England.

Wright, R.N., 2011. Chapter Eleven - Mechanical Properties of Wire and Related Testing. In: R.N. Wright, ed. Wire Technology. Oxford: Butterworth-Heinemann. pp.127–155.

Wu, L., Murphy, J.B., Quesada, C., Li, Z.-X., Waldron, J.W.F., Williams, S., Pisarevsky, S. and Collins, W.J., 2020. The amalgamation of Pangea: Paleomagnetic and geological observations revisited. GSA Bulletin, 133(3–4), pp.625–646.

Yeats, R.S., 2018. The Federal Government and Earthquakes.

Young, M.K., Tkalčić, H., Bodin, T. and Sambridge, M., 2013. Global P wave tomography of Earth's lowermost mantle from partition modeling. Journal of Geophysical Research: Solid Earth, 118(10), pp.5467–5486.

Zaroli, C., Lévêque, J.-J., Schuberth, B.S.A., Duputel, Z. and Nolet, G., 2014. Global S-wave tomography using receiver pairs: an alternative to get rid of earthquake mislocation. Geophysical Journal International, 199(2), pp.1043–1057.

Zekollari, H., Goelzer, H., Pattyn, F., Wouters, B. and Lhermitte, S., 2020. Towards a 3-D model for large-scale glacier simulations.

Zekollari, H., Huss, M., Farinotti, D. and Lhermitte, S., 2022. Ice-Dynamical Glacier Evolution Modeling—A Review. Reviews of Geophysics, 60(2).

Zhang, X., Feng, M., Zhang, H., Wang, C., Tang, Y., Xu, J., Yan, D. and Wang, C., 2021. Detecting Rock Glacier Displacement in the Central Himalayas Using Multi-Temporal InSAR. Remote Sensing, 13(23), p.4738.

Zhao, D., 2008. New advances of seismic tomography and its applications to subduction zones and earthquake fault zones: A review. Island Arc, 10(1), pp.68–84.

Zhao, D., 2019. Importance of later phases in seismic tomography. Physics of the Earth and Planetary Interiors, 296, p.106314.

Zhao, G., Wang, Y., Huang, B., Dong, Y., Li, S., Zhang, G. and Yu, 2018. Geological reconstructions of the East Asian blocks: From the breakup of Rodinia to the assembly of Pangea. Earth-Science Reviews, 186, pp.262–286.

Zhao, X. and Coe, R.S., 1987. Palaeomagnetic constraints on the collision and rotation of North and South China. Nature, 327(6118), pp.141–144.

Zheng, Y.-F., Xiao, W.-J. and Zhao, G., 2013. Introduction to tectonics of China. Gondwana Research, 23(4), pp.1189–1206.

Zhu, T., Cheadle, S., Petrella, A. and Gray, S., 2000. First-arrival tomography: Method and application | SEG Technical Program Expanded Abstracts 2000. SEG Technical Program Expanded Abstracts.

Zimmerman, D., 2002. Paul Langevin and the Discovery of Active Sonar or Asdic. The Northern Mariner, 12(1), pp.39-52.

Chapter 3 Image References

Figure 3.1: Map of the idealized Pangaea-A ("Wegenerian") configuration. Iberian-Appalachian connection is the missing link between Gondwana and Laurasia that confirms a Wegenerian Pangaea configuration, Pedro Correia & J. Brendan Murphy, 2020. CC BY - NC

Figure 3.2: Photograph of Professor Alfred Lothar Wegener. Wikimedia Commons. 1924-1930

Figure 3.3: Maps of the world published in Alfred Wegener's fourth edition of Die Entstehung der Kontinente und Ozeane. Die Entstehung der Kontinente und Ozeane Fourth Edition, Alfred Wegener, 1929.

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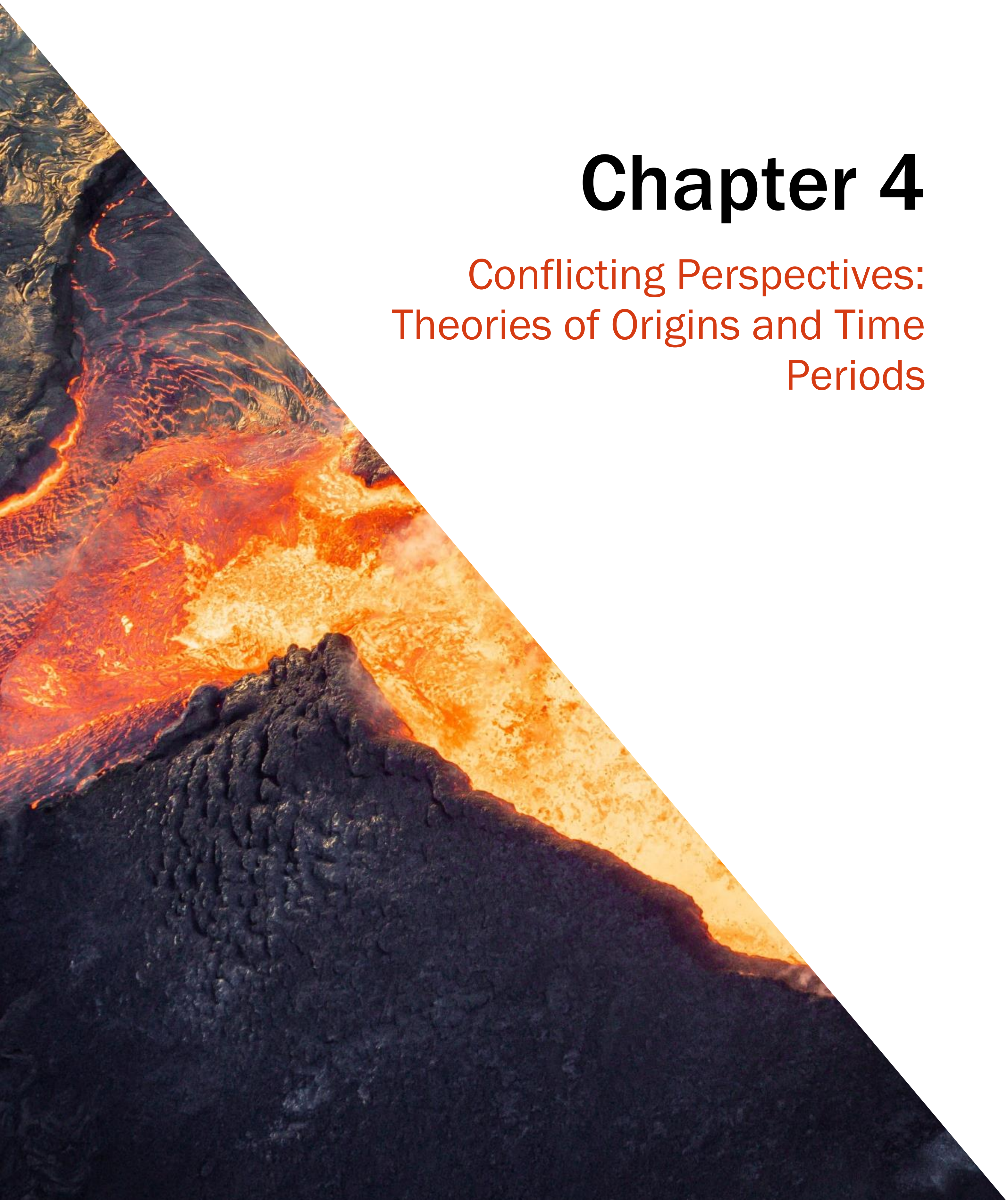
Chapter 4

Conflicting Perspectives: Theories of Origins and Time Periods



Introduction

There are some questions about the history of the Earth that have been the subject of numerous debates and controversies since the dawn of scientific thought. Questioning and critiquing theories forms the basis of science. However, these scientific debates have undermined emerging evidence and allowed widespread ideologies to prevail over newer theories that held merit. At the same time, numerous diverse belief systems, including those governed by religion, played important roles in defining the ways in which the history of the Earth has been and continues to be studied.

Conflicting theories and ideologies have clashed countless times as different groups fought to convince the world of the truths they believed. The theories surrounding the Earth's origin, the nature of the earliest fossils, and the formation of rock types on its surface have been the basis of extensive debate. Historical thinkers have looked to different sources for their theories, with some being faith-based, others being empirically based, and some consulting both in combination. For many groups, it was important to seek explanations that aligned with their beliefs, and as new scientific evidence emerged, the quest to discover Earth's past was further complicated. Long held beliefs were challenged by those who dared to think differently, while opposing theories were maintained by those with just as strong will and reasoning for their points. Many theories which were initially perceived with immense skepticism later became well accepted. When controversies remained heated for a long time, an agreement regarding Earth's history could only be reached years after the main theorists involved had passed.

The stories of how these theories developed, morphed, and evolved is of great interest for present studies. In Chapter 4, we compare our modern knowledge to the knowledge of our predecessors and appreciate how our theories and theirs may converge or diverge. The skills of inquiry they developed serve as an example towards how we can apply the scientific method to new discoveries in the future. If there is one thing to be learned from all the controversy in the study of Earth's history, it is that questioning beliefs and daring to present new ideas is a valid pursuit.

Evolving Theories of Earth’s Origin

Throughout the course of history, the origins of Earth have long been a perplexing subject that has sparked controversial debates between scholars and commoners alike. As such, society has persistently pursued developments in diverse geologic concepts and principles. However, the history of geological thought and our understanding of Earth’s origins have fluctuated dramatically between varying perspectives, such as the idea of natural processes or the belief in creationism. Perhaps one of the most influential eras that catalysed a new wave of geological thinking was the 14th to 17th century Renaissance period. Nevertheless, it is necessary to recognize the perspectives of earlier scholars, whilst discussing the scientific revolution of this era.

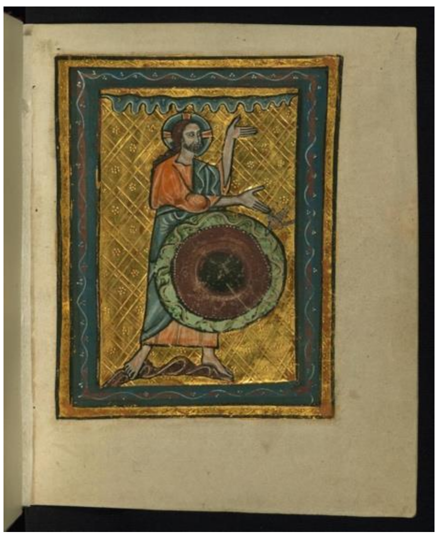


Figure 4.1: The first two days of creation as depicted in Genesis 1:1-8. *The artist and scribe, William de Brailes, created this folio during the mid-13th century as a part of a collection of Bible pictures.*

Contrasting Views on Early Earth

Creation stories detailing the origin of the Earth date back to the many ancient civilizations that prevailed before modern society. As with most ideas in a pre-scientific world, many recorded thoughts or ideas were fragmented and relied on a theistic approach. As humanity evolved, there is evidence of scholars considering evolution rather than blindly believing in the existence of deities (Roux, 2005). This detail is important as this perspective of thinking develops into a key characteristic of scientists in the Renaissance period. Often thought to have originated with ancient Greek philosophers, early scientists developed a process of theoretical science (Leroi, 2014). This method was highly dependent on making observations of the world. Furthermore, there was a conjoined effort to provide naturalist reasoning for how creatures developed and adapted to their environment. Scholars began making deductions without relying on religious and mythical interpretations involving a higher being (Roux, 2005). Some of the first philosophers that demonstrated evolutionary thought were Anaximander (611-547 BCE), who proposed that humans evolved from fish, and Empedocles (492-432 BCE) who posited that the evolution of organic life occurred in a four-stage cycle (Weller, 1960). At this time, early Greek philosophers believed the world of organisms was organised with intent and design (Ruse, 2011). Another prominent perspective on Earth’s origin pertained to the religious faith of creationism. While still prominent today, in the past, creationism was known to be a set of beliefs centred around the concept that the universe, Earth, and life were formed by a higher power through divine creation (Scott, 1997). The origin of this ideology began in 27-30 CE, which saw the rise of the ministry of Jesus and the new religion of early Christians (Grant, 1933). The main principles of creationism revolve around religious creation stories, such as the Bible’s Genesis, in which the story’s narrative was taken as a direct interpretation of Earth’s origin (Figure 4.1). Following 30 CE, it was believed that the process of Earth’s formation occurred through creation acts over six days (Strauss, 1981). As creationism evolved, many subtypes delineated from each other, producing groups that were similar in biblical basis, but each had slight variations. In the following centuries, such groups remained prominent and maintained deeply rooted intentions to reject evolutionary theory, unlike the early Greek scholars who strived to understand evolution.

External Influences on Eurocentric Beliefs

To understand how perspectives on the origins of Earth shifted, it is important to consider the socio-political influences at the time. Following the fall of the Macedonian empire in the fourth century BC, Greek thought and influence dwindled as Christianity spread west. The loss of Greek and Roman text signified the beginning of the Middle Ages, as well as a “dark age” for European sciences. While Europe lost its connection to Greek literature, the Church became a powerful institution, influencing European scholars and the general public to reject ideas that did not conform to religious beliefs (Rather and Kanth, 2018). There was a clear distinction of authority between clergies, the religious officials, and laity, the people of religious faith (Macy, 1996). However, in contrast to European scholars who experienced stunted scientific discovery, Muslim philosophers continued to study Greek thought. Most notably, a Persian physician known as Ibn Sina (981-1037 CE) combined Aristotelian philosophies with creationism, believing in not only the existence of a higher power, but also that Earth was shaped by natural processes (Weller, 1960; Nomozov, 2022). His ground-breaking encyclopaedia, *Kitab Al-Shifa* (the Book of Healing), contained complex concepts such as the formations of mountains and minerals, knowledge of the diversity of Earth's terrain, and the origins of earthquakes (Al-Rawi, 2002). In a significant contribution to the field of earth sciences, Ibn Sina discovered the law of sequential occurrence of sedimentary rocks. This concept was also understood by the Italian polymath, Leonardo da Vinci (1452-1519). However this was only later solidified as the law of superposition of strata by the Danish scientist Nicolas Steno (1638-1686) (Nomozov, 2022). Similarly, Ibn Sina's book proposed the initial concepts of catastrophism and uniformitarianism, which were later thoroughly investigated by Georges Cuvier (1769-1832) and James Hutton (1726-1797). Ultimately, in a time when the Church and religion dominated science, Muslim scholars continued to explore geography with a Greek perspective of inquiry, laying foundations for the Renaissance to flourish.

The Renaissance: Rebirth of Secular Science

Following the Middle Ages, scholars of the Renaissance period were eager to begin discovering cultures, art, political views and sciences again. Despite the gripping influences of the Church in this era, scholars sought to challenge the principles of the Bible and revive Greek science and literature (Hall, 1994). As such, the Renaissance pursued, improved and recreated accurate translations of past work, bringing about many sub-movements with different points of view. One of the most influential intellectual themes was known as the Humanist movement. Beginning in the early 14th century, it placed heavy emphasis on classical studies and created the foundation of many new philosophies, theologies, and sciences (Kristeller, 1978). The concept that humans have the right to shape and give meaning to their lives was a central ideology of the humanist movement. More importantly, in comparison to the deep biblical beliefs of the Church, this notion was non-theistic (Copson, 2015). Additionally, the rediscovery of many classical pieces of distinguished literature during the Renaissance impacted how earth science was perceived. One illustrative example is the rediscovery of the written piece, *Geography*, by the Greek mathematician Claudius Ptolemy (100-170 CE) (Figure 4.2). His gazetteer not only described early ideas of scientific cartography, but presented the latitude and longitude system, and included detailed topography of Europe, Africa, and Asia at the time (Berggren, Jones and Ptolemy, 2000). Overall, the Renaissance period's fixation on classical literature encouraged scholars to become analytical of what was written in the Bible and develop new, monumental views on Earth's origin.

Figure 4.2: Ptolemy's Geography, *rediscovered by scholars of the Renaissance, was* a *gazetteer which contained some of the first maps of the world. It was the first use of longitudinal and latitudinal lines, revolutionising the field of cartography.*

In addition to analysing and interpreting previous theories, a lasting impact on geology was the development of artistic movements. Although this period of history had many subsections, its art is often defined by a shift in interest toward realism (Schroeder and Borgerson, 2002). Renaissance realism led to the understanding that form and position were relative and not absolute, forming the basis of single-, two-, and three-point linear perspectives (Ermarth, 1981; Erskine-Hill, 2004). As well, vanishing points and horizon lines proved to be significant qualities of art that influenced the work of Leonardo da Vinci (1452-1519). As an artist, he sought to improve the quality of his realistic paintings, but he was also an avid learner who pursued other interests such as the natural sciences. It is fair to say that da Vinci's explorations lead him to interpret the sedimentary origin of strata that coincidentally contained trace fossils. In combination with his artistry, da Vinci recognized geometric perspective and created some of the world's first scaled, proportionate, and 3-dimensional illustrations of Earth's geology (Rosenberg, 2001). Most famously, da Vinci's earliest known work is his drawing of the *Hills of Tuscany*, which correctly illustrates how horizontal strata gave structure to the countryside (Figure 4.3). He also accurately depicts laterally continuous strata in a sequence; thin-bedded at the bottom and thicker beds towards the middle and surface (Rosenberg, 2000). Da Vinci's painting also noted sandstone with wavy, blue and brown bedded laminations, describing what was later discovered to be turbidites (Vai, 2021). Consequently, the advancement of realistic scientific illustrations was a powerful tool that continued to be improved upon in the later years of geologic thought.

Figure 4.3: Created in 1417, The Hills of Tuscany *regarded as Leonardo da Vinci's earliest known work. It is widely considered one of the first accurate portrayals of geometric perspective, utilising two vanishing points and a horizon.*

The Renaissance: Eccentric Ideas

Over time, European scientists who studied works from classical antiquity began hypothesising and improving on previously postulated theories. With a particular interest in the origins of the Earth's surface, Nicholas Steno (1638-1686) was one of the first to apply natural history to create conceptual ideas that explained the formation of geologic structures of Earth (Guntau, 1989). In 1669, Steno published his book, *Prodromus*, wherein he detailed three principles of geology; superposition, original horizontality, and lateral continuity (Rosenberg, 2001). Using geology to study various eras of Earth's history was first introduced through these concepts. By extension, this provided more evidence to prove that Earth had an extensive origin and existed for longer than 6000 years, as proposed by biblical theories. Despite founding the study of geology, Steno had a deep Christian faith. Since he observed how biblical interpretations vary from region and time, his philosophy of science made a distinction between scientific research and religious arguments (Hansen, 2009).

Moreover, the transition from the High Middle Ages to the early Renaissance served as a period of exposure, introducing Arabic and Middle Eastern literature to Europeans. There was an effort made by many scholars in the Byzantine empire to translate literature from Arabic to Latin (Weller, 1960; Mavroudi, 2015). Thus, the principle of uniformitarianism proposed by James Hutton (1726-1797) would cumulatively apply foundational knowledge from Ibn Sina, da Vinci and Steno. This principle proposed that geologic forces and processes that shaped the Earth in the past are consistent with those still in operation. As a result, Hutton argued igneous processes had a significant impact on the formations of rocks on Earth. This principle supported evidence that the Earth had existed for a long time and allowed for slow processes to act, producing the geologic structures observed today (Bushman, 1983). However, due to conflict with biblical chronology, uniformitarianism was largely overshadowed by catastrophism - the other prevailing principle at the time (Koutsoukos, 2005). Hutton did not discredit the ideas of catastrophism, but he believed changes must be made in accordance with the laws of nature (Bushman, 1983). Despite initial criticism, uniformitarianism eventually became the most accepted philosophy of geologists. By the 18th-19th century, scholars reinforced the idea of deep time and that the Earth had an extensive history (Stern and Gerya, 2021).

Early Developments of Seismology

Entering the 19th century, natural phenomena such as major earthquakes became frequent occurrences, which drove scientific discovery towards understanding the inner Earth. The perception of Earth's interior was still largely unknown and in its infancy. Although earthquakes have wreaked havoc on this planet for centuries, the lack of resources and knowledge on Earth's inner components prevented earlier scholars from deducing any conclusive interpretations. The Lisbon earthquake of 1755 may have been the first major event that piqued the curiosity of scientists as a display of powerful distant motion at large distances (Lee, International Association of Seismology and Physics of the Earth's Interior and International Association for Earthquake Engineering, 2002). However, the first recording of a distant earthquake took place almost two centuries later in 1889. While situated in Germany, Ernst von Rebeur-Paschwitz (1861-1895) was able to record an earthquake in Japan, creating the first remote seismogram (Figure 4.4). This motivated an international effort to create seismological observatory alliances throughout Europe (Rose, 2022). Coincidentally, the study of modern seismology continued to thrive during the 1868 Meiji restoration in Japan, a region with intense seismicity (Lee, International Association of Seismology and Physics of the Earth's Interior and International Association for Earthquake Engineering, 2002). The East Asian country began bringing foreign professionals to find solutions to their natural disasters. One of these experts was known as John Milne (1850-1913), who championed the study of earthquakes and became recognized as a founder of modern seismology (Davison, 1921). He later developed the first prototype of the modern seismograph with help from his Japanese colleagues, cementing the study of earthquakes and seismicity as a modern science (Ben-Menahem, 1995).

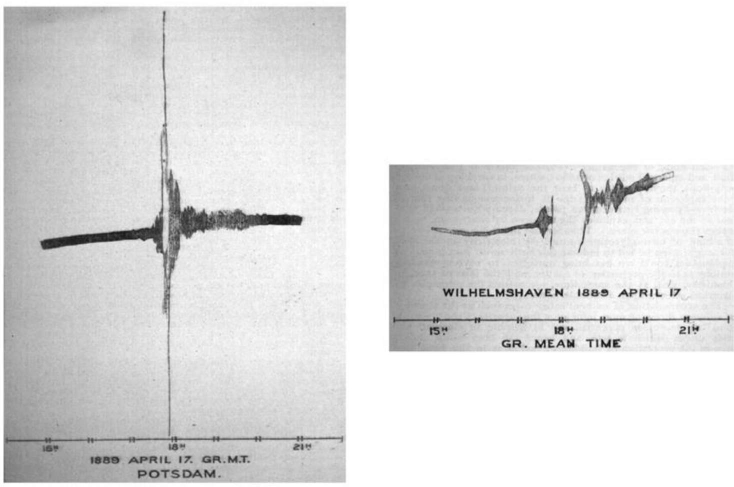


Figure 4.4: The first remote seismograms recorded by Ernst von Rebeur-Paschwitz in 1889. While situated in Potsdam and Wilheimshaven, Germany, he recorded an earthquake that occurred in Japan.

Another impactful geoscientist of the 19th century was known as Andrija Mohorovičić (1857-1936), a Croatian physicist best known for the Mohorovičić discontinuity (The Editors of Encyclopaedia Britannica, 2022). His interest in earthquakes was first piqued when a Kupa valley earthquake struck his home country Croatia. Luckily, at this time, seismological stations inspired by Rebeur-Pacshwitz's first seismogram had already been established over Europe (Rose, 2022). Using collected data from these stations and his knowledge of geophysics, Mohorovičić examined seismic waves. Mohorovičić noticed two P-waves and S-waves at distances between 300 km and 720 km (Prodehl et al., 2013). With this knowledge, he suggested a discontinuity with a velocity jump from 5.68 to 7.75 km/s, at a depth he calculated of 54 km (Cook, et al., 2010). He claimed that since P-waves can only go down 50 km, this depth represents the upper layer of the Earth, the Earth's crust (Cook, et al., 2010). Consequently, because of the shift in seismic wave velocity at this surface, he concluded that the Earth's interior must be made of a different material than the Earth's crust (Prodehl, et al., 2013). Soon after, this crust-mantle barrier was named the Mohorovičić discontinuity (Moho), which came to be known as the surface separating the felsic crust of the Earth from its mafic mantle. The discontinuity is predicted to have an average velocity of 6.0-6.8 km/s from the uppermost mantle (Prodehl et al., 2013). After this remarkable feat, Mohorovičić's theories were only fully understood years after investigating deep-focus earthquakes, locating the earthquakes epicentre, seismographs, Earth models, and other related fields of geoscience (Prodehl, et al., 2013).

Throughout history, many brilliant minds have theorized about the origins of Earth. The impact of the Renaissance, a period of social reform and discovery, revealed that scientific perspective often reflected changes in society. Advancements in art and geometry further aided the establishment of geology as modern science. As with other evolving disciplines, scholars of geologic thought actively developed new concepts while challenging prior notions, despite the powerful influence of religion. Early geoscientists built the basis for modern society's understanding of both surficial processes and the components of Earth's core. Furthermore, after Mohorovičić's monumental discoveries, a new wave of geoscientists was galvanized, developing the study of seismology in various parts of the now-modern world. In 1936, the inner core of Earth was thought to be the same temperature as the Sun's surface and to be made of iron and nickel (Rafferty, 2022). Observations of travel times, reflections, refractions, and phase transitions of seismic body waves provided almost all information currently available on the structure of the Earth's deep interior (McSaveney, 2006). Advancing geoscientists understood that P-waves travel through the fluid layers of the Earth's interior, and are slightly refracted as they cross the boundary between the semisolid mantle and the liquid outer core (Rafferty, 2022). However, a significantly new model of Earth would soon be proposed by a Danish seismologist and geophysicist, Inge Lehmann (Rafferty, 2022). As the chief of the seismological department of the Danish Geodetic Institute, Lehmann's work would place her at an epicentral distance from large earthquakes in the South Pacific (Bolt, 1994). Along with advances in seismology, Lehmann was particular and exact with her research, pinpointing the necessary details to propose a two-shell Earth model (Kölbl-Ebert, 2001). She arrived at such conclusions by examining the 1929 Murchison earthquake. With an estimated magnitude of 7.3, New Plymouth – located more than 250 kilometres away, could hear its rumbling. Applying her extensive seismic knowledge, in 1936, Lehmann proposed that the Earth had a solid inner core with a radius of approximately 1220 kilometres, inside of a molten outer core (Rafferty, 2022).

Nonetheless, modern seismic technology will continue to progress, expanding on our knowledge of unmapped features under the Earth's surface.

Contemporary Explorations of Earth's Interior

With the phenomenal discoveries of our precursors, seismic technology has continued to develop in the late 20th century. In particular, Keita Aka advanced an imaging technique known as seismic tomography, which uses seismic data to make computer-generated, two and three-dimensional images of the Earth's interior (Rawlinson, Pozgay and Fishwick, 2010). These images help geologists better understand plate tectonics/continental drift and mantle convection (Rawlinson, Pozgay and Fishwick, 2010). With current technology, there are two applications of these images in the studies of subduction slabs and large low-shear velocity provinces (LLSVPs) in the Earth's mantle. There are several different types of subducting slabs in the mantle as we know it. While some are stagnated in the transition zone, like beneath the Izu-Bonin region, South-Kuril and Japan, others seem to penetrate the lower mantle, like beneath Peru, the Marianas, and Central America (Agrusta, Goes and van Hunen, 2017). A study published in 2018 by Spakman, et al., shows a slab subducting east, 700 km beneath the Mediterranean Sea, between Africa and Spain (Spakman, et al., 2018). As the slab subducts east, it is also being pushed north by Africa. This complicated subduction zone creates regional fault patterns closer to the surface, which may help geologists determine which faults are active and more likely to cause earthquakes in the future (Spakman, et al., 2018). It also explains the "enigmatic tectonic evolution of the western Mediterranean region, such as the closure of the Moroccan marine gateway before the Messinian salinity crisis and the ongoing shortening and crustal thickening of the Moroccan Rif" (Spakman, et al., 2018).

Secondly, shear seismic tomography reveals two LLSVPS, otherwise known as superplumes, with lower-than-average seismic wave speeds in the lower mantle beneath Africa and the Pacific (Figure 4.5) (Davaille and Romanowicz, 2020). Together, they cover approximately 25% of the surface of the core-mantle boundary (Davaille and Romanowicz, 2020). It is crucial to understand how these LLSVPS differ from other parts of the mantle since this could affect how quickly heat conduction occurs. This ultimately means that areas of the core covered by LLSVPS may lose heat at a different rate than those without them (Davaille and Romanowicz, 2020). Understanding this process is important as the variation in the rate at which heat leaves the core can affect the motion of the lower mantle and outer core (Davaille and

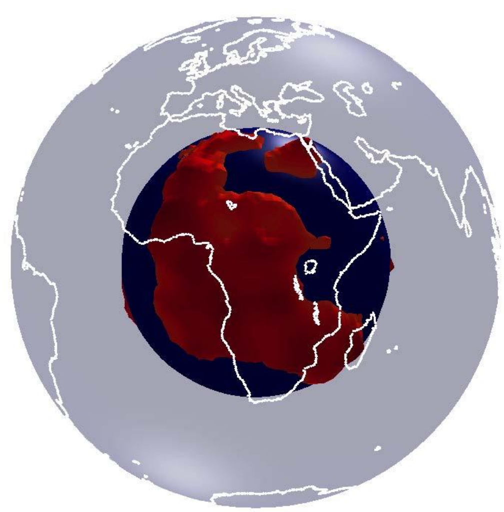


Figure 4.5: An illustration of the African LLSVP (shown in red), sitting above the Earth's core (shown in blue).

Romanowicz, 2020). While the motion of the outer core is responsible for creating the earth's magnetic field which protects us from cosmic radiation, the motion of the lower mantle has direct effects on volcanoes and continental uplift (Davaille and Romanowicz, 2020). Through shear seismic tomography, geologists can determine the location of these blooms. The near future holds even more improvements in geoseismic technology, increasing our ability to determine the origin of LLSVPs. A more holistic understanding will ultimately help geologists better recognize global mantle convection, chemical and heat transport, and geologic evolution over time.

Radiometric Dating

Though in the modern study of geology, the most commonly thought of field often includes the structures and processes that occur on the surface of the Earth, explorations of the Earth's interior are equally as important to understand our home planet. Since the discovery of radiometric dating in 1905, new methods have been designed to determine the age of the Earth, and calculate the age of fossils and/or rocks (Heilbron, 2003). Advancements in this technology have led to developments in mass spectrometry, specifically thermal ionization mass spectrometry and inductively coupled plasma mass spectrometry (ICP-MS) (Kinny, 2003). These techniques can be applied in geoscience work to locate zircon, which is roughly 4.3 million years old. Zircon is formed in carbonate-rich igneous rocks, pegmatites, and limestones that have undergone hydrothermal metamorphism (Figure 4.6) (McCall, 2005)) Determining the age of zircon is beneficial as it is commonly found in the Earth's crust. Due to its initial formation through the crystallization of magma or metamorphic rocks, zircon is very durable (McCall, 2005). Furthermore, studies examining the Hf isotopic ratios of megacrystic zircons offer information into the composition and evolution of the Earth's mantle, without fear of crystal contamination (Kinny, 2003). Additionally, prehistoric streams indicate homogenous oxygen isotope ratios in Earth's mantle and the presence of zirconium silicate crystals (Shige Abe, 2001). This evidence suggests that shortly after Earth formed approximately 4.3 billion years ago, the planet had continents, water, and possibly oceans and an environment suitable for life (Shige Abe, 2001). Ultimately, this implies that the Earth existed for much longer than 6000 years.

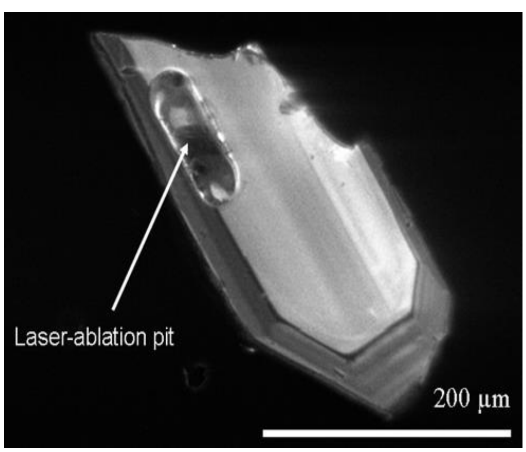


Figure 4.6: A laser ablation pit on a grain of zircon. To identify rare earth elements, laser ablation-inductively coupled plasma-mass spectrometry is used.

To better understand how the Earth's mantle reservoirs formed and have changed since their origin, it is important to determine the geochemical makeup of the planet's lower silicate mantle. Understanding the evolution of Earth's hydrosphere and atmosphere requires geologists to further determine the makeup of mantle plumes. A study published in 2016 by Hastie, et al., used thermal ionization mass spectrometry to look at traces of Sr-Nd-Pd-Hf isotope data on basalts from Curacao, a Dutch island in the southern Caribbean (Hastie, et al., 2016). More specifically, this technique was applied to determine the composition of the primary mantle plumes in the Caribbean Oceanic Plateau and Ontong Java Plateau (Hastie, et al., 2016). Isotopic ratios were determined using an inductively-coupled plasma optical emission spectrometer and ICP-MS. Hastie, et al., findings prove that the Earth's mantle is made of many different veins, blobs, and streaks, overall forming a complex mosaic (Hastie, et al., 2016). This study gives new information on major, trace, and radiogenic isotopes for the primary oceanic plateau lavas from Curaçao (Hastie, et al., 2016). This study also demonstrates the possibility to determine the composition of Earth's interior and the evolution of the lower mantle over geological time from the formation of these primary magma and mantle plume reservoirs (Hastie, et al., 2016). As modern geologists work towards determining lower mantle processes, new technology will continue to aid our creation of updated geochemical models. The future holds endless potential for young geoscientists and it is safe to say science will continue to probe the question of how Earth originated for years to come.

Shaping Earth: Religion and Science

The Earth has been humanity's home for over a million years. As such, many questions and theories regarding the Earth's origins, shape, and composition have arisen. Particularly, the Earth's shape has been a topic of much debate. Modern understanding of our Earth has firmly asserted it to possess an ellipsoid shape. This is a result of mathematical and scientific reasoning,

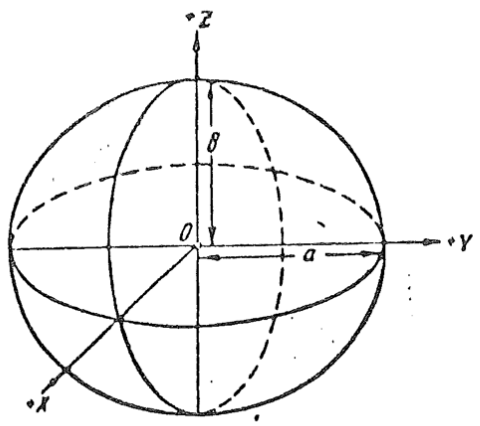


Figure 4.7: A Geometric representation of an ellipsoidal Earth. The three planes (x, y, and z,) and spherical coordinates are used to demonstrate the 3 dimensional nature of the representation. This is the modern and most accurate understanding of the Earth's shape.

which uses geometric representations to accurately depict the Earth's shape (Figure 4.7).

However, scientists and philosophers have had to explore many vast and immensely incorrect theories before reaching the widely accepted understanding of today. The success in determining the shape of the Earth is mainly attributed to Western and European scientists such as Aristotle (384 – 322 BC) (White, 1896).

However, it is important to recognize that despite the dominance of Western ideologies in this field, this discovery is the product of many diverse contributions. As such, the name Aryabhata (476-550 AD) will mean little to most readers, even though the Hindu mathematician was the first to accurately calculate the circumference and diameter of the Earth, providing concrete evidence for its spherical shape (Aryabhata and Clark, 499 AD/1930). Despite these calculations, and similar works by Aristotle, much later during the Medieval Middle Ages, most Europeans continued to believe in a flat Earth. Along with proving its sphericity, Aryabhata's work also contributed to Islamic scholars' works, such as Al Khwarizmi' (780-850 AD) who used the Hindus' findings to produce astronomical tables and mathematical findings regarding Earth (Al-Khwarizmi & Rosen, 499 AD/1831).

Indeed, these findings remain esoteric and removed from modern genealogies of the development of theories of the Earth. This may be due to the cultural barriers; texts written in Sanskrit or Arabic far preceded Medieval Europe, which had little regard for the East's scholars (White, 1896). Despite this, the Middle East and South Asia were ahead in their understanding of Earth. Although theories of Earth History are often recounted through the Western and European historical perspectives, one must give credit and recognition to other early scientists whose works were integral in forming modern understandings. To those scientists whose works were deemed of little interest or note, we must acknowledge and commend their efforts. History is often recounted from a particular perspective, in today's age we strive to diversify and broaden this singular story.

Shaping Earth: Religious Ideas

Humanity has been intertwined with religion for several millennia, and as such, religion has impacted people's understanding of the natural world. Various peoples from different cultures and religions have sought the answer to the shape of the Earth and looked towards spiritual guidance in this matter (Kenton, 1928). This resulted in the theory of a spiral-like shape, which could reach from Earth to Heaven. Similar ideas include a hemisphere, upturned as if floating on the surface of water (Kenton, 1928).

The Babylonians combined spiritual and geometrical ideologies to propose a unique pyramidal shape containing a series of steps

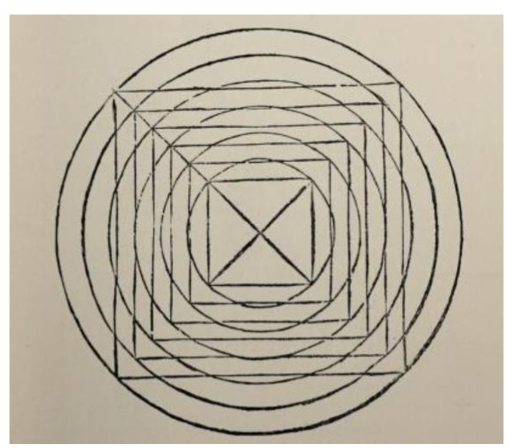


Figure 4.8: A bird's eye view representation for the Babylonian's theorized 3 dimensional Earth, comprised of concentric spheres enclosing a square pyramidal shape. The concept was a product of both symbolic and of religious significance.

enclosed by concentric spheres (Figure 4.8). This was drawn from the concept of Heaven being round and Earth being square shaped, hence the steps representing Earth and circles representing Heaven (Kenton, 1928).

Alternative geometrical iterations such as a cube, dodecahedron, and tetrahedron have also been posed by various groups (Kenton, 1928). For example, a Siberian tribe believed the Earth to be octahedral in shape. These little-known hypotheses were vast in nature and creativity — Johannes Kepler (1571-1630), the famous mathematician, theorized an Earth in the shape of an Icosahedron, essentially a polyhedron with 20 faces (Kenton, 1928). These were a few of many shapes discussed, and complex, irregular shapes and planes have all been appraised, not for their religious and spiritual significance, but for aesthetic and supposed ergonomic design.

However, one of the most prominent hypotheses is that of a flat Earth. The simplicity of this theory drew the interest of many ancient civilizations. This theory is based in cultural and religious teachings, such as the common understanding that the heavens exist above the Earth, a prominent belief held by Chaldeans, Egyptians, and Assyrians alike. This belief led to the concept of a flat Earth, in which Earth can be imagined as a disc, or flat table, that is covered above by the sky supported by towering mountains (White, 1896).

The Christian Perspective

The Christian scriptural understanding of the world proclaimed the Earth to be a flat surface, for it was the location of heaven and hell (Draper, 1875). During the Middle Ages in Europe, some individuals subscribed to a theological understanding of the shape of the Earth, believing it to be the center of the universe. In many religions the belief of an anthropocentric universe, with the world revolving around the Earth, was popular.

Many theories in the Middle Ages not only supported, but originated from scripture, such as the Byzantine monk Cosmas Indicopleustes's (270-303) work known as Christian Topography (Draper, 1875) written in the 6th century. He was a notable Christian who emphasized the flat Earth shape, likening it to a parallelogram surrounded by four seas (White, 1896). He also believed that the sky above could be likened to a half cylinder lying horizontally above the flat Earth (Figure 4.9).

His belief was based entirely on Biblical ideas, using evidence from texts such as from the book of Hebrews, where it is written in the ninth chapter about the tabernacle, which he interpreted along with other scholars to have been likened to the universe (White, 1896). He placed the word of God before any other interpretation to explain astronomical phenomena, such as the daily disappearance of the Sun and the arrival of nightfall. Notably, he had deduced that the northernmost region of the flat Earth possessed large mountains which shrouded the rest of the Earth from the Sun, resulting in night (Draper, 1875).

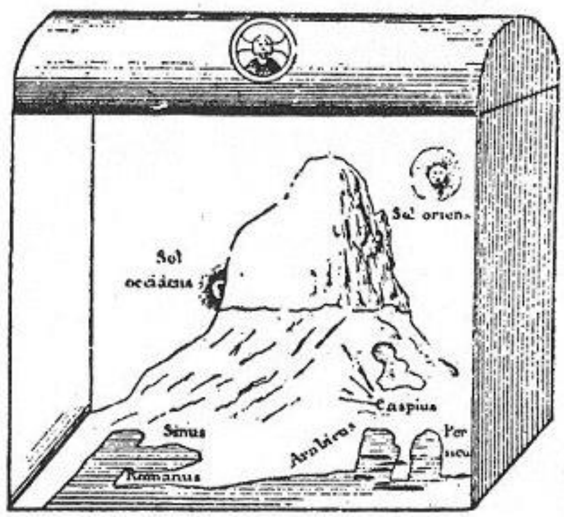


Figure 4.9: Schematic of the world as described by the geographer Cosmas in his book The Christian Topography. He stated the world was a plane enclosed above by the sky creating a unique box-like shape.

Indicopleustes, along with Saint Isidore Seville (560 - 636), are two key proponents of the flat Earth theory. Seville was a renowned natural philosopher who interpreted the universe to be round and potentially disk-like (Cormack, 1994). These two individuals' works were in line with Christian philosophy, known as the Patristic philosophy, which only allowed strictly Biblical ideas. This ensured the concept of a flat Earth, with Jerusalem in the center (Cormack, 1994).

Despite this, the later churchmen and philosophers of the 8th century CE and later, such as St. Thomas Aquinas (1225-1274) and Dante (1265-1321) were inclined to agree with a spherical Earth as proposed by Aristotle and Eudoxus (400 – 350 BC) (White, 1896). Dante was a renowned poet who often noted the spherical shape of the Earth in his *Divine Comedy*

(Cormack, 1994). St. Thomas Aquinas further advocated for Aristotle's findings, and discovered more evidence for the Earth's spherical shape through demonstrating the ever-changing position of constellations in sky as one moved across Earth (Cormack, 1994). This was a stark contrast to the early fathers of the Church, such as Lactantius of the 3rd century, who had been eager to crush the pronouncements of those whose beliefs misaligned with Biblical origins.

This sheds light on common misconceptions of absolute adherence to flat Earth ideologies by Middle Ages' churchmen. While many currently believe that this era was misinformed, in reality, a shift in scientific ideology had begun. There had been disaccord between the Church's beliefs and many of its clergy. Even those who were devout Christians could no longer overlook the scientifically sound findings of past mathematicians and scientists, which led to greater agreement and belief in a spherical Earth by the 15th century in Europe.

The Ancient Greek Perspective

Despite the common belief of a flat Earth, the prevalence of the spherical Earth theory eventually became. Although the exact person to first state the theory of a spherical Earth is unknown, one of the first documented proposals of this notion was by the Greek philosopher Pythagoras (570-495 BC). Pythagoras was the head of his own philosophical and religious school of thought (Riedweg, et al., 2008). His devotion to the heavens may have led to his belief that the shape of the Earth was a sphere. However, this idea was not supported by any physical evidence, rather, it was postulated due to the aesthetics of this concept. His fascination for the heavens led him to believe that the world was simple. At this time, it was widely accepted that the Earth was at the center of the universe and the sun revolved around it. This theory was eventually coined geocentrism (Omodeo, 2015). It was also believed that the universe was composed of ten celestial objects, as ten was considered the perfect number (Riedweg, et al., 2008). Such notions encouraged him to deduce that as the most perfect creation residing in the perfect universe, humans inhabit the most perfect shape: a sphere (Riedweg, et al., 2008).

By 500 BC, many Greek philosophers continued to believe in a spherical Earth despite little evidence to support the claims. Plato (428-347 BC) also nurtured the incomplete belief that the Earth was a spherical orb resting in the middle of the heavens (Boccaletti, 2019). In 387 BC, Plato founded a school in Athens called The Academy (Lindberg, 2008). One of his most notable students was Aristotle, who studied at The Academy for 27 years between 367 - 347 BC (Russell, 2007). Aristotle was determined to provide proof for the shape of the Earth. In his publication, *On the Heavens*, he demonstrated that the placement of constellations changes as one changes their position towards the north or south. He observed that certain stars and constellations seen in Egypt and Cyprus could not be seen in the Northern region (Aristotle & Guthrie, 1939). He also observed that all objects on Earth tended to fall towards the center of the Earth. This led him to believe that pressure from the heaviest objects on Earth would compress the planet into a spherical shape (Aristotle & Guthrie, 1939).

Additionally, Aristotle mentioned that the length of days changed as one travelled to different parts of the world. Theoretically, if the Earth were flat, days should be uniform in duration (Aristotle & Guthrie, 1939). He also postulated that the Earth was spherical in shape since boats disappeared quickly over the horizon despite their large appearance. This observation did not align with the concept of a flat Earth. If the world were flat, boats would simply decrease in size until they became a point in the horizon, as they would remain in the same plane (Aristotle & Guthrie, 1939).

Another piece of evidence suggested by Aristotle regarded shadows cast by Earth onto the moon during a lunar eclipse. He noted that the boundary between the light and dark portions of the moon during an eclipse was always convex. It was believed at the time that the eclipse of the moon was caused by the shadows of the Earth. Aristotle determined that for a convex projection to be produced, the shadow must have been dependent on the circumference of the Earth, therefore he deduced its shape to be spherical. For a convex shape to be produced, the shadow must be circular in shape (Aristotle & Guthrie, 1939).

Around this time, Greek philosophers started to believe that various phenomena in the world could be explained through natural processes and were not necessarily entirely dictated by the gods. As a result, astronomers began analyzing quantitative data and measurements to forge their own conclusions. This change led to (276 – 194 BC) determining the circumference of the Earth. Eratosthenes was known as one of the greatest scholars of his time and was even appointed as the chief librarian in the Library of Alexandria by King Ptolemy III of Alexandria (Roller, 2010). Eratosthenes had an interest in geography and endeavoured to design a map of the world. To do so, he needed to know the size of the Earth. He set about attaining this value through the exploration of shadows. He heard stories of a well in Syene, where the bottom of the well became entirely illuminated at exactly noon on June 21, the summer solstice (Roller, 2010). He had determined that at this time, the sun was positioned directly above the Earth. He measured the angle of a shadow cast by a stick (Figure 4.10) and found it to be 1/50th of a complete circle (Nicastro, 2015). Eratosthenes then measured the distance from Alexandria to Syene and calculated the circumference of the Earth to be 250,000 stadia, approximately 39,000 kilometers (km) (Nicastro, 2015).

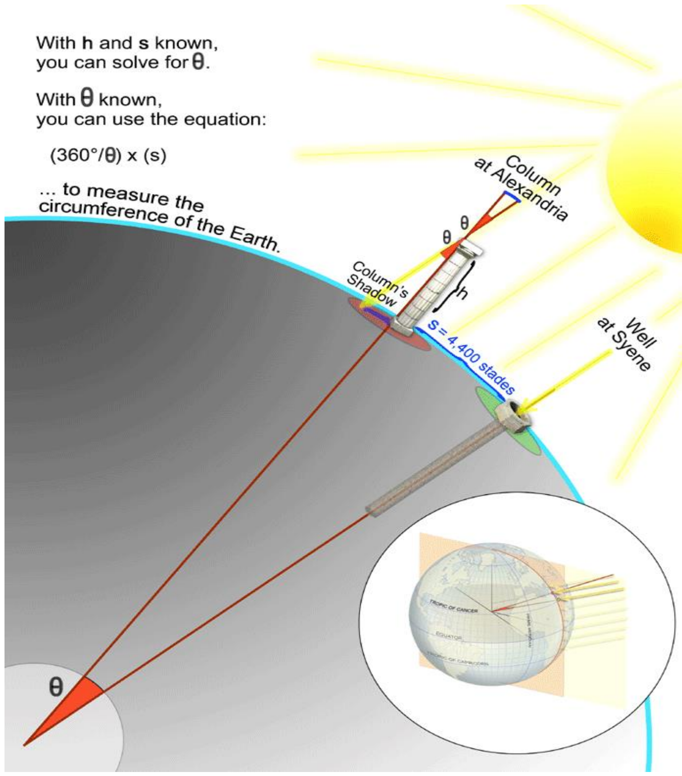


Figure 4.10: Diagram of the method used by Eratosthenes' to determine the circumference of the Earth.

The circumference of the Earth is currently known to be about 40,100 km around the equator (Longhorn & Hughes, 2015). Using his method, Eratosthenes was able to make an accurate approximation of the circumference of the Earth simply by using the angles of shadows and distance. Many other Greek scholars attempted to determine the circumference of the Earth following Eratosthenes using similar methods but were not able to determine a value as close as Eratosthenes successfully had. In the 2nd century CE, Ptolemy (100-170 AD), an Egyptian astronomer and geographer, created a map of the spherical Earth using latitudinal and longitudinal values in degrees for 8,000 locations (Pàpay, 2022).

Spherical Earth Theory became a widely accepted belief throughout the world by the end of the Middle Ages. However, reaching a general consensus did not come without disputes and arguments from various perspectives. For many theological figures of the earlier Middle Ages, it was of great importance to adhere to Biblical proclamations. This aversion to science which was often against scripture eventually withered away. The evidence as aforementioned above became undeniable in nature, especially upon the onset of Age of Exploration near the end of the Middle Ages. This led to a breadth of affirmations regarding a three-dimensional Earth, as had been confirmed by explorers such as Christopher Columbus (1451 - 1506) (Cormack, 1994). Thus, the spherical Earth reigned as the primary theory accepted by the people as the 15th century neared a close.

The European Exploration of Earth

The Age of Exploration was a key era in the progression of understanding the shape of the Earth. This continued concept of world exploration and firsthand experimentation continued throughout 16th century Europe and onwards aiding in the refinement of the spherical Earth theory. In 1671, French physicist Jean Richer (1630-1696), used a pendulum clock in an experiment in Cayenne and Paris (Greenberg, 1995). He found that the clock's pendulum swung slower in Cayenne resulting in a loss of 188 seconds per day, showing that length of the pendulum swing varied based on one's latitude (Greenberg, 1995). His findings inspired Sir Isaac Newton (1643-1727), a member of the Royal Society of

London, to theorize that the magnitude of the gravitational force per unit of mass was smaller closer to the equator than in France. This was evident from Richer's experimental findings, as the pendulum would swing a different distance depending on the clock's location. In addition to Christian Huygens (1629-1695) hypothesis that the centrifugal effect is strongest at the equator, Newton concluded the effect to be a result of the decrease in Earth's centrifugal force of rotation with latitude (Greenberg, 1995). This meant that the centrifugal force exerted varied with one's location on Earth. He published in the Principia, in 1687, that the centrifugal force of rotation caused discrepancies in the gravitational force on Earth, the spherical shape to flatten at the poles, and create an oblate spheroid shape. This finding was further corroborated in 1668, when the Italian mathematician, Giovanni Domenico Cassini (1625-1712) discovered that Jupiter was also flatter at its poles, confirming Newton's postulate (Greenberg, 1995).

Despite Newton's proven theories, his beliefs were not widely accepted in France. The Académie Royale des Sciences in Paris was hesitant to discredit their theory on the shape of the Earth proposed by René Descartes (1596-1650). He had proposed that the poles of Earth were elongated, forming a prolate spheroid. His views were supported by Jacques Cassini (1677-1756), who had made a series of measurements by 1734 of meridian and parallel arcs in France (Hoare, 2004). The difference in opinions sparked debate regarding the shape of the Earth (Figure 4.11). In response, Charles Marie de la Condamine (1701-1774) and Pierre Maupertuis (1698-1759) set off to determine the validity of each claim. Condamine led the Peru expedition from 1735-1743, while Maupertuis led the Lapland expedition from 1736-1737 (Hoare, 2004). Each group measured the Meridian arc in approximation to the length of one degree. Peru was chosen as a location due to its proximity to the equator, while Lapland was chosen due to its proximity to the pole.

It was postulated that if the arc length in Peru were to be longer than Lapland, then Earth's shape is a prolate spheroid. If the opposite was found, then Earth's shape would be an oblate spheroid. The arc in Lapland was found to be 57, 437.9 toise (111.9 km), while the arc in Peru was found to be 56,753 toise (110.6km), proving the British correct and supporting the claim that the shape of Earth was an oblate spheroid, then asserted to become the common belief in present time (Hoare, 2004).

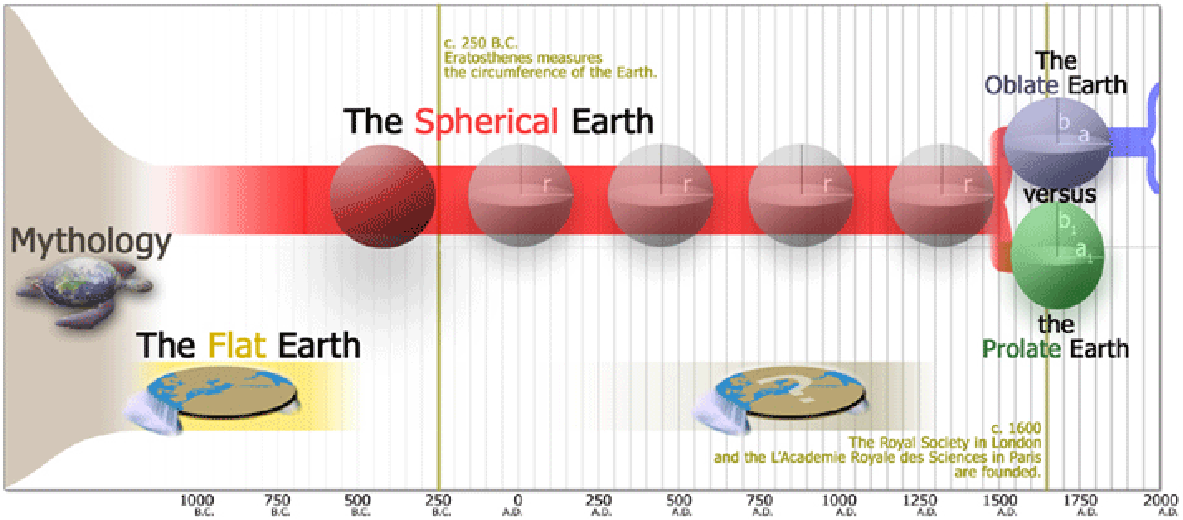


Figure 4.11: A timeline showing the general beliefs of the public regarding the shape of the Earth from 1000 B.C to 2000 CE. The theories range from the flat Earth to the oblate and spheroid and prolate spheroid theories, demonstrating their coexistence.

Modern Structure of Earth: GRACE-FO

Modern technology has greatly aided in the precision and accuracy to measure the Earth. Geodesy is a relatively new field of science dedicated to measuring Earth's geometric shape, field of gravity, and rotation in space

(Burkholder, 1987). The significant developments in geodesy have provided accurate measurements of Earth's size and shape to the closest millimeter using satellites.

Geodesy was initially explored in order to aid in navigation for the military and improve the ability of missiles to reach their target. To properly hit a target, both the force of gravity acting upon the object and the distance between the launch and the intended landing area must be determined (Burkholder, 1987). The Earth has a slight curve of 0.08 m for every kilometre. Therefore, when measuring distance and direction over large areas, the curvature of the Earth must be accounted for. Geodetic surveying is a method where satellites measure the distance between points on the surface of Earth. It provides the ability to measure angles and distances to a high degree of accuracy (Burkholder, 1987).

Tracking the measurements of Earth has many applications including assisting in the understanding of climate change. In 2002, twin satellites, Gravity Recovery and Climate Experiment (GRACE) were launched into space to record measurements of Earth (Chen, et al., 2022). This system was designed to further the understanding of climate change by measuring Earth's gravitational filed. Overtime, changes in the field can determine changes in the distribution of mass on the planet (Figure 4.12). Understanding changes in mass distribution can help examine climate factors such as the movement of water and ice on the surface of the Earth (Chen, et al., 2022). This mechanism allows for further exploration into the Earth's processes and environmental issues through large-scale investigation. The approach is multi-faceted, combining physics and mathematics with geological science. The GRACE mission ended in 2017, though its techniques are still used by its successor, GRACE Follow-On (GRACE-FO), launched in 2018. GRACE-FO is equipped with more advanced instruments to record the same data, allowing for increased precision in Earth's gravitation field and inadvertently, Earth's shape (Chen, et al., 2022).

Although the GRACE mission was not intended to prove the shape of the Earth, the collected information allowed for further insights. The GRACE mission consisted of twin satellites flying at a low altitude 220 km apart from one another in the same near-polar orbit (Zheng & Xu, 2015). A microwave ranging system was used for the satellites to measure any changes in distance between the satellites. The distance between the two satellites would increase as the lead satellite passed over areas with stronger a gravitational force, increasing the distance between its twin due to the slight acceleration in speed (Zheng & Xu, 2015).

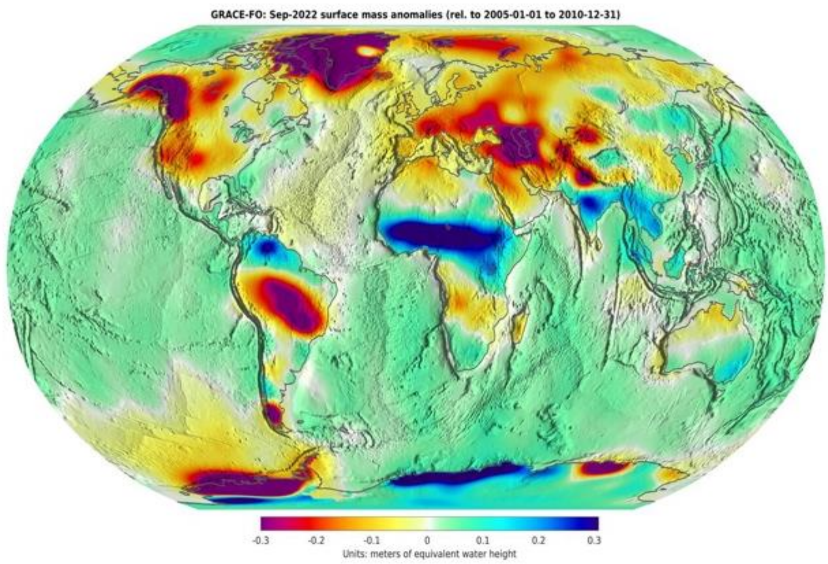


Figure 4.12: Map of the global surface mass anomalies measured by GRACE-FO in September 2022. The quantities measured by GRACE-FO also allows for the map of the Earth to be an oblate spheroid.

Each satellite also carried high-precision GPS receivers and high-accuracy accelerometers, allowing for data collection enabling the creation of precise maps of Earth's gravitational field without the effects of non-gravitational forces (Kang, et al., 2006). GRACE-FO uses similar techniques. However, it opts for the use of lasers rather than microwaves to measure changes of distance between the two satellites (Flechtner, et al., 2016). GRACE-FO uses ice-density through gravitational influence to detect any changes in groundwater levels (Tapley, et al., 2019).

The maps created by GRACE and GRACE-FO illustrate the change of mass distribution on Earth's surface. These maps provide information on the structure and the overall shape of Earth, concluding that the shape of the Earth is an oblate spheroid that flattens at the poles and bulges at the equator.

The Neptunist-Plutonist Controversy

The Earth's formation has been greatly debated throughout human history. A particularly notable controversy was the debate on the origin of igneous rocks in the 18th to 19th century, known as the "Neptunist-Plutonist" debate. Neptunists believed that igneous rocks precipitated out of a primordial ocean, while Plutonists believed they were formed by the melting, cooling, and hardening of rocks (Sanders, 1981). In a time of religious dominance, where the field of geology was in its infancy, the Neptunist-Plutonist debate was an important controversy which greatly shaped the future of Earth's history. The works and discoveries of the scientists who participated in this debate diverged from the concept of a God-created world, laying the foundation of our modern understanding of the Earth's formation.

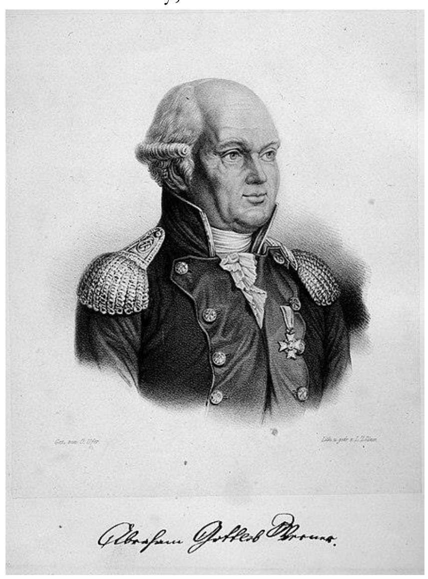


Figure 4.13: Illustration of Abraham Gottlob Werner (1749-1817), who was most commonly associated with his theory of Neptunism.

Neptunism

In the late 1700s, one man dominated the field of geology with his new and innovative ideas. Abraham Gottlob Werner titled his ideas of historical geology "geognosy" (Mintz, 1981). Werner hailed from a German mining family and spent his adolescent years at the University of Leipzig training to be a mining engineer. His initial introduction to the scientific world was through a publication titled "*Of the external characters of fossils,*" the first significant mineralogy textbook. This book developed a systematic method to identify various minerals based on their observable external features, and was used by many geologists for rock and mineral identification. Werner further went on to join the new Freiberg Mining Academy as a professor and inspector, as well as a mine counsellor. For almost the entirety of his bachelor life, Werner received international fame for his theories, research and publications (Şengör, 2002).

The main theory Werner was associated with is called "Neptunism." During the late 18th century, it was strongly believed that all crystalline rocks were created at one point in time, while sedimentary rocks were formed successively later on. Proposed by Nicolaus Steno, the theory of superposition states that sequences of rock layers, undeformed by either folds or faults, were formed later than the layer below and earlier than the layer above (Mintz, 1981). Using only the theory of superposition, Werner explained the Earth's history and determined rocks' ages by composition. Neptunism postulates that all rock layers existing in the Earth's crust are the precipitates of a worldwide primeval ocean (Cooper, Miller and Patterson, 1990). This ocean regressed over time, leaving behind precipitated layers of rock which were arranged in a superpositional order (Cooper, Miller and Patterson, 1990), mostly during Noah's Flood. Werner thought of this universal ocean as a hot and steamy body of water that was saturated with several dissolved materials that would form rocks (Levin, 2006). Since all layers were precipitated from the same ocean, they must all have been the same age with unique compositions (Mintz, 1981). In the late 1700s, Werner's theory was widely accepted and named "Neptunism," after the God of the sea Neptune, due to the theory's suggestion of a primeval ocean (Sanders, 1981).

Werner acknowledged four main successive rock groupings that he recognized to be the four primary stages that occurred during Earth's crust formation. He understood the lowest layer to be the "primitive series", containing granite and gneisses at the very bottom, followed by schists and crystalline rocks of other varieties. He predicted these rocks formed the mountain ranges' cores (Levin, 2006). Above this layer laid the "transition series", which Werner recognized as slates, graywackes, quartzites, and limestones. This was a sparsely fossiliferous layer, containing fossils of the earliest lifeforms. Werner believed that the primitive and transition series once covered the entirety of the

Earth's surface (Cooper, Miller and Patterson, 1990). Following the transition series, he believed the stratified fossiliferous secondary series came next which consisted of sandstone, limestone, slate, and coal. It was postulated that this series had been created through chemical precipitation and settling as the water regressed. As well, some designs and features in rocks were hypothesized to be caused by surface running water (Cooper, Miller and Patterson, 1990). The final layer in Werner's sequence were the "alluvial rocks", which contained ash and cinder beds, sand, gravel, clay, and peat. He believed that as the ocean regressed below the mountain tops, large areas of bare land were left behind. Additionally, ocean deposits were created via delivery of materials to the ocean by running water that existed over the land (Cooper, Miller and Patterson, 1990). Throughout this ocean regression, the water's composition was changing constantly, causing the successive deposition of different rocks (Şengör, 2002).

Werner's theory garnered a massive following in the scientific world. There was a strong appeal to Neptunist philosophy as it did not infringe religious beliefs. This was important due to the strong religious beliefs of the time, such as the Earth being 6000 years old. These beliefs had a great impact on the accepted theories relating to physical processes like geology. The belief that God had placed all things on Earth after the Noachian flood conformed to the ideas proposed by Neptunism (Cooper, Miller and Patterson, 1990). This theory garnered popularity through its simplicity, conformity to Biblical chronology, and Werner's passionate confidence (Cloud, 1970). As well, Neptunists had several backing beliefs, such as hexagonal crystals being precipitated out of water as shown in six-sided prisms of rock outlined by cracks (Sanders, 1981).

Werner had many disciples and spent much of his time teaching them his geological theories and beliefs strongly rooted in Neptunism at his Neptunist school. He was described by students as having somewhat of a dictator-like teaching style, demanding much from his students with no distractions. As he was first a miner before becoming a teacher, his teaching style along with his attitude and biases, were deeply rooted in those of the central German mining community. This caused many of his postulates to not be tested through observations, which may have been a contributing factor to discrepancies in his theories (Şengör, 2001). Werner's students were known by geologists to fall under a seemingly hypnotic trance during his teaching, and most went out into the world to further establish their mentor's theory (Cloud, 1970).

Figure 4.14: Image of Alexander von Humboldt, one of Werner's most notable students.

One of his notable students was Alexander von Humboldt who was accepted into the academy after agreeing on Neptunism. For two years, Werner taught Humboldt how to recognize minerals and rocks, as well as methods used in mines around the area. Humboldt eventually decided to embark on an expedition to South America, during which he began to question the truthfulness of all he had learned from his teacher. Werner had informed Humboldt that volcanoes only act as a secondary factor in mountain formation, which he began to believe was incorrect after collecting volcanic rocks (Ramos, 2022). By setting out to find more evidence on Neptunism, Humboldt unknowingly began to conform to Huttonian ideologies, as occurred to many believers of Neptunism (Ramos, 2022). Despite the great influence Werner had on Neptunism, none of his geological theories survived due to his methods in teaching and research.

Like many theories from early scientific research, Neptunism had various flaws that were detrimental to its longevity. Largely after

Werner's death in 1817, several indisputable issues arose, such as the water's disappearance, how lava deposits flowed into oceans, and several more (Golubchikov, 2021). Features that were believed to be shaped by water began to be interpreted as being formed by other processes, such as glacial, nivational, and denudational movements (Golubchikov, 2021). Additionally, something that greatly impacted Werner's ideologies was his tendency of staying in the same area. Although Leopold von Buch was his traveling disciple, many of his observations were generalized and based solely in Freiberg with the assumption that these were a worldwide phenomenon (Cloud, 1970). Werner did not explain what happened to the extreme volume of water that once covered all of Earth's surface. He also insisted lava flows had been deposited in a parallel manner to the limestones and shales that enclosed them, despite the majority of geologists disproving this through the volcanic origin of molten lava (Levin, 2006).

Plutonism

The alternative theory to Neptunism is Plutonism, named after the Roman god of the underworld, Pluto. Alternative to the belief that rocks originated from the ocean, Plutonists believed that rocks, such as granite, were of intrusive origin and had solidified from a molten state (Coleman, Mills and Zimmerer, 2016). The pioneer of this viewpoint came about in the late 18th century, when geology was a budding field. At this time, religious viewpoints permeated society. However, James Hutton, a Scottish farmer and naturalist would begin to change geological history (Repcheck, 2008). Hutton's life as a farmer led him to carefully observe land and how it withstood natural forces such as wind and rain. These observations led to the generation of a new theory on how rocks and land were formed. Hutton proposed that sediments and soil were washed into the sea and were further compacted into bedrock and buried. These rocks would eventually resurface through volcanic processes, returned to the surface as lava where they cooled into rock (Repcheck, 2008). These newly formed rocks would eventually be worn down back into sediment and the cycle would repeat indefinitely. Here lies the basis for Plutonism, rocks were eroded, buried, metamorphosed, and released as either lava, or igneous intrusions called plutons (Tex, 1990).

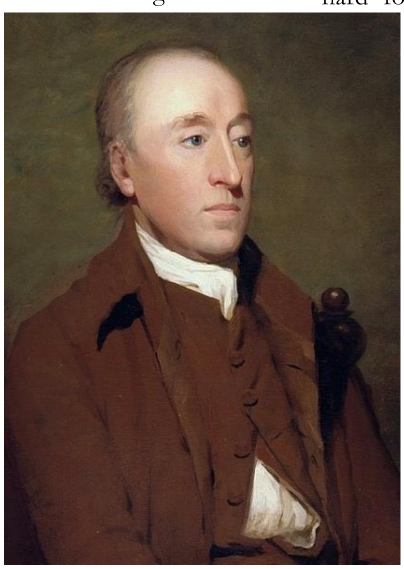


Figure 4.15: A portrait of James Hutton (1726-1797), the founder of Plutonism.

Many of Hutton's ideas about Plutonism were recorded by Scottish mathematician and geologist John Playfair, in his book; "*Illustrations of the Huttonian Theory of the Earth*." It recounts Hutton's observations of granite veins, which at the time, were proposed to be formed by infiltration of sediments (Playfair, 1802). Hutton claimed that it was not possible for the veins to be formed by infiltration, as water would need to dissolve the ingredients of granite. Additionally, water would be unable to carry the sediment in the direction of the veins, as many rose upwards from the granite mass (Playfair, 1802). Another objection to an infiltration origin is the number of schist fragments present in granite veins. Hutton stated that if these fragments were introduced by water, it would be hard for them to be stable until they were surrounded by sediment. However, it would be easier to believe the schist was carried by melted granite instead. Hutton also observed the granite of Portsoy, Scotland, which he described as having pieces of quartz moulded on feldspar in rows, giving the stone the appearance of "rude alphabetical writing" (Playfair, 1802). This arrangement suggested a more instantaneous formation, which does not give time for sediment to precipitate. Hutton proposed that it would have only been possible through simultaneous consolidation as a result of the granite mass cooling (Playfair, 1802).

Prior to Hutton, there had been discoveries alluding to plutonism. Located in South Africa, lies Table Mountain, a vast formation composed mainly of greywackes overlain by orthoquartzites (Master, 2009). Its most remarkable feature is the 550-million-year-old granite intrusion known as the Cape Granites. It was discovered in 1772 when the Scottish botanist Francis Mason accompanied Swedish botanist Carl Peter Thunberg on a trip to observe plants. During this trip, Mason took interest in the Table Mountain formations, but had no time to observe them, instead convincing naturalist William Anderson to look at them instead (Master, 2009). Anderson's most important observation was of a compact granite vein that cut perpendicularly across the sandstone; however, he was unable to determine if it cut right through the sandstone or if it was merely superficial. Anderson had observed was an aplite dyke, a feature that would only be described 17 years later by Hutton (Master, 2009).

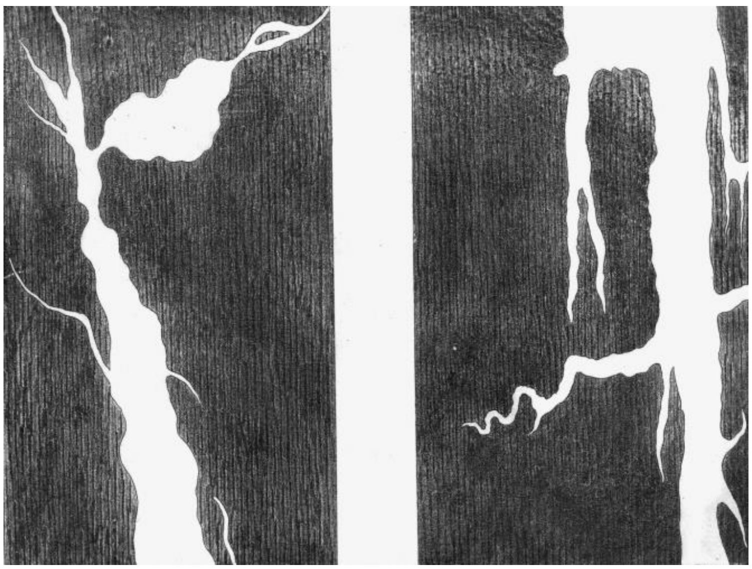


Figure 4.16: A sketch by Captain Basil Hall of the granite veins he saw at Table Mountain. The white parts represent the veins, while the black is the surrounding sandstone. This drawing was published by Playfair and Hall and was later viewed by Darwin during his trip.

Another important figure was Captain Basil Hall, second son of Sir James Hall, who was a chemist, geologist, and student of Hutton (Master, 2009). Captain Hall started to dabble in geology upon meeting John Playfair, leading to his excursion to Table Mountain. Here, he would describe the contact between the Cape granite and the Malmesbury greywacke. James Hall wrote about his findings to his father and Playfair, who published them as proof of plutonism (Master, 2009). They argued that the granite had to be intrusive, as it formed veins that dug into greywacke. Ultimately, this meant the surrounding rock must be older in origin, and the granite must have intruded later on. In 1836, English naturalist, Charles Darwin, would visit the Cape of Good Hope and witness the Cape granites at Green Point for himself (Master, 2012). After reading the accounts by Basil Hall, he recognized the three principal formations: granite, overlain by clay-slate, and sandstone. While observing granite dykes surrounded by clay and slate, he noted that the dykes were arranged in lines parallel to the slate's cleavage (Darwin, 1844). Additionally, Darwin noted isolated pieces of clay and slate in the middle of the granite veins, which followed the same cleavage patterns, despite their isolation. Darwin remarked that this formation would have been difficult to achieve if aqueous granite had been injected into the veins. Rather, he proposed that this formation came about from clay and slate being violently arched by molten granite (Darwin, 1844). This event would form fissures parallel to the planes of cleavage, which the molten granite would then fill. As the resulting rock was worn down, masses of slate would remain in the granite and appear as isolated fragments (Darwin, 1844). In 1844, Darwin would publish his observations on the Green Point granite–schist contact, causing the Plutonist position to become more widely accepted (Master, 2012).

While Plutonsim had gained popularity, there were still issues with the theory. To the Neptunists, Hutton's rock cycle lacked evidence, as it could not be observed and seemed improbable that it would last long periods of time (Tex, 1990). Furthermore, quartz, a main component of granite, could not be fused at the time, and the water contained in its cavities supported Neptunist formation. In 1947, Herbert H. Read of Imperial College, London, UK, brought up two glaring issues with Plutonism (Tex, 1990). One was called the 'room problem,' and questioned how the space for the granites are created if granites intrude as magma. Specifically, the mechanisms for how the surrounding rock accommodates intrusions was poorly understood (Coleman, Mills and Zimmerer, 2016). His second question regarded the pace at which plutonic magmas accumulate, as the age of plutons was greatly debated by geologists at the time. In reality, these two problems are connected, as understanding how the earth shifts to accommodate these intrusions required knowing the rate by which they move (Coleman, Mills and Zimmerer, 2016). There are several theories to solve the room problem, such as ballooning, which is the idea that as magma rises, its outermost layer cools and crystallizes. As the rest of the lava ascends, it deforms the outer margin, expanding it. In spite of these theories, the room problem is still debated at present day (Chen and Grapes, 2007).

The Neptunist-Plutonist controversy was one that dominated the field of geology for a large part of the 1700-1800s, and which saw many individuals repeatedly switch their viewpoint as more discoveries were made. However, Werner and Hutton firmly held onto their beliefs, adapting their theories to account for new evidence. Werner adapted the descriptions of his universal ocean, while Hutton continued to develop his ideas of the primordial Earth. The battle between the God of the underworld and the God of the Ocean for would continue for years to come with the introduction of new discoveries.

Current Understanding of Igneous Rocks' Origin

Leading into the 21st century, our understanding of the origin of rocks has greatly changed from that of 18th century geologists. Werner and Hutton were crucial characters in developing the understanding of igneous rocks using their theories of Neptunism and Plutonism, respectively. Werner has incorrect in his belief that rocks were deposited out of a universal ocean (Ospovat, 1976). Regardless, this opened the door to the popularity of geology and paved the way for many other great discoveries, especially through his enthusiastic teaching of others. Despite Neptunism being mostly incorrect, it impacted many other geologic ideas, such as the basis of stratigraphy, which was created with strong influence from Neptunism (Cooper, Miller and Patterson, 1990). Additionally, Werner played a large role in the current techniques geologists use in the field through popularizing methods like rock and mineral identification, dip and strike measurements, geological map creations, and stratigraphic correlations (Şengör, 2001). Hutton, however, was closer to what is now considered to be the actual origin of rocks. His assertion that igneous rocks, such as granite, originated as magma from within the earth is correct (Neng-Chen, 2007). Thus, it is thought that Hutton gave geology its brains, while Werner provided geology with techniques.

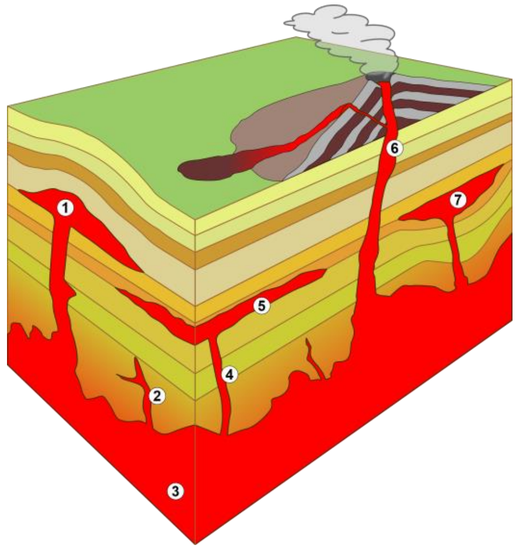


Figure 4.17: A diagram showing modern understandings of how plutons would be formed from under the Earth's surface. 1. Laccolith, 2. Dike, 3. Batholith, 4. Dike, 5. Sill, 6. Volcanic neck, 7. Lopolith.

Igneous Rock Formation

Currently, it is known that magma is a very hot liquid located beneath Earth's surface, and is called lava once it emerges onto the surface (Sanders, 1981). Intrusive, or plutonic, rocks are those which form deep within the Earth's crust by the gradual cooling and solidifying of magma, leading to crystalline materials. Plutons are usually coarser-grained materials such as granite or diorite. When intrusive rocks rise to the upper portion of Earth's crust, they have the ability to incorporate host rock blocks, forming xenoliths. Extrusive, or volcanic, rocks are those formed at the Earth's surface near volcanic vents. These rocks are formed through ejected lava, either explosive or nonexplosive, and this process is typically too rapid for coarse-grained, mineral crystal formations. Instead, fine-grained crystalline materials are typically created, such as rhyolites and basalts (Frascá and Del Lama, 2018). Primarily, igneous rocks are made of silicon and oxygen-rich magma, with its viscosity having a directly proportional relationship to silica content. Additionally, silicates are igneous rocks' constituent minerals which form as the ideal temperature is reached for crystallization. Iron and magnesium silicates, termed mafic or ferromagnesian minerals, are typically the first to crystallize. Felsic materials form as temperature lowers, and include potassium aluminosilicates, muscovite, and quartz. However, the first to crystallize are typically accessory materials like zircon and titanite. Mafic materials are typically less stable beneath shallower areas of Earth's surface due to high temperature and pressure crystallization conditions that can result in chemical and crystal alterations. These alterations could be caused by either interactions with magmatic liquid that is late-stage, or weathering. In the case of weathering and atmospheric element exposure, secondary minerals such as iron oxides and clay minerals can form (Frascá and Del Lama, 2018). Due to technology limitations and lack of research, Werner and Hutton were unable to discover these specifics in igneous rock formations and instead inferred a lot of conclusions on their observations. Particularly, Werner had continued to widen the abilities of his primordial ocean in attempt to account for certain criticisms and new discoveries (Cloud, 1970).

Modern Plutonism

Another one of Hutton's correct suppositions was that veins, or dykes, were formed by the intrusion of molten rock instead of infiltration. Currently, it is understood that dykes are formed either when magma forces its way through a rock, or fills a pre-existing fracture. It is suggested that this process is controlled by stress from a pressurized magma reservoir. However, in some cases, dyke propagation is driven by regional tectonism (Acocella and Neri, 2009). Dykes often feed into volcanoes and can transport lava for kilometers, which eventually leads to volcanic eruptions, another source of igneous rocks (Bonaccorso, Aoki and Rivalta, 2017). While his hypothesized origin was correct, Hutton did not provide much of a mechanism to explain what drove the movement of magma. This could have been influenced by the fact that Hutton was a deist, one who believes in a creator God (Repcheck, 2008). This God is responsible for creating and setting things in motion; however, it does not interfere with everyday life. Therefore, Hutton was of the belief that God was the one who originally set all these processes in motion (Repcheck, 2008). Hutton was unable to take into account concepts such as plate tectonics, which only became known in the 20th century (Frisch, Meschede and Blakey, 2010). Igneous rocks can be found in Archean granite-greenstone terranes, locations where exposed rock is approximately 2.5 to 4 billion years old (Anhaeusser, 2014). Dating back to earth's beginnings, these igneous rocks lend critical insights into the formation of the earth's crust. For example, the granites found in the Pilbara Craton in Western Australia lend insights about magmatic changes form the past 750 million-years (Petersson, et al., 2020). This is due to the granite complex forming over hundreds of millions of years by the coalescence of magmatic pulses. Zircon U-Pb, O, and Hf isotope data obtained from these granites can be used to determine the process and timing by which the craton formed, which lends insights into the rate of continental growth during the first billion years of Earth history (Petersson, et al., 2020).

Modern Techniques

While rock records can lend valuable insight into the formation of igneous rocks, these processes can be modeled using thermodynamic, kinetic, and fluid dynamic models in modern times (Ghiorso, 2003). These models are calibrated with data collected from the field, which their accuracy is dependent on. John Verhoogen, 1949, is assumed to be the first person to create a model based on thermodynamic analysis. He tried to examine the volatile degassing of magmas; however, he was hindered by lack of quantitative data (Ghiorso, 2003). Since then, models have increased in complexity, with Aladejare, et al. 2022, using artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) to better predict the characteristic impedance of igneous rocks (Aladejare, et al., 2022). The parameters were set by recording the wave velocity, density, and water absorption of 100 rock samples from the Karelia province of Finland. This data was imputed into a computer using the software MATLAB to get an estimate of the rock's impedance. ANFIS is a variant of ANN that approximates nonlinear functions, which was used as a comparison to ensure both models were reliable. The results showed that using models can be a reliable way to predict igneous properties (Aladejare, et al., 2022).

In conclusion, while Hutton and Werner were not completely right about their respective theories on Plutonism and Neptunism, they were not completely wrong. Their research, combined with that of their successors, helped lay the foundation of our modern understanding of igneous rocks, and gave us a better understanding of the origin of the Earth. What was once a heated debated of the 18th to 19th century exists today as a snapshot into history, and the constant changes that our current history of the earth endured. The controversy is put to rest today, with the Plutonist theory seemingly prevailing.

The Rise and Fall of Diluvial Theory

Derived from the Latin *diluvialis*, meaning of, or brought about by, a flood, diluvialism is the geological theory that many of Earth's features can be explained by one or more universal floods. These features, referred to as diluvium, consist of superficial deposits that could not seemingly be explained by the ordinary action of water as an erosional agent. Instead, geologists attributed diluvium deposits and features such as boulder clay, abraded and polished rock surfaces, and ossiferous gravels to the extraordinary action of water on a very large scale, a violent universal flood. Initially, diluvial theory acted to reconcile unexplainable geologic features with religious beliefs (Huggett, 1989).

The earliest ideas of diluvialism were derived directly from the Book of Genesis in the Hebrew Bible and the Christian Old Testament. Ancient diluvialism was a literal interpretation of Genesis Chapters 6-9, which recounts the story of a great flood imposed by God. Ancient diluvial thought was prominent for thousands of years, lasting from the writing of the Book of Genesis to the Middle Ages. Prevailing beliefs of this period did not consider geologic features, but rather absolute belief in Genesis (Huggett, 1989).

Figure 4.18: Artist's depiction of the biblical deluge. Large catastrophic waves can be seen crashing against rough terrain, with numerous humans struggling to stay afloat in the rough water.

Genesis Chapters 6-9 tells of God's distaste for the development of humankind and his decision to return the Earth to its pre-creation state by unleashing the deluge, a great flood. God instructs Noah to build an ark to protect himself, his family, and two of each animal from the deluge. God then sent rain on the Earth for forty days and forty nights, raising water levels above even the tallest mountains (Figure 4.18). (The Bible, Genesis. Ch. 6-9). This flood, referred to as the Noachian Flood, is the basis for the theory of diluvialism.

Modern Diluvialism

Modern diluvial thought began during the Renaissance, in the 15th and 16th centuries. Most writers in this period blindly accepted the events of Genesis. Despite this, seeds of doubt were planted in some scholars' minds regarding the literal interpretation of the events of Genesis, though few ever publicly denied the Noachian Flood due to the power the Church held at the time. Thus, most developments in diluvial thought during this period surrounded the effects the Flood may have had on the Earth's surface. The prevailing theories could be divided into two schools of thought. Members of the first believed the Flood to be "a divine instrument which in a single climacteric act had destroyed not only all pre-diluvial life, but also the pre-diluvial world itself" (Huggett, 1989). Conversely, proponents of the second believed the Flood had little effect on the Earth's surface and only significantly affected life (Huggett, 1989).

Diluvialism in the Renaissance began considering the geologic perspective, with early geologists attributing various phenomena like fossils to the Noachian Flood. As the understanding of fossils improved, Renaissance geologists were faced with a dilemma: accept fossils as the remains of former plants and animals and risk conflict with the Church or accept that fossils were created by God and go against their geologic knowledge. To avoid this conflict, most geologists invoked the Noachian Flood to explain why marine fossils had been found in mountains and plains. This solution birthed the first true diluvialists, who contended that the Noachian Flood was the only significant cataclysmic event in the history of the Earth (Huggett, 1989).

By the late 17th century, diluvialism had become a prominent theory in the British geological community. Perhaps the most influential diluvialist of the time was John Woodward, whose *Essay Toward a Natural Theory of the Earth* published in 1695 had a profound effect on diluvial thought for the following century. In his essay, he proposed 5 tenets of the impact of the deluge on the Earth's surface (Clark, 1946):

1) All rocks and metals of the Earth were totally dissolved and their "constituent corpuscles" completely separated during the deluge.
2) This mixture, together with plant and animal remains, was collected in the water as one mass.

3) This mass was gradually precipitated, forming the strata of Earth.
4) Bodies of animals were precipitated last, leaving their scattered remnants on the surface of the Earth.
5) Irregularities on the Earth's surface were formed by the elevation and sinking of the originally flat strata (Woodward, 1695).

Woodward's essay provided an explanation for the existence and distribution of fossils that did not conflict with religious beliefs and aligned with the geological understanding of fossils at the time. His conclusions defined 18th century diluvial thought and his theory was the last to invoke only the Noachian Flood as an explanation for geological phenomena (Clark, 1946).

Cuvier and Buckland

As the understanding of Earth history improved and the Church's influence on science faded in the 18th century, the belief that the Noachian Flood was the only significant cataclysmic event began to dwindle. There was little evidence that an individual flood could sculpt the Earth's strata in the manner that had been observed. As such, diluvial thought began shifting towards a series of floods, rather than the Noachian Flood alone (Huggett, 1989). This development was spearheaded by Georges Cuvier, whose views were radically different than any expressed before him (Clark, 1946).

Despite his Christian faith, Cuvier never showed published interest in reconciling the geological record with Genesis. Instead, he focused on determining a precise record of Earth's history, primarily through investigation into fossil distribution and stratigraphic succession. His conclusion, that a series of successive catastrophes sculpted the Earth, was predicated on a variety of otherwise unexplainable stratigraphic patterns. Such patterns included the identification of alternation between freshwater and marine strata in the London and Paris Basins (Hallam, 1983). Cuvier recognized that rocks in the basins exhibited evidence of cyclic deposition, indicating that the depositional environments had repeatedly changed. He attributed these observations to a succession of floods, thereby exposing the sediments to a series of distinct depositional environments (Clark, 1946). Cuvier suggested that these catastrophes moved and overturned the entire outer crust of the Earth and resulted in the extinction of animal species in Western Europe (Clark, 1946, Hallam, 1983). These animals were thought to have been replaced by species who migrated from other continents or seas. This implies that, contrary to the prevailing beliefs, not all deluges were necessarily worldwide (Hallam, 1983).

As Cuvier was leading diluvial thought into uncharted territories, geologist William Buckland was at the helm of the English school of catastrophism, holding the belief that geological features were sculpted by one or more cataclysmic events (Huggett, 1989). Buckland was a proponent of a recent and universal deluge, maintaining that the Noachian Flood occurred and was one of a series of floods had a distinctive impact on the Earth. Therefore, Buckland's theory did not entirely correspond with the recent Cuvierian revolution. While they agreed that there was a series of floods that sculpted the Earth, they disagreed on the magnitude of these floods and the validity of the biblical account (Hallam, 1983).

Although his approach was quite different to Cuvier's, Buckland's beliefs were essentially Cuvierian in character. In his 1820 publication *Vindicae Geologicae*, Buckland discussed the connections between his geological observations and the Bible (Clark, 1946). He described the creation of the modern Earth by a series of massive and catastrophic floods under God's guidance. He observed that even the most violent modern fluvial environments are incapable of forming valleys and basins, instead attributing these features to the extreme erosive capabilities of the Noachian Flood (Buckland, 1820). Buckland's conclusions were based on the following key arguments:

1) A retiring flood would produce the general shape and position of hills and valleys.
2) The arrangement of valleys and the existence of detached masses of strata at considerable distances from the beds indicates violent water action.
3) The deposits of gravel that occur on the summits of hills and in valleys can only be explained by a great flood.
4) The above features are uniform around the world.
5) Modern rivers are incapable of producing such features (Buckland, 1820).

Based on these arguments, Buckland concluded the Noachian Flood was entirely responsible for the formation of the modern geologic landscape.

Figure 4.19: Buckland's sketches of portions of hyena jaws. The sketch on the right shows a portion of the upper-left jaw of modern hyenas. The sketch on the left shows the analogous portion of the upper-left jaw of a hyena fossil found in the Kirkland Cave. Their morphological similarities led Buckland to conclude that the fossils he found were of hyenas who lived in the Kirkland Cave prior to the deluge.

In 1823, Buckland published his book *Reliquiae Deluvianae*. Unlike Buckland's previous works, which focused more on patterns in deposition, landforms, and stratigraphy, *Reliquiae Deluvianae* was centered around fossil deposits. In the book, he reported on his work at the Kirkdale Cave in Yorkshire, England (Hallam, 1983; Huggett, 1989). He found a wide variety of animal teeth and bones, including the remains of hyenas, elephants, horses, deer, rhinoceroses, hippopotami, lions, and bears (Figure 4.19). He concluded that this collection of fossils was likely a hyena den, with the other animal remains having been dragged into the cave. The uppermost layer of bones was perfectly preserved, indicating they must have been buried quickly, leading Buckland to believe that they were covered by a layer of mud washed in by the waters of the deluge. The mud in the cave was also uniformly deposited, suggesting that only one flood had occurred since the deposition of the fossils (Buckland, 1823).

Buckland initially assumed this flood to be the Noachian Flood, but later determined that it must have predated man's creation due to the lack of human fossils in the cave (Hallam, 1983). This theory, referred to as the Hyena Cave Theory, became extremely popular, despite being inconsistent with traditional diluvial theory. While traditional diluvialists concluded that many of the bones found in the cave (particularly those native to tropical environments) were transported by flood waters from Africa and deposited in the cave, Buckland believed these animals lived and died in Yorkshire. The disagreement between Buckland's Hyena Cave Theory and traditional diluvial thought caused a stir among geologists and theologists, despite Buckland confirming his biblical interpretation of Earth history in *Reliquiae Deluvianae* (Huggett, 1989).

Among those that criticized Buckland's conclusions was American geologist and chemist, Benjamin Silliman. Silliman wrote that fossils could not have been deposited in the strata of the Earth by the deluge. Instead, he was of the belief that proof of the Noachian Flood could only be found in the deposits of loam and gravel spread over the entire globe. The rise of this school of thought, that the deluge could only have a lasting impact on sediments rather than the strata of the Earth, was the last major evolution of diluvial thought prior to its demise (Clark, 1946).

Criticisms of Diluvialism

From its birth to its death, diluvialism faced heavy criticism. Some of the earliest critics were Biblicists and writers in the Oxford and Edinburgh schools of geology. In England, biblical literalists took issue with the severe "downgraded significance" of the deluge presented by diluvial theory, by restricting its geological effect to superficial phenomena and gravel deposits (Rupke, 1983). Contrastingly, Scottish opposition to diluvial theory was based on the belief that it over-attributed geological significance to the biblical deluge. Holding more secular views than English scholars, Scottish writers argued that the biblical deluge was more a subject for theological inquiry than geological, and that the Bible should "tell only the moral destiny of a man" rather than try to explain science (Rupke, 1983). While it may seem as though Scottish geologists were amidst a crisis of faith, their push for secular geology was in fact inspired by critical interpretation and thought rather than disbelief (Rupke, 1983). They recognized that the biblical deluge did not account for the violent tidal waves described by diluvial theory and observed the lack of human fossils to occur in the deposits of supposedly deluge-drowned animals (Hallam, 1983). Scottish priest John Fleming openly opposed diluvial theory, publishing an article in 1820 arguing that any extinct fossils had not been caused by geological catastrophes, but occurred gradually. A year later, Fleming progressed his theory using evidence from Buckland's Hyena Cave Theory. He argued it was more likely that the regional extinction of hyenas was caused by human activity and the expansion of civilization than by diluvial activity. After this proposition, he expanded his argument against diluvialism from fossils to diluvial gravel deposits, claiming these as well could be explained by gradual events (Rupke, 1983).

In addition to opposition from both biblical literalists and secularists, there were two main issues revealed later in the diluvial debate. The first issue stemmed from the fact that diluvial phenomena must be explained by either uniformitarianism or cataclysmic flooding. Diluvialists used evidence from a region in England heavily impacted by glacial activity (though they were unaware of this fact at the time) to prove the catastrophe-based diluvial theory due to the unnatural complexity of valley morphology. Opposing them, anti-diluvialists George Scrope, Charles Lyell, and Roderick Murchison used evidence from the Auvergne valley in France to conclude that a single catastrophic deluge could not have produced the observed structures. The valleys were discovered by Scrope to have been repeatedly filled by lava flows and excavated by continuous fluvial erosion, eliminating the possibility of a biblical origin (Rupke, 1983). After this discovery, Scrope advised other geologists to be cautious attributing similar geological phenomena to catastrophes due to the absence of volcanic activity. After visiting the same valley, Lyell and Murchison noted that diluvial gravel deposits appeared below the volcanic deposit that formed the valley. The valley must have been older than the diluvial gravel deposits and therefore older than the catastrophic event previously believed to have formed the valley's morphology (Rupke, 1983). However, nearly all geologists noticed the complexity of valley morphology present in England and believed that some diluvial phenomena could only be explained through a catastrophic lens. It was from this thought that Louis Agassiz's Glacial Hypothesis originated in 1840 (Rupke, 1983).

The second issue in the debate was whether the catastrophe explaining the phenomena was identical to the biblical deluge or was more characteristic of an event with an earlier date, predating the first humans. Many geologists began to theorize that the most recent geological deluge occurred much earlier than the biblical deluge, likely not producing any significant geologic phenomena at all. This redating was mostly put forward due to the lack of human fossils found in diluvial deposits, as mentioned previously by Buckland (Rupke, 1983). Geologists began to credit the formation of valleys and diluvial deposits to several, potentially regional, naturally caused deluges occurring long before the dawn of man. Consequently, numerous geologists proposed indefinite cyclical periods of deluges (Page, 1963).

Glacial and Iceberg Theory

William Buckland was a unique geologist whose work aligned almost perfectly with the development, argument against, and eventual abandonment of diluvial theory. Thus, an ideal and analogous way to examine the evolution of diluvial thought is through the changes in his ideas and work in geology.

Despite other criticism by Scrope and Fleming, the lack of human fossils remained the fatal flaw in diluvial theory throughout the 1820s. Buckland, reluctant to renounce diluvialism, was convinced that human fossils would eventually be found (Rupke, 1983). He argued that since it was unlikely humans dispersed from Central and Southern Asia, deposits in other countries must house the evidence he was searching for. The lack of human fossils eventually persuaded him to separate the biblical deluge from the last geologic one, as so many geologists had begun to. It was not until 1836 that Buckland finally rejected diluvialism and was shortly thereafter brought under the wing of Swiss geologist Louis Agassiz, who introduced him to Glacial Theory (Rupke, 1983). In 1838, Agassiz observed polished, striated, and furrowed surfaces on the slopes of the Jura Mountain range on the Swiss-French border. After this observation and careful examination of glaciers in the Alps, he was convinced that the structures he saw were from glacial activity. He found similar structures and geologic phenomena in Great Britain but did not associate them with glacial activity until later (Hallam, 1983). After Buckland and his wife visited the same geological phenomena on their honeymoon to the Alps, he joined forces with Agassiz to present the Glacial Theory to the British Geological Society in 1840 (Rupke, 1983). The Glacial Theory had 3 main postulates made from observations of active glaciers:

1) Moraines in the alps indicated that the alpine glaciers had once stretched further down the valleys and across the Swiss plains.
2) Ice covering the Jura Mountains is responsible for leaving erratic boulders or blocks.
3) The geographical distribution of erratics serves as evidence for the ice sheet theorized to have covered the majority of the Northern Hemisphere (Agassiz, 1840).

The evidence found by Agassiz for a glacial period extends beyond moraines, deposits, and erratic boulders. It was also exemplified by Roche moutonnées, polished and scratched surfaces or sculptured rocks, all of which are indicators of the movement of giant ice. Based on this evidence, Agassiz believed that at some point, all of Northern Europe, Asia, and America were covered by an ice sheet. This ice sheet embedded the mammals whose remains are now found in the gravel and mud of arctic regions. He concluded that once this sheet melted, the massive currents transported and deposited most diluvial phenomena seen, from glacial erratics to the gravel underlying English valleys (Rupke, 1983).

However, many of Buckland's colleagues believed the idea of a large-scale period of land ice to be implausible. For Buckland, the idea was the missing piece to solve his conflicting biblical and geological views, explaining the phenomena previously justified by the deluge (Rupke, 1983).

The same observation of glacial erratics and boulders spread across Northern Europe and America was also used as the evidence giving rise to Lyell's Iceberg Theory. Iceberg Theory attributed the unexpectedly placed boulders to be transported by ice floating across an epeiric sea (Lyell, 1835). The theory was developed further by Murchison in 1836 using marine fossils found in diluvial debris at the summits of mountains. Murchison postulated that Northern Europe had been covered by water with depths high enough to create islands from mountain summits capped in ice. In his publication, Murchison cited Charles Darwin's unpublished work of glacier observations to theorize that icebergs had emerged at the ice-capped mountain tops and transported diluvial deposits and erratics across Great Britain (Rupke, 1983).

The Shift Away from Diluvialism

While both Glacial and Iceberg Theory faced criticism from the geological community, Glacial Theory had what appeared to Buckland as an insurmountable wall of skepticism. Without the approval of his colleagues and students, Buckland's confidence in Glacial Theory dwindled. In 1841 he began to consider Iceberg Theory while maintaining belief in an ice age. He divulged that floating icebergs might have had the potential to create glacial scratches along the beds of shallow marine environments as they drifted (Rupke, 1983). For many geologists, smaller pieces of ice, such as icebergs, were much easier to conceptualize than a continental-sized ice sheet. As a result, Iceberg Theory trumped Glacial Theory for many years. Despite this, the intellectual shift from diluvial to glacial mechanisms of geological phenomena was well underway. Glaciers offered a unique advantage over a deluge in explaining geological phenomena due to their sheer power and force to create scratches and grooves. The melting of massive land ice also allowed geologists to retain their beliefs in a flood, but to modify the theory of its origin from biblical to glacial (Rupke, 1983). Glacial Theory had bigger implications than explaining the transportation of erratic boulders or the appearance of rock scratches; it implicated evidence of an ice age that may be responsible for a mass extinction of animals, heavily impacting the understanding of species evolution (Rupke, 1983). Eventually, the Iceberg and Glacial Theories merged, with geologists believing that the glaciation of Great Britain was likely followed by its submergence beneath an epeiric sea and a reappearance of glaciers that generated moraines and valleys. After this, Glacial Theory critics such as Murchison and Lyell shifted to believe in land ice, although the widespread shift to the modernly accepted Glacial Theory was not complete until the late 19th century (Hallam, 1983).

Modern Evidence of the Noachian Flood

Glacial Theory is widely accepted today and is often used as an explanation for the geological phenomena seen around the world. Numerous findings have outlined periods of glaciation within Earth's history, with the most recent period occurring around 21 Ka (Otto-Bliesner, et al., 2006). This glacial maximum is likely the culprit of numerous diluvial features such as Roche moutonnées, glacial erratics, striations, and deep valleys. However, the true origin of the myth of Noah's Flood remains unexplained. Similar flood myths are present in numerous cultures around the world, suggesting the existence of a great flood, albeit of much smaller magnitude than described in the Bible (Yanko-Hombach, 2007).

While theologists predict the myth of Noah's Flood originated in ancient Mesopotamia, William Ryan and Walter Pitman's Flood Hypothesis pinpoints the historical Flood far from Mesopotamia, on the Black Sea's northwestern shelf (Ryan and Pitman, 1998). In their 1998 book *Noah's Flood: The New Scientific Discoveries About the Event*, Ryan and Pitman proposed a catastrophic flood in the Black Sea during the early Holocene, analogous to the biblical deluge. Using extensive seismic profiles, sediment cores, and C^{14} dating of fossilized shells, they concluded that between 14.7 and 10.0 Ka, the Black Sea was a freshwater lake with a surface roughly 140 m below modern sea levels. According to Ryan and Pitman's Flood Hypothesis, water broke through the narrow Bosphorus Strait roughly 7.2 Ka, connecting the freshwater Black Sea to the saltwater Mediterranean Sea (Figure 4.20). Saltwater was funneled through the Strait at a speed of approximately 22 m/s, which rapidly filled and salinized the lake. This caused the sea level of the Black Sea to rise at a rate of 15 cm/day, resulting in a sea level increase of 100 m within two years. This flood supposedly caused the submergence of more than 100,000 km^2 of exposed shelf, displacing many foragers and farmers from the region, and acting as the historical basis for Noah's Flood (Ryan and Pitman, 1998).

Ryan and Pitman's theory inspired research interest in the geology of the Black Sea, both in support and opposition of their hypothesis. Others began to investigate the Black Sea, finding coastal dunes, wave-cut terraces, numerous freshwater mussels, and drowned beaches as evidence of a submerged coastline. The same coastline was found to have an overlapping cover of mud containing molluscs native to the Mediterranean Sea. The age of the molluscs was found to vary between 7.8 and 4.0 Ka, which was used to determine that saltwater had broken the barrier and flushed into the Bosphorus Strait around 7.8 Ka (Yanko-Hombach, 2007).

Contradicting evidence from offshore sedimentary successions on the Southern coast presented by Gőrűr, et al., (2001) showed that the water level of the original Black Sea freshwater lake likely rose gradually between 8.0 and 7.2 Ka. Only when it had reached a level of 18m did the influx of Mediterranean water commence. Further refuting the theory was the suggestion that the sea level of the Black Sea had been higher than the Sea of Marmara and had been consistently flowing into the ocean from 10.5 Ka. The bedform asymmetry and climbing mid-shelf delta found in the Sea of Marmara directly south of the mouth of the Strait provided evidence to suggest the Strait could not flow two ways. It also suggested that the salinization of the Black Sea must have occurred closer to 8.5 Ka (Yanko-Hombach, 2007). In response to these criticisms, Ryan and Pitman modified their hypothesis, adjusting the date of the Black Sea flooding through the Bosphorus Strait from 7.2 Ka to 8.4 Ka (Yanko-Hombach, 2007).

Figure 4.20: Map of the Black Sea during the Crimean War. The Black Sea is connected to the Sea of Marmora in the bottom left corner by the Bosphorus Strait. According to the Flood Hypothesis, when sea levels rose in the Mediterranean Sea (south-west of the Sea of Marmora), it flooded the Sea of Marmora, consequently sending massive amounts of water through the Bosphorus Strait and into the Black Sea. The subsequent flooding of the coastal communities surrounding the Black Sea is the proposed historical basis for Noah's Flood.

Opposition to the Flood Hypothesis

Western scientists, like Ryan and Pitman, have traditionally used data and materials from outside the Black Sea to justify their hypotheses. There is abundant scientific data recovered directly from the Black Sea by former Soviet and Eastern Bloc scientists that have been ignored in the global debate due to language barriers and a lack of collaboration between Eastern and Western scientists (Yanko-Hombach, 2007).

Yanko-Hombach (2007) utilized data from a marine geological survey of the Black Sea shelf to propose a non-catastrophic and gradual rise in sea level. Data from the survey included short sediment cores, high-resolution seismic profiles, and biostratigraphy from molluscs and foraminifera serving as paleoenvironmental indicators, which collectively contradict Ryan and Pitman's Flood Hypothesis. Sea levels of the Black Sea were found to have risen and lowered in an oscillating manner throughout the interglacial period, averaging around 3 cm/100 years rather than the 15 cm/day presented in the Flood Hypothesis. A gradual increase of sea level by 3 cm/100 years would likely not have impacted the lives of coastal inhabitants and is therefore unlikely to have been the historical site of Noah's Flood (Yanko-Hombach, 2007).

Geologists and historians have yet to come to a consensus on the period, location, or existence of a real catastrophic deluge analogous to the cross-culturally occurring myth of the Flood. Despite nearly 200 years of developments in geological understanding, the debate regarding the existence and impacts of Noah's Flood remains just as divided today as in the early 1800s.

Chapter 4 References

Acocella, V. and Neri, M., 2009. Dike propagation in volcanic edifices: Overview and possible developments. Tectonophysics, 471(1), pp.67–77.

Agassiz, L., 1840. Études sur les glaciers. Neuchâtel.

Agrusta, R., Goes, S. and van Hunen, J., 2017. Subducting-slab transition-zone interaction: Stagnation, penetration and mode switches. Earth and Planetary Science Letters, [online] 464, pp.10–23. https://doi.org/10.1016/j.epsl.2017.02.005.

Aladejare, A.E., Ozoji, T., Lawal, A.I. and Zhang, Z., 2022. Soft Computing-Based Models for Predicting the Characteristic Impedance of Igneous Rock from Their Physico-mechanical Properties. Rock Mechanics and Rock Engineering, 55(7), pp.4291–4304.

Al-Khwārazmi, M.A.A.A.M.ibn A.ibn and Rosen, F.A., 1831. The algebra of Mohammed Ben Musa. London: Printed for the Oriental Translation Fund.

Al-Rawi, M.M., 2002. The Contribution of Ibn Sina (Avicenna) to the developement of Earth Sciences. Foundation for Science Technology and Civilisation. [online] Available at: <https://holypearls.com/Bayanaat%202015/Books/islamicbooks/ibnsina.pdf> [Accessed 11 December 2022].

Anhaeusser, C.R., 2014. Archaean greenstone belts and associated granitic rocks – A review. Journal of African Earth Sciences, 100, pp.684–732.

Aristotle and Guthrie, W.K.C., 1939. On the Heavens. Cambridge, MA: Harvard Univirsity Press.

Āryabhaṭa and Clark, W.E., 1930. The aryabhatiya: An ancient indian work on mathematics and Astronomy. Chicago: University of Chicago Press.

Ben-Menahem, A., 1995. A Concise History of Mainstream Seismology: Origins, Legacy, and Perspectives. Bulletin of the Seismological Society of America, [online] 85(4), pp.1202–1225. Available at: <https://engineering.purdue.edu/~ce597m/Handouts/ConciseHistory_BenMenahem.pdf> [Accessed 11 December 2022].

Berggren, J.L., Jones, A. and Ptolemy, 2000. Ptolemy's Geography: an annotated translation of the theoretical chapters. Princeton: Princeton University Press.

Boccaletti, D., 2019. The shape and size of the Earth: A historical journey from homer to artificial satellites. Cham, Switzerland: Springer.

Bolt, B.A., 1994. Inge Lehmann. Physics Today, [online] 47(1), pp.61–61. https://doi.org/10.1063/1.2808386.

Bonaccorso, A., Aoki, Y. and Rivalta, E., 2017. Dike propagation energy balance from deformation modeling and seismic release. Geophysical Research Letters, 44(11), pp.5486–5494.

Buckland, W., 1820. Vindicae Geologicae. Oxford: Oxford University Press.

Buckland, W., 1823. Reliquiae Diluvianae. 2nd ed. London: Whitefriars Press.

Burkholder, E.F., 1987. Geodesy. The Surveying Handbook, pp.390–433.

Bushman, J.R., 1983. Hutton's Uniformitarianism. Brigham Young University Studies, [online] 23(1), pp.41–48. Available at: <https://www.jstor.org/stable/43040912> [Accessed 11 December 2022].

Chen, G.-N. and Grapes, R., 2007. Granite Genesis: In Situ Melting and Crustal Evolution. Dordrecht: Springer Netherlands.

Chen, J., Cazenave, A., Dahle, C., Llovel, W., Panet, I., Pfeffer, J. and Moreira, L., 2022. Applications and challenges of Grace and grace follow-on satellite gravimetry. Surveys in Geophysics, 43(1), pp.305–345.

Clark, H.W., 1946. The New Diluvialism. Angwin: Science Publications.

Cloud, P., 1970. Adventures in Earth History. San Francisco, CA: W. H. Freeman and Company.

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

Cook, F.A., White, D.J., Jones, A.G., Eaton, D.W.S., Hall, J. and Clowes, R.M., 2010. How the crust meets the mantle: Lithoprobe perspectives on the Mohorovičić discontinuity and crust–mantle transitionThis article is one of a series of papers published in this Special Issue on the theme Lithoprobe — parameters, processes, and the evolution of a continent . Canadian Journal of Earth Sciences, [online] 47(4), pp.315–351. https://doi.org/10.1139/E09-076.

Cooper, J.D., Miller, R.H. and Patterson, J., 1990. A Trip Through Time: Principles of Historical Geology. Second ed. United States of America: Merrill Publishing Company.

Copson, A., 2015. What Is Humanism? In: A. Copson and A.C. Grayling, eds. The Wiley Blackwell Handbook of Humanism. [online] Chichester, UK: John Wiley & Sons, Ltd. pp.1–33. https://doi.org/10.1002/9781118793305.ch1.

Cormack, L.B., 1994. Flat earth or round sphere: Misconceptions of the shape of the Earth and the fifteenth-century transformation of the world. Ecumene, 1(4), pp.363–385.

Darwin, C., 1844. Geological Observations on the Volcanic Islands, Visited During the Voyage of HMS Beagle: Together with Some Brief Notices on the Geology of Australia and the Cape of Good Hope. Cambridge Library Collection - Earth Science. Cambridge: Cambridge University Press.

Davaille, A. and Romanowicz, B., 2020. Deflating the LLSVPs: Bundles of Mantle Thermochemical Plumes Rather Than Thick Stagnant "Piles". Tectonics, [online] 39(10). https://doi.org/10.1029/2020TC006265.

Davison, C., 1921. Founders of Seismology.—III. John Milne. Geological Magazine, [online] 58(9), pp.385–396. https://doi.org/10.1017/S0016756800104807.

Draper, J.W., 1875. History of the conflict between religion and science: By John William Draper. Bildet Vol. XIII von the International Scientific Series. London: King.

Ermarth, E., 1981. Realism, Perspective, and the Novel. Critical Inquiry, 7(3), pp.499–520. https://www.jstor.org/stable/1343115.

Erskine-Hill, H., 2004. Renaissance Realism: Narrative Images in Literature and Art by Alastair Fowler. The Review of English Studies, [online] 55(221), pp.615–617. Available at: <https://www.jstor.org/stable/3661457>.

Flechtner, F., Neumayer, K.-H., Dahle, C., Dobslaw, H., Fagiolini, E., Raimondo, J.-C. and Güntner, A., 2016. What can be expected from the grace-fo laser ranging interferometer for earth science applications? Remote Sensing and Water Resources, pp.263–280.

Frascá, M.H.B. de O. and Del Lama, E.A., 2018. Igneous Rocks. In: P.T. Bobrowsky and B.

Frisch, W., Meschede, M. and Blakey, R.C., 2010. Plate Tectonics: Continental Drift and Mountain Building. Springer Science & Business Media.

Ghiorso, M., 2003. Thermodynamic models of igneous processes. Annual Review of Earth and Planetary Sciences, 25, pp.221–241.

Golubchikov, Y.N., 2021. Return to neptunism: review article. International Journal of Hydrology, Volume 5, pp.1-7.

Grant, F.C., 1933. The Beginning of Jesus' Ministry. Journal of Biblical Literature, 52(4), p.189.

Greenberg, J.L., 1995. The problem of the Earth's shape from Newton to clairaut: The rise mathematical science in eighteenth-century Paris and the fall of Normal science. Cambridge: Cambridge University Press.

Guntau, M., 1989. Concepts of Natural Law and Time in the History of Geology. Earth Sciences History, [online] 8(2), pp.106–110. https://doi.org/10.17704/eshi.8.2.02w88w234323x503.

Hall, M.B., 1994. The scientific renaissance 1450-1630. New York: Dover.

Hallam, A., 1983. Great Geological Controversies. New York: Oxford University Press.

Hansen, J.M., 2009. On the origin of natural history: Steno's modern, but forgotten philosophy of science. Bulletin of the Geological Society of Denmark, [online] 57, pp.1–24. https://doi.org/10.37570/bgsd-2009-57-01.

Hastie, A.R., Fitton, J.G., Kerr, A.C., McDonald, I., Schwindrofska, A. and Hoernle, K., 2016. The composition of mantle plumes and the deep Earth. Earth and Planetary Science Letters, [online] 444, pp.13–25. https://doi.org/10.1016/j.epsl.2016.03.023.

Heilbron, J.L., 2003. Ernest Rutherford: and the explosion of atoms. Oxford portraits in science. Oxford ; New York: Oxford University Press.

Hoare, M.R., 2004. The quest for the true figure of the earth: Ideas and expeditions in four centuries of geodesy. Burlington (VT): Ashgate Pub.

Huggett, R. J., 1989. Cataclysms and earth history: the development of diluvialism. New York: Oxford University Press

Kang, Z., Tapley, B., Bettadpur, S., Ries, J., Nagel, P. and Pastor, R., 2006. Precise orbit determination for the Grace Mission using only GPS Data. Journal of Geodesy, 80(6), pp.322–331.

Kenton, E., 1928. The book of earths. New York: Morrow.

Kinny, P.D., 2003. Lu-Hf and Sm-Nd isotope systems in zircon. Reviews in Mineralogy and Geochemistry, [online] 53(1), pp.327–341. https://doi.org/10.2113/0530327.

Kölbl-Ebert, M., 2001. Inge Lehmann's paper: " P' " (1936). Episodes Journal of International Geoscience, [online] 24(4), pp.262–267. Available at: <https://courses.seas.harvard.edu/climate/eli/Courses/EPS281r/Sources/Inner-Core/Lehmann-1936-extracts+interpretation.pdf>.

Koutsoukos, E.A.M., 2005. Stratigraphy: Evolution of a Concept. In: E.A.M. Koutsoukos, ed. Applied Stratigraphy, Topics in Geobiology. [online] Springer Netherlands. pp.3–19. https://doi.org/10.1007/1-4020-2763-X_1.

Kristeller, P.O., 1978. Humanism. Minerva, [online] 16(4), pp.586–595. https://doi.org/10.1007/BF01100334.

Lee, W.H.K., International Association of Seismology and Physics of the Earth's Interior and International Association for Earthquake Engineering eds., 2002. International handbook of earthquake and engineering seismology. International geophysics series. Amsterdam ; Boston: Academic Press.

Leroi, A.M., 2014. The lagoon: how Aristotle invented science. New York, New York: Viking.

Levin, H., 2006. The Earth Through Time. Eighth ed. John Wiley & Sons, Inc.

Lindberg, D.C., 2008. The beginnings of western science: The European scientific tradition in philosophical, religious and institutional context, prehistory to A.D. 1450. Chicago, IL: University of Chicago Press.

Longhorn, M. and Hughes, S., 2015. Modern Replication of Eratosthenes' measurement of the circumference of Earth. Physics Education, 50(2), pp.175–178.

Lyell, C., 1835. Principles of Geology. London.

Macy, G., 1996. Was there a 'the Church' in the Middle Ages? Studies in Church History, [online] 32, pp.107–116. https://doi.org/10.1017/S0424208400015369.

Marker, eds. Encyclopedia of Engineering Geology, Encyclopedia of Earth Sciences Series. Cham: Springer International Publishing. pp.504–509.

Master, S., 2009. Plutonism versus Neptunism at the southern tip of Africa: the debate on the origin of granites at the Cape, 1776–1844. Earth and Environmental Science Transactions of The Royal Society of Edinburgh, 100(1–2), pp.1–13.

Master, S., 2012. Darwin as a geologist in Africa - dispelling the myths and unravelling a confused knot : research article. South African Journal of Science, 108(9), pp.1–5.

Mavroudi, M., 2015. Translations from Greek into Latin and Arabic during the Middle Ages: Searching for the Classical Tradition. The Medieval Academy of America, 90(1), pp.28–59.

McCall, G.J.H., 2005. Zircon. In: Encyclopedia of Geology. [online] Elsevier. pp.358–367. https://doi.org/10.1016/B978-0-08-102908-4.00271-X.

McSaveney, E., 2006. Historic earthquakes - The 1929 Arthur's Pass and Murchison earthquakes. In: Te Ara - the Encyclopedia of New Zealand. [online] Available at: <http://www.TeAra.govt.nz/en/historic-earthquakes/page-5> [Accessed 11 December 2022].

Mintz, L.W., 1981. Historical Geology: The Science of a Dynamic Earth. Third ed. Columbus, OH: Charles E. Merrill Publishing Co.

Nicastro, N., 2015. Circumference: Eratosthenes and the ancient quest to measure the Globe. New York: St. Martin's Griffin.

Nomozov, A.N., 2022. The Contribution of Scientists of the Near and Middle East to the Development of World Science. Vestnik magistratury, [online] 4(1), p.127. Available at: <https://www.magisterjournal.ru/docs/VM127_1.pdf#page=24>.

Omodeo, P.D., 2015. Geocentrism. Encyclopedia of Renaissance Philosophy, pp.1–6. Cham, Switzerland: Springer.

Ospovat, A.M., 1976. The Distortion of Werner in Lyell's 'Principles of Geology'. The British Journal for the History of Science, 9(2), pp.190–198.

Otto-Bliesner, B.L., Brady, E.C., Clauzet, G., Tomas, R., Levis, S. and Kothavala, Z., 2006. Last Glacial Maximum and Holocene Climate in CCSM3. Journal of Climate, 19(11), pp.2526–2544.

Page, L.E., 1963. The Rise and Fall of Diluvial Theory in British Geological Thought. Ph. D. University of Oklahoma.

Pápay, G., 2022. Ptolemy's methodological principles in the creation of his map projections. KN - Journal of Cartography and Geographic Information, 72(2), pp.89–101.

Petersson, A., Kemp, A.I.S., Gray, C.M. and Whitehouse, M.J., 2020. Formation of early Archean Granite-Greenstone Terranes from a globally chondritic mantle: Insights from igneous rocks of the Pilbara Craton, Western Australia. Chemical Geology, 551, p.119757.

Playfair, J., 1802. Illustrations Of The Huttonian Theory Of The Earth. Urbana, University of Illinois Press.

Prodehl, C., Kennett, B., Artemieva, I.M. and Thybo, H., 2013. 100 years of seismic research on the Moho. Tectonophysics, [online] 609, pp.9–44. https://doi.org/10.1016/j.tecto.2013.05.036.

Rafferty, J.P., 2022. Inge Lehmann. In: Encyclopedia Britannica. [online] Available at: <https://www.britannica.com/biography/Inge-Lehmann> [Accessed 11 December 2022].

Ramos, V.A., 2022. Humboldt's Interpretation of the Andean Geology. In: G.C. Falk, M.R. Strecker and S. Schneider, eds. Alexander von Humboldt: Multiperspective Approaches. Cham: Springer International Publishing. pp.117–134.

Rather, G.M. and Kanth, T.A., 2018. Contribution of Muslim Scholars and its Impact on Development of Geography. International journal of movement education and social science., [online] 7(2). Available at: <https://www.researchgate.net/profile/G-Rather-2/publication/354777240_Contribution_of_Muslim_Scholars_and_its_Impact_on_Development_of_Geography/links/614c1a8b3c6cb31069878c27/Contribution-of-Muslim-Scholars-and-its-Impact-on-Development-of-Geography.pdf>.

Rawlinson, N., Pozgay, S. and Fishwick, S., 2010. Seismic tomography: A window into deep Earth. Physics of the Earth and Planetary Interiors, [online] 178(3–4), pp.101–135. https://doi.org/10.1016/j.pepi.2009.10.002.

Repcheck, J., 2008. The Man Who Found Time: James Hutton and the Discovery of the Earth's Antiquity. New York, NY: Basic Books.

Riedweg, C., Rendall, S. and Schatzmann, A., 2008. Pythagoras: His life, teaching, and Influence. Ithaca, NY: Cornell University Press.

Roller, D.W., 2010. Eratosthenes' geography. Princeton: Princeton University Press.

Rose, A., 2022. Seismographs at Eskdalemuir Observatory, 1908–1925: tools for rethinking the origins of international cooperation in seismology. Science Museum Group Journal, [online] 16(16). https://doi.org/10.15180/211607.

Rosenberg, G.D., 2000. Making Space for Art in the Earth Sciences. Journal of Geoscience Education, [online] 48(3), pp.273–275. https://doi.org/10.5408/1089-9995-48.3.273.

Rosenberg, G.D., 2001. An Artistic Perspective on the Continuity of Space and the Origin of Modern

Geologic Thought. Earth Sciences History, [online] 20(2), pp.127–155. Available at: <https://www.jstor.org/stable/24138750>.

Roux, S., 2005. Empedocles to Darwin. The Fifth Biennial Conference of Greek Studies. .

Rupke, N.A., 1983. The Great Chain of History: William Buckland and the English School of Geology, 1814-1849. New York: Oxford University Press.

Ruse, M. ed., 2011. Evolution: the first four billion years. 1. paperback ed ed. Cambridge, Mass.: Belknap Press of Harvard Univ. Press.

Russell, B., 2007. A history of western philosophy, and its connection with political and social circumstances from the earliest times to the present day. New York: Simon and Schuster.

Ryan, W.B.F. and Pitman, W.C., 1998. Noah's Flood: The New Scientific Discoveries About the Event That Changed History. New York: Simon & Schuster.

Sanders, J.E., 1981. Principles of Physical Geology. United States of America: John Wiley & Sons, Inc.

Schroeder, J.E. and Borgerson, J.L., 2002. Innovations in Information Technology: Insights from Italian Renaissance Art. Consumption Markets & Culture, [online] 5(2), pp.153–169. https://doi.org/10.1080/1025386029001559.

Scott, E.C., 1997. Antievolution and Creationism in the United States. Annual Review of Anthropology, [online] 26, pp.263–289. Available at: <http://www.jstor.org/stable/2952523> [Accessed 17 November 2022].

Şengör, A.M.C., 2001. Is the present the key to the past or is the past the key to the present? : James Hutton and Adam Smith versus Abraham Gottlob Werner and Karl Marx in interpreting history. Boulder, CO: Geological Society of America.

Şengör, A.M.C., 2002. On Sir Charles Lyell's Alleged Distortion of Abraham Gottlob Werner in Principles of Geology and Its Implications for the Nature of the Scientific Enterprise. The Journal of Geology, 110(3), pp.355–368.

Shige Abe, 2001. Earth's Oldest Mineral Grains Suggest an Early Start for Life. NASA Astrobiology. Available at: <https://astrobiology.nasa.gov/news/earths-oldest-mineral-grains-suggest-an-early-start-for-life/> [Accessed 11 December 2022].

Spakman, W., Chertova, M.V., van den Berg, Arie. and van Hinsbergen, D.J.J., 2018. Puzzling features of western Mediterranean tectonics explainedby slab dragging. Nature Geoscience, [online] 11(3), pp.211–216. https://doi.org/10.1038/s41561-018-0066-z.

Stern, R. and Gerya, T., 2021. Earth Evolution, Emergence, and Uniformitarianism. GSA Today, [online] 31(1), pp.32–33. https://doi.org/10.1130/GSATG479GW.1.

Strauss, L., 1981. Sur l'Interprétation de la Genèse. L'Homme, [online] 21(1), pp.21–36. https://doi.org/10.3406/hom.1981.368160.

Tapley, B.D., Watkins, M.M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., Sasgen, I., Famiglietti, J.S., Landerer, F.W., Chambers, D.P., Reager, J.T., Gardner, A.S., Save, H., Ivins, E.R., Swenson, S.C., Boening, C., Dahle, C., Wiese, D.N., Dobslaw, H., Tamisiea, M.E. and Velicogna, I., 2019. Contributions of grace to understanding climate change. Nature Climate Change, 9(5), pp.358–369.

Tex, E.D., 1990. Punctuated equilibria between rival concepts of granite genesis in the late 18th, 19th, and early 20th centuries. Geological Journal, 25(3–4), pp.215–219.

The Bible: 1952. New York: Sheed & Ward.

The Editors of Encyclopaedia Britannica, 2022. Andrija Mohorovičić. In: Encyclopedia Britannica. [online] Available at: <https://www.britannica.com/biography/Andrija-Mohorovicic> [Accessed 11 December 2022].

Vai, G.B., 2021. Leonardo da Vinci's and Nicolaus Steno's Geology. Earth Sciences History, 40(2), pp.293–331.

Weller, J.M., 1960. Development of Paleontology. Journal of Paleontology, [online] 34(5), pp.1001–1019. Available at: <https://www.jstor.org/stable/1301025> [Accessed 11 December 2022].

White, A.D., 1896. A history of the warfare of science with theology in christendom: Volume 1. New York: D Appleton and Co.

Woodward, J., 1695. An Essay towards a Natural History of the Earth: And Terrestrial Bodyes, Especially Minerals. London.

Yanko-Hombach, V.V., 2007. Controversy over Noah's Flood in the Black Sea: geological and foraminiferal evidence from the shelf. In: Yanko-Hombach, V.V., Gilbert, S.G., Panin, N., Dolukhanov, P.M., eds. 2007. The Black Sea Flood Question: Changes in Coastline, Climate, and Human Settlement. Dordrecht: Springer. pp. 149-203.

Zheng, W. and Xu, H., 2015. Progress in satellite gravity recovery from implemented champ, Grace and Goce and future Grace follow-on missions. Geodesy and Geodynamics, 6(4), pp.241–247.

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Conclusion

Humanity's progress throughout all of history has been driven by one thing: our curiosity. It is what inspired us to tame fire. It is what inspired us to fully utilize our surroundings during the agrarian revolution. Most of all, it is what inspired us to understand the world around us. At the end of the day, that is what defines all of science – the pursuit of knowledge about our environment. Be it a biologist interested in understanding living systems, a chemist analyzing the behaviour of matter, or an astronomer investigating outer space, every scientist is merely curious.

The basis of geology as a scientific discipline took root as far back as Ancient Greece. The field was born from human curiosity, with early scholars particularly interested in the origin of the Earth and its subsequent change over time. As these questions were investigated and in turn became better understood, our curiosity persisted, with geologists growing interested in novel ideas and patterns to broaden our understanding. This pattern has persevered throughout history facilitating the development of geology from its infancy to its expansive and comprehensive nature today.

Throughout this book, we investigated the progression of geology and all its aspects over time by chronicling stories investigating the history of the Earth. Here, we considered the progression of a specific theory, or a particular scientist's contributions to the field, as well as the development of entire subfields of geology. By considering both the historical developments in understanding as well as the modern implications and perspectives, we have exemplified the value of human curiosity in scientific progress.

Human curiosity is undying. When a new problem or question is identified, we as humans strive to solve it. As time progresses, and the unknown becomes the known, our curiosity does not stagnate. Rather, when our current problem is solved, we push forward and begin to identify new problems and ask new questions. It is this enduring push towards a comprehensive understanding fueled by our curiosity that makes us human.

Book Image References

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