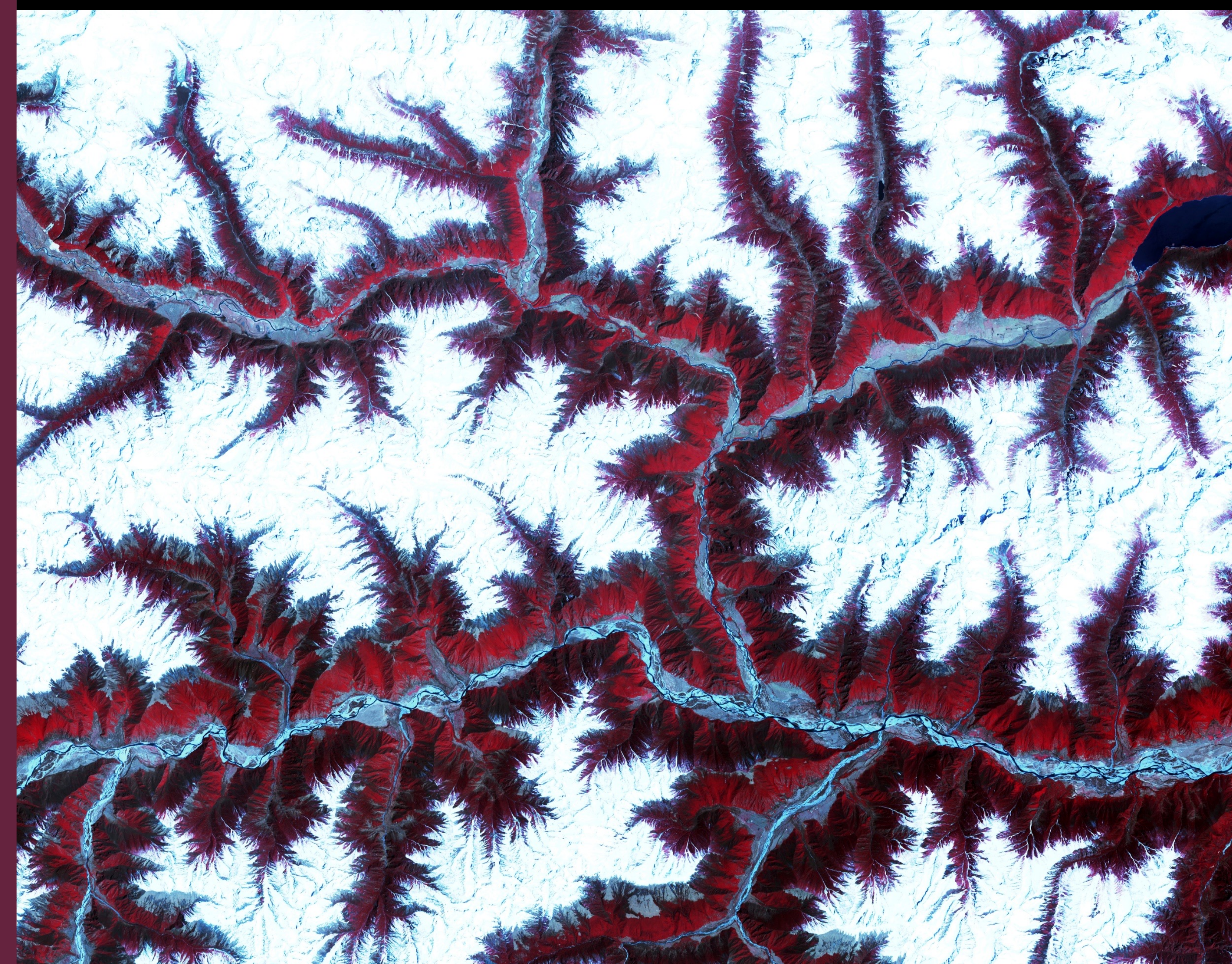
History of the Earth

Vol X

ISCI 2A18 2019/20



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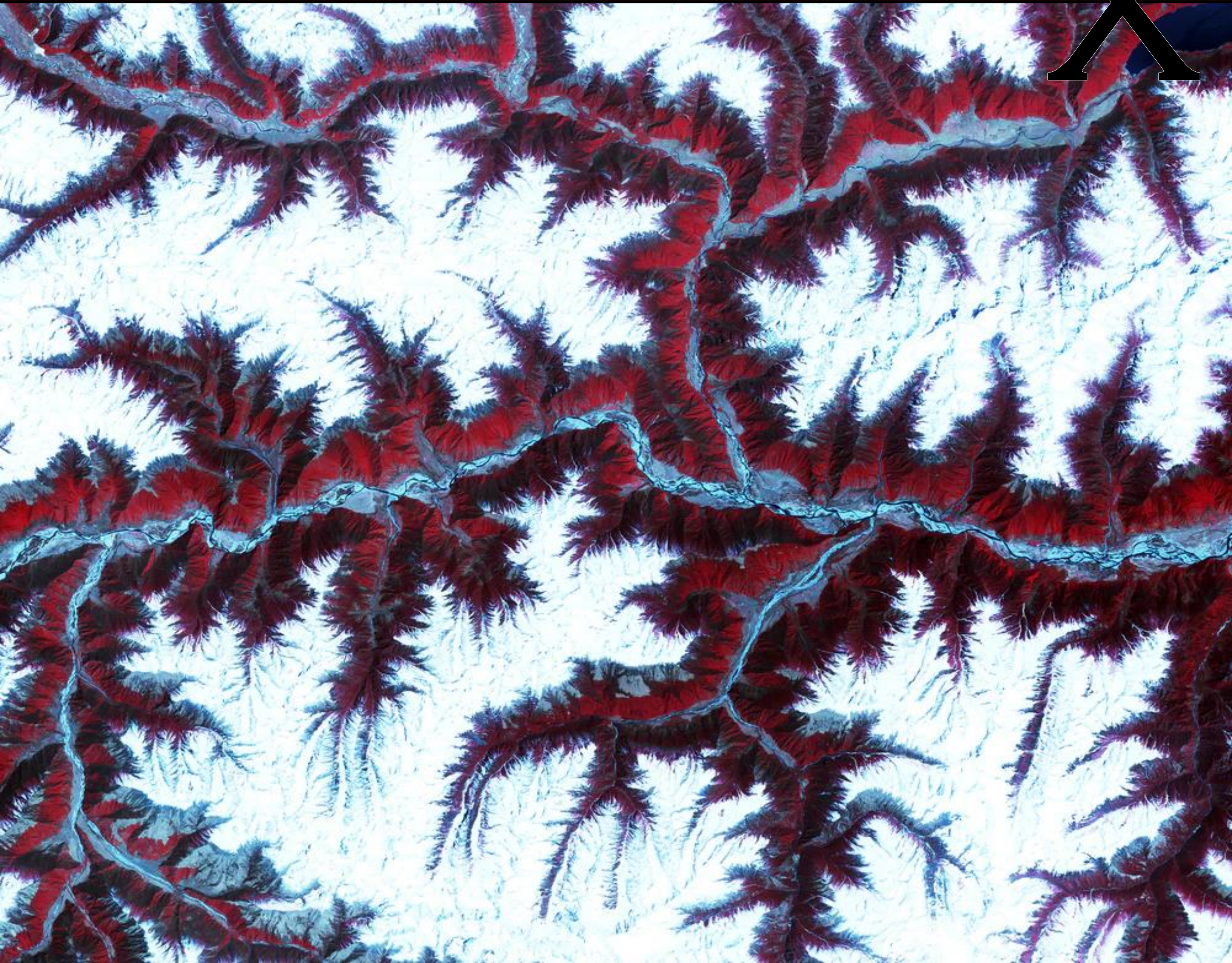

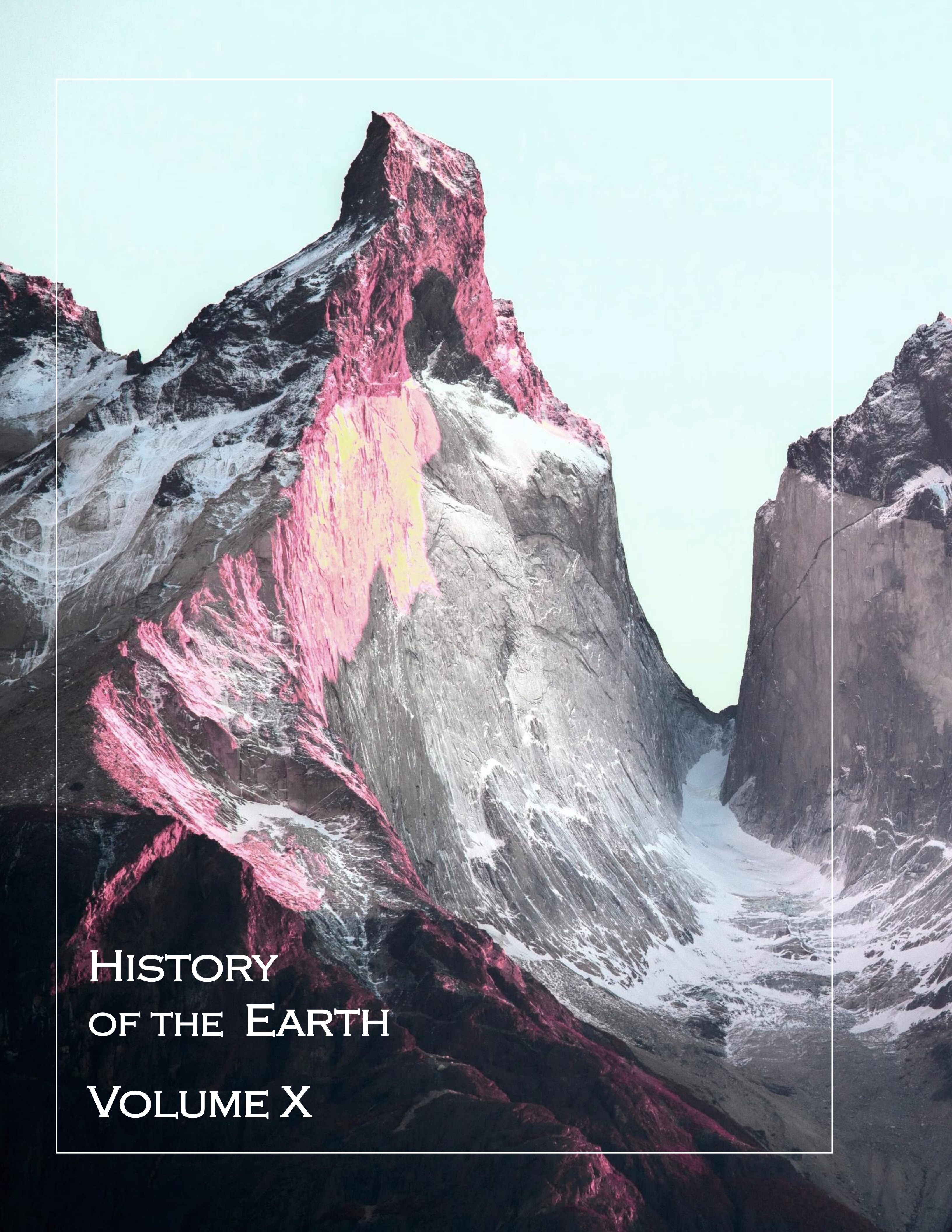

History of the Earth

Volume X

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Foreword

What science promises is immense: a method for discovering knowledge about the world; a set of tools for distinguishing true from false claims; a global community dedicated to the pursuit of truth regardless of nation, sex, gender, religion, or political difference.

But as a scientific community, we are still some distance from achieving this promise.

The distance is not merely the difficulty in specifying what exactly the scientific method *is* - though that is a problem, as philosopher Paul Feyeraband argued in his book *Against Method*. Thomas *Kuhn's Structure of Scientific Revolutions* remains the best theory we have of how science advances, and it is acknowledged to be incomplete – philosophy of science is hard. Noam Chomsky has argued that, since scientists are not waiting for philosophers to define exactly what it is they do before they work, that philosophy should follow science, not the other way around. If we agree with that, then the history of science must also be re-evaluated, such that science becomes a method that humans have always used for trying to understand the world, and not an activity that started with the Royal Society and Isaac Newton in the UK. To fulfill science's promise, we may have to discard eurocentric assumptions about knowledge radiating out from specific point sources into the world and embrace a more diffuse model of knowledge coming from everywhere – we could look at George Gheverghese Joseph's Kerala *Mathematics: History and its Possible Transmission* to Europe or Jack D. Forbes's *The American Discovery of Europe* (or indeed some of the historical chapters in this very volume) and see where these sorts of threads lead.

How is the scientific community doing in helping society distinguish true from false claims? It seems that the flower of our community is either working for, or preparing youth to work for, tech giants whose business model depends on the constant production of ever more compelling falsehoods. Or, as Jeff Hammerbacher from Facebook put it, "The best minds of my generation are thinking about how to make people click ads. That sucks." It isn't just the advertising industry either – the military-industrial complex, the financial industries, mining, industrial agriculture – all eagerly absorb scientific talent and wait eagerly for the flow of graduates. Under cover of a neutral education, young professionals' world-views are shaped to enable them to exercise human beings' innate creativity within the narrow confines of what an employer needs, as Jeff Schmidt wrote in the book *Disciplined Minds*. Schmidt noted that many of the purest scientific pursuits, like condensed matter physics, had military application.

Many of our earth sciences were developed to serve Western states and corporations as they spread out to Asia, Africa, and the Americas to take the wealth that lay in the earth's crust (or just above it, in the case of forestry), generating private profit and devastating the natural basis for life where they went (a process that, for Canada, was documented by Robert Davis and Mark Zannis in their 1973 book *The Genocide Machine in Canada*). Harsh realities lurk behind the joys of discovery.

We scientists may trace our origins back to Galileo, Kepler, and Newton, but the scientific establishment was built up in the time of Galton, Gobineau, and Pearson – racists who deployed their scientific powers to justify slavery, colonial plunder, and mass slaughter (Gobineau was specifically refuted by Haitian anthropologist Antenor Firmin, a story for another day). Are their eugenicist assumptions still alive today, corrupting the work of scientists even now? It is a concern, as Jonathan Marks notes when he asks in his book *Is Science Racist*?

We are not a global community either, but a planet of wars, sieges, and crushing sanctions, where scientists are themselves military targets. In *Nature*, journalist Declan Butler noted in 2019 how sanctions were "crippling" science in Iran. On November 27, Iranian scientist Mohsen Fakhrizadeh was assassinated in his vehicle outside of Tehran. Fakhrizadeh was a nuclear scientist, but there is no legal doctrine in operation anywhere in which nuclear scientists are targetable. If there were, there are many scientists in Canada that would be at risk of murder. As part of the global community, we should view the assassination of an Iranian scientist as being as illegitimate as we would view the assassination of a civilian of any other nationality. Those of us holding the scientific world view should be the most difficult to convince of propaganda demonizing entire populations or justifying murders of civilians.

For all that it remains unfulfilled, I still believe that science is the best promise we have. We are uniquely lucky in that to fuel our work to see to it that its promise is fulfilled, we have the continuing joys of discovery. The chapters gathered in this volume were quite evidently prepared in that spirit, and so these are joys that I wish on the you, the reader, as well.

Dr. Justin Podur, York University
November 29, 2020

Introduction

While it may seem as though humans are nothing more than a small speck within our ever-expanding universe, the idea of Earth's development and dynamics has occupied the minds of some the most remarkable individuals for centuries. It is a common point of reflection to wonder how it all came to be. Was the Earth always able to sustain life? Were dinosaurs the first animals on earth? Humanity's innate and insatiable curiosity has guided us to unlocking the mysteries of the universe that were once thought to be unfathomable. Perhaps it is this shared idea of wanting to know more about our home, Earth, that ultimately brings meaning to the very existence of humanity.

DNA, the biological molecule of life, has a unique way of telling us life stories. From being able to pinpoint where our genes originated from, to the origin of DNA itself, DNA is the determining factor of what makes humans special. But how do we find what makes the Earth special? Whether it is by diving down into the deepest, darkest parts of our seas, or catapulting ourselves into the vastness of outer space, or simply looking at the surface of our world, we can reveal some of Earth's greatest stories. Earth is the ultimate storyteller, but it is up to us to go out and find those stories. However, this is not a task for one, but a collective challenge taken up by many. The extensive process of collecting information from the Earth can take years, decades, or even centuries, and piecing the information together can take even longer.

From studying the composition of the Earth, to its geological changes, to the primitive life of some of the most extraordinary organisms, and to past theories and controversies, humanity has made a small dent into revealing the truth about how we got to where we are today. There is a famous saying which states "only time will tell". Well, time has spoken, and it is up to us to discover what it has said. This is her story. Our Earth's story.

Chapter 1. Inside The Earth

Aerial view of a network of geysers and hot springs in Yellowstone National Park.

Chapter 1.
Inside the Earth

The complexity of the Earth is unparalleled. Since the earliest of civilizations, we have been preoccupied with unraveling the mysteries that lie within this planet. And while the surface of the Earth has been thoroughly studied, the real treasure lies deep within. Understanding the internal structure, namely, Earth's composition, has been of considerable interest to researchers for centuries. To dive further into this, scientists have used a variety of avenues, ranging from the extraction of diamonds to the application of magnetic phenomena to understand the *Inside of the Earth*.

It is in our wildest of imaginations that the most subtle geological discoveries can provide insight into understanding the world around us. As one of the most prized commodities to ever graze the Earth, diamonds are widely recognized as one of the most precious stones to have ever been discovered. Their discovery not only permitted inhabitants to collect and wear highly valued jewellery but also helped to facilitate the uncovering of salient pieces of information pertaining to Earth's composition. Further, the applications of seismology, isotope ratios, and biostratigraphy in the Earth Sciences are far-reaching. The effective use of various techniques, ranging from seismic tomography to dating rock strata, provide a plethora of new opportunities for one to analyze and uncover all facets of the interior of the Earth.

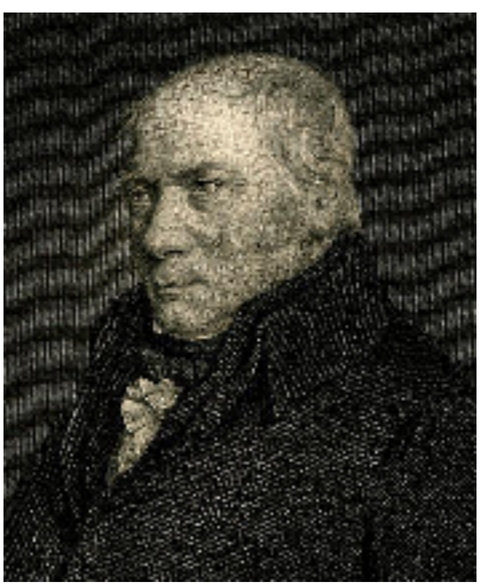
As you begin your journey to uncover more about the History of the Earth, it is in Chapter 1 that you will delve into the exploration of the historic and modern advances of mineralogy, biostratigraphy, and gemology, and learn more about the interior of the Earth.

The Beginnings of Biostratigraphy

Understanding the events that led to Earth's formation and its current composition has been of interest in researchers for many centuries. Particularly, different ways of dating the layers of rock beneath the ground were beginning to emerge towards the end of the 18th century. A common theme with many dating techniques lies within the idea that there is correlation and continuity within different layers of strata. However, what differs are the elements which provide information about each layer. Specifically, William Smith and George Cuvier made some integral contributions to our understanding of biostratigraphy as we know it today. These two figures were crucial in gaining insight into the importance of fossils and former life in understanding the age of different layers of strata.

These ideas were eventually brought forth across the Atlantic, to Canada, where a young William Logan helped develop the Geological Survey of Canada. The concepts underlying biostratigraphy were used in the creation of geological maps and stratigraphic correlations.

Figure 1.1. A portrait of William Smith, one of the key figures in studying fossils in strata as a chronological tool.



William Smith and The Somerset Canal

William Smith, born in 1769, was an engineer and geologist best known for the creation of the first geological map of England and Wales. In 1793, while working as a geological surveyor for the creation of the Somerset Coal Canal, Smith was analyzing rock cores to determine the best location for the canal (Winchester, 2001). It was during this time that he discovered a predictability in the layers of rock strata, observing patterns that pointed towards continuity in the stratigraphy of London. He noticed there were dips in rocks of different regions, indicating that strata was not always found in a horizontal manner. While working on the canal project, Smith took part in a 900 mile trip across England and Wales to observe the creation process for other canals (Cullen, 2005). He noticed that rocks which were deposited during different time periods, but under the same conditions would look alike. Initially, it was due to the difficulty in characterizing the different layers of sediment that Smith turned to studying the fossil species present in each layer as a way of establishing a chronology.

After many years of surveying land for the construction of the canal, Smith stated in what is now known as the Principle of Faunal Succession, that the regularity of the fossil sequence in rocks can be used to determine which rocks they are embedded in. With this information, the fossils could be used to create a sequence of the rocks, based on their age. This principle set the path for other geologists such as Cuvier to gain more knowledge on biostratigraphy and paleontology. It was later claimed that the real significance of Smith's work lies in the idea that different regions of London, though very distant, had similar compositions in their strata. This discovery set the stage for the concept of stratigraphic correlation (McGowran, 2008). Indeed, stratigraphic correlation later became recognized as a useful tool to gain understanding of depositional processes and environments, as it allows for geological reconstruction of regions that may be physically separated.

Georges Cuvier's Work with Mineralogy and Fossils

Georges Cuvier was born in 1769 in Montbéliard, a French speaking town which, at the time, belonged to the duke of Württemberg. Though his parents originally wanted him to go into priesthood, he eventually studied at the Karlsschule in Stuttgart, taking a variety of subjects, including zoology and dissection (Rudwick, 1997). Upon graduation, Cuvier began working as a private tutor for an aristocratic family in Normandy. It was during this time that he began to study and gain interest in natural history. Soon after, he wrote two letters to Christian Pfaff, a friend from Stuttgart, about his interest in mineralogy. Cuvier later gained recognition for these letters, as they were the first record of his geological work, including information about his personal scientific endeavours, as well as other work that was being published in scientific journals in Paris. In these letters, he discussed the topic of mineralogy, describing the geology of Normandy and layers of flint nodules in chalk. However, he spent a long time commenting on the theories of Jean-André Deluc, whose work focused more on the history of Earth, rather than the phenomena themselves. Cuvier's primary critique came from questioning Deluc's theoretical approach to the Earth sciences (Rudwick, 1997).

Figure 1.2. A portrait of Georges Cuvier, upon his arrival in Paris in 1795.

Three years later, in 1795, Cuvier started working at the Muséum National d'Histoire Naturelle, where he served as an understudy to a professor of animal anatomy. It was at the Muséum that he first came up with the idea of comparative anatomy, referring to organisms as "animal machines" (Rudwick, 1997). He chose to focus on quadrupeds and chose not to examine marine fossils, as he believed it was impossible for a single person to study the fossils of all organisms. Cuvier believed that studying fossils had the great advantage of making light of the anatomical and geographical relationship for fossil organisms, by comparing them to extant analogues. Furthermore, he discovered that studying the layers of minerals in which fossils are found provided more valuable information (Ardouin, 1970).

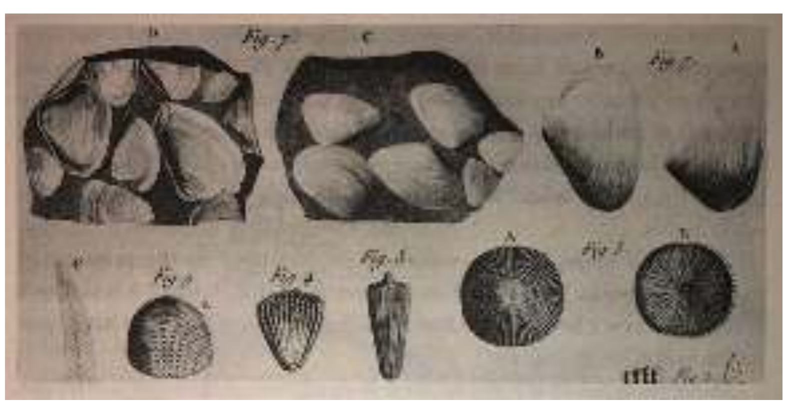


Figure 1.3. Fossils from the region around Paris from Cuvier and Brongniart's report.

Cuvier began working with Alexandre Brongniart, another French geologist, on studying the strata of the region surrounding Paris. The fossils they identified in the region indicated a younger geology in the area. In fact, Cuvier stated that the fossils found in older formations would become increasingly dissimilar to extant animals and that knowledge could be used as a method for dating layers of strata (Rudwick, 1997). It was while studying the Paris Basin that he proposed the theory of Catastrophism, that is, the idea that the differences in the succession of fossils found in various layers of strata is a result of "catastrophic" events, which altered the deposition of sediments.

The geology of the region surrounding Paris pointed towards younger, marine sediments. The oldest stratigraphic layer was Chalk (soft white limestone), which contained characteristic fossils of marine organisms, signalling a marine depositional environment, possibly a sea or an ocean. The next layers followed an orderly succession, all indicating ancient marine environments. From the bottom up following the Chalk, was Plastic Clay, Coarse Limestone, Gypseous Formation, Marine Sandstone, Siliceous Limestone, Sandstone without Shells, and Freshwater Formation. There was one final layer which differed from the others, the Detrital Silt, which was deposited after the other layers that composed the stratigraphy of Paris (Rudwick, 1997). The alternating succession of marine and freshwater conditions was determined with fossil evidence from the layers of strata. Some of the fossils Cuvier had identified included mammoths, which were relatively recent, signifying that the region surrounding Paris was young, in geological terms.

The Creation of the Geological Survey of Canada

It was not long before paleontology and stratigraphy made their way to Canada. Inspired by the geologists before him, namely Smith and Cuvier, a young Canadian named William Logan pursued his interest in cartography and stratigraphy while working in Europe.

Born in Montreal in 1798, Logan was first interested in medicine. At the age of 18, he moved to Scotland, the birthplace of his father, to further pursue his education. After one year of studying medicine, Logan made the decision to leave Edinburgh University and work for his uncle in London. It was this introduction to coal mining and copper smelting that inspired Logan's venture into geology. In 1831, William Logan was appointed manager of the smelting operation and began mapping a region of Wales in the hopes of creating a strategic plan for coal mining. Studying books about mineralogy and the geologic maps of William Smith, Logan was able to create his own maps with a high degree of accuracy, even earning him a publication by the British Geological Survey (Bell, 1907).

Logan continued his geologic mapping of Wales until 1842, when news of a Canadian project had made its way overseas. The Province of Canada, now the modern regions of southern Ontario and Quebec, had plans to create the Geological Survey of Canada. This decision was based on a desire to increase the country's industrial economy. In order to compete with more developed areas like Europe and the United States, Canada needed to gain economic independence. One important way for the country to develop its economy was through the establishment of a mining industry. To ensure Canada had the resources for this, a geological survey was required. With a £1500 grant from the United Kingdom, the Province of Canada set out to locate the region's optimal sources of coal.

Upon hearing about this opportunity, Logan made his interest in working with the Geological Survey of Canada well known. With recommendations from a variety of prominent European scientists, Logan was appointed director of the Geological Survey of Canada, also known as the GSC, in April 1842. He then began compiling the known geology of Canada with his assistant, Alexander Murray, in Montreal (Vodden, 1992). The pair began by mapping and dividing the Devonian rocks in the Gaspe Peninsula, later investigating the Paleozoic formations in Quebec and near Lake Superior. They soon discovered that none of these divisions would produce a sufficient amount of coal. It was clear to Logan that all of the rocks in these areas were older than the earliest known coal-containing formations. Despite this revelation, Logan provided good

Figure 1.4. The first geological map of Canada, created by William Logan for the Geological Survey of Canada.

reason for the GSC to continue. During his work, Logan discovered mineral-rich areas and found connections between formations in the St. Lawrence Region. Logan was passionate about geology and knew that the GSC should not be halted over the region's lack of coal. Putting his own money and efforts towards the survey, Logan continued his geologic studies and put forth one of the greatest accomplishments of the GSC, the Geology of Canada. Published in 1863, this book contained all of the work completed by Logan and the GSC up to that time, including the first geologic map of Canada (Figure 1.4). Logan's style of writing is critically acclaimed and his dedication to geology is easily noted throughout. Logan stresses the importance of stratigraphic logging and determining temporal sequences. He believed that knowing the depositional history of a region was an important part to learning the land's current geography (Eagan, 2009). He also recognized that fossils were key to finding connections and claimed that determining a rock's fossil makeup was "a fundamental principle of geology that different formations are characterized by different groups of organic remains" (Eagan, 2009). Logan later hired a paleontologist named Elkanah Billings to focus specifically on the biostratigraphy of Canada.

Billings spent his 20 years with the GSC collecting fossils and creating stratigraphic correlations, focusing on the St. Lawrence river valleys. Sediments of the same age can differ drastically in appearance, but they may contain the same fossil types, an idea first brought forth by Smith and Cuvier. Billings was able to correlate and date rocks based on the fossils they contained. The stratigraphy done by Billings on the St. Lawrence river valleys, and later Ottawa and Nova Scotia, paved the way for many other paleontologists of the GSC. One highly notable deposit investigated by the GSC later in the century was the Burgess Shale, now famous for its well-preserved fossil content (Russell, 2012).

The Fossils of the Burgess Shale

Geologic investigations of Canada continued throughout the 1800s and by 1886, the GSC sent their field geologist, Richard McConnell, to map the Rockies on both sides of the Canadian Pacific Railway. It was here that McConnell became the first geologist to collect fossils from the Burgess Shale. Located in British Columbia, this exposed region of the Rockies was particularly interesting to geologists, due to the amount of well-preserved fossils contained within. Despite McConnell's discovery, the Burgess shale was not truly investigated until the early 1900s by Charles Walcott.

Walcott was a paleontologist who became interested in studying the stratigraphy of the Burgess Shale's Cambrian regions after reading McConnell's initial report. Walcott began his studies in 1907, making note of the highly exposed strata and easily accessible fossils found in this region. Walcott had been to the Rockies before to examine trilobite beds on Mount Stephen, dating back to the Middle Cambrian period. For this reason, he was expecting to find similar beds in the area. He was pleasantly surprised to find a vast array of invertebrate fossils, immaculately preserved due to their soft body tissues and their depositional environment. The reason for the preservation was later discovered to be due to the former marine environment of the Burgess Shale, which helped with the preservation of the fossils (Caron and Rudkin, 2009).

The Cambrian organisms of the Burgess Shale lived in underwater mud banks called phyllopod beds. Currents would flow over the sediments periodically, causing landslides that buried the soft-bodied organisms in mud. This explains why Walcott found the fossils randomly oriented throughout the shale. The preservation of the fossils also gave paleontologists reason to believe that the organisms died instantly when buried. Usually, marine organisms curl up in anaerobic environments before they die but

Figure 1.5. Fossil specimen of Wiwaxia from the Burgess Shale.

none of these fossils demonstrated this curling. These observations have led to the belief that the organisms died instantly, allowing preservation to begin very quickly. Thus, the Burgess Shale was found to contain large amounts of fossilized crustaceans, sponges, and arthropods in good condition to be studied (Morris, 1989).

Walcott was able to extract about 1300 kg of fossilized specimens that were later passed on to the GSC. He studied these fossils for years, determining their Cambrian origin and developing their taxa. He continued his studies and eventually produced his written work, the "Pre-Devonian Paleozoic Formations of the Cordilleran Provinces of Canada" before his death in 1927. It was his years of field work and devotion to paleontology that allowed the GSC to revisit his studies years later and produce more exact stratigraphic findings.

In 1996, the GSC sent out a new group of geologists to the Burgess Shale once again. The purpose of this study was to determine if any undiscovered fossils remained in the shale and what other information they could derive from the original fossils. Geologists Harry Whittington, David Bruton, and Chris Hughes studied Walcott's collection in conjunction with the shale and found information regarding both the organisms and the depositional environment. Their findings changed the perception of Cambrian life as they discovered that the fossils from the Burgess Shale were not seen at any point before the Cambrian period. This gave more evidence to the growing idea of a "Cambrian Explosion" where invertebrate lifeforms became much more diverse and abundant during that time.

Further evidence of the Burgess Shale's marine past also came to fruition as investigations of the alternating shale and limestone strata appeared similar to other known marine environments. Like these other regions, the Burgess Shale had a continental shelf that would have acquired clastic sediments during high sea levels. Fine grained sediments would have accumulated on the outer edge of the shelf and created the mudstone formations. This information, along with the well-preserved fossils gives enough evidence of the Burgess Shale's previous marine environment. Thus, from comparing the lithology and organic remains of the Burgess Shale to other formations, the GSC was able to determine the time frame of the structure's formation (Caron and Rudkin, 2009). This is a great example of ways in which fossils allow researchers to date certain regions and learn more about their past environmental conditions.

Modern Day Geological Survey of Canada

The establishment of the GSC in 1842 brought about many changes in Canada, leaving both positive and negative impacts that are still relevant to this day. The original formation of the GSC created entirely new fields of work within the social and natural sciences. It helped create a new generation of geologists who were passionate about the scientific history of their country. Despite being created out of a desire for wealth and status, the GSC proved to positively impact Canada as more was discovered about the land and its geologic history.

Although the GSC opened doors for the scientific community, the organization directly contributed to the colonization of Indigenous lands. Those pushing for economic growth and independence were also forcing the settlement of white subjects who were loyal to the United Kingdom. Indigenous lands were taken over in the process of "building a nation" and the GSC played a key role in pushing the public's attitude toward growth. During the earlier days of the GSC, many Indigenous lands as well as important geological resources were exploited in the search for coal and minerals. These impacts cannot be forgotten and are still relevant to modern conversations. Although the GSC was first created for monetary gain, today the goal is rooted in science and technology that will improve Canada as a whole.

The GSC is now considered to be a part of the Earth Sciences sector of Natural Resources Canada. It now aims to develop Canada's mineral, water, and energy resources in a sustainable way. It also manages natural hazards and aids in the development of new technology relating to Earth science (Vodden, 1992).

There are seven main divisions of the GSC, based on geological requirement. These are the Institute of Petroleum Geology (ISPG) in Calgary, The Regional and Economic Geology Division (REGD) in Ottawa, the Terrain

Sciences Division (TSD) in Ottawa, the Resource Geophysics and Geochemistry Division (RGGD) in Ottawa, the Central Laboratories and Technical Services Division (CLTSD) in Ottawa, the Geological Information Processing Division (GIPD) in Ottawa, and the Atlantic Geoscience Center (AGC) in Dartmouth. The ISPG is responsible for northern and western Canadian basins and assesses the natural fuel resources. The REGD examines the geology of crustal rocks and determines mineral resources in the Western Cordillera, Canadian Shield, and Appalachian Belt. The TSD investigates and surveys the mantle of unconsolidated bedrock throughout Canada, specifically looking at how people have made use of this land. The RGGD is associated with national surveys that aid in the investigations of Canadian geophysics and geochemistry. The CLTSD is involved in the study of mineralogy and analytical chemistry as well as the operation of an instrument shop. The GIPD processes reports and maps to provide to the public. It is also in charge of the library and data systems. The AGC looks at the geology of the Atlantic Continental Shelf for the appraisal of fuel potential for the Hudson Bay Lowlands and St. Lawrence River (Robinson, 1972). In addition to these sectors is The Geological Survey of Canada building in Ottawa. This building is a Recognized Federal Heritage Building as it was constructed in the 1950s for exploration and mapping purposes. Today, it is used for administration, laboratory research and storage (Figure 1.6). (Parks Canada Directory of Federal Heritage Designations, 2017; Robinson, 1972)

Figure 1.6. A photograph of the office of the Geological Survey of Canada in Ottawa.

In terms of biostratigraphy, the GSC still archives all records of previous and current studies. With modern information and access to more fossil records, it is easier to correlate and date strata of newly discovered formations. As the field of Earth science continues to grow, geologists must use a variety of methods to identify and date rock formations. Biostratigraphy should be used in combination with chemostratigraphy and magnetostratigraphy. Chemostratigraphy is a method of correlating strata through investigations of chemical composition of strata, by looking at the elements and isotopes present. Magnetostratigraphy aids in correlating strata through examination of a sample's magnetic orientation and polarity. New information and technology is constantly simplifying the dating process, allowing for more accurate estimates of geologic history. What began as connecting similar looking rock formations and fossil species has become a diverse science that aims to discover the origins of Earth (Miall, 2014).

Application of Biostratigraphy to Petroleum

More recently, paleontology has played a role in the petroleum and oil industry. In this case, biostratigraphy is primarily used for understanding paleoenvironmental conditions that are necessary for locating hydrocarbon reservoirs. When it comes to this industry, biostratigraphy refers to microfossils that are used to identify rock content, depositional environment, and age of a specific reservoir (Wescott et al., 1998)

One method is graphic correlation, that is, plotting two stratigraphic logs of similar composition and cross plotting the layers of strata that appear to be similar in composition. Using information on the fossil content of each layer solidifies our knowledge on the depositional environments of that particular layer. This provides a better understanding of the accumulation of certain sediments within a basin, allowing for better models and use of hydrocarbon sinks (Wescott et al., 1998).

Discovering the Internal Structure of the Earth

The earliest European theories describing the internal structure of the Earth developed as a consequence of the quest to understand some magnetic phenomena that could not be explained. Sailors in the 15th century observed that magnetic needles in compasses do not point to the true north or south, but rather are set at an angle to the celestial meridian; this angle of offset is called the variation of the compass, and it changes slowly over time (Armitage, 1966). Additionally, a freely suspended magnetic needle tends to incline horizontally; this is known as the magnetic dip.

Figure 1.7. English astronomer, geophysicist, mathematician, meteorologist, and physicist, Edmond Halley (1656-1742).

Many scientists have hypothesized possible explanations for the existence of this variation. One well-known theory came from an English physician, William Gilbert; in 1600, he suggested that the Earth is one large lodestone magnet with a dipole, with overlapping magnetic and geographic poles (Armitage, 1966). He associated variations of the compass needle's direction with regional irregularities in the surface of the Earth, possibly caused by the movement of continents, and believed that the needle deflected away from large bodies of water because they have no magnetic properties. The idea of Earth acting as one large magnet was built upon by other scientists, including French philosopher René Descartes. Descartes generally agreed with Gilbert's theory; however, he believed that the geographic and magnetic poles were in separate positions, and that compass variation was due to the accumulation, formation, and transportation of iron ores.

Long after these hypotheses were published, an English astronomer and member of the Royal Society of London named Edmond Halley decided to explore the topic for himself (Armitage, 1966). He traveled to Saint Helena, where he observed and recorded variations in the compass dip. Most peculiarly, he noted that the dip disappeared 15° North of the equator. On his voyage, Halley noticed that along the coast of Brazil, the compass needle deflected toward the sea, effectively disproving Gilbert's hypothesis. He also noted that, while large amounts of iron ore could cause a slight disturbance in the needle when placed close to the compass, the iron weaponry on his ship did not cause a significant deflection, which challenged Descartes' theory. Halley then offered his own hypothesis: The Earth has four magnetic poles, two placed on either side of the equator, and variations in the compass needle are caused by the compass aligning with whichever pole is closest. Halley published his theory in a paper in 1683, before abandoning this idea for many years, with no intention to return to it.

Newton's Influence

Halley was a close friend and admirer of Sir Isaac Newton; recognizing Newton's brilliance, he encouraged him to organize his miscellaneous ideas and proofs by compiling them into a single text to be published by the Royal Society. In response to Halley's request, Newton spent the next 18 months focused on writing his treatise, which was eventually divided into three books, and was to be named *Philosophiae Naturalis Principia Mathematica* (The Mathematical Principles of Natural Philosophy). Because the Royal Society was facing financial difficulties, Halley paid for the production of the treatise himself, convinced that it held information that would change the world of science (Ronan, 1969).

Newton's *Principia* was enormously influential to scientists everywhere, including Halley. However, as revolutionary as Newton and his Principia were, he was not immune to mistakes. In the third book, Newton correctly calculated the density ratio of the moon to Earth to be 9:5; however, he miscalculated the mass ratio by a factor of three, incorrectly citing it as 1:26 instead of 1:81 (Kollerstrom, 1992). This information led Halley to believe that the moon was significantly denser than the Earth, which affected his future studies of magnetism.

Years later, Halley, who had intended to leave the subject of the magnetic poles at rest, had the epiphany that since the slow, regular variations of the compass exhibited the same trend over a wide area of Earth's surface, this motion must be due to the rotational movement of material beneath the surface. With this idea in mind, combined with his belief at the time that the Earth was significantly less dense than the moon, Halley proposed the idea of a Hollow Earth, stating "The External Parts of the Globe may well be reckoned as the Shell, and the Internal as a Nucleus or inner Globe included within ours, with a fluid medium between" (Armitage, 1966). He believed that inside the Earth were at least two concentric shells of matter which rotate at different speeds, causing the magnetic variations observed by a compass. His ideas inspired other Hollow Earth theories and went uncontested until Pierre Bouguer and other scientists found contradictory evidence.

18th Century Experiments

In the wake of Newton's publication, a number of scientists devised attempts to learn more about features of the world using his principles. Newton's law of universal gravitation seemed to prove that any mass large enough would exert a measurable force on another mass. This force could pull a weight on a string towards the mass, causing a deviation from the vertical, or change the time period of a pendulum's swing (Smallwood, 2010). Since gravitational force is proportional to mass, this relationship promised a new method to measure the density of the Earth, and thus learn about its internal structure.

The French Geodesic Mission

The first to test this theory was Pierre Bouguer, a professor of hydrography in France. In 1735, he joined an expedition led by the French astronomer Louis Godin to the Andes (Danson, 2006). During the two years he spent in Ecuador, Bouguer formulated and conducted two important experiments.

First, he tested Newton's inverse square law of gravitational attraction by comparing the force of gravity on a pendulum at sea level, and at 2860 metres in altitude. Bouguer reported a smaller decrease in the gravitational force of Earth at the higher elevation than he would have predicted based on altitude alone; he attributed the difference between the expected and measured values to the layers of rock between sea level and his observation station (Smallwood, 2010). From these deviations, he further calculated that the mean density of the Earth was 4.7 times higher than the density of the Cordillera rock strata at the planet's surface. Despite the inaccuracy of his measurements, Bouguer was able to recognize that the Earth's interior was far denser than its exterior, and therefore neither hollow nor filled with water as his contemporaries believed. Nowadays, Bouguer's erroneous numbers are attributed to a regional gravity anomaly in the Cordillera caused by crustal thickness variations (Smallwood, 2010).

In his second experiment, Bouguer tested whether a mountain would exert gravitational attraction on a hanging plumb weight and deflect the angle of the plumb-line away from the vertical. He travelled to Mt. Chimborazo and set up two testing stations on opposite sides of the mountain. Unfortunately, harsh weather conditions constantly interfered with his work. Bouguer calculated a significantly smaller gravitational attraction than he expected; he concluded that the experiment should be performed again in more benign conditions and with a better mountain.

The Schiehallion Experiment

Bouguer succeeded in establishing a viable method for experimentally measuring the density of the Earth. His endeavors did not go unnoticed, and in 1761, the experiment was attempted once more by Nevil Maskelyne (Danson, 2006). The British astronomer had left for Saint Helena on an expedition to observe the transit of Venus, a plan which failed due to heavy cloud cover. Maskelyne instead turned his efforts towards measuring the gravitational attraction of mountains, using the same methods as Bouguer, but the faulty alignment of his instruments prevented him from collecting meaningful data.

Figure 1.8. Schiehallion in Scotland, known for its characteristic symmetrical appearance.

In 1765, Maskelyne was appointed the British Astronomer Royal. From reading about Bouguer's experiments, Maskelyne realized that inconsistencies often found in experiments relying on a plumb line were likely caused by the gravitational attraction of topographic features on the plumb weight, causing it to tilt away from the vertical and give incorrect measurements. He decided to repeat Bouguer's experiment to determine the magnitude of this effect. In 1770, Maskelyne designed and commissioned the production of a zenith sector with a modified plumb line to improve the accuracy of his measurements (Davies, 1985). Just two years later, he presented a preliminary proposal to the Royal Society detailing his plan for measuring the density of a mountain (Maskelyne, 1776). It was enthusiastically approved, and a committee consisting of several notable scientists — including Benjamin Franklin — was assembled to oversee the experiment (Danson, 2006). Maskelyne assigned his colleague, Charles Mason, to travel across the countryside and find a mountain suitable for the experiment; Mason selected Schiehallion, in Scotland. Maskelyne also intended to put Mason in charge of the expedition, but offered him an insultingly low salary. Naturally, Mason refused the job, and Maskelyne personally led the expedition in the summer of 1774 (Davies, 1985), accompanied by a team which included the brilliant but ill-natured mathematician Reuben Burrow.

The team used advanced land surveying methods to find the true ground distance between two observatory points, while Maskelyne used the sector and plumb-line to chart the same distance by observing the movement of stars. When the distance values were compared, any irregularity in the astronomical data was assumed to represent the deflection of the plumb-line due to gravity. This data could then be used to calculate the magnitude of the gravitational attraction, and thus the mass and density of the object when provided a known volume. Maskelyne's preliminary calculations showed that the Earth's mean density was at least twice that of Schiehallion, a finding which disproved "the hypothesis of some naturalists, who suppose the Earth to be only a great hollow shell of matter" (Maskelyne, 1775). When he returned to the Royal Society in late October, Maskelyne was quick to show off his success, and gave himself credit for many of Burrow's contributions.

Later, mathematician Charles Hutton computed a density value for Schiehallion using Maskelyne's data (Hutton, 1821). To find the volume of the mountain, he enlisted the help of mathematician Henry Cavendish and created the world's first contour map. His calculations showed that, on average, the Earth was denser than the mountain by a factor of 9:5. Knowing the density of stone, he calculated that the Earth's interior had a mean density between 4.5 and 5 times that of water. Cavendish performed a separate experiment to measure the density of the Earth, which yielded a density value of 5.48 times that of water; modern experiments have shown that Hutton and Cavendish were close, and the density of the Earth hovers around 5520 $m \cdot kg^{-1}$ (Hughes, 2006). Together, these experiments not only disproved any Hollow Earth theories, but foreshadowed the discovery that the Earth's core is largely composed of very dense metals and showed that the density of the Earth's crust could differ from the Earth's interior (Danson, 2006).

The Era of Seismology

The idea of a differentiated Earth first originated about 2000 years ago. Inspired by Hades, the King of the Underworld in Hellenic mythology, Ancient Greeks believed that the Earth was composed of a thin crust of rock containing an inner fire, with a molten centre (Jarchow and Thompson, 1989). The experiments of Bouguer, Maskelyne, and Cavendish provided preliminary evidence for the heterogeneity of the Earth's structure, which was further elucidated by seismological experiments in the 20th century.

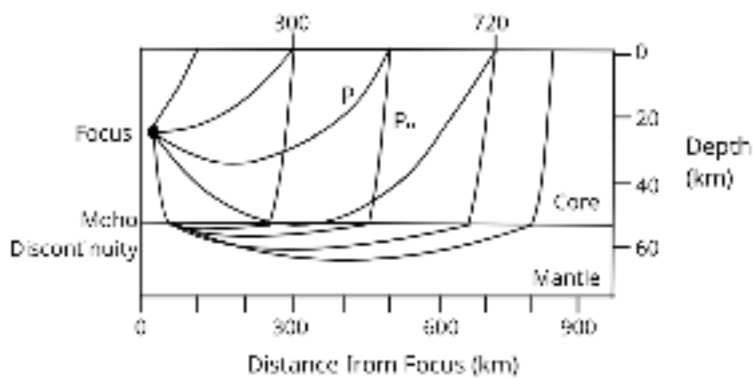


Figure 1.9. P waves become P_n waves as they are refracted when moving through the mantle to the crust. Between 300 and 720 km from the focus, the P and P_n waves overlap.

Andrija Mohorovičić was a Croatian meteorologist and seismologist. For the first half of his scientific career, Mohorovičić was a meteorologist by trade, and a fairly successful one who studied a wide range of meteorological phenomena. Around the start of the 20th century, he decided to change fields to seismology, and joined the Earthquake

Committee of the Yugoslav Academy. What drove this change is unknown, but he must have been very motivated to enter a new field at this stage of his scientific career, especially one in its infancy. However, this switch eventually led to what is considered the greatest contribution to science published in a Croatian journal: the Mohorovičić (or Moho) discontinuity (Herak and Herak, 2007).

On October 8th, 1909, an earthquake hit a town called Pokupsko in the Zagreb region of Croatia. After the earthquake, the committee received macroseismic data from offices, schools, and civilians, and seismographs from all European seismic stations. Mohorovičić meticulously examined each seismograph and eliminated those affected by clock errors of ± 4 s (Mohorovičić, 1910).

Upon examining the remaining data, Mohorovičić noticed that between 300 and 720 km from the Earthquake focus, there were two P phase seismic waves and two S phase seismic waves present; however, outside this range, there was only one of each phase. Mohorovičić was the first to observe this and hypothesised that this was due to a change in velocity caused by a sharp velocity discontinuity: a boundary between materials of different densities which refracts the P waves (Jarchow and Thompson, 1989). P waves refracted in the 300-720 km zone are referred to as Pn waves. To determine the depth at which the velocity discontinuity occurred, Mohorovičić used the mathematical model:

$$v(r) = v(r_o)\left(\frac{r_0}{r}\right)^k$$

Where r_o is the distance from the centre of the Earth to the earthquake focus, r is the distance of a point from the centre of the Earth, $v(r)$ is the velocity at a given r, and k is the exponent governing the increase in velocity with depth. Using the mathematical model, Mohorovičić determined that, in his calculated location, there must be a sudden change in material composing the interior of the Earth at a depth of 54 km (Jarchow and Thompson, 1989). This change is known as the Mohorovičić discontinuity and represents the boundary between the crust and mantle.

Additional Discontinuities

In the first decade of the 20th century, shortly after the discovery of the Mohorovičić discontinuity, a German-American seismologist named Beno Gutenberg was responsible for the next great advancement of the field (Knopoff, 1999). In 1913, he observed that the seismic phase P´ decreases in amplitude between 95° and 143°; he deduced that the P-wave "shadow zone" was caused by seismic waves travelling more slowly through denser material deep inside the Earth, which he recognized as the core. Gutenberg was able to calculate the depth of this core to be about 2900 km below Earth's surface. More than twenty years later, seismologist Harold Jeffreys repeated Gutenberg's calculations with a greater level of detail and found the depth of the core to be 2898 ± 3 km, in accordance with Gutenberg's value. Despite his lofty reputation among geoscientists, Gutenberg was unable to find a permanent paid faculty position in Germany in the face of growing anti-Semitism due to his Jewish background. Thus, in 1930, Gutenberg moved to the United States and began working in the Seismological Laboratory at the California Institute of Technology.

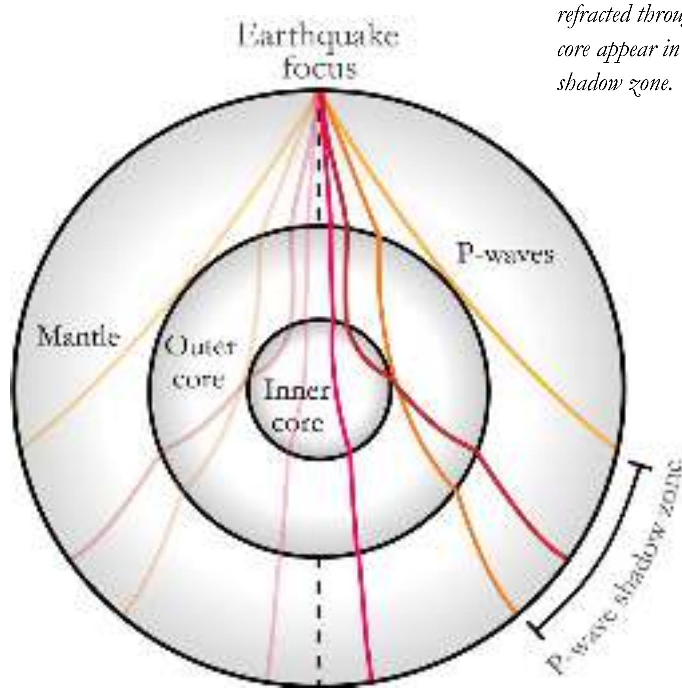


Figure 1.10. Deflection of P-waves passing through the Earth's mantle, outer core, and inner core. P-waves refracted through the inner core appear in the P-wave shadow zone.

Three years before he left for California, in the summer of 1927, Beno Gutenberg briefly mentored a Danish geoscientist by the name of Inge Lehmann. Lehmann had graduated from the University of Copenhagen with qualifications in physical science and mathematics. In 1928, she was appointed the state geodesist, and became chief of the new Seismological Department at the Danish

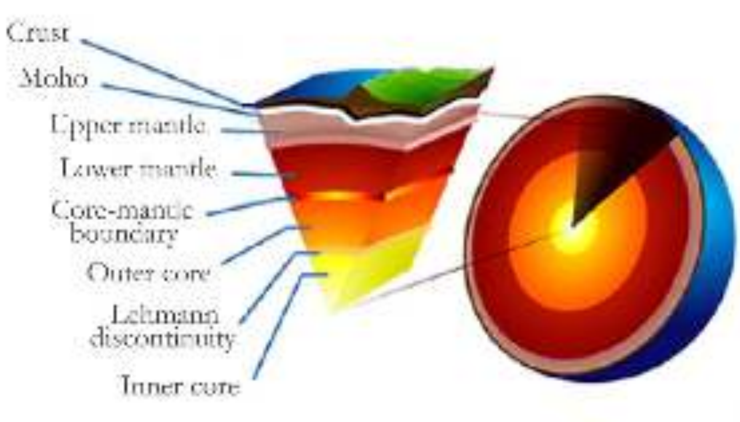
Geodetic Institute, which collected and catalogued data from seismic stations (Jacobsen, 2016). Lehmann was the only academically trained staff member, and so she was responsible for all administrative duties. Since the department had no research agenda or budget, all of her research was accomplished in her spare time between administrative tasks, without funding.

As the only professional geoscientist in Denmark, Lehmann collaborated extensively with other geoscientists outside her country, such as Harold Jeffreys (Erik, 2010). In her correspondence with Jeffreys, she noticed small inconsistencies in the seismic data he collected — namely, unusually large P' amplitudes in the shadow zone previously described by Gutenberg. A letter sent to Jeffreys dated to May 31, 1932 is the first record of her discovery: "I am afraid we shall have to be troubled with another discontinuity surface after all" (Lehmann, 1932). Her theory, published in a 1936 paper, was that the unusually high amplitudes represented P' waves refracted or reflected by an inner core, which differed in composition from the outer core. Jeffreys responded to her letter with disinterest and was slow to believe her theory (Erik, 2010). However, Gutenberg readily accepted the existence of an inner core (Gutenberg and Richter, 1938). It was not until 1970 that the existence of the inner core was confirmed (Engdahl, Flinn and Romney, 1970).

A Contemporary Perspective on the Earth's Composition

In the decades since Inge Lehmann's detection of the inner core, and the numerous geological discoveries made since then, our methods for studying the Earth's interior have evolved. Recent research has further developed our understanding of the composition and structure of the material that lies under the Earth's crust. An ongoing challenge in geology is the integration of geochemical and geophysical data to build an accurate understanding of the Earth's mantle (Bennett, 2003). With the advent of new information, it has become clear that the mantle is neither stationary nor homogeneous; its composition is distinct from the core and the crust, and the flow of mantle material drives a number of important processes, such as plate tectonics . The mantle is further divided into the upper mantle, transition zone, lower mantle, and core-mantle boundary, with differences in the temperature and composition of each distinct layer. Recent efforts have used seismological research, radiometric isotope analysis, and laboratory simulations to better characterize the anatomy of the mantle.

Figure 1.11. Structure of the Earth's mantle.



Seismological Studies

Seismology is a relatively young science in North America, only emerging in the 20th century. However, the field of seismology is continually advancing as new technology is developed, and seismic data can now be used to create detailed models of our planet (McNamara, 2019). The creation of images using seismic waves is known as seismic tomography. These images are the most effective way to peer into the Earth and learn more about its interior.

An example of this is the use of seismic tomography to locate and model superplumes within the mantle called Large Low-Shear-Velocity Provinces (LLSVPs). Within the last decade, two LLSVPs have been discovered in the lower mantle, underneath Africa and the Pacific Ocean (Lynner and Long, 2014). These LLSVPs were identified using global shear wave tomography. Furthermore, shear wave tomography has allowed us to determine the position and geometry of these provinces through analysis of different wave travel times. It was determined that the provinces are located on opposite sides of the Earth. The LLSVPs have been discovered to extend laterally for thousands of kilometers, and vertically for about one thousand kilometers. Knowing the location of the LLSVPs has allowed scientists to associate LLSVPs with overlying surface features. There is generally a larger number of hotspots on the surface above the provinces, indicating a correlation between LLSVPs and geochemical reservoirs.

Measuring Isotope Ratios

Another important technique that has developed in parallel with seismology throughout the 20th and 21st centuries is isotope analysis. The first mass spectrometer was invented in the mid-1900's; (Dickin, 2018) over the next several decades, mass spectrometry became an increasingly widespread technique. In 1985, a process called laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS) was first invented, in which a sample is vaporized and ionized by a powerful laser and concurrently analyzed by mass spectrometry (Sylvester and Jackson, 2016). LA-ICP-MS has since evolved towards higher sampling resolution, and nowadays offers a rapid, accurate, and versatile way to measure isotope ratios. This technique has a variety of applications in the Earth sciences.

In May 2019, Sarah Lambart and her team of researchers at the University of Utah published a paper showing that the Earth's mantle is a geochemically diverse mosaic of different minerals, with a composition that is vastly different from the highly homogenous lavas that emerge from mid-ocean ridges and form the basaltic ocean crust (Lambart et al., 2019). Using LA–ICP–MS, Lambart and her team examined cores from magmatic intrusions in the oceanic crust and found that early cumulate minerals, the first minerals to crystallize when magma enters the crust, had seven times as much variability among neodymium and strontium isotopes than minerals in basaltic lava. This finding indicates that magma deep inside the Earth is highly heterogeneous, most likely because minerals have different melting points, and is not well-represented by homogenous basaltic lava. The heterogeneity is inconsistent with contemporary models of mantle convection, and may be the starting point for the development of a new model of magma mixing.

More recently, in a paper published in September 2019, geochemists at the Universities of Münster and Amsterdam, led by Andreas Stracke, revealed new insights into the relationship between the Earth's mantle and crust (Stracke et al., 2019). Previously, it was understood that some of the mantle in contact with the crust at the Moho discontinuity solidifies to form new crust, and elements called incompatible elements — such as rare earth minerals, uranium, and strontium — are preferentially incorporated into the new crust (Bennett, 2003). The mantle which remains after crust forms is known as "depleted mantle" and contains fewer incompatible elements. Using LA–ICP–MS, Stracke et al. analyzed neodymium isotope ratios in melt inclusions from the Azores archipelago and found far fewer incompatible elements than expected. Since the Azores mantle plumes originate from deep inside the lower mantle, Stracke and his team concluded that a very large proportion of the Earth's mantle must be depleted. This has implications for the rate of mass exchange between the crust and mantle, and may play a role in how the layers of the mantle are arranged.

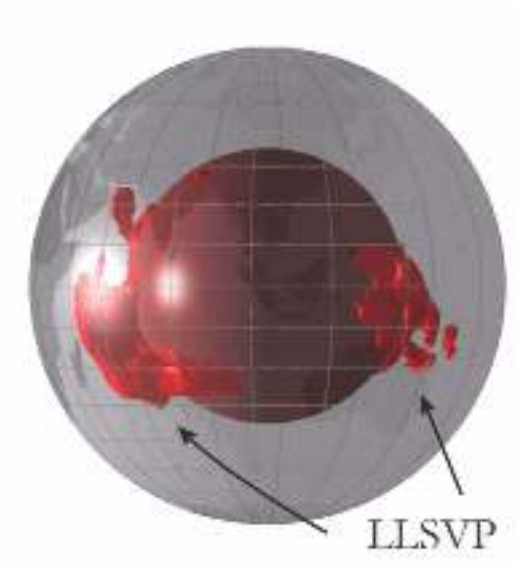


Figure 1.12. Model of the Earth's interior showing the shape and location of the large low-shear-velocity provinces.

As technology advances, we can expect to build our understanding of the Earth's internal composition and structure. This, in turn, may allow us to learn more about the availability and abundance of natural resources, model how our planet originally formed, and relate the phenomena we observe on Earth's surface to the processes occurring under our feet.

The Influences of the Phlogiston Theory on Mineralogy

Many scientific theories are driven by observation, resulting in their dissolution when a seemingly more valid hypothesis arises, and the phlogiston theory is no exception. Originally proposed by Johann Joachim Becher and developed by Georg Ernst Stahl in the seventeenth and eighteenth centuries, this superseded theory was revolutionary in its integration of the distinct fields of mineralogy and chemistry within the natural sciences. The phlogiston theory suggested an explanation for the varied combustibility observed between different natural substances (White, 1973).

Combustibility, a substance's "capability of catching fire and burning" (Merriam-Webster, 2020), was a phenomenon that bewildered members of the ancient scientific community for thousands of years. Chemists and mineralogists alike puzzled over the compositional differences that allowed some natural materials to burn, while others could not.

Figure 1.13. A portrait of Johann Joachim Becher, the man credited for the postulating the foundational ideas of the phlogiston theory.

Development of the Phlogiston Theory

As a multi-faceted German scholar, Johann Joachim Becher (Figure 1.13) possessed many titles throughout his life, including that of physician, economist, author, and professor (1635-1682). Being the oldest child of a widowed mother, Becher's early passion for the natural sciences and teaching was driven by a need to provide for his family. Regardless of his diverse professions, Becher's scientific fascination remained the study of alchemy (Smith, 1994). The transition from the obsolete field of alchemy to modern chemistry was neither smooth nor instantaneous. The phlogiston theory, like many other scientific breakthroughs of this time, contributed to the birth of present-day chemistry (White, 1973).

Thousands of years prior to Becher's revolutionary chemical advancements, Empedocles and Aristotle both postulated different concepts regarding the four basic elements that comprise all matter—water, earth, air, and fire, and moist, dry, hot, and cold respectively (Bolzan, 1976; Kingsley, 1994). Becher's 1667 book, *Physica Subterranea*, was one of the first published documents in history to suggest that fire itself could not be an element (Laudan, 1987; White, 1973). This novel, along with his other works, demonstrates that Becher was influenced by many historical schools of thought, including Aristotelianism, Stoicism, alchemy, and Hermeticism. Much like other cosmogonists at the time, Becher postulated a "theory of the Earth" (Oldroyd, 1974, p.270) explaining his views on the "creation of the globe" (Oldroyd, 1974, p.271). He hypothesized the existence of water and three distinct forms of earth—terra lapidea, terra fluida, and terra pinguis, each with a varied ability to burn (White, 1973). The phlogiston theory was not directly proposed by Becher, but his publications on the topic of combustion provided the foundations for this superseded theory. Terra pinguis, classified as "oily, sulphurous, and combustible" was later renamed as the element of "phlogiston" by one of Becher's students and a German medical professor, Georg Ernst Stahl (Figure 1.14) (Mason, 1962).

Stahl approached medicine and chemistry from a similar perspective—physical and chemical processes needed to be explained by elements rather than the theory of individual atoms. During this era, mechanistic views were discouraged in many natural sciences, including medicine, mineralogy, and alchemy (Oldroyd, 1974). He theorized that phlogiston was the element present in all combustible minerals; its properties included negative weight and ignitability. Stahl proposed that phlogiston was not fire itself, but a catalyst for the production of flames. Becher's theories gained a plethora of support after Stahl provided experimental evidence for the existence of phlogiston, otherwise known as terra pinguis. The word "phlogiston" was not coined by Stahl but derived from an ancient Greek term meaning "inflame" (White, 1973).

Many historians believe that Stahl's development of this theory originated due to his reverence for Becher, his mentor and professor. Many of the later contributions to the phlogiston theory were made by other members in his field, following Stahl's death in 1734. The longevity of this theory resulted not from Stahl's own confidence in its validity, but from his pupils' blind conformity to the theories he proposed. The list of scientists who adopted Stahl's doctrine is lengthy and the individuals were from diverse locations across Europe (White, 1973).

Figure 1.14. An artist's rendition of Georg Ernst Stahl, who is credited with the further development of the phlogiston theory.

For almost a century, the core beliefs of many scientists were deeply rooted in this now apparently illogical ideology, labelling them as phlogistonists. The dissolution of this well-accepted theory began during the late eighteenth century arrival of Antoine Lavoisier, a French nobleman dubbed as the "father of modern chemistry" (Pai-Dhungat and Parikh, 2015). Even following Lavoisier's introduction of a more well-founded explanation for these complex chemical observations, many phlogistonists remained loyal to their prior beliefs. In hindsight, as stated by J.H. White in his 1932 book titled *The History of the Phlogiston Theory*, "One cannot blame chemists for adopting the theory at its outset, but one can blame certain of them for clinging to it long after it was a creed outworn." (White, 1973, p.57)

From the vantage point and hindsight of modern chemistry, the phlogiston theory might seem near impossible to believe. However, any experimental data collected during this era was consistent with the expected results of the time. Hundreds of years from now, there may be scientists that provide alternative theories to the ones that we currently accept. No scientific theory is absolutely factual—all theories, even modernly, are driven by observations.

Several hundred years prior to the establishment of the phlogiston theory, during the sixteenth century, mineralogy began to emerge as an all-encompassing term for the study of non-living things (Putirka, 2015). Although distinct from the fields of both alchemy and chemistry, discoveries in these fields greatly impact the world of mineralogy. Many of the eighteenth century phlogistonists' investigations revolved around mineralogy, specifically the mining industry (Oldroyd, 1974). Subsequent to the introduction of the phlogiston theory, the classification of minerals began to revolve around inner chemical components rather than outward appearances. The correlation between these fields was recognized by D.R. Oldroyd in his 1974 *Annals of Science* article which states, "It is, therefore, a matter of some interest to examine the relationship between the mineralogical theories of our period and the chemical doctrines that were emerging at the same time." (Oldroyd, 1974, p.270)

Figure 1.15. An artist's rendition of Torbern Bergman; a phlogistonist, chemist, and mineralogist who made significant contributions to the fields of chemistry and mineralogy.

Influences on Mineralogy: Bergman

Humans have and always will be fascinated with trying to make sense of the world, and this was no exception for those in the seventeenth century. With the mining industry on the rise, the need to properly identify and classify rocks to further benefit a country's economy became more and more prevalent (Porter, 1981). It was during this time that the streets of Bohemia (now called Germany) were hustling and bustling with select phlogistonists, who at the time commonly held the title of both a chemist and a mineralogist. Among them stood a man by the name of Torbern Bergman (Figure 1.15) (Oldroyd, 1975; Porter, 1981). Unlike most well-known scientists, Bergman began his post-secondary education in a discipline far from sciences, as a philosophy student (Smeaton, 1984). However, it did not take long before he started to yearn for some form of knowledge pertaining to the discipline of natural sciences. It was through the retirement and replacement of Bergman's first chemistry professor, J. G. Wallerius, that one could argue Bergman found his passion for chemistry and its application to various industries. This passion is seen to be derived from Wallerius' successor who was appointed by the chancellor of Bergman's university at the time, Crown Prince Gustav. When interviewing applicants, Gustav made it clear that whoever would replace Wallerius must be capable and willing to teach the importance of chemistry in the industry of mining and metallurgy; "the branch of science and technology concerned with the properties of metals and their production and purification" (Oxford University Press, 2019).

Determined to make a change in both the industries of mining and chemistry, Bergman spent most of his days developing his very own method of classifying minerals. Being a phlogistonist himself, Bergman's method was highly influenced by the well-accepted phlogiston theory. He argued that minerals should be classified based on composition rather than physical appearances, and that one could use this knowledge to gain insight into their potential practical uses (Oldroyd, 1975). According to his system, he classified all minerals under four classes: "salts, earths, metals, and phlogistic bodies" (Porter, 1981, p.563). However, like any newly published method, Bergman's classification system was not free from critiques. In order to defend his theory against those who rejected it, Bergman put forth the idea that unlike physical appearance, which could present itself differently in two of the same minerals, a mineral's chemical composition would remain constant (Oldroyd, 1975; Porter, 1981). As such, looking back, Bergman's work can be seen to be heavily influenced during his time of study under his chemistry professor.

Unfortunately, it was already well-known at the time that the constituents within a material may decay, or even completely disappear over time, thus introducing uncertainties (Porter, 1981). As a chemist and mineralogist, Bergman was well aware of this fact and even went so far as to state that mineral classification should only be done for minerals that had been isolated in a lab setting (Porter, 1981). It was because of this fact, that minerals need to be classified both in the field and lab, that Bergman's classification system was later rejected.

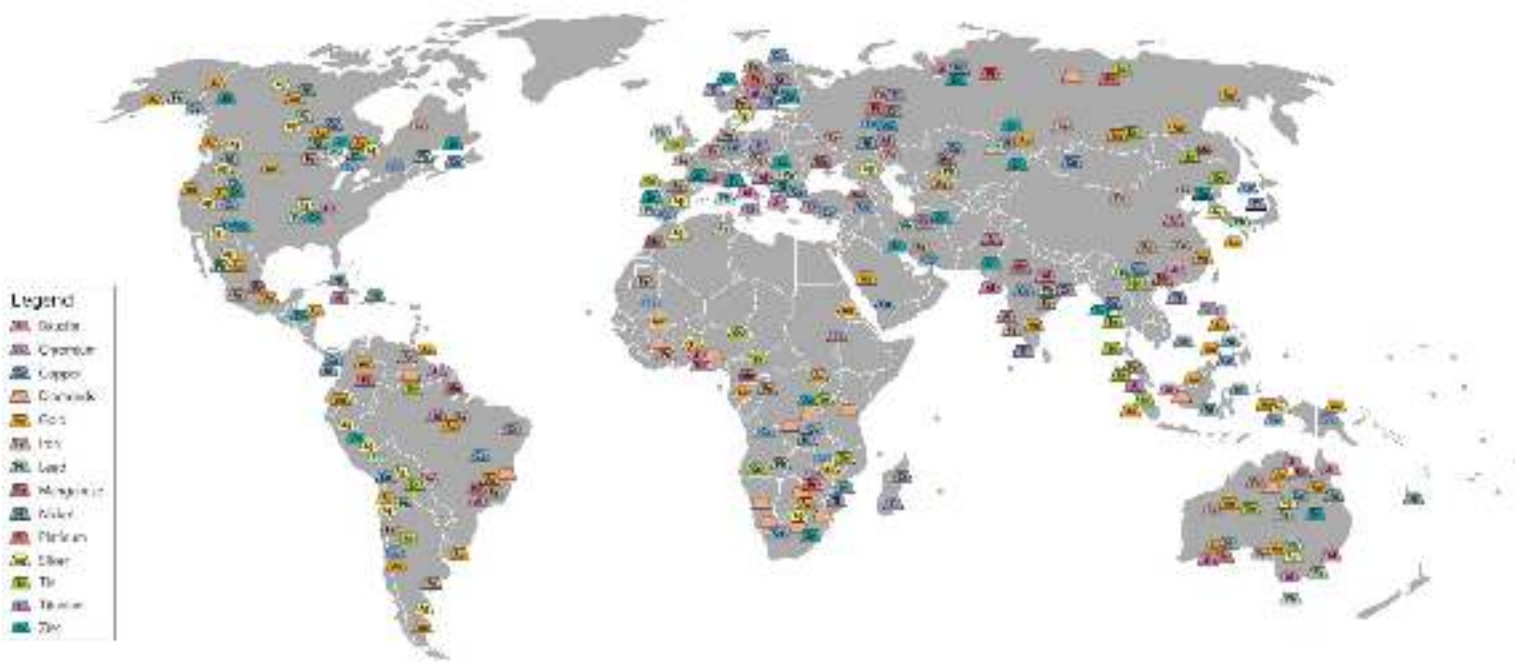


Figure 1.16. A map of the world showing the distribution of common minerals throughout the globe, suggesting the importance of the mining industry in the economic success of various countries.

Dissolution of the Phlogiston Theory: Lavoisier

It was not until the late seventeenth century that the phlogiston theory started to be questioned and disproved. Concerned less with acquiring basic general knowledge, more and more mineralogists were following in the footsteps of Bergman and focusing their efforts on the advancement of mining (Porter, 1981). It was the realization that in order to acquire intended resources, miners would need to know exactly what they were looking for that acted as a catalyst for this change. From this, a shift in political and institutional views and practices were then seen—paving the way for mineralogists to make their vision a reality. At the time, mining was an industry that was fairly unregulated, but it was its significance in a country's economic success that fueled its importance. As noted by Figure 1.16, minerals are seen to be dispersed throughout the globe. Thus, the advancement in mining was perceived as not only a nationwide benefit, but also a global one. This became the driving force for chemists and mineralogists to strengthen their relationships in order to optimize the extraction and refining process—in return, strengthening the economy (Porter, 1981). To the then-modern mineralogist, advancing the mining industry meant that miners should be educated in terminology and methods for identifying minerals that are just as meaningful as an in-depth chemical analysis. It was through disproving the phlogiston theory that mineralogists were able to move away from the idea that a common set of properties implied a shared constituent and move towards a system better suited for them.

This new era of mineralogy and chemistry was led by Antoine Lavoisier (Figure 1.17), who as of today, is known for disproving the phlogiston theory, as well as discovering oxygen (Duveen and Klickstein, 1956). This mere action was seen to have a multitude of implications in the scientific community, with some of them still holding significant weight in today's society. During his work, Lavoisier set out to create a table which was later entitled *Traité élémentaire de chimie* (Siegfried, 1982). However, Lavoisier did not completely reinvent the wheel. As stated, one of Bergman's classifications included the subgroups of salts, earths, metals, and phlogistic bodies. It was from taking each of Bergman's classifications and analyzing their members that Lavoisier was able to conclude that what Bergman classified as earths were actually oxides of metals (Duveen and Klickstein, 1956). Finding more common constituents among minerals, Lavoisier's table was organized into three different categories; substances abundantly present in light, the atmosphere (oxygen), and water (hydrogen) (Duveen and Klickstein, 1956; Siegfried, 1982). It was innovations such as this one that led many miners and mineralogists at the time to begin modifying how they classified minerals.

However, the discovery of oxygen did not result in an instantaneous solution to how mineralogists would continue to classify minerals. The debate pertaining to whether a material should be classified by its artificial (external) or natural (internal) constituents was still ongoing and was witnessed to create a divide within the mineral community (Simon, 2002). On one side of the divide were those that argued for the validity artificial classification, as meteorologists in the field often did not have a means of conducting a chemical analysis. This was seen to differ from the other side, as those fighting for a natural classification were passionate believers that a chemical analysis provided the foundation to allow for determining external features (Simon, 2002). Moreover, it was additionally argued that it was the chemical constituents of a mineral that determined its class, and that external features were only useful as a substitute. Looking back, it is apparent how today's

Figure 1.17. A portrait of Antoine Lavoisier, who is credited with the disproval of the phlogiston theory and discovering the element of oxygen.

mineral classification system can be seen to stem from a combination of both sides.

Returning to the idea that all this change was catalyzed by countries wanting to improve their economy, questions surfaced regarding how mineralogists were supposed to distinguish between rocks in the field. How could they start to associate topography with the rocks and minerals that they were expected to find? And why were certain minerals and constituents only present in certain rocks and not others (Laudan, 1987)? These questions paved the way to shaping mineralogy as it is today.

Modern Methods of Mineral Classification

Flashforward to today and mineralogy is still seen to be heavily linked with a general understanding of chemistry. While the contribution of the mining industry to society has not drastically changed, the mining industry is continually being revamped with new practices and technologies to further benefit the economy. To date, minerals are seen to play an important role in our everyday lives. Whether it be opening a laptop, taking a pill, or applying a face care regime, minerals play a foundational role in our daily activities. Thus, their importance over the years has grown exponentially as their function is now valuable in aspects outside of just providing energy for transportation and industries (Azapagic, 2004). It is through the work of scientific figures such as Bergman and Lavoisier that lead to our modern understanding of what materials are comprised of.

With advancements in technology and a growing understanding in what elements a mineral is comprised of, minerals can now be identified based on their depositional environment and mode of formation in addition to a chemical analysis (Plumlee, 1999). To the modern-day mineralogist, this method is cost-friendly and allows them to gather valuable insight into what materials may be present before investing time and money into a given site. Yet, as many predecessors have suggested, this method still comes with uncertainties. However, going back to the nineteenth century, a saving grace was introduced to the mining industry by a man named Max von Laue (Reventós, Rius and Amigó, 2012). It was through his discovery that X-rays can be diffracted by crystals that led to X-ray crystallography being implemented in the analysis of minerals. From methods such as this, mineralogists were starting to make more accurate conclusions about the composition of given minerals and their classes. Thus, from analyzing what mineralogy looks like today, a hybrid of sorts can be seen between these two methods—creating the ultimate dynamic-duo. Such a pairing allows mineralogists to use a depositional environment in order to pin-point a prospective location for mining, before investing all of their resources. For example, magmatic deposits are those that form directly from the cooling of magma. Therefore, when looking for a site to extract such deposits, mineralogists will often focus their attention towards regions where volcanoes are or were once present (Plumlee, 1999). Modern day technology is then often used as a means to verify that the material found is the intended material.

Emerging Technologies

This verification can be conducted using a variety of technological methods that have been discovered and developed over recent decades—the majority of these methods having roots in either the physical or chemical sciences. The field of mineralogy has evolved exponentially since the era of the phlogiston theory, the seventeenth and eighteenth centuries. Modern mineralogists rely heavily on these advanced technologies to determine mineral composition and identification (Oldroyd, 1975). However, until recently, the technological classification of minerals was an inexact, expensive, time-consuming science; sets of collected data were frequently too incomplete to use in statistical analyses (Fandrich et al., 2007).

One of the greatest innovations in mineralogy is analysis by scanning electron microscopes (SEM)—this technique employs energy dispersive X-ray spectroscopy (EDS) and backscattered electrons (BSE). This microscope allows high resolution imaging of extremely fine particulates in a rock specimen (Senthil

Kumar and Rajkumar, 2014). During this lengthy process, sections of particles within a sample are divided and identified, with individual grains being analyzed for mineralogy (Fandrich et al., 2007).

Another recent innovation in mineral classification is time-of-flight secondary ion mass spectrometry (ToF-SIMS). This form of spectrometry uses a series of previously identified reference minerals, whose elemental and molecular ion signals are compared to that of unknown minerals to provide an accurate identification (Rinnen et al., 2015).

Macroscopically, coarse-grained minerals can also be classified by data from a colour image scanner. This device electronically scans the sample, splitting the output into either grey level, or red, blue, and green components. These results are then analyzed by a complex computer algorithm, which recognizes and identifies each individual mineral. The final outcome of this method is the composition of your sample, by percentage and distribution of each mineral (Marschallinger, 1997).

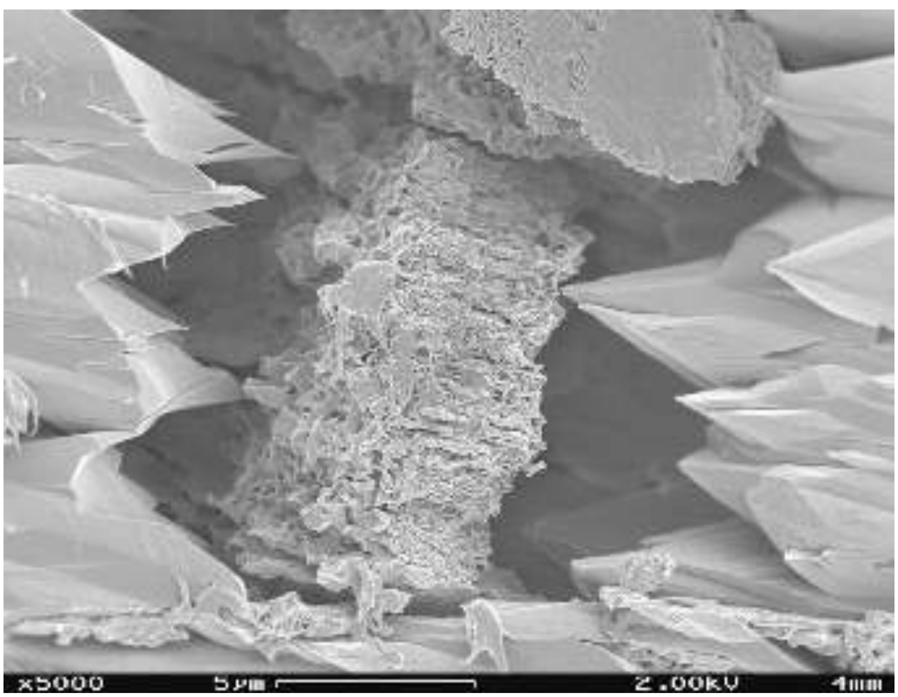


Figure 1.18. A microscopic image of clay as taken from a scanning electron microscope (SEM). From this image, features such as grain size can be analyzed.

Like many of today's fields, mineralogy has been influenced by the ever-changing field of computer science, specifically the introduction of machine learning. An article published in *Minerals Engineering* in November 2019 discusses the application of machine learning in the classification of heavy minerals (Hao et al., 2019). Heavy minerals, high density components of sand and sandstones, provide information regarding sediment flow, sediment origin, and strata correlation, which when combined, can be useful for mining, in addition to other industries. Using a wide range of heavy minerals from several distinct locations, machine learning was used in conjunction with EDS and SEM, to become the most effective classifier of heavy minerals (Hao et al., 2019).

Mineralogy, like many other natural sciences, has not yet reached a plateau; since its ancient establishment, it has been growing with each new discovery in related fields, such as the phlogiston theory and machine learning. As such, with an ever-growing population and the economical and industrial benefits that come from the use of minerals, the classification of minerals will continue to be a focal point for many mineralogists.

It is human nature for individuals to always desire to be correct and stay on the "right side" of things. As such, one of the greatest challenges a successful scientist will ever have to learn to understand is accepting defeat and admitting that they are wrong. However, it is through revising old theories and adapting new ones that society is able to move forward. This dissolution of the phlogiston theory and the sequence of events that followed it, is no exception to this process. It was because of the work done by Bergman that Lavoisier was able to discover oxygen—and it was because of Lavoisier's discovery of oxygen that we now have several of today's practices. Thus, from this one can observe a key takeaway—never stop asking questions as one never knows where it could lead.

Diamonds: Discovery and Distribution

Diamonds: king of gems, gem of kings. Cloaked in mystery, lore, and intrigue over the course of human history, diamonds are the royalty of the gem world. For thousands of years, humankind has travelled far and deep to search for and collect these precious stones. From legends to labour to love, diamonds are as valuable as they are useful. Diamonds are one of the most precious commodities recognized on Earth and the hardest substance ever discovered by man (Bruton, 1979). They occupy the top spot—number 10—on the Mohs scale of mineral hardness, establishing their reputation (Mohs and Haidinger, 1825).

The following pages aim to provide readers with information about the history of diamonds, including their discovery, how they provide information about our Earth, and the techniques we use to mine them. These topics will be explored section by section—rather than in chronological order—for both clarity purposes and to enhance readers' comprehension. Many papers and reference books were consulted during the writing process. Three sources were exceptionally informative, and readers are encouraged to explore them further. These are: *Diamonds* by Bruton (1979), *The Diamond Compendium* by Cunningham (1988), and *Diamond Deposits: Origin, Exploration, and History of Discovery* by Erlich and Hausel (2002).

Discovery of Diamonds

The first discovery of diamonds is uncertain, but their presence has been acknowledged since ancient times (Erlich and Hausel, 2002). One of the earliest references of diamonds was in the Old Testament by the prophet Ezekiel who wrote, "As an adamant harder than flint have I made thy forehead." (Erlich and Hausel, 2002, p.3). The word "adamant" implies extreme hardness and is used to describe diamond (Erlich and Hausel, 2002).

The Roman philosopher Pliny the Elder also describes diamonds in his work, *Natural History*, completed in 77 AD. He wrote, "These stones are tested upon the anvil, and will resist the blow to such an extent as to make the iron rebound and the very anvil split asunder", describing diamond's extreme hardness (Bruton, 1979, p.1). He also stated that "the most valuable thing on earth is the Diamond, known only to kings, and to them imperfectly" reinforcing society's veneration of these gems (Streeter, 1892, p.54).

All early diamond mines were alluvial gravels in the banks or beds of rivers where diamonds had been deposited by moving water (Bruton, 1979). Diamonds were found in sands and gravels of riverbeds, compact sandstones, and conglomerates (Bruton, 1979). Alluvial deposits near rivers were known as "river diggings" or "wet diggings", while alluvial gravels containing diamonds that were found in locations where rivers used to flow thousands of years ago were called "dry diggings" (Bruton, 1979). All early diamond mines were alluvial gravels in the banks or beds of active or dried-up rivers where diamonds had been deposited in high concentrations by moving water (Bruton, 1979).

Alluvial diamonds were discovered in both India and Brazil as early as 800 B.C. (Bruton, 1979). In India, the diamonds usually came from the region of Golconda where the locals had established a successful diamond mining operation, as observed by gem merchant Jean-Baptiste Tavernier during his travels (Bruton, 1979). Tavernier found that the locals excavated 14-foot holes then added water and waited until it had evaporated to pick out diamonds (Bruton, 1979). Brazilian diamonds were discovered at the beginning of 18th century by gold miners who found crystals in the gravels of rivers in Minas Gerais in Tejuco and used them as tokens while playing cards (Bruton, 1979). A government official who had seen diamonds in India identified these stones and upon evaluation, found that they were comparable in quality to Indian diamonds (Bruton, 1979). Many other deposits were located, and production increased so quickly that prices fell steeply, causing diamond mining to become a royal monopoly in 1772 (Bruton, 1979).

The most significant discovery of diamonds was in Africa. The first ever diamond found was the Platberg diamond, retrieved at the junction of the Vaal and Orange Rivers in South Africa by a local in 1859 (Bruton, 1979). The first authenticated find was on the De Kalk farm in Hope Town, just south of the Orange River (Bruton, 1979). The Jacobs family lived on this farm, and their 15-year old son, Erasmus, found a glittering stone one day (Bruton, 1979). The De Kalk's stepson, Schalk Van Niekerk, found the stone lying about and thought it resembled the drawings of diamonds he had seen in a book

(Bruton, 1979). He was gifted the stone by Mrs. Jacobs and proceeded to test it on a windowpane after recalling that his book had mentioned that diamonds could scratch glass (Bruton, 1979). To further test its authenticity, it was sent to Dr. William G. Atherstone, a prominent South African geologist who determined its specific gravity, and deduced the stone was a 21.25 carat diamond worth £500 (Bruton, 1979).

Diamonds were found elsewhere in the world, though not in abundance like in South Africa. A major diamond discovery in the Western United States in 1871 garnered continent-wide attention (Erlich and Hausel, 2002). The discovery was so remarkable that a number of diamond companies were formed (Erlich and Hausel, 2002).

The discovery was revealed to be fraudulent by a group of geologists from the Fortieth Parallel Survey who dug test pits at the site (Erlich and Hausel, 2002). After a thorough field investigation, it was concluded that the stones had been salted, meaning the diamonds were artificially placed in the ground (Erlich and Hausel, 2002). An emergency meeting was called, and several facts were presented that proved that the diamonds were salted (Erlich and Hausel, 2002). It was determined that the numerical ratio of rubies to diamonds was nearly identical, which was naturally impossible (Erlich and Hausel, 2002). Microscopic examinations of the sandstone showed no gemstones, and prospect pits dug around the disturbed area at Table Rock produced no gemstones (Erlich and Hausel, 2002). Not too long after the hoax, great advances in the discovery and naming of diamond host rock—kimberlite—would ensue, providing sound geologic evidence for the authentic occurrences of diamond.

Kimberlites

The discovery of kimberlites is closely intertwined with the events that occurred after the discovery of alluvial diamonds at the Vaal and Orange Rivers in South Africa in 1866-1867 (Mitchell, 1986). In 1870, a terrestrial source rock for diamonds was located and led to the discovery of dry diggings near two mines at the Orange and Vaal Rivers (Erlich and Hausel, 2002). These dry diggings were discovered in yellow ground and blue ground, which are heavily weathered and oxidized kimberlite (Erlich and Hausel, 2002). Yellow ground occurs closer to the Earth's surface and may be exposed, while blue ground (Figure 1.19) is found deeper in the Earth's crust (Erlich and Hausel, 2002). Many miners deemed the dry diggings unimportant as they believed they were dried up riverbeds from when the Vaal River had previously overflowed (Erlich and Hausel, 2002). In 1872, geologist Ernst Cohen identified that the areas of blue and yellow ground were volcanic pipes (Erlich and Hausel, 2002). In 1873, geologist E.J. Dunn introduced the term "pipe" to describe these diamond deposits found in cylindrical, volcanic pipe-like structures (Mitchell, 1986). Cohen stated that the pipes were composed of eruptive tuff, and the diamonds were brought to the surface by volcanic action, thus definitively characterizing this type of diamondiferous deposit (Mitchell, 1986). At an 1886 meeting of the British Association for the Advancement of Science, geologist Henry C. Lewis described then-unnamed kimberlite as a porphyritic mica-bearing peridotite and correctly classified it as a type of volcanic breccia (Mitchell, 1986). In 1887, he coined the term "kimberlite" after Kimberley, South Africa (Erlich and Hausel, 2002). However, controversies persist to this day over the complexities regarding the mineralogy, chemical composition, and texture of the rock, though kimberlites are generally defined as a magmatic, igneous rock sometimes containing diamond (Erlich and Hausel, 2002).

In 1914, esteemed geologist P.A. Wagner divided kimberlites into two types: basaltic (olivine-rich rocks with >5% phenocrystal mica) and lamprophyric (olivine-rich rocks bearing mica phenocrysts in a groundmass with >5% mica) (Erlich and Hausel, 2002). This classification is widely acknowledged, though the term basaltic is presently considered to be misleading: basalt and kimberlite are neither mineralogically nor genetically related, so using the term "basaltic" to describe them is inaccurate (Erlich and Hausel, 2002). Mitchell (1970) suggested that there are actually three

Figure 1.19. Sample of blue ground kimberlite containing uncut and unpolished clear diamonds.

mineralogic types of kimberlite, based upon the amounts of olivine and other minerals (Erlich and Hausel, 2002). These categories include kimberlite (identical to Wagner's basaltic kimberlite), micaceous kimberlite (identical to Wagner's lamprophyric kimberlite) and calcite kimberlite (Erlich and Hausel, 2002). The final category was created to account for the primary magmatic calcite present in kimberlite; however, many geologists regard calcite to be the product of autometamorphism (Erlich and Hausel, 2002).

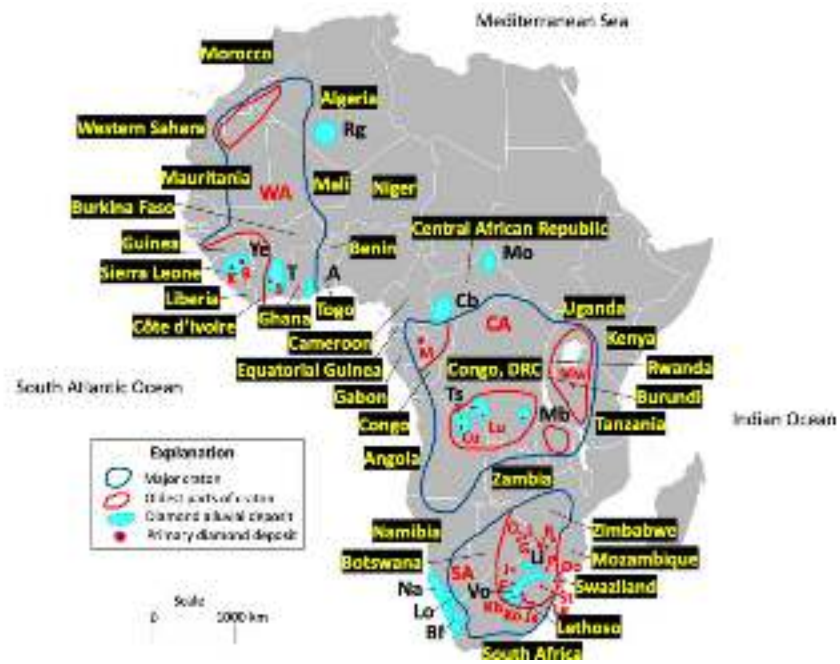


Figure 1.20. A map of Africa displaying the locations of the cratons and the diamond deposits in relation to them. The legend indicates major cratons in Africa, with their oldest parts circled in red. Alluvial deposits are shown as light blue areas with primary deposits depicted as red dots. This helps to show Clifford's Rule, which states that many diamond deposits are on the oldest, most stable, Archean cratons (Mitchell, 1986).

Kimberlite pipes are numerous, though few are diamondiferous (Bruton, 1979). Between pipes and even within one pipe, kimberlite has variable composition and appearance, from fine and compact to conglomerates of different rock types (Bruton, 1979). Diamondiferous kimberlites vary in crystal shape from pipe to pipe, though the gradation of colour change between yellow ground and blue ground is consistent throughout individual pipes (Bruton, 1979). Microdiamonds—perfectly formed crystals less than a millimeter in size—are found in addition to diamonds in kimberlites and suggest that kimberlite pipes include the magma in which diamonds originally formed (Bruton, 1979).

In 1966, geologist Tom Clifford wrote and published about the association between diamondiferous kimberlite and stable Archean cratons (Clifford, 1966). He did so in an attempt to delineate the metallogenic provinces in Africa, which are regions characterised by certain types of ore mineralization (Clifford, 1966). Previous unsuccessful efforts classified mineral deposits in terms of time of formation or geographical distribution, rather than structural environment (Clifford, 1966). Clifford, however, proposed that diamondiferous kimberlites are restricted to cratonic regimes that have been relatively stable for approximately 1.5 billion years—this is now known as Clifford's Rule. Clifford identified that regions of kimberlite magnetism are restricted to areas of the continental crust underlain by old cratons (Figure 1.20) (Mitchell, 1986). He did so through a combined usage of the results of radiometric dating studies (i.e. origin of orogenic belts) and knowledge of the location of kimberlite diamonds and their alluvial sources (Clifford, 1966). These regions are composed of a core of rocks greater than 2.4 gigayears old fused with younger belts of deformed rocks greater than 1.0 gigayears (Mitchell, 1986). Clifford and his colleague Dawson commented that the diamonds of highest economic value are found in the kimberlites located in central regions of stable Archean cratons from 2500-3800 Ma (Mitchell, 1986; Cunningham, 1988).

Diamonds in Africa

Diamond mining is a prominent industry in Africa, particularly in the southern parts of the continent (Bruton, 1979). The most famous diamond mines are the De Beers Mines, which belonged to the de Beers brothers, but were repeatedly sold, since no diamonds were found. Diamonds were eventually discovered in July of 1871, under the ownership of Fleetwood Rawstone, leading to the scramble that created the "Big Hole" of Kimberley (Bruton, 1979). The mine grew to one mile in circumference and a quarter of a mile deep (Bruton, 1979). Many investors became interested and the craze for diamond mining grew (Cunningham, 1988). Among this group was Cecil Rhodes, who was born in 1852 and had travelled to South Africa at the young age of 17, initially not to prospect for diamonds, but he eventually became captivated by the thought of the diamonds (Cunningham, 1988). Rhodes had attempted to buy a claim to the De Beers mines but was initially unsuccessful (Bruton, 1979). However, after working a few years to make enough money, he and his partner purchased claims in the De Beers Mines, Rhodes eventually became one of the largest shareholders of the mines (Cunningham, 1988). In 1880, Rhodes successfully partnered with two other groups and formed the De Beers Mining Company (Bruton, 1979; Cunningham, 1988).

The De Beers mines were able to provide insight into the geology of diamonds, as well as the composition of the kimberlite pipes and the materials present in the Earth's core (Cleasby, Wright and Davies, 1975). In the "Big Hole" of Kimberley, it was determined that the top layers were made of shales and concordant dolerite sills, which overlie 300-1000 m of Ventersdorp lavas, with intervening quartzite horizon (Cleasby, Wright and Davies, 1975). These layers rested on top of granite-gneiss, and the entire kimberlite walls were banded with ironstone, along with dolomite, limestone, shale, and chert (Cleasby, Wright and Davies, 1975). These observations allowed geologists to develop a better understanding about what was below the surface of the Earth. Another geologist who had expanded his work through the diamond mines in Africa was Wagner, who first described dikes in diamond mines, which are composed of kimberlite, and kimberlite sills, which are intrusive bodies along fracture zones found between consolidated rocks (Erlich and Hausel, 2002).

Mining Techniques

The basics of diamond mining were developed in South Africa once the diamond rush began (Bruton, 1979). There were three main steps to the process of alluvial diamond mining: 1) screening for diamonds, 2) washing the larger particles out of the mix, and 3) hand sorting to pick out the diamonds (Bruton, 1979). The first step of screening for diamonds was often done using sieves made of mesh (Bruton, 1979). This technique evolved over time, with the first modification being made when J.L. Babe travelled to South Africa in 1865 and invented the Yankee Baby—a rocking cradle with a double sieve that allowed for more efficient screening of diamonds (Cunningham, 1988). The Yankee Baby was able to discard both the larger particles, as well as the smaller particles of clay and sand, thus keeping only the medium sized diamonds (Bruton, 1979). This was replaced by the Trommel in 1975, a cylindrical barrel with wire netting that could be rotated to remove mud and break down conglomerates (Cunningham, 1988). The washing process was done using more preliminary methods, but in 1975, J. Mackway invented the rotary washing pan, which suspended the lighter material in water while the diamonds and heavier minerals settled to the bottom (Bruton, 1979).

Underground mining was developed in 1883 by Edward Jones (Bruton, 1979). Jones was working at the Kimberley mines when he proposed to mine by creating a shaft down into the kimberlite pipes. This proved to be unsuccessful, as the pillars put in place collapsed due to the immense amount of pressure (Bruton, 1979). The mining systems proposed in the late 19th century found more success than their predecessors. In 1890, the general manager of De Beers, Gardner Williams, developed a system known as chambering (Bruton, 1979), whereby a shaft is sunk into the kimberlites and then tunnels are created from the shaft (Cleasby, Wright and Davies, 1975). This technique was further refined into block caving in 1955, which reduced the number of tunnels in the mine, and greatly improved mining safety (Erlich and Hausel, 2002).

Canadian Diamonds

The first Canadian diamond mine was opened in the Northwest Territories (NWT) in 1998 (Hall, 2013). In 1899, Professor W.H Hobbs first gave the argument that diamonds were present in Canada and had been transported by glaciers (Kjarsgaard and Levinson, 2002). Diamond exploration in Canada is difficult, so there was not much observational supporting evidence. The potential locations for diamonds were thought to be in the Archean craton rocks in the NWT, but it was very hard to access these locations since transportation was challenging, and the climate conditions only allowed for fieldwork in May to September (Kjarsgaard and Levinson, 2002). While there were many small kimberlite discoveries across Canada throughout the 20th century, they were not profitable, and were not pursued further (Erlich and Hausel, 2002). Charles Fipke was the researcher who was given credit for the first major diamond discovery in Canada, as well as in North America (Erlich and Hausel, 2002). He worked with his partner Dr. Stewart Blusson (Fipke et al., 1995). Fipke had spent 20 years exploring Canada, and was looking for indicator minerals, which gave information about whether diamonds are present in that location (Erlich and Hausel, 2002). Fipke had determined that diamonds were found where old rocks were preserved and the Canadian Shield was a desirable location (Fipke, Gurney and Moore, 1995). He determined that the best indicator minerals for diamonds were garnets and chromites, which have a distinctive composition, making it easier for them to be detected (Fipke, Gurney and Moore, 1995). Fipke followed these diamond indicator minerals and travelled 1200 km along the flow of glacial deposits in the NWT (Erlich and Hausel, 2002). He eventually discovered kimberlite indicator minerals at Point Lake in the Lac de Gras region of the NWT, and after drilling in 1991, 81 microdiamonds were found in 59 kg of the samples taken (Erlich and Hausel, 2002).

The Point Lake kimberlite pipe discovery was the discovery that began the course of diamond mining in Canada (Fipke et al., 1995). Fipke partnered with the Broken Hill Proprietary, an Australian company, and on October 14, 1998, the Ekati Diamond Mines were opened in the NWT (Hall, 2013). The next Canadian mine opened in 2003, just southeast of the Ekati Diamond Mines (Hall, 2013). This was followed by the Snap Lake Mine, which opened in 2008, and owned by De Beers Canada, and became the first De Beers owned mine that was opened outside Africa (Hall, 2013).

Diamonds in the Earth and Beyond

While the first reference of diamonds may have been in the Old Testament, diamonds are still integral to culture and science (Erlich and Hausel, 2002). Diamonds provide an avenue to learn about the Earth through dating techniques, and they can also allow insight into the environment of our solar system, through the discovery of extraterrestrial diamonds (Vdovykin, 1970).

Figure 1.21. Image of a diamond, with a red inclusion that could be used to date the diamond (Erlich and Hausel, 2002).

The Age of Diamonds

Diamond dating has been a very important advancement that has allowed scientists to learn about the age of diamonds. While it is quite difficult to date diamonds because they are composed of carbon, and carbon cannot be radiometrically dated, diamond inclusions are used to approximate the age of certain diamonds (Erlich and Hausel, 2002). Some diamonds have inclusions of garnet, pyroxene, olivine, sulfides, chromites, or other materials that can be extracted and dated (Figure 1.21) (Erlich and Hausel, 2002). There are many methods for dating diamond inclusions, including 145Nd/ 144Nd, 87Sr/86Sr, and Rb-Sr isochron methods (Erlich and Hausel, 2002). Argon dating methods can reflect the age of kimberlite emplacement, and the Neodymium method indicates the time of diamond formation. Using these dating methods, diamonds have been found that date back to between 3.3 Ga and 990 Ma (Erlich and Hausel, 2002).

While there have been several attempts to date diamonds via their inclusions, the most popular methods were developed by Kramers and Richardson et al. in the late 1970s and early 1980s (Kirkley, Gurney and Levinson, 1991). Kramers was able to measure K, Rb, and Sr levels in silicate inclusions of diamonds using lead isotopic compositions and was able to use this information to determine the ages of diamonds (Kramers, 1979). Due to the success of this method, it is still used to this day. Another popular method was established by Richardson et al., who were able to date garnet inclusions in diamonds from African kimberlites, using Sm-Ds and Rb-Sr dating techniques to date diamonds that were 3300-3200 million years old (Richardson et al., 1984).

Diamond inclusions are very important, not only for dating, but also for detailing information about the mantle of the Earth, as they can be representative of the diamonds' growth environment and the fluids from which they crystallized (Klein-BenDavid et al., 2004). Some inclusions in diamonds have been found to contain H_2O, CO_3^{2-}, SiO_2, K_2O, CaO, and Fe_2O_3 (Navon et al., 1988). As scientists have reason to believe that the original materials trapped inside the diamonds were in a liquid state, this would indicate that there are liquids present in the mantle (Navon et al., 1988).

This information has allowed geologists to learn more about the Earth's composition based on extracted diamonds. This knowledge is useful for developing diamond extraction techniques and has shaped the growth and expansion of the diamond mining industry.

Now that we have discovered diamonds on Earth and established a thriving mining industry, scientists are looking to infinity and beyond. The exploration of diamonds in space is a new area of research that has the potential to provide us with even more information about Earth and our solar system.

Extraterrestrial Diamonds

We still have much to learn about diamonds. For example, research conducted in recent years shows that diamonds and other forms of carbon exist in extraterrestrial locations. Similar to diamond dating of Earth, diamonds in our solar system can tell us about its formation, evolution, and the type of matter that can be found floating around (Szurgot, Karczemska and Kozanecki, 2006). We now have the techniques required to synthesize diamonds in a laboratory, but for the longest time, scientists had incomplete knowledge about the thermodynamic relationship between temperature and pressure. (Cunningham, 1988). It was assumed that extraterrestrial diamonds were formed the same way under the same conditions (high temperature and high pressure), but modern research suggests otherwise (Vdovykin, 1970). Diamonds are cosmically abundant and exist in several different forms, though meteorites have been most helpful in providing information about diamonds in space (Szurgot, Karczemska and Kozanecki, 2006).

About 30 years ago, meteorite analysis showed the presence of very small diamonds whose isotopic composition of noble gases and structure were distinctly dissimilar to diamonds on Earth (Tielens, 2013). They were either hexagonal or cubic, indicating the cause of their formation (Vdovykin, 1970). Hexagonal diamonds do not occur on Earth, though they have been experimentally formed as a result of impact—like those in meteorites (Vdovykin, 1970). One method by which we can elucidate information about the crystallinity and structure of diamonds found in meteorites is Raman spectroscopy (Szurgot, Karczemska and Kozanecki, 2006). This technique is non-destructive and quite powerful in identifying and characterizing extraterrestrial minerals, carbonaceous materials, and carbon phases, in particular (Szurgot, Karczemska and Kozanecki, 2006). Once the Raman spectra of carbonaceous matter in meteorites is generated, it is analyzed to determine the phase and structure of the carbon material (Szurgot, Karczemska and Kozanecki, 2006). Since carbon is plentiful and exists in all forms in the universe, its presence in meteorites represents solid manifestations of the gaseous nebulae that birthed our solar system (Szurgot, Karczemska and Kozanecki, 2006).

The morphologies and compositions of the meteoritic diamonds evince their formation, while their chemical and isotopic compositions relate them to their parent star, equivalent to the star's "fingerprint" (Szurgot, Karczemska and Kozanecki, 2006). Based on this information, more theories have been proposed about these diamonds' formation, including chemical vapour deposition (CVD) from stellar outflows, impact shock metamorphism caused by supernovae, UV annealing of small carbon grains, and radiation-induced methods (Szurgot, Karczemska and Kozanecki, 2006). These theories also have supporting research. In 1987, Polish physicist Stanislaw Mitura first demonstrated that diamonds can be formed under low pressure using a CVD process with the aid of electrons, and these conditions resemble those in space (Mitura, 1987). The collisions of gas molecules with electrons transmitting radio-frequency electric energy cause the formation of bonds in the gas phase (Mitura, 1987). The amount of energy transferred to the gas molecules from the radio-frequency electric field determines the type of bond—and therefore structure—formed (Mitura, 1987). A high collisional frequency among all these elements permits the formation of the optimal crystalline structure (i.e. that of a diamond) (Mitura, 1987). Diamonds found in space allows us to glean more information about the environment in our solar system and give us a better understanding of how our world was formed.

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Figure 1.2 A portrait of Georges Cuvier. Georges Cuvier Promoteur de l'idée Evolutionniste et Créateur de la Biologie Moderne, 1795.

Figure 1.3 Fossils from the region around Paris. Georges Cuvier, Fossil Bones, and Geological Catastrophes, 1811.

Figure 1.4 The first geological map of Canada. Geological Survey of Canada, William Logan.

Figure 1.5 Fossil specimen of Wiwaxia from the Burgess Shale. Wikimedia Commons, 2009.

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Figure 1.19 Sample of blue kimberlite. Flickr, James St. John, 2010.

Figure 1.20 Image adapted from: A map of Africa. Geology and nonfuel mineral deposits of Africa and the Middle East, USGS Open-File Report, Taylor, C.D., Schulz, K.J., Doebrich, J.L., Orris, G.J., Denning, P.D., Kirschbaum, M.J., 2005.

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Figure 1.21 Diamond with red inclusion. Mindat, Robert M. Lavinsky, 2010.

Chapter 2. Geological Processes

A drying water hole in Florence, Arizona.

Chapter 2.
Geological Processes

Since the beginning of time, humans have been enthralled with Earth's fascinating and intriguing processes. From the waterways that sustained early civilization to the earthquakes that destroyed entire villages, a common pattern among all processes discussed within this chapter is the evolution of thought that led to our current understanding of such events.

Earth is a dynamic system, with plate tectonics shifting and weather patterns changing constantly. Despite its dynamic nature, some processes have shown to remain quite constant, allowing us the opportunity to analyze how humans have approached the puzzling questions posed by these processes. This chapter also explores the utilization of technology to explore these processes before the birth of the scientific method

As you dive into this chapter, you will learn about the notable characters within each story told, as well as their role in the development of their respective geological fields. You will learn of how they altered the course of history in an attempt to answer some of their most perplexing questions. This historical perspective allows for a deeper understanding of Earth processes that we likely spend little time thinking about in our daily lives, simply because our predecessors did the work for us.

Throughout this chapter, you will learn of the notable discoveries about Earth's most captivating phenomena, from the water that runs through the Nile to the auroral skies painted neon. You will learn about the progression of technology that led to the modern instruments used today. You will also gain a better understanding and appreciation for Earth's wonderous—and in some cases, disruptive—processes.

History of Seismology

Our awareness of earthquakes dates back to ancient times; however, their cause was yet to be completely understood at the time. Two pre-modern cultures, the Greeks and the Chinese, both developed naturalistic explanations for earthquakes which lasted throughout the eighteenth and nineteenth centuries. However, it wasn't until this past century that seismology––the study of earthquakes—became recognized as its own scientific field of study. Destructive cataclysmic events, such as Lisbon in 1755 and the Great Ansei in 1855, were critical in spiking the interest of scientists and philosophers, as well as promoting social support for seismic studies. Within the last century, seismology has progressed to be integrative of geology, physics, and engineering disciplines. Thus, understanding the historical development of how seismology has progressed, specifically through the analysis of catastrophic events, may prove to be vital in improving how research is conducted in this field today.

Historical Explanations

Early ideas pertaining to the causes of earthquakes were largely attributed to classical ancient sources. It was thought to either be a divine act of God or supernatural power that visited mankind as punishment for misbehaviour (Howell, 1990). In Norse mythology, earthquakes were caused by the subterranean writing of the imprisoned God, Loki, in his attempt to avoid venom dripping from a serpent's tooth (Lay, 2004). Whereas, in Greek mythology, various philosophers developed their own theories for earthquakes. Anaximenes of Miletus (586-528 BCE) hypothesized Earth to be a sponge filled with holes (Smits, 2013). Rainwater would then fill the holes, leading to rising waters and accumulated pressures, ultimately causing these destructive events to occur. Democritus (460-370 BCE) adopted a theory that linked earthquakes to groundwater displacement, wherein the Earth was encapsulated with water. As such, excessive rain would cause the water to overflow, resulting in earthquakes (Smits, 2013). However, the most recognized theory during the medieval periods was that proposed by Aristotle between 384 and 322 BCE (Smits, 2013). Originating from Anaxagoras, Aristotle linked earthquakes with atmospheric events—specifically wind blowing in underground caverns that produced fires, similar to thunderstorms producing lightning. The bursting fires through the rocks would cause earthquakes, and he believed that they tended to occur in areas with caves (Lay, 2004). As such, he linked wind to be the main cause of earthquakes and he saw the world as consisting of five elements: earth; fire; air; water; and ether. Aristotle's theory lasted all the way into the nineteenth century. His views were brought to Japan through Christian missionaries in the late Muromachi (1336 to 1573) and Edo/Tokugawa (1603-1868) periods (Smits, 2013). Aristotelian view heavily resembled theories of Buddhist cosmology, which is why many theories of earthquakes based on Aristotle often appeared of Buddhist origin.

In the seventeenth century, Buddhist cosmology, notably the Five Seed Elements of earth, water, fire, wind, and space—that describe the structure of the planet—were recognized as the main explanation of earthquakes in Asia. "Above space is wind. The agitation of wind causes it to blow upward, likewise agitating fire. When fire becomes agitated, water is no longer calm, and it functions as a substance (ki) that can long support things floating on it" (Smits, 2013). This passage describes the upward and downward forces in equilibrium similar to yin and yang balancing each other. According to the *Supreme Ultimate Earthquake Record*, this balance is preserved by "the ki of the two *kami*", whereby the ki denotes matter or material force (Chinese: *qi*), and *kami* indicates willful cosmic forces (Smits, 2013). In this theory, it is thought that "when the people offend against the will of the *kami*, that offence penetrates heaven and the Earth." As such, angry deities cause winds that turn into earthquakes, typhoons, floods, and other natural catastrophes (Smits, 2013). Intrinsically, this means that human behaviour plays a key role in influencing cosmic forces, similar to many medieval conceptions of natural hazards.

The Turning Point in Earthquake Science

In European and Japanese societies, there are two noteworthy earthquakes that impacted and marked the turning point in our understanding of seismology.

Perhaps one of the most historically significant earthquakes is the 1755 Lisbon earthquake. It struck at approximately 9:40 am on Sunday November 1, 1755, the same day as the catholic holiday of "All Saints Day", where a majority of the citizens were at the church (Kozák and Cermák, 2010). The quake lasted between three and six minutes and caused catastrophic damage to most city edifices, leading to fissures five metres wide in the city center (Kozák and Cermák, 2010) (Figure 2.1). A tsunami wave entered the mouth of the Tagus river forty minutes later and hit the coastal quarters of Lisbon and other settlements located along the riverbank, killing over 50 000 citizens (Mendes-Victor et al., 2008; Kozák and Cermák, 2010).

Figure 2.1 Copper engraving showing Lisbon in ruins and in flames during the earthquake.

Following this tragedy, under the leadership of the Prime Minister, Marquis of Pombal, the Government of Portugal immediately took the necessary measures to minimize material damage, reconstruct the town, and help its people return back to their daily life. One significant contribution was a questionnaire that Pombal ordered to be sent to all parishes of the country. It was a systematic collection of quantitative information about the earthquake and its effects, and included the following questions: 1) how many aftershocks were felt?; 2) what kind of damage was caused?; 3) how long did the earthquake last?; and 4) what happened in the wells and water (Kozák and Cermák, 2010)? Currently, the answers to the questions are archived in the national historical archive, Torre do Tombo (Kozák and Cermák, 2010). Pombal's actions played a critical role in the current understanding of seismology as he was the first to find an objective description of the broad causes and consequences of the earthquake. By studying and cross-referencing people's responses, scientists today were able to reconstruct the event from a scientific perspective. As such, the events that occurred in Lisbon in 1755 mark the beginning of what is now considered seismological research.

John Michell's Discovery

Another one of the earliest responses in the scientific community following the Lisbon earthquake was from Reverend John Michell (1724-1793)—a former Woodwardian Professor of Geology at the University of Cambridge. At the time, seismology remained poorly understood amongst the majority of scientists, with one major concern lying in understanding the concept of "action at a distance" (Musson, 2013). In the context of earthquakes, it refers to a medium that allows for the transmission of effects. When the event took place, it was widely accepted that this source medium consisted of either air or gas and as such, the shocks were able to transmit from one location to the next (Musson, 2013).

However, it was John Michell who first postulated in his paper, *Conjectures concerning the Cause and Observations upon the Phenomena of Earthquakes*, that the true means of propagation of seismic shocks were via elastic waves through a solid medium (Michell, 1759). He claimed that, "earthquakes were waves set up by the shifting masses of rock miles below the surface … the motion of the earth in earthquakes is partly tremulous and partly propagated by waves which succeed each another" and with this said, he essentially put forth the idea that earthquakes originated from wave motions within the Earth (Michell, 1759). This notion was a result of his observations that the Earth consisted of varying successive layers of soil and rock (Keller, 1998). Moreover, introducing the idea of elastic waves also correlated with his ability to estimate the earthquake's location, as wave energy is known to disperse outwards from a small source.

Through identifying the direction and velocity of wave shocks at varying locations, Michell noted the possibility of tracing the earthquake back to a single origin where his plotted lines intersected. He hypothesized the epicentre of the Great Lisbon earthquake to be located in the eastern Atlantic Ocean, at latitudes between Lisbon and Oporto (Oldroyd et al., 2007). He also engaged in measuring the speed of the earthquake transmission in various regions and recorded the disturbance to travel an estimated 1200 miles per hour. It is worth noting that while he did gather the data observationally, he acknowledged his results may not have been completely accurate as waves have different speeds when travelling through land and water. Another contribution he made, although rejected today, was his idea to support the "explosion theory"—whereby the cause of earthquakes is directly linked to the production of vapours generated by the mixing of water with subterranean fires (Oldroyd et al., 2007). In efforts to communicate his findings, he drew sketches of the geological stratification of the ground (Keller, 1998).

In his paper, he explained that there is initially a continuous stratum with an underground subterranean fire located beneath. Upon ignition, the rock strata are raised and arched by the heat. This leads to the amalgamation of water vapour from the mixing with fire, and consequently, the generated pressure causes the production of earthquakes (Keller, 1998). Overall, while his physical theory of earthquake generation did not hold through the modern era, Michell's contributions were of great worth as he was the first to observe that earthquakes propagated as waves, he was able to determine a method of locating the epicentre of the earthquake, and finally, he was a pioneer of implementing his knowledge of geological strata to seismology.

The Great Ansei Earthquake

While seismological studies were significantly promoted following the tragedy of Lisbon in 1755, another major cataclysmic event that prompted and reshaped the understanding of this field was the Great Ansei earthquake in 1855. This major catastrophe hit Edo (modern day Tokyo) during a time of special religious significance. The earthquake, with an estimated magnitude between 6.9 and 7.1 hit the region near 10 pm, killing around 7000 to 10 000 people (Smits, 2006). It is reported that at least 14,000 structures were damaged and as many as 80 aftershocks continued each day for nine days after the earthquake. It is claimed to have shaken the city because according to the prevailing understanding of earthquakes at the time—mainly the yin-yang belief, where yin represents the power of sun and wind (hot and dry), and yang is the realm under the crust (dark and moist)—this event was "impossible" and should not have occurred (Smits, 2006). In the eighteenth century, people in Japan started digging their own wells instead of using water through pipes brought from upstream areas of the major rivers: Kanda, Tama, and Mita (Smits, 2013). With this new way of retrieving water, people thought it would have released the underground pressure (yang energy), consequently lowering the number of earthquakes (Smits, 2013).

Two days after the initial earthquake, broadsheets and images began to appear for sale around the city. Within a few weeks, over 400 varieties of earthquake-related prints were on the market featuring a giant catfish, Namazu (Smits, 2006). These images were believed to have appeared because of the folk image that the movements of a giant subterranean Namazu was behind the cause of this earthquake (Figure 2.2). However, more importantly (and less scientifically), the Ansei Earthquake shook not only the Earth's crust, but the social and political foundation of Edo (Smits, 2006). Thus, Namazu was a reaction and outcry of the common people. These metaphoric catfish ultimately became an important part of the study of earthquakes in later years.

Figure 2.2 The women of the pleasure quarters blaming the catfish for the earthquake

Initially, the early modern earthquake signs included extreme weather conditions, such as: hot weather; thunder; and well water increasing or decreasing while becoming muddy. After 1855, came the new idea of the strange behaviour of catfish. People noticed that many of the fish began to jump in a pond a day prior to earthquakes occurring (Bhargava et al., 2009). In 1932, Shinkishi Hatai and Noboru Abe became the first to investigate the response of catfish to earthquakes (Bhargava et al., 2009). By testing their degree of sensitivity when exposed to various external stimuli, Hatai and Abe concluded that catfish became sensitive to a knocking sound six to eight hours before an earthquake was recorded (Hatai and Abe, 1932). Similar research studies also noted that aquatic animals were responding to changes in electric fields because of their special electrosensory systems (Bhargava et al., 2009). Naturally, catfish became a promising tool for earthquake prediction. In 1977, the government funded the project to put American and Japanese catfish in aquariums to sense earthquakes (Smits, 2013), with a device in the tank to detect movements and sound an alarm. This project cost 120 million yen ($1.5 million USD) and continued until 1993, with a 30% success rate.

Earthquake Architecture

After the Great Ansei, individuals became more receptive to new ideas regarding the causes of earthquakes. People started to question scientifically and look into various books for more evidence-based theories. Designs for earthquake warning devices and scientific literature published after the event reflected optimism for the possibility of predicting earthquakes. For example, in 1856, Utagawa Kosai published the paper *Earthquake Prevention Theory* (*Jishin yobosetsu*) based upon a Dutch periodical, *Nederlandsche magazijn*. He believed that earthquakes were caused by electricity occurring under the Earth, similar to how it produces lightning (Smits, 2013). He urged the need to place lightning rods in the Earth, which would conduct electricity up and out into the air. Moreover, Yamazaki Bise's thoughts on the earthquake may have provided the earliest example of explicit instructions for constructing earthquake resistant buildings (Smits, 2013). He suggested that a wooden pole be placed in the center of a structure, wrapped in a stone base, and protruding above the roof with iron extensions attached to its top (Smits, 2013). Four large jars would sink into the earth like wells, with iron chains attached to the top. The system would conduct electricity from storms or within the Earth to the top of the rod. The energy would then be dissipated into the air or into the pole made up of non-conducting materials. In theory, this method would be able to combat both lightning strikes and earthquakes. While it is unclear if this method was ever implemented, or if it would have been effective, this however did show early evidence of an active approach to mitigating earthquake hazards.

From understanding the behaviour of catfish to improving earthquake predictions, the acceleration of socio-political trends was underway. The 1855 Ansei earthquake served as a challenge for the emerging disciplines of seismology. It became a baseline to measure improvement in prevention and detection and is often used as a point of comparison about different aspects of earthquakes today.

Understanding Fault Slippage in Nineteenth Century Seismology

Following the events of Lisbon and Ansei, many subsequent earthquakes also served great importance in understanding the geological causes of earthquakes. An interesting question similar to the chicken or the egg causality dilemma can be asked: Did the ground-breaking shake the earth or did the earth-shaking break the ground? While the conclusion that earthquakes resulted from slippage on geological faults became widely accepted in the late nineteenth century, many earthquakes did not have surface faulting (Lay, 2004). Therefore, field studies were done in order to prove the point. These include G.K. Gilbert in California (1872), A. McKayin in New Zealand (1888), B. Koto in Japan (1891), and C.L. Griesbach in Baluchistan (1892). The Nobi earthquake in 1891 was a major event that consolidated the idea of fault slippage as the cause of earthquakes (Lay, 2004). B. Koto, a Professor of Geology at the Imperial University of Tokyo was able to elaborately trace a long train of surface fault breaks that appeared (Mikumo and Ando, 1976). In his paper, *On the Cause of the Great Earthquake in Central Japan, 1891*, he noted the infamous Midori fault in the Neodani village which extends over 400 metres, where one side of the flatbed of the valley tipped off, causing an abrupt step measuring 5.5 to 6 metres (Figure 2.3) (Kotô, 1893). He stated that cracks occur in specific areas because of the greater motion experienced at those planes, especially at unsupported cliff faces and banks of rivers with

Figure 2.3 Photograph taken in 2007 of the Neodani Fault (in the centre) in Motosu, Gifu Prefecture, Japan

steep slopes, where waves of shock can emerge on a free surface. He also noted that slips and fissures depend on the structure of rocks and occur "on a particularly grand scale where the strata dips into or against the slope of the walls of a valley". He concluded that "The sudden elevations, depressions, or lateral shiftings of large tracts of country that take place at the time of destructive earthquakes are usually considered as the effects rather than the cause of subterranean commotion; but in my opinion, it can be confidently asserted that the sudden formation of the 'great fault of Neo' was the actual cause of the great earthquake" (The Japan Weekly Mail, 1893).

New Seismology

The period after 1880 until 1920 can be called the birth of "New Seismology". With a deeper understanding of the causes of earthquakes and an emphasis on disaster management, there was a shift in focus to recruit experts in this area to create new earthquake detecting instruments. Some important figures include John Milne, who arrived in Japan in 1876 to be a Professor at the Imperial College of Engineering in Tokyo (Agnew, 2002). He founded the world's first academic society of earthquake research, the Seismological Society of Japan (SSJ), in 1880 (Matsu'ura, 2017). SSJ continues to publish journals annually to "promote studies of earthquakes, share results, and contribute to earthquake disaster mitigation" (SSJ, 2020). Milne was important because of his desire to not only study all aspects of earthquakes, but to accompany it with quantitative analysis using instrumental measurements, many of which he designed himself. Milne, Sir James Alfred Ewing, and Thomas Gray were all credited with the invention of the horizontal pendulum, which was used to detect the ground's lower limit of strong motion. Soon after, their device and ideas were implemented by other scientists around the world. Interestingly, E. von Rebeur-Paschwitz in Germany built horizontal pendulums to measure tidal tilts for his astronomical studies and was able to record transient disturbances and correlate it to a distant earthquake offshore of Tokyo.

Milne, Ewing, and Gray also trained the world's first professor of seismology, Seikei Sekiya (1855-96). Sekiya made immense contributions to the field, including his remarkable model exhibiting the Earth's surface movement during an earthquake on January 15, 1887. Using a complete earthquake record from Ewing's seismographs, he followed the motion using stiff copper wires, representing the first 72 seconds of the earthquake. This model was significant as it served to show the complex nature of earthquake motion and shed light to seismologists of the improvements of earthquake measurements through history (Lockyer, 1888). Aside from the model, he continued to work with seismographs, became the secretary to the Imperial Earthquake Investigation Committee, and helped in the extension of seismic survey in Japan. At the time of his death, he had risen the number of seismic observing stations from around 600 to 968 (Davison, 2014).

Modern Era: Seismological Advances

Earthquake Prediction

While there have been significant advances in the field of seismology since the great earthquakes of Lisbon and Ansei, one remaining challenge for geoscientists post-1980 and into the twenty-first century continued to be earthquake prediction. This entails predicting the earthquake's epicentre, time, and magnitude (Panakkat and Adeli, 2007).

Originating in the early 1980s, the "VAN method" is an earthquake prediction model named after Greek scientists: Varotsos; Alexopoulos; and Nomicos. Following the 1981 earthquake in Athens, these scientists hypothesized that prior to a seismic event, there must be an electric current that is generated in the area (Moustra, Avraamides and Christodoulou, 2011). As such, they modelled their system to track geoelectric potential changes. This system allows for the detection of seismic electric signals—which are signals of 1 Hz of frequency or less and come from measuring the variation in Earth's electric field. To measure these signals, electrodes are placed into the ground at select distances and orientations. Based on the signals generated and recognized, an estimated time of occurrence for when an earthquake might strike in the future can be calculated (Moustra, Avraamides and Christodoulou, 2011). The measurement of magnitude and epicentre location are also identifiable, primarily by means of estimating from prior data and through a process of elimination of seismic areas, respectively. Using this model, the team is reported to have successfully predicted 60% of earthquakes of magnitudes greater than 5.3 on the Richter scale that have occurred in Greece (their success criteria involves predicting the earthquake within days or weeks in advance, noting the epicentre correctly to a distance of 100 km, and predicting the magnitude to 0.7 units on the Richter scale) (Moustra, Avraamides and Christodoulou, 2011). While this novel method has been able to accurately predict earthquakes thus far, it has been the centre of great debate, with certain scientists arguing the strong success rates being linked to chance.

As such, seismologists have continued to look for different mechanisms that may serve to help earthquake prediction. With the surge in modern technology in recent decades, the use of artificial intelligence (AI) in seismology—notably, machine learning—has also been critical in advancing this field. Machine learning, a subset of AI, consists of systems that are able to learn from data sets, identify patterns, and make decisions (Chowdhury, Apon and Dey, 2017). Specifically, it is based on either supervised or unsupervised learning. The former entails training a model with known data such that it can create responses and predict future outputs, while the latter consists of recognizing unseen patterns in existing data. This technology is reportedly able to far exceed the human intuition of data analysis—a rare feat that stems from its probability theory based algorithms (Kong et al., 2019). In laboratory-simulated trials, scientists have been able to predict artificially-generated quakes using machine learning approaches (Rouet-Leduc et al., 2017). Their system is able to analyze the acoustic signal that is emitted from the fault and as such, determine the time that remains before an earthquake's occurrence. Likewise, similar machine learning approaches, such as neural networks—a system used to model non-linear relationships with several variables—has also been implemented in China to successfully determine the occurrence of seismic events (Asim et al., 2017; Liu et al., 2004).

Earthquake Early Warning

Alongside earthquake prediction methods using novel technology, modern seismology is also involved in developing new forms of precautionary measures regarding disaster prevention. Specifically, in recent years, there has been increased use and implementation of Earthquake Early Warning systems in various countries. The main objective of this system is to detect an event, its time, and epicenter, and to use the generated data to deliver alerts and notifications to areas under threat (Tajima and Hayashida, 2018). One of the largest systems that currently exists is in Japan and is reported to have been of substantial aid during the 2011 Tohoku-Oki earthquake. The system itself has 4000 stations at intervals of about 20 km around the country. As such, it was able to identify P-waves and notify areas at risk from damage in approximately eight seconds (Tajima and Hayashida, 2018). With only 18 500 individuals affected by this 9.0 magnitude earthquake, many associate the low number of casualties to the successful ability of the Earthquake Early Warning system to warn citizens in advance. With alerts reaching those living in the region prior to the destructive shaking of the ground (i.e. S waves arriving), it allowed for people to take necessary action and avoid injury and/or damage (i.e. enter safe locations and deactivate equipment; Figure 2.4) (Minson et al., 2018). The United States of America is now implementing a similar warning system called the "ShakeAlert Earthquake Early Warning" system. This is designed specifically for the west coast of the US, a region prone to earthquake activity (Minson et al., 2018).

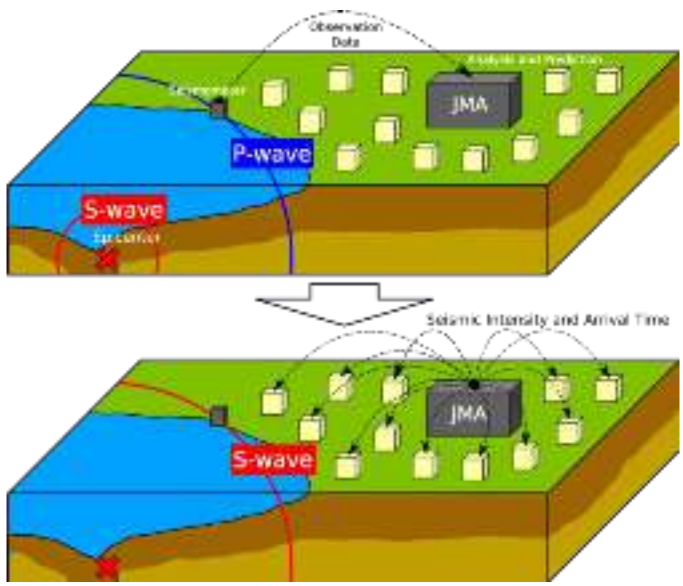

Figure 2.4. Earthquake Early Warning system in Japan, with data being delivered to and sent from the Japan Meteorological Agency (JMA).

Thus, the understanding of seismology has progressed significantly through history. From the many ancient theories regarding the origin of earthquakes developed in the past, to modern, evidence-based theories that are supported by numerous research studies, scientists have shifted their focus from understanding earthquake causes to earthquake detection. As earthquakes continue to affect many parts of the world today, seismology research aims to develop methods to improve the accuracy of earthquake predictions. This ever growing and emerging field of seismology will help in the development of preventative measures to deal with potential earthquake threats in the future.

Tracking Tides: A History of Measuring Sea Level

Evidence of changing seas through tides and floods have been well known by humans for many years. Practical knowledge of the sea was a necessary criterion for sailors much before science went to work on the topic. Many scientific minds played a role in understanding how the sea worked.

Understanding Tides

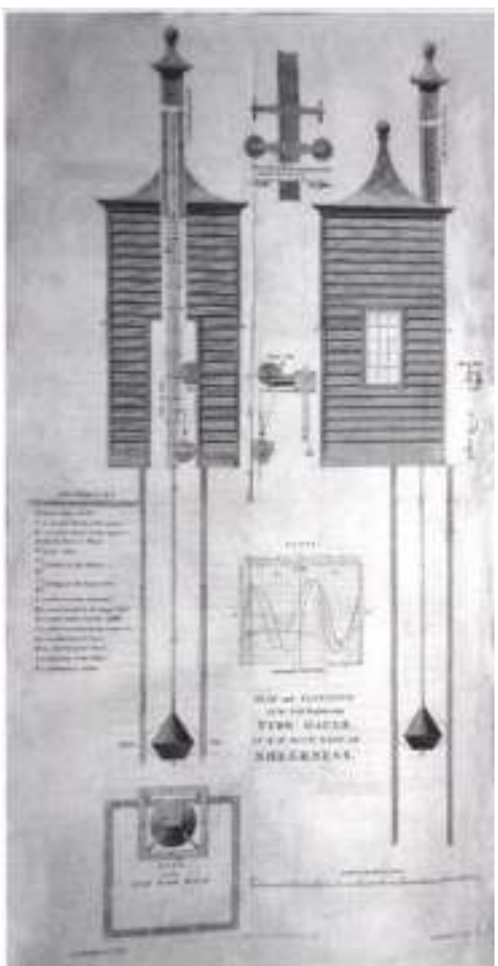

Figure 2.5 Sketch of Mitchell's self-registering tide gauge. This machine was the first of its kind to make observational data.

Although it has been known for hundreds of years that the Moon and Sun affect tides, early physicists such as Johannes Kepler and Isaac Newton first attempted to mathematically describe the role of celestial bodies in the daily rise and fall of the ocean (Lubbock and Treas. R.S., 1833). Kepler (1596-1650) first suggested that the gravitational pull of the Moon may be responsible for the tides (Pugh, 2004). At the beginning of the eighteenth century, new attempts at explaining orbits were made by prominent figures such as Edmund Halley, Robert Hooke, and Newton. Newton eventually published his Principia in 1687 thanks to this encouragement, and funding of Halley (Cartwright, 2000). In it he expanded on Kepler's work with his laws of universal gravitational energy which explained mutual gravitational pull between objects of mass (Cartwright, 2000). This theory would say that not only does the Earth exert gravitational force on the Moon, but the Moon exerts force on the Earth, which was assumed to be seen through waves. The observation that tidal patterns repeated every day supported this hypothesis. Halley, using Newton's work, created an account of the tides; he also developed a map of the English Straight using measurements of the sea (Pugh, 2004). Other notable scientists who built off of this primary work include Marquis de Laplace who derived the Laplace Tidal Equations from fluid dynamics and Daniel Bernoulli who developed a series of equations to predict sea level for ports where the major contributing factor to the rise and fall is semidiurnal tides (Cartwright, 2000).

This work by Newton and his contemporaries laid a foundation for understanding how sea level may change over time. A necessary technology to continue this investigation is a device to measure these changes. Developed around this time was the first tidal gauge (Pugh, 2004).

Measuring Tides

As early as the seventeenth century, technology has been used to measure and record sea level. One of the first records of sea level observation dates back to 1682 in Amsterdam, Netherlands where tide poles were placed in harbour entrances (Woppelmann and Pirazzoli, 2005). The poles were marked in one foot increments that indicated water level relative to a fixed point on land (Rozwadowski and Keuren, 2004; Woppelmann and Pirazzoli, 2005). Only the highest and lowest tides were recorded along with the time of the occurrence. Similar technology emerged across Europe into the eighteenth century. Tide poles were first used in Liverpool, England in 1768, and Stockholm, Sweden in 1774 (Woppelmann and Pirazzoli, 2005). Data obtained from tide poles, tide gauges and automated tide-recording systems have been crucial in navigation, managing ship traffic, coastal engineering, and storm surge prediction throughout history.

The beginning of the 1830s saw a renewed interest in tidal observations as the successful invention and use of self-registering tide gauges improved accuracy and efficiency of measuring sea levels. The first gauge to make observational data was constructed by the civil engineer J. Mitchell and was used at the Sheerness Dockyard in England (Rozwadowski and Keuren, 2004). The design for the gauge was motivated by Mitchell noting that although the dockyard had a tide pole, attendants were not usually present to record the data. The device consisted of a stilling well with a vertical rod attached to the float so the reading could be made against a vertical scale (Figure 2.5). Attached to the rod was a pen that recorded the float's movement on a cylindrical drum that made a complete rotation once a day by clockwork (Figure 2.6) (Cartwright, 2000). As with most technology, the tide gauge was subject to change over time. Thomas G. Bunt constructed another version of the device in 1837 which was used until 1872 on the River Avon below Bristol (Cartwright, 2000). During its operation, automatic tide gauges were being implemented worldwide in countries such as France, India, and the United States of America.

Geodetic Survey, 1893). Several versions of the self-registering tide gauge were used in this survey, each with a design similar to that envisioned by Mitchell. Water was allowed into a small opening in a vertical tube containing a float. As the water level changed the float moved up or down and this movement was transmitted to a pencil moving along a piece of rotating paper. The time was noted periodically on the tide tracing.

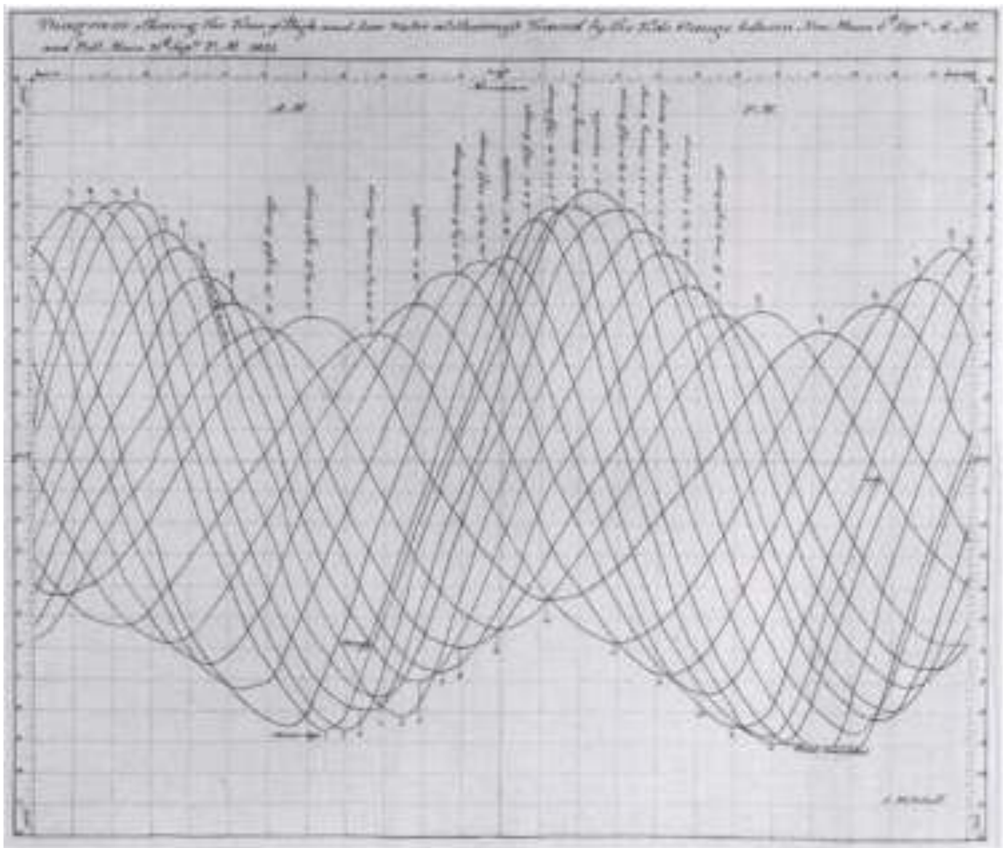

Figure 2.6 The first tide tracings from Mitchell's gauge. Four 15-day tide traces are mapped onto this sheet of paper. The record ran from September 6th to 21st, 1831 at Sheerness Dockyards, England. This sheet would have been wrapped around the cylindrical drum upon which the pen recorded the rising and lowering of the tides.

The United States saw many uses of tide gauges. There is some dispute as to who should be credited with the first installation of these devices because similar ideas were being explored across the globe around this time. Joseph Saxton made the first American self-registering tide gauge in 1851 for the U.S. Coast Survey (Shennan, Long and Horton, 2015). This technology became incredibly useful in understanding processes on the coast and generated valuable data. In 1893, the U. S. Coast and Geodetic Survey reported their methods for recording and results of their surveys. Tables were developed to record times and heights of the tides at ports across the North American coast. Metrics such as direction and strength of tidal currents, and relative densities of water specimens were also reported (U. S. Coast and

Another intriguing tool used in the survey was something called the "tide-predicting machine", invented by Professor William Ferrel in 1885 during his involvement with the Survey (Hicks, 2006). Ferrel's tide predictor was used in preparing annual tide tables for the coast. This machine reduced the time to record water heights from forty days to merely one. An operator would set the machine for a particular port and year, turn the crank with one hand, and record the times of high and low tides from the dial (U. S. Coast and Geodetic Survey, 1893).

Sir Robert Moray, one of the founding members and first president of the Royal Society of London, played an instrumental role in the widespread installation of tide measuring devices across England (Cartwright, 2000). In the 1660s, Moray suggested tidal observatories be constructed and specific measurements be recorded. He advised that the following be noted by observers (in Moray's words):

1. The degrees of the Rising and Falling of the water every quarter of an hour… from the Periods of the Tides and Ebbs; to be observed night and day for 2 or 3 months.

2. The degrees of the velocity of the Motion of the Water every quarter of an hour for some whole Tides together; to be observed by a second Pendul-Watch; and a logg fastened to a line of some 50 fathoms, wound about a wheel.

3. The exact measures of the Heights of every utmost High-Water and Low-Water, from one Spring-tide to another, for some Months or rather Years.

4. The exact heights of Spring-tides and Spring-ebbs for some years together.

(Moray, cited in Hutton et al., 1809)

In addition to these guidelines, Moray recommended weather parameters be recorded (Cartwright, 2000). Unfortunately, the resources necessary for the implementation of measuring devices across England and such extensive observations to be recorded were not yet available, and Moray's guidelines were not successfully met in his lifetime (Rozwadowski and Keuren, 2004).

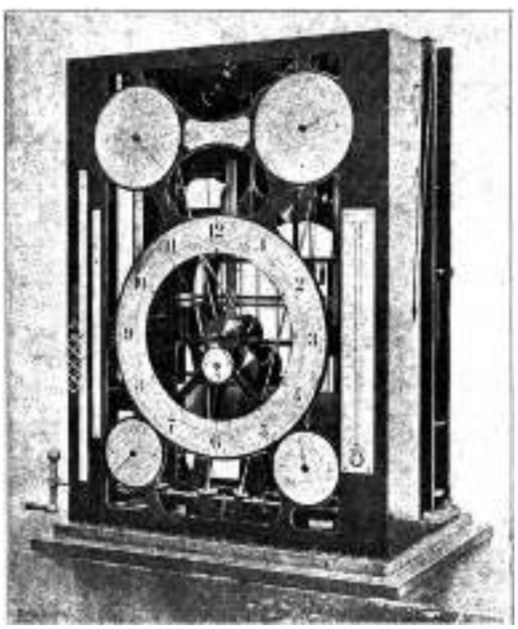

Figure 2.7 William Ferrel's Tide-Predicting Machine. The front face of the machine features a clock from which the times of low and high tides could be read. The crank spun by the operator can be seen on the bottom left of the machine.

It was not until 1807, almost 150 years after Moray's work, that Thomas Young advocated for the measuring of intermediate height of water or the sea level between high and low tide (Rozwadowski and Keuren, 2004). Young, best known for his contributions to the wave theory of light and the double slit experiment, applied his understanding of physics to treat tides as propagating waves. It was the lack of intermediate tidal measurements that limited the work Young and his successors could do to develop hydrodynamic tidal theory (Reidy, 2008).

In 1822, Young received a letter from Benjamin Bevan, a civil engineer who would make his dreams a reality. In the letter, Bevan expressed interest in digging a well equipped with a tide pole and float to gain a better understanding of tides and mean sea level (Rozwadowski and Keuren, 2004). By spring of 1823, Bevan was surveying the region surrounding Greenwich, England for an appropriate location for the tide pole and in July of that year, the well was under construction. But the process was costly, largely due to the depth of well required for low tide to be recorded. In 1824 the device was complete, however, it never worked properly, and the funds needed for successful use were no longer available. Additionally, many of these wells were needed across the country to obtain useful data, a feat largely beyond the scope of Young and Bevan's resources (Rozwadowski and Keuren, 2004).

While measuring sea level due to changes in tides has become relatively routine with the technologies previously discussed, understanding sea levels of the past is not so straight forward. Scientists have had to turn to Earth's own history books to understand where our oceans were long ago and what has caused their levels to change. More complex techniques have been developed to piece together where Earth's historic oceans were.

Causes of Sea Level Rise

It is important to note that although the technologies previously described are often called "tidal gauges", they are more correctly known as sea level measuring devices as the sea level is not only changing due to daily tides, but other factors as well. Some of these include atmospheric pressure, basin change, and water volume change.

James Clark Ross, an important British Naval officer in the mid-1800s confirmed the relationship between atmospheric pressure and water level (Pugh, 2004). On one of his expeditions to the Arctic, his ships became trapped as an ice sheet moved to cover the harbour's mouth (Ross, 1854). Ross stayed in Port Leopold (now Nunavut)—where they had anchored—for the winter of 1848-1849 (Pugh, 2004). Due to concern for the integrity of the ship's structure should a large decrease in the water level occur, Ross decided to start measuring the sea level (Ross, 1854). When he began to see changes not explained by diurnal tides, he looked for an alternate explanation. He noticed a relationship between water levels and barometer readings (Ross, 1854). Starting with observations four times a day (and then increasing to every 15 minutes, but eventually only recording every hour) Ross and his crew kept record of the sea level and the barometer reading (Ross, 1854). After 47 days he analyzed his findings and created a mathematical expression relating the sea level rise to the barometric pressure and the specific gravity of mercury which was used within the barometer (Ross, 1854). His finding confirmed the inverse relationship between sea level and pressure (Ross, 1854).

Although the concept is often attributed to Ross, a French scientist referred to by his peers in their writing as "M. Daussy" was also working in this field (Lubbock and Treas. R.S., 1833; "The Tide a True Barometer," 1840). Daussy had previously measured the sea level in a number of locations, and pointed out a 1:13 relationship between barometer mercury rise and sea level rise on the French coast; he even extended to say that the specific gravity of mercury is 13.3 (a very similar conclusion to Ross) and thus perhaps the sea was the true barometer ("The Tide a True Barometer," 1840). Ross did add a postscript to his paper in 1854 acknowledging the similarity between his and Daussy's work (Ross, 1854). However in it he argued the variability in Daussy's measurements across different ports differed so greatly that "their practical application became limited to the correction of the height of high water at the places where the observations were made" whereas his own findings had a more "universal application" (Ross, 1854).

More recent proposals reveal the two primary causes believed to explain why and how sea level changes globally (and over long periods of time) aside from tidal forces: changes in volume of water and changes in the volume of ocean basins (Kominz, 2001). Sea level has been steadily rising since the last glaciation, approximately 20 000 years ago (Kominz, 2001). As less and less water is retained in the glaciers in the form of ice, the volume of water in the oceans and other reservoirs increases, causing sea level to rise. Alternatively, and perhaps at the same time as the first mechanism, ocean basins also change in volume. This process is driven by tectonic activity which changes the shape and area of ocean basins. Throughout Earth's history, tectonic activity has caused the formation and break up of supercontinents, spreading of seafloor, the emersion of large igneous provinces, and formation of new continental crust (Kominz, 2001). All of these processes have an effect on how much space is available for the water to take up and the relative zero point from which sea level can be measured.

Harold Wanless and J. Marvin Weller were instrumental figures in presenting substantial evidence and explanations for cyclical sea level changes (Witzke, Ludvigson and Day, 1996). They developed the theory of cyclothems in the 1930s which states that repetitive successions of marine and nonmarine strata in coal beds are due to changes in sea level (Wanless and Weller, 1932). Wanless and Weller wrote that fluctuation in sea level causing the predictable succession of sediments was likely due to warping of the seafloor and changes in basin size. In addition to these factors, variation in atmospheric moisture and storing of ocean water in the form of glaciers and inland seas or lakes contributed to changes in ocean water volume. As sea level fluctuated, terrestrial environments were repeatedly covered and uncovered in water allowing for both marine and nonmarine sediments to be found in succession (Wanless and Weller, 1932).

Oxygen Dating

Oxygen dating is another important technique in determining the magnitude and timing of sea level changes (Kominz, 2001). Cesare Emiliani was one of the first to analyze the oxygen isotope composition of deep-sea cores to support the cyclic phenomena of ice ages and the resulting changes in sea level (Berger, 2002). While working at the University of Chicago in the 1950s, Emiliani began to experiment with using oxygen isotopes to understand the climatic conditions under which ancient sediments of the deep ocean were deposited (Hay and Zakevich, 1999). His studies were inspired by the work of Harold Urey, with whom he had worked, who was investigating the relationship between oxygen isotopes and temperature. It was Emiliani who discovered the periodic fluctuation in oxygen-18:oxygen-16 ratio in core samples. He concluded that the ratio was influenced by temperature and ice volume; therefore, information about sea level at the time of deposition could be extrapolated (Hay and Zakevich, 1999). Without Emiliani's ground-breaking techniques, our understanding of

Earth's past sea levels and climates would still be very limited. His findings are crucial contributions to explorations into the past and considering how sea level and climate will change in the future.

Contributions by Lyell

Charles Lyell could be described as the leading geologist in the 1800s. His contributions to scientific community built off actualism and uniformitarianism first proposed by James Hutton. These theories rely on an analysis of current processes to assess ancient ones. His Principles of Geology outline his observations from around the world and the evidence they provide towards his theories of geologic change.

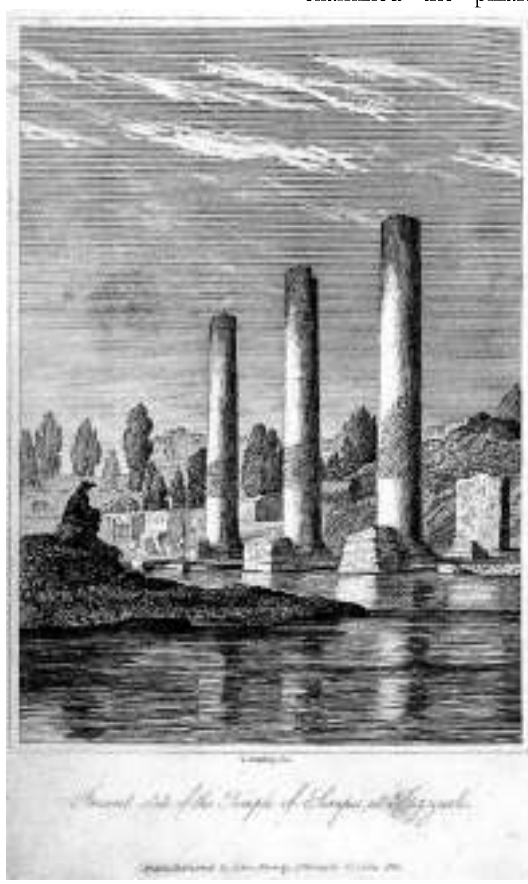

Figure 2.8 The frontispiece of Lyell's Principles of Geology *depicts the pillars of the Temple of Serapis in Naples. These pillars represent a 200 year rise and fall of the sea level (Lyell, 1970).*

The frontispiece of the first volume, the pillars of the Temple of Serapis in Naples, can be seen in Figure 2.8. Lyell travelled briefly to see these pillars for the first time in 1828 (Dolan, 1998). The pillars have three main sections that give clues to the geologic processes taking place; the bottom 12 feet of the pillars are uninjured; the next portion is damaged and had several shells and fossils embedded and the top portion shows signs of erosion (Lyell, 1970). From this Lyell (1970) could extrapolate that the temple within the past 2000 years had undergone a change in rise and subsequent fall in sea level. He proposed that nearby volcanic activity was responsible for the smooth base of the pillar, suggesting that a sudden dumping of volcanic ash protected the base while water raised and allowed life to survive and eventually have their shells preserved in this structure (Lyell, 1970). He further proposed the current displacement of the pillars from the sea was due to uplift of the land (Lyell, 1970). Frequent earthquakes in the area made this hypothesis likely (Ager, 1989).

Babbage, a contemporary of Lyell's, also examined the pillars and came to similar conclusions, although differed on the mechanism of the preserved pillar base (Dolan, 1998). Babbage believed a much slower process had occurred, covering the base (Dolan, 1998). He relied more heavily on quantitative data than Lyell; he took measurements of sea and air during his long stay in Naples and also received a chemical analysis of the rock from Michael Faraday, whom he had sent the sample to (Dolan, 1998). Babbage was also well known for his attempt to describe processes such as changing strata through mathematical equations (Dolan, 1998). Both these geologists in different ways demonstrate this attempt to understand previous processes based on the current knowledge, an important scientific method still used currently.

Modelling Sea Level Rise

In recent years, the topic of sea level rise has become a prominent concern in society. A quick review of recent literature would suggest in many cases sea level rise is synonymous with climate change. The warming of the atmosphere due to anthropogenic effects has both caused glacier melting and expansion of the ocean due to surface heating. This poses a threat to modern economical and political structures throughout the world (Lindsey, 2020). Many shorelines will become flooded causing displacement of people, destruction of crops, and disturbance to ports. Governments of all levels have had to assess and create policies for the future when greater impact will be seen. For instance, in New Zealand, James et al. (2019) reviewed gaps in municipal policies that show severe oversight, such as underfunding for updates to infrastructure along the coast, and Sammler (2019) discussed legal issues with the potential for country borders worldwide to be shifted once sea level changes. These are just two basic examples of what the dialogue about sea level now looks like. Current circumstances highlight the need for accessibility of information on this topic to non-scientists. Although the scientific community has been working to model the effects of climate change on sea level for many years, this need for public accessibility has resulted in more interactive models, such as those from NASA or NOAA which are available online.

The IPCC categorizes the main model types as geodynamic surface-loading models, semi-empirical models, and storm-surge and wave-projection models (Church et al., 2013).

Geodynamic Surface Loading Models

Geodynamic surface loading models can simulate relative sea level using changes in water volume from redistribution between ice sheets/glaciers and oceans, and changes in atmospheric pressure (Church et al., 2013). These models do not take into account key factors such as circulation patterns which may affect specific coastal areas when calculating the water levels (Church et al., 2013). Tamisiea (2011) points to common flaws and identifies the need to acknowledge uncertainty in the models and cautions against using a universal glacial isostatic adjustment, which he argues varies significantly according to the technology used and locations assessed (2011). Despite the flaws, these models provide a useful tool for predicting annual variability in coastal water levels.

Semi-Empirical Models

Semi-empirical models rely on statistical modelling of global mean sea level and temperature to make predictions and are commonly used by the IPCC (Church et al., 2013). The name "semi-empirical" is used because these models are based on pre-existing data. It is important to note, however, that underlying causes of sea level rise are not accounted for (Church et al., 2013). Using these models, Grinsted et al. (2010) argue that the IPCC estimates in their 2007 summary for policymakers are three times lower than they should be. The IPCC estimates of approximately 0.21 m global sea rise are similar to Grinsted et al.'s (2010) estimates, made assuming no temperature change. The increase in global temperature has a large impact on sea level, which demonstrates the inaccuracy of these initial predictions. In the 2013 IPCC report, the authors acknowledge that plausible sea level estimates extended far beyond the confidence interval calculated in the 2007 estimates (Church et al., 2013).

Storm Surge and Wave Projection Models

Storm-surge and wave-projection models predict wave extremes using mean sea level and storminess (Church et al., 2013). Wang et al. (2010) compare a dynamic storm-surge and wave-projection model with their statistical model. The difference in these methods is that the former uses simulated atmospheric conditions to create a wave model whereas the latter relies on observational data between atmospheric conditions and wave height (Wang et al., 2010). Using these models to exploring sea level in the North Atlantic, Wang et al. (2010) noted predictions that better matched current sea level change observations.

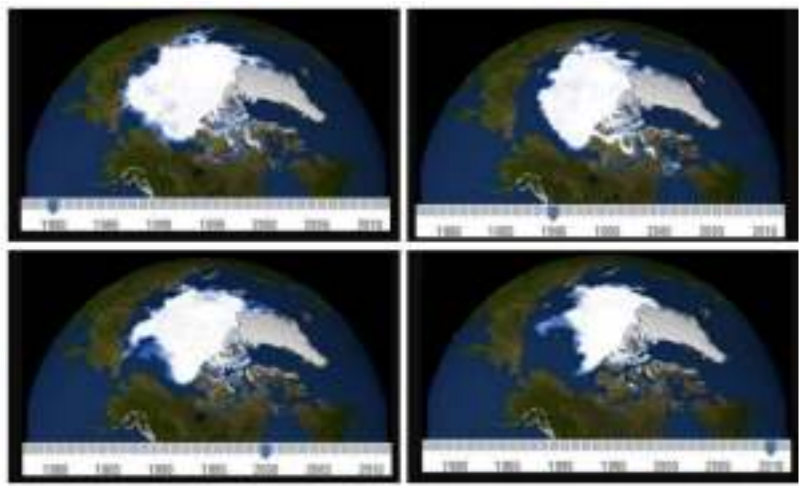

Figure 2.9 Changes in the Artic Sea ice such as melting ice sheets and glaciers due to global climate warming increases the volume of the ocean resulting in sea level rise. Models such as geodynamic surface loading models use data from images such as this to predict future sea level changes (NASA, 2011)

No one model will perfectly describe the impact of climate change on sea level rise because each of the above models includes biases and assumptions. However, each model has its place in furthering knowledge for both the scientific community and the public. Building off the technology and observations of both previous and current scientists will allow for more precise estimates that will assist in developing solutions to climate change and sea level rise problems.

The Auroras and Geomagnetism

The auroral lights have amazed people for thousands of years. Although the first sighting of the aurora by humans is unknown, evidence of auroral sightings date back to thousands of years ago (Brekke and Egeland, 1983). The first account of the aurora dates to 567 BCE in ancient Babylon, whereby a clay tablet that describes a red glow in the night sky, most likely caused by auroral activity, was discovered (Stephenson, Willis and Hallinan, 2004). The aurora has also been incorporated into the mythology and belief systems of multiple cultures, including Canadian indigenous peoples, Northern European indigenous peoples, and for the aurora australis, New Zealand's Māori—New Zealand's first settlers (Holzworth, 1975). These peoples had various explanations for the floating lights that they saw in the sky – the manifestation of warriors' spirits, messages from the Creator, omens of war, and many more interpretations (Brekke and Egeland, 1983).

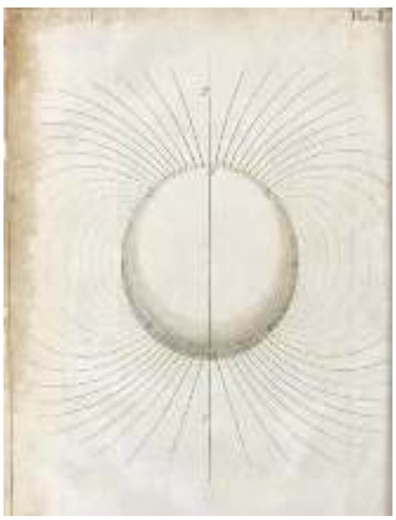

Figure 2.10 Diagram of Edmund Halley's experiment studying the placement of iron filings around a magnet where A and B represent the poles of Earth.

Although speculation about the nature of the aurora has existed in mythology for centuries, at the start of the eighteenth century, the development of auroral theories contributed to humankind's understanding of geomagnetism. The initial connection between the aurora and Earth's magnetic field was made by Edmund Halley (1656-1742) in 1714 (Halley, 1714). Halley was a British astronomer best known for mapping the orbit of Halley's comet (Sanford, 1933). Thanks to his reputation as a successful astronomer, when a spectacular display of aurora lit up London's night sky on March 6, 1713, Halley was asked by the Royal Society to explain the origins of the floating lights (Halley, 1714).

In an article published by the Royal Society in 1714, Halley described the auroral display and hypothesized the cause of the lights. He proposed that the aurora was caused by a magnetic fluid released from the poles that flowed along the magnetic field lines and that the light was caused by friction between the particles (Halley, 1714). Although this theory has been shown not to be fully accurate, it was the first theory to connect the aurora to Earth's magnetic field (Briggs, 1967).

Halley supported his theory by studying the geographic distribution of auroral sightings. He noted that auroral sightings were centred around the magnetic poles, of which he believed there were four, two in each hemisphere (Halley, 1714). In his publication, Halley argued that the relation between the magnetic poles and the aurora explains "why these Lights are rarely seen anywhere else but in the North, and never, that we hear of, near the Equator (Halley, 1714, p.423)". Additionally, Halley's four-pole theory was able to explain the vast expanse of the aurora around the globe, as it described two-point sources of magnetic fluid in the Northern Hemisphere.

Additionally, Halley conducted an experiment to model his theory. By placing iron filings in the presence of a magnet, used to represent Earth's magnetic field, Halley noted that at the poles of the magnet, the iron filings were arranged perpendicularly to the magnet, as illustrated in Figure 2.10 Moreover, the iron filings were closer to the magnet near the poles, and the distance between the iron filings and the magnet increased further from the magnetic poles, supporting the geographic distribution of the aurora (Halley, 1714).

Halley's hypothesis correlated with observations made by Anders Celsius and his assistant Olaf Hiorter in 1741 (Enebakk, 2012). While studying magnetic variation by monitoring disturbances in compass needles, Celsius and Hiorter associated disturbances in the magnetic field with auroral activity. The geographic extent of the magnetic variation was noted on April 5, 1741, when Celsius noted variations in Uppsala, Sweden. At the same time, another scientist, George Graham, also noted variations in London, England, and that same evening, the aurora borealis was seen above Sweden (Hansteen, 1827). These observations allowed scientists to conclude that variation in the magnetic needle is related to the intensity of the magnetic field. Moreover, the widespread geographic variation of the magnetic field indicated that auroral activity had widespread magnetic influence (Hansteen, 1827). Additionally, confirmation that the auroral lights occurred at both the North and South Pole was provided by Captain James Cook, who was the first European to observe the aurora australis, while circumnavigating the South Pole from 1772 to 1775 (Cook, 1961).

Christopher Hansteen's Contributions

Figure 2.11 A portrait of Christopher Hansteen, who advanced humankind's understanding of the connection between the auroral lights and geomagnetism.

Although Halley made the initial connection between the aurora and geomagnetism, the technology at the time prevented him from advancing his theory. In the early 1800s, Christopher Hansteen (1784-1873), pictured right in Figure 2.11, continued Halley's research investigating Earth's magnetic field as well as the aurora and magnetism (Enebakk, 2012). In 1823 and 1829, Hansteen travelled to Siberia to take measurements of the magnetic field in an attempt to locate one of the believed magnetic north poles (Enebakk, 2012; Falck-Ytter, 1985). On these trips, Hansteen was able to determine that the horizontal component of the magnetic field would increase prior to a display of the aurora, and would decrease, if not disappear, when the aurora became visible, further providing evidence of the connection between the aurora and geomagnetism (Falck-Ytter, 1985). Furthermore, he noted that the highest point in the auroral arc is near the magnetic meridian of the observer, which is the highest point above the observer on the magnetic field lines, indicating the aurora occurs at high altitudes (Brekke and Egeland, 1983). He argued that the curving of auroral displays was due to the auroral lights forming in rings at high altitudes at the magnetic pole, providing additional support for Halley's initial theory that the aurora formed at the poles (Enebakk, 2012). More support for Halley's theory came when Hansteen noted that in more northern countries, the aurora occurred south of their location. Hansteen's research was able to provide evidence supporting and build upon Halley's theory of the nature of the aurora.

Using information about the frequency of the auroral lights in different regions, in 1860, Elias Loomis mapped the area where the greatest auroral activity occurred (Milan, 2007). The end result of the mapping yielded an irregular oval shape, known as the "auroral oval" or "auroral belt", which was centred around the North Pole, and that crossed the northern regions of Greenland, Scandinavia, Canada, and Siberia (Milan, 2007). Lommis's research, along with Hansteen's, provided another layer on the growing pile of evidence supporting the significance of the magnetic poles to the formation of the aurora (Enebakk, 2012).

After Hansteen's continuation of Halley's work and the mapping of the auroral oval, there was limited research on the relationship between the aurora and magnetism until the early 1900s, when Kristian Birkeland (1867–1917) proposed the first modern theory surrounding the auroral lights and gasses found in the upper atmosphere. Birkeland proposed the auroral lights were caused by electron currents that follow the Earth's magnetic field (Arnoldy, 1974; Egeland and Burke, 2005). At the time of his proposal in 1908, his theory was unlike any proposed before him, and many scientists did not support his claims (Egeland and Burke, 2005; Jacobs, 1991).

Kristian Birkeland's Advancements

Birkeland was a Norwegian scientist who wrote many publications and papers in Norwegian. Additionally, Birkeland is not very well known in the English-speaking scientific community, making it difficult to find information about his work in English. A comprehensive, English book, Kristian Birkeland: The First Space Scientist, was written by Alv Egeland and William J. Burke in 2005 to bring greater attention to Birkeland's accomplishments.

Birkeland gathered information to support his theory—that particles come from the Sun (Sun plasma) and are directed to Earth by field lines—through a variety of methods, including three Arctic missions (1897, 1899-1900, 1902-1903), and experiments.

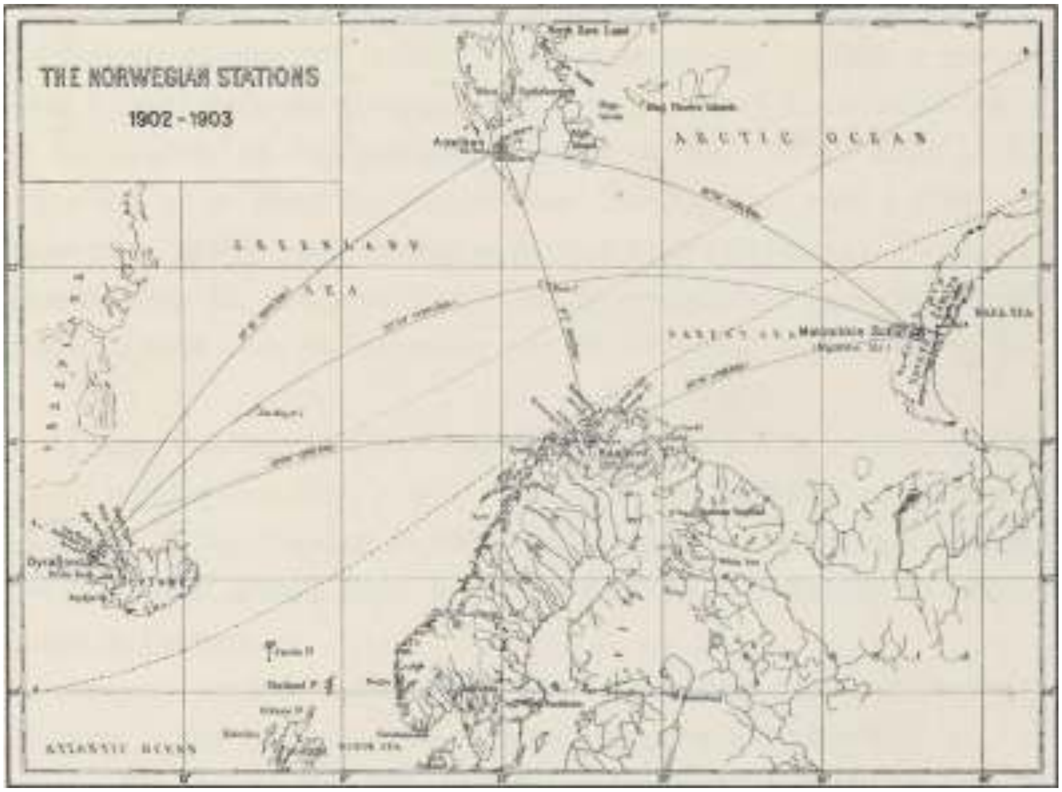

Figure 2.12 The map of the Atlantic Ocean that shows the four stations of Birkeland's 1902-1903 Arctic mission (Birkeland, 1913).

In his last Arctic mission in 1902-1903, several sites were set up along the auroral oval, as pictured in Figure 2.12 (Egeland and Burke, 2005). Sites were in Iceland, Norway and Russia, all approximately 1000 km apart, making the mission logistically challenging (Egeland and Burke, 2005). On the other hand, this was a monumental experiment, as it was the first time the arctic region was mapped using the same equipment and at the same time. The data collected provided scientists with consistent data to work with, allowing conclusions to be made with higher confidence.

Each station was staffed with a leader and an assistant, both of whom were experienced with the harsh arctic conditions, but also highly educated in electricity and magnetism (Egeland and Burke, 2005). Birkeland was careful in his selection of men, as his previous two expeditions to the Arctic had detrimental effects on the participants, thus having an understanding of the arctic conditions was vitally important to participate (Egeland and Burke, 2005).

On the 1897 mission, one of his assistants, a surgeon by training, suffered from frostbite, resulting in the amputation of his fingers—the amputation ended his career, while on the second mission in 1899 and 1900 one of his assistants died in an avalanche (Egeland and Burke, 2005; Borowitz, 2008). The men on the 1902-1903 mission would take daily measurements of the air pressure, temperature, and wind speeds, Earth's magnetic currents, and air conductivity, along with general observations (Egeland and Burke, 2005). This final arctic mission was a great success, and much of the data that was collected supported Birkeland's theory.

To further support his theory, Birkeland also experimented with spherical electromagnets (Egeland and Burke, 2005; Rypdal and Brundtland, 1997). Glass spheres were used to represent Earth, with Earth's magnetic field and currents being represented by a cold cathode that discharged magnetic currents between two electrodes, representing the incoming particles, as shown in Figure 2.13 (Rypdal and Brundtland, 1997). In this way, Birkeland was successfully able to recreate a miniaturized version of the auroral lights in his lab (Egeland and Burke, 2005). By interpreting how the currents moved around the sphere, and by changing variables within the experiment, Birkeland was able to further support his theory. He later renamed the experiment *terrella*, or the "little Earth" experiments (Egeland and Burke, 2005).

Based off of the *terrella* experiments, Birkeland proposed that there exists a system of currents that come from Earth and are related to why auroral lights can be seen. The proposed currents were thought to explain the relationship between what is now known as the magnetosphere (Earth's magnetic field) and the auroral ionosphere—the area where the particles in the Earth's atmosphere are ionized, or charged, from solar radiation.

After Birkeland published his theories, some scientists did not agree with his ideas, with the most vocal being Sydney Chapman (1880-1970) (Egeland and Burke, 2005; Borowitz, 2008). Chapman began studying the auroras three years after Birkeland's death and was continually attempting to disprove all of Birkeland's work. Chapman went so far as to slander Birkeland at the 100-year anniversary of Birkeland's birth. Other scientists, for example Hannes Alvén, actively promoted Birkeland's ideas and also conducted their own independent research to support Birkeland's claims. Alvén even went so far as to ensure that he was present at many of the meetings where Chapman would try to illustrate that his theories were far superior compared to Birkeland's. Additionally, Chapman was invited to Alvén's lab several times to see Alvén's experiments first hand, but Chapman refused every time (Egeland and Burke, 2005; Borowitz, 2008). It has been proposed that perhaps Chapman's attitude towards Birkeland might have been prejudice towards Scandinavians, as Chapman was an Englishman, but it has also been proposed that Chapman's behaviour was due to xenophobia, as Birkeland was not Chapman's only target (Borowitz, 2008).

Birkeland's work remained continuously disputed for 50 years after his death but was more concretely backed up when satellite data became available, allowing for confirmation (Borowitz, 2008). In 1966, direct evidence was provided by the U.S. Navy TRIAD satellite, proving that currents from the Sun to Earth exist (Egeland and Burke, 2005). Shortly thereafter, the name of these currents was unanimously changed to "Birkeland currents", or the "auroral electrojet", by the International Union for Geomagnetism and Aeronomy (Egeland and Burke, 2005).

Birkeland had proposed that during a magnetic storm, Birkeland currents follow the magnetic field lines, which guide electrons emitted from the Sun to the magnetic poles. However, a mathematician named Henri Poincaré pointed out that the electrons must be reflected from regions of intense magnetic fields, like those of the magnetic poles (Stern, 2002). Instead, the electrons that caused the auroras would have to occur in a ring-shape area with the pole in the center, which would remain consistent with the observation of the auroral lights in the aurora oval (Stern, 2002). Birkeland, during his research, had been unable to understand why this phenomenon was occurring (Stern, 2002).

Earth's Magnetic Field

Years later, in 1930, Chapman and Vincent Ferraro proposed a slightly different variation on Birkeland's theory in hopes of explaining why the auroras occurred in the ring shape (Stern, 2002). Chapman and Ferraro thought that the Sun emitted clouds of plasma during a magnetic storm (Stern, 2002). These plumes would have equal amounts of electrons and positive charges, making the cloud of plasma neutral, and thus allowing it to travel through space without repelling one another (Stern, 2002). However, this theory had one caveat—only terrestrial plasma (plasma that originates from the Earth rather than the Sun) can enter Earth's magnetic field. The only way it would be possible for the Sun's plasma to enter Earth's magnetic field would be through terrestrial magnetic field lines that merge at the poles. However, particles cannot move from one field line to another (Stern, 2002). Thus, by this theory, the Sun plasma could not join the terrestrial field lines and terrestrial plasma. This led the duo to propose the existence of a cavity, which they named the Chapman-Ferraro cavity, where the terrestrial field lines that connected to the Earth's poles would be confined. The cavity would allow the Sun plasma to join the terrestrial plasma and enter the Earth's magnetic field. This cavity was later renamed as the magnetosphere (Stern, 2002).

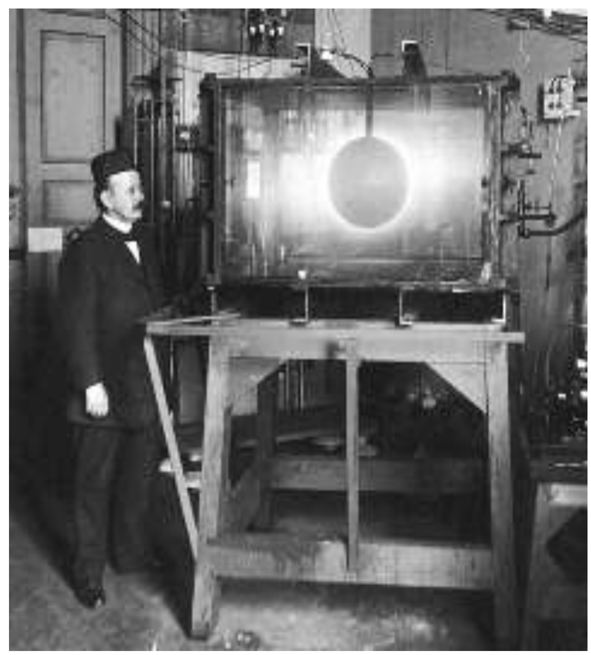

Figure 2.13 Kristian Birkeland standing beside one of his "terrella" experiments.

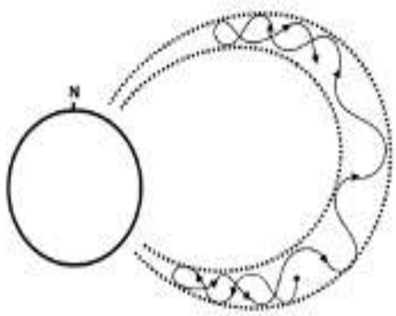

Figure 2.14 A schematic of the particles moving between Earth's two poles, modified from (Stern, 2002).

A mathematician, Fred Singer, showed that the plasma particles would move along terrestrial field lines, using a series of equations. However, when the particles approach the strong magnetic forces of the poles, they would be reflected, causing them to float around between the poles, as illustrated in Figure 2.14. He hypothesized that this would only occur during a magnetic storm when there was a large quantity of particles moving around. Additionally, Singer thought that there was another factor involved in the transportation of the particles. He proposed that there was a force that would slowly move the trapped particles from their current field line to the next one, eventually transporting them all the way across the Earth (Stern, 2002).

The Space Age

The advent of the space age was very important for the current understanding of the auroras and geomagnetism. As already noted, satellites were used in the conformation of the presence of Birkeland currents, but they were also able to confirm many other theories. After the first satellite was launched in 1957, teams were able to confirm that Singer was correct in his hypothesis that particles were reflected at the poles by magnetic field lines, but discovered that this phenomenon did not only occur during magnetic storms, but constantly (Stern, 2002). On later satellite launches, it was also confirmed that plasma from the Sun was emitted, though unlike Birkeland and Chapman's predictions, the plasma was not only emitted during magnetic storms, but continuously (Stern, 2002).

In 1958, Eugene Parker predicted that the Sun was constantly sloughing off plasma based on the new information that there was continuous emission of plasma. Through mathematical equations, he reasoned that hot plasma, such as the plasma found on the Sun, could not be held in gravitational equilibrium on the Sun. He, therefore, proposed that the plasma would be a supersonic stream that was constant and occurred in all directions. Although at first this was a controversial theory, it was confirmed in 1961 by satellite and reconfirmed on a different mission in 1962. This theory explains why the plasmas arrive at Earth, even when there is no magnetic storm (Stern, 2002). Also, during this time, space technology confirmed that there is a distinguishable auroral oval that occurs at 70° N latitude (Feldstein and Starkov, 1967).

An additional finding during the Space Age was the proper identification of the electron source creating the auroras (Stern, 2002). Plasma sheets, dense regions of plasma moving towards Earth, were able to be mapped with the technological advancements. With this knowledge, it was determined that there is an unstable region in the plasma sheets that come from the Sun and make it to Earth (Stern, 2002). Magnetic field lines located within the unstable region of the sheet are connected to the reflection of particles causing the auroral oval, rather than the field lines connected to the poles (Stern, 2002). The rare occurrence of the aurora lights at the poles is attributed to the lack of plasma flowing to the poles. The field lines that are connected to the poles, feed back to a different area on the plasma sheets that is plasma poor, thus the auroras are not viable at the magnetic poles (Stern, 2002). Many of the observations that Birkeland made were correct with modifications that were made, once space data become available.

Planetary Aurora

The presence of the aurora on Earth is well documented and studied, but Earth is not the only planet to experience the auroras. The processes happening on Earth that cause aurora are mirrored on other planets in our solar system, and doubtlessly, in other solar systems. The study of auroras on other planets is a growing field of research, and unique characteristics of the auroras offer the potential to be used to discover distant planets. Auroral activity causes the release of low frequency radio emissions (LFRE) that can be detected on Earth (Vidotto, Feeney and Groh, 2019). The first of these emissions to be detected was from Jupiter in 1955 (Zarka, 2007), and this detection started the study of planetary magnetospheres. The Voyager missions in the 1980s provided more information about auroral activity on other planets in our solar system and it was determined that Saturn, Uranus, Jupiter, and Neptune have auroral lights (Zarka, 1998). An auroral event on Jupiter's north pole can be seen in Figure 2.15 In addition, the auroral activity on these planets all release LFRE (Grießmeier, Zarka and Girard, 2011). The LFRE from each planet are different, but due to the strength of Jupiter's magnetic field, it has the greatest strength of emissions. Earth's aurora also produces LFRE, but the frequencies are too low to be detected from the surface (Grießmeier, Zarka and Girard, 2011). Therefore, Earth's LFRE were not detected until the 1960s when satellites were deployed (Zarka, 2007). On Earth's surface, the detectable range of LFRE are limited to between 10 and 40 MHz (Zarka et al., 2003). This is because the Earth's magnetic field deflects higher frequencies (Zarka et al., 2003), and lower frequencies are excluded to avoid detecting internal magnetosphere processes (Zarka, 2007). Jupiter is the only planet in our Solar System to produce LFRE within the detectable range of 10 to 40 MHz. The other magnetized planets' (Neptune, Saturn, and Uranus) LFRE are too low to be detected on Earth's surface (Zarka et al., 2003). As a result, studying their LFRE and magnetospheres is limited to being studied from space. Jupiter, on the other hand, produces LFRE in a range from a few kilohertz to tens of gigahertz (Zarka et al., 2003), allowing its LFRE to be detected on Earth's surface.

Figure 2.15 An image from the Hubble Telescope capturing the auroras on Jupiter.

The Search for Exoplanets

In the last two decades, LFRE have been studied as a potential way to identify exoplanets (Nichols and Milan, 2016). The LFRE produced by auroras have an order of magnitude difference compared to low frequency radio emissions from stellar sources (Zarka, 2007). They are, therefore, a unique identifier of an exoplanet. Researchers estimate that detection of LFRE would provide information about the planetary magnetic field, rotational period, interior structure, and the presence of extrasolar moons (Turner et al., 2017). The potential challenges with using LFRE as a possible exoplanet detection method is that necessary emissions are estimated to be between 10^3 and 10^4 times greater than emissions from Jupiter, in order to be detected at stellar distances (Grießmeier, Zarka and Girard, 2011).

Theoretical modelling has been used to determine potential exoplanet candidates for identification via LFRE. There are a limited number of candidates, but one particular type of exoplanet, hot Jupiters, are predicted to produce intense radio emissions. These radio emissions are estimated to be strong enough to be detected on Earth (Zarka, 2007). Hot Jupiters are approximately Jupiter-sized planets that orbit very close to their star (Knutson, Howard and Isaacson, 2010). Many of these planets have been identified, with over 58 000 being discovered during the Kepler mission alone (Wright et al., 2012). Due to a hot Jupiter's close proximity to its star, it is estimated that the energy flux from these planets is 10^3-10^5 times greater than that of Jupiter, causing a similar increase in the intensity of the LFRE emissions produced by the planet (Zarka, 2007).

Despite the limited candidates available for LFRE detection, observational analysis has been undertaken (Grießmeier, Zarka and Girard, 2011). As of 2017, there have been no exoplanets detected via LFRE, but research groups continue to refine their observational parameters to optimize their equipment for exoplanet identification (Turner et al., 2017).

The appealing nature of floating, colourful auroras has helped to accelerate the understanding of geomagnetism here on Earth. Additionally, the research of the auroras has contributed to space exploration and holds promise for discovering exoplanets in the future.

History, Hydrology, & Humanity

Life is adorned not only with rare and distinguished pleasantries which we notice and thank the universe for bringing, but also those often underappreciated and misunderstood. It is not customary to give thanks for each individual lungful of air one inhales, though take away this luxury for mere minutes and one can think of nothing more incredible than to do just that. Water on Earth is one such luxury to which not many, at least in the developed world, pay mind to. The source and very nature of this, the vital substance, is one of the oldest problems in geology. It should come as solace that dating back to Greek philosophers, the development and existence of hydrologic theories has not lacked in its breadth of knowledge, nor documentation. A star-studded cast of characters spanning millennia have painstakingly constructed the basis of knowledge on which our understanding of water's cycling stands, and the achievement of such a feat cannot remain unacknowledged. It is, after all, our *eau de vive.*

Figure 2.16. The first nilometer, or water meter, Kom Ombo Temple. It was used to measure water levels of the Nile in Ancient Egypt (c.3000 B.C.) based on water staining at measurement marks along the walls. A good year would be 16 cubits, less would be a drought, and more would be destructive to the fields.

The Gift of the Nile & the Roots of Hydrology

Around the year 3200 B.C. in Northern Africa, one of the oldest civilizations placed its fate and livelihood in the hands of one mystical river (Biswas, 1970). The Nile meanders through green valleys of Egypt, chasing away the scorch of one thousand suns from the neighbouring Sahara Desert, and pours its waters into the fertile soils of the Mediterranean Sea. The Ancient Egyptians in the time of 'King Scorpion' were the first to understand the flow of water downhill and, though their contribution to hydrologic thought is insignificant, their mastery of hydrologic engineering such as the construction of canals and nilometers—as pictured in Figure 2.16—were vital to their vitality, so to speak (Biswas, 1970). The Nile floods once annually, and the sustenance of this civilization was the spark that ignited many later philosophers' interests in understanding its source, and inevitably, eventually understanding the hydrologic cycle. And thus, it is here the story begins.

Knowledge for Its Own Sake

The following 2600 years saw the development of water meters to measure the Nile's level, the rise of complex irrigation systems, and the utilization of groundwater (Koutsoyiannis and Angelakis, 2003). Knowledge for its own sake, however, was a development of the Ancient Greeks, and in their search to resolve nature were uncovered the roots of what would later become empiricism (Bowen, 1981). At a time of cobbled streets, exquisite statues, and columned temples, philosophy was the map one followed which sought to understand the essence of everything which nature had to offer. Before there were scientific disciplines and quantitative data, there was observation and philosophy. The greatest names of the time were of those who feared not, and rather perfected, the art of walking blindly and quizzically into the mass abyss of the universe, for Ancient Greece was a literate society, and anyone who wanted to learn, beyond the preferred oral word, could (Thomas et al., 1992). Thales of Miletus (624-548 B.C.) was one such wanderer, and is often named the father of hydrology itself, having postulated the foundations of water science in two simplistic statements; (1) The Earth floats on the water, and (2) Water is the original substance, and hence the material cause of all things (O'Grady, 2017). It was from Thales' observation of the Nile from which his second principle, and focus of the present paper, came. Though seemingly nonsense to the modern reader, this idea was in reference to the incredible dependence with which the Egyptians relied on the flooding of the Nile, and as later argued by Aristotle, was also a result of Thales' observation of how all things contained moisture (O'Grady, 2017). Thales' popularity led to his consideration as a sage of the times, and the mystique surrounding his title ignited a ponderance of the nature of water into the profound minds which would one day revolutionize hydrologic science. Water was of interest, as it could change states readily and gaseous, liquid, and solid states were easily observed in nature (Biswas, 1970).

After Thales came many, though none as influential as Aristotle who shook the very ground of thinking with his development of and passion for logic (Warmington, 1934). The Greeks were not only at the misfortune of having observation and experience as their only tools, but also at the mercy of not absorbing the larger painting which nature's details comprised. Aristotle's procedure of beginning with a fact and expanding upon it an argument led to the overlooking of the greater schema of the universe (Biswas, 1970). The greatest powers of philosophy could not accede any one principle of nature, and though their reality was uncertain, the debate which Aristotle's rules of logic sparked saw the birth of scientific collaboration, and ultimately the scientific method. His contributions will be discussed later, for here was interrupted the chronology which unto history breathes context.

Anaximander (610-545 B.C.) was the first to propose that precipitation is a result of the evaporation of water on earth, which was brought about by the sun (Freeman, 1948). Though it seemed unlikely at the time and sparked debate, it serves today as a major step in the hydrologic cycle. Anaximenes (circa 528 B.C.) believed that hail was the result of rain frozen midair, whereas snow was the imprisonment of air within water (O'Grady, 2017). Xenophanes (570-490 B.C.) believed that clouds, rains, springs and streams originated from the sea, and exist only because the sea exists (Freeman, 1948). Hippocrates, the father of medicine (460-400 B.C.), was drawn to the conceptualization of water in two components: one which was dark, thick, and turbid, and one which was light, clear, and thin (Hippocrates, 1886). The latter was that which evaporated from the sun, and the darker, turbid component was left behind, an idea later reiterated by Vitruvius (Hippocrates, 1886). This hypothesis was perhaps the first which came as an observation of halite deposits in past epeiric seas, of which artful carving and glimmering salts wove the indices of an aqueous presence (Biswas, 1970). It was this succession of small observations and their intermittent condensation made by ingenious minds, which were later layered, analyzed, and scrutinized for hundreds of years.

Aristotle and Theophrastus

A man of stature, of breadth, of curiosity and logic, that made not only himself a name, but one for his mentor, Plato, as well. Aristotle contended that elements were of each other and spontaneously turned into each other (Aristotle., 1952). And, as with many of his contentions, that became the normative view for a long time and well beyond the Middle Ages. In one of his greatest works, the *Meteorologica* (1952), Aristotle writes:

"We maintain that fire, air, water and earth are transformable one into another, and that each is potentially latent in the others, as is true of all other things that have a single common substratum underlying them to which they can in the last resort be resolved."

And, whilst Aristotle's works and logic were of grand importance to the formation of streams and to the later hypothesizing by philosophers of the Middle Ages, it was his student, Theophrastus who was the first to demonstrate a nearly thorough understanding of the hydrologic cycle.

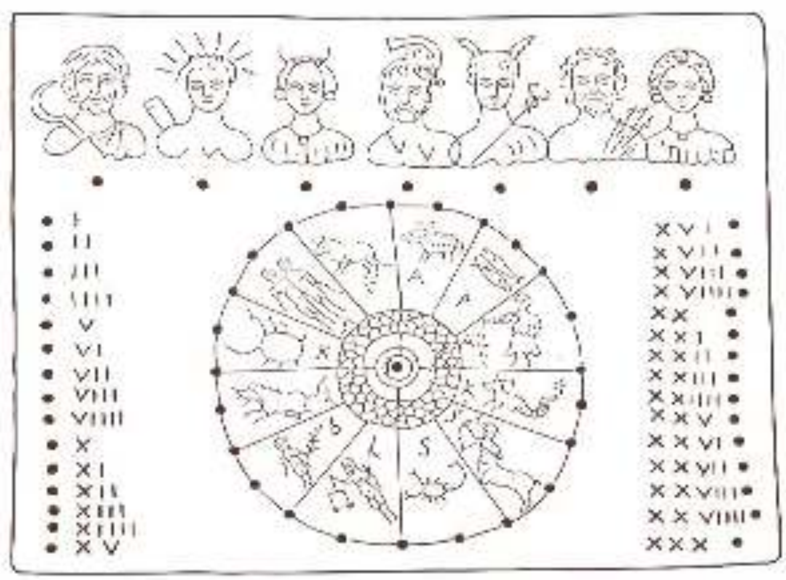

Figure 2.17. Rough sketch of a parapegma tablet depicting a Roman, or pre-Julian, calendar. Parapegmata contained both astrological insights and weather change pattern recordings.

Theophrastus proposed that the primary wing on which vapour departed the embrace of Earth was wind. In *De Ventis* (On Winds and Weather Signs), Theophrastus discusses wind patterns and their influence on weather, including the contraction of air with colder temperature, as well as the presence of air within snowflakes as being the reason for their increased volume compared to water, a refined reiteration of Xenophanes' proposal (Theophrastus, 1894). Another comical addition to his work is of such weather sign treasures as: *"Sheep copulating early indicates an early winter."* Theophrastus also mentions, for the first time in recorded history, that the Greeks were the first to note meteorological observations, around 500 B.C. in Athens (Biswas, 1970). An entertaining concept to the modern reader, these would be presented publicly as *parapegmata* (refer to Figure 2.17) and were mere observations of weather such as: *"March 24: It rained"* (Lehoux, 2005). It was, in fact, the ancient Chinese, as early as the 7th century B.C. that maintained a complicated system of measurements of river levels and rainfall, which seems not to have reached the bickering Greeks (Duffy, 2017).

The Middle Ages

The concepts pioneered by Theophrastus were later reinstated in the early Middle Ages by Vitruvius, the Roman Architect and Seneca, who was the main authority on natural sciences in the time of Nero the Tyrant (Seneca, 1910). The Romans were a powerful military force and masters of hydrologic engineering, with indoor plumbing, aqueducts, and sewer systems that are held to the present day in glory by historians and tourists. However, this mastery and sense of dominance led to a waning interest in bettering their knowledge on any one matter of natural science; they were practical masters of war and water, not hunched-over scholars spending time in self-constructed realities (Stahl, 1962). This mentality was widespread throughout the Roman Empire, such that the intellectual proposals of Seneca and Vitruvius, admirers of Hellenic and Greek philosophy, were overlooked and gracefully discounted. In fact, even scholars of their sort were favorable of encyclopedic knowledge, and offered few of their own insights, preferring to recapitulate (Biswas, 1970). There exists a large gap in time between ancient Greek insights and those of Vitruvius, and an even greater gap between this time and the beginning of the Renaissance.

Marcus Vitruvius was familiar with the meteorological works of Aristotle and Theophrastus, and so was reasonably lucid on the water cycle, his conceptualization which is illustrated in Figure 2.18 (Pollio, 1826). He maintained that precipitation atop mountains infiltrated the surface of the Earth, leading to rivers and streams in the Lowlands. The matter of how remained a mystery which would have to wait for a potter.

200-1500 A.D.

Scientific development between 200 and 1500 A.D. was impeded by the advent of power which came from the Christian Church (Biswas, 1970). Theories were proposed solely to serve the holy purpose of backing up doctrines, and the ultimate function of knowledge became championing theology and salvation (Dampier and Cohen, 1989). Towards the end of the first millennium A.D., however, the spirit of free inquiry was rekindled, universities funded by the church were erected, and once more, Aristotle became trendy (Dampier and Cohen, 1989). The thirteenth century saw the questions that had been plaguing philosophers come close to the answers we have stumbled upon today. Of primary intrigue was the matter of where water in rivers and streams came from and how it was that sea level could remain constant despite the copious and infinite pouring of rivers.

With evaporation as a settled matter from the ever-burning sun and carried by a restless wind, the focus was on whether precipitation could in any fathomable measure be sufficient for Earth to run her course. This question had to await a time when science was once more not inferior to theology: the sixteenth century. Be it resolved, dear reader, that the mark left by the

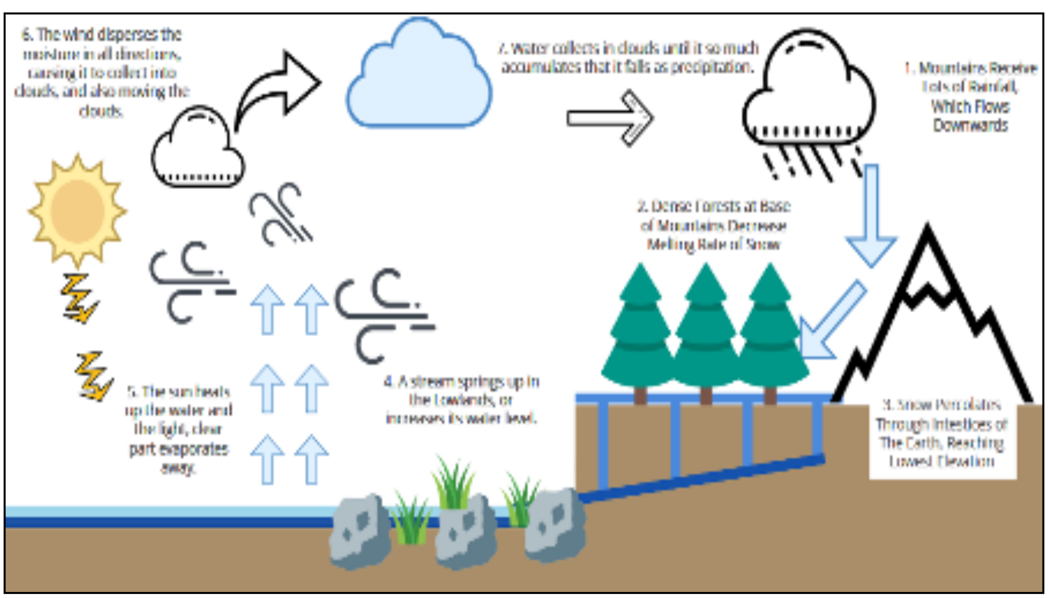

Figure 2.18. Vitruvius' conceptualization of the water cycle (above). Clarity around the formation of springs was minimal and thus the process through which they form was a topic of debate for years to follow (step 4).

overtaking of the Christian church was of no small magnitude. It left the intellectuals of Europe, to whom the entirety of her attainment was credited, in the supreme hopes of being good Christians, and so the scholars were in pursuit of salvation, whilst it breathed somewhat more softly than before, down their necks (Dampier and Cohen, 1989).

Palissy in the Sixteenth Century

Leonardo Da Vinci (1452-1519 A.D.) made a few currently acceptable statements regarding the water cycle, though he was paralleled independently by a greater naturalist herein discussed: Bernard Palissy the French potter (1510-1590 A.D.) (Karterakis et al., 2007). Palissy was the first to reject the notion of interchangeable elements fiercely reinforced through wars and rulers since the time of Aristotle (Deming, 2005). To the disgust of most scholars, he was convinced that an understanding of gravity was more plausible than spontaneous formation of water or that streams originated directly from seawater, notions which led him to be the first to truly grasp the water cycle (Deming, 2005). Influenced greatly by the works of Vitruvius, he argued that if the latter were true, mountain streams would be saline and sea water would be higher than the mountains through which it flowed, lest water flow uphill (Palissy, 1957).

He agreed with the notion that air could condense, in this way becoming water, but a spontaneous and mystical interchangeability was lost on him. A foremost potter, Palissy at 65 gave lectures on the Art of the Earth (Deming, 2005). He is amongst the more entertaining characters in this charade, with a history of burning furniture and floorboards in his kiln amidst a manic anger as his horrified wife, along with most of the southern French town of Saintes, looked on (Deming, 2005). Nonetheless his mastery of craft led to his theory that the only possible source of water atop mountains was precipitation, which proceeded to flow endlessly downwards, slipping through crevices and rocks, coming to rest only when the falling acquiescence reached a wall of stone, or a barricade (Palissy, 1957). It then collected and carved its own path through softer earth, fed by other trickling brooks from nearby, and all creating a beautiful accumulation of infuriated mass which demanded its own presence (Palissy, 1957). It was beyond this theory which Palissy told no man to look, for he had fiercely solved geology's oldest problem, and it was he of no stature (and not of completely sound mind) who demonstrated the power of questioning and challenging the pack; a cornerstone of modern science. Palissy added his own unique observations to the more obvious statement, having noticed that some coastal areas contained both freshwater and seawater. In combination with his observation of freshwater wells on islands surrounded by seawater, Palissy contended that the only possible source was rainwater and melting snow, successfully rejecting the notion that springs came from seawater pushed through earth's interstices by air pressure in deep tunnels (Palissy, 1957). A long time prior, the resounding agreement demanded that it was air, mixed with water, which forced it out of the earth (Seneca 4 B.C.-65 A.D.), whence it spontaneously turned into water itself, by means of the *"perpetual darkness, everlasting cold, and inert density"* underground (Seneca, 1910). If the sea was the source of rivers and streams, how was it they tended to dry up in hot summer months? He asked scornful scholars, knowing that gravity was a smug acquaintance.

Perrault, Mariotte, and Halley

Since Palissy, many built on the background which would be demanded for the development of the final hydrologic cycle. Athanasius Kircher (1602-1680) devised a U-tube experiment tried

Figure 2.19. Athanasius Kircher's drawing of the uphill flow of water to mountain streams (above) as a result of air pressure.

to contest that seawater did, in fact, run under mountains and it was by air pressure that it was forced atop them (Biswas, 1970a). Kircher's illustration of this concept is included in Figure 2.19. Of course, the scientific revolution begun by Descartes was of no small magnitude and influenced the quantitative hydrology that ultimately solved the water cycle experimentally in the seventeenth century (Biswas, 1972). Three giants were responsible, in succession and building upon the works of the others. Pierre Perrault (1608-1680), Edmé Mariotte (1620-1684), and Edmond Halley (1656-1742) mirrored the Ancient Greek succession of scientific collaborators, though armored now with quantitative tools and the newfound age of empiricism (Deming, 2014). The seventeenth century was marked by the belonging of nearly all scientific endeavors to some Royal Society, the evolution of alchemy into chemistry, and the invention of the printing press which revolutionized international collaboration (Bowen, 1981).

It began with Pierre Perrault, the French naturalist, who translated Vitruvius' work on architecture and showed that precipitation was sufficient to supply the continuous flow of rivers. His comprehension of stratigraphy was vital, and he envisioned a bed of impermeable clay which prevented rivers from sinking lower and was overlain by pebbles and sand (Deming, 2014). He demonstrated this using approximate measurements of rainfall and discharge in the Seine River basin, concluding that "one-sixth part of the rain and snow water that falls is therefore needed to cause this river to flow continually for one year." (Perrault, 1967, 97). He attributed the rest to plants drawing water along the way, though he neglected the infiltration of water into the ground whilst accounting for additional waste (Perrault, 1967). These back-of-the-envelope calculations were later quantified more precisely by the French physicist, Edmé Mariotte, who provided a mathematical solution to strengthen Perrault's foundation (Deming, 2018). Mariotte noted the percolation of rainwater on hills and mountains, noting that upon reaching an impervious layer, water would flow until it reached some point of give below the mountain, where it would flow out as a spring (Deming, 2018). He demonstrated that fluctuations in spring flow were directly related to the amount of precipitation, which Mariotte measured in Dijon (Biswas, 1970a). A spring will lose half of its flow in a two-month period without rain and should drought last a year, would run dry (Deming, 2018). With precipitation a settled matter, there came a need to justify that the amount of evaporation was also sufficient to supply the cyclic seedlings which had taken nearly two millennia to be sown. Edmond Halley, the English astronomer, was a versatile genius and the man who would complete the cycle based on the works of Palissy, Perrault, and Mariotte (Biswas, 1972). He placed a known mass of water in a pan and heated it to the temperature of air in "the hottest summer". After two hours, he noted that 233 grains (0.03 lbs.) of water had escaped the pan (Biswas, 1972). Factoring in the 12-hour summer days of heat, the depth of evaporation from the pan, and the amount of water the Mediterranean received from its nine tributaries, Halley mathematically and experimentally demonstrated that evaporation could seamlessly supply rivers and streams. Duly noting that the wind he had neglected provided a conservative estimate, his proof was infallible (Biswas, 1972). And it was so, dear reader, that history came back full circle from a succession of Greeks to that of scholars to settle, once and for all, the splendour of the circle of life. Or at least the substance which makes it all possible.

The Hydrologic Cycle Today

Modern hydrology is a science which is growingly highlighted by a global understanding of the effects of anthropogenic climate change. While in the stories of contributors to our understanding of the hydrologic cycle were often motivated by local water crises, modern data is widespread, and statistical analysis has provided us with the clues that there is a more global impact to understanding the hydrologic cycle. Whether those who must understand it do so for the pure science or engineering aspects of the science, the understanding remains the fundamental idea of hydrology (Berner and Berner, 1987). While the roots of hydrology were more in line with modern hydrologic engineering and hydraulics, the resulting science has applications extending to anything and everything held within the closed system of the hydrologic cycle. While hypotheses of the hydrologic cycle were increasingly accurate, especially that of Theophrastus, the barrier which separated these inquisitive characters from modern understanding was the lack of modern knowledge on the components. From determining the structure of water to the development of software for computing evaporation and condensation rates in any body of water, today's wealth of data and parameters outshines the most valiant efforts history has preserved..

Vital Discoveries on Water

Water is a highly unique substance. It is not only the one common factor in all known forms of life. Its physical characteristics are highly unique as well, mostly stemming from its molecular structure. A molecule of two hydrogen atoms and one oxygen, water is asymmetrical and dipolar, as shown in Figure 2.20 (Marechal, 2006). The bonding associated with this structure results in its climate ameliorating effects and the movement of energy associated with the movement of water in the hydrologic cycle (Berner and Berner, 1987). There are also different isotopes of water which are used to track the origins of water and understand Earth's history. The discoveries of these properties merit a history of their own but play an integral part in the hydrologic cycle as a whole.

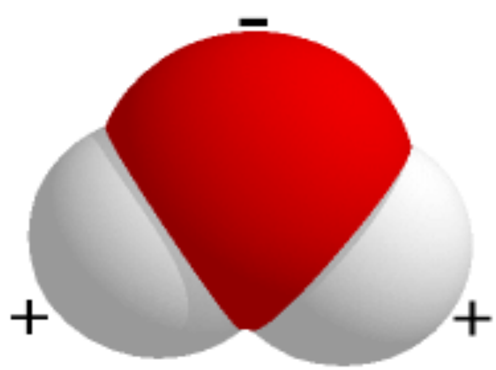

Figure 2.20. The atomic structure of a water molecule (left). Areas of positive and negative charge are marked; Hydrogen atoms (white) hae a partial positive charge and the oxygen atom (red) has a partial negative charge.

Theories Combined

The hydrologic cycle is a conceptual representation of the global process of water transition and transportation driven by energy from the sun (Viessman and Lewis, 2003). Earth's hydrologic cycle is contained in a closed system where water cycles through the same repeated processes and subcycles over varying lengths of time (Brutsaert, 2005). The movement of water through different processes is represented in Figure 2.21, where the fundamental processes of hydrology are delineated and their quantities represented in km^3 per year.

The hydrologic cycle is a simplified representation of a highly complex series of interactions on a global scale. For a given system, the budget is condensed into a simple equation known as the continuity equation (Brutsaert, 2005). Change in storage is given by the inflows minus the outflows, employing the law of conservation of mass (Brutsaert, 2005). More specifically, inputs can be separated into precipitation, groundwater flow in, and surface flow (or runoff) in, and outputs as evapotranspiration, groundwater flow out, and surface flow or runoff out (Brutsaert, 2005). For different stores in the hydrologic cycle, water remains for different lengths of time. The time from which water enters a system to the time it leaves is defined as the residence time and varies to a great degree between desert playa lakes and polar glaciers (Berner and Berner, 1987).

The Hydrologic Budget

The hydrologic budget is a calculated change in storage of a given hydrologic system based on known measurements of inflow and outflow. Despite technological advances, measurements of the fluxes into and out of hydrologic systems across the earth remain very difficult: high variability in climatic as well as physical conditions mean that fluxes change frequently. There are a number of conventions which are used by hydrologists to aid the transfer of data and understanding of hydrologic systems. The most important of which is the conversion to standard units; precipitation and evapotranspiration are described in depths (mm) while runoff is measured in depth per units of time.

Components and Measurements

Precipitation is likely the most measured hydrologic variable because of the ease of its measurement. Rain gauges (like the one pictured in Figure 2.22) are placed throughout desired study systems and measure the depths of precipitation and may or may not record the passage of time (Berner and Berner, 1987). The most common measurement tool is a standard 8 inch gauge which records the depth of precipitation over a period, and must be tracked, usually on a daily basis (Viessman and Lewis, 2003). Point measurements of precipitation data are amalgamated across systems using different methods of weighted averages to maximise accuracy. Modern techniques have evolved to minimise error as well, as measurement equipment has become more and more specialized to counter over- and underestimation of precipitation (Viessman and Lewis, 2003). Evapotranspiration is the broader category of water which returns to the atmosphere from the Earth's surface. Evaporation includes the sublimation of surface snow and ice or evaporation of liquid water to water vapor in the atmosphere (Berner and Berner, 1987). Since much of Earth's surface is inhabited by flora which photosynthesize, transpiration from the stomata of plants plays a large role in evapotranspiration and the reuptake of water vapor into the atmosphere, a concept pioneered by Palissy. Evapotranspiration is difficult to measure as many components contribute to the broader flux and these components differ greatly with changing landscapes. For instance, the rate of evapotranspiration over a desert region will differ greatly from that of an ocean. Methods of estimation range from physical measurements by direct and indirect methods, to calculation based methods. One method which remains from the past is the use of evaporation pans, or lysimeters (Viessman and Lewis, 2003).

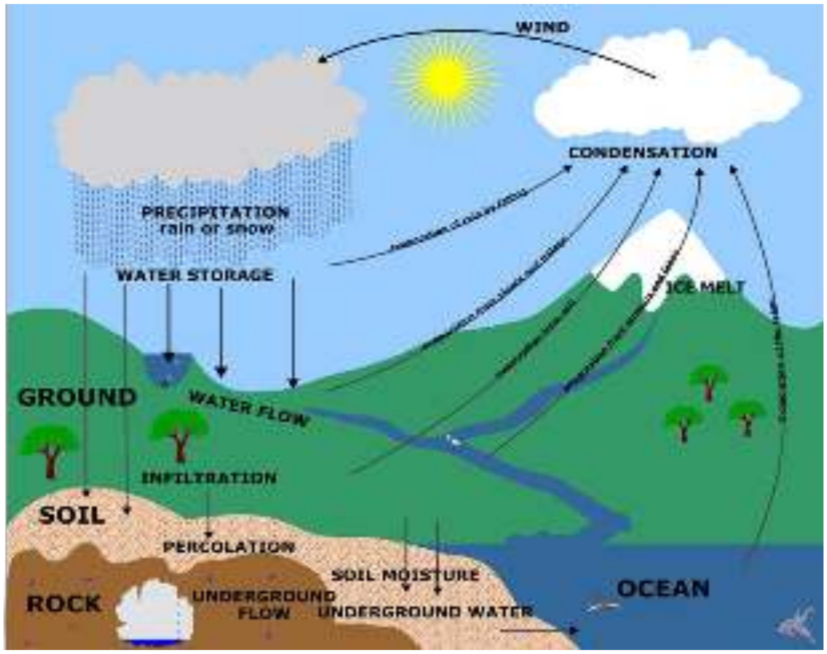

Figure 2.21 A diagram of the global hydrologic cycle. The direction of arrows indicates the direction of water movement in the labelled processes.

Figure 2.22 A modern rain gauge placed in the field and measuring over 6.5mm of rain. At the top of the gauge is a funnel (not pictured) that directs water inside the measurement cylinder. The funnel is 10 times the cross-sectional area of the cylinder. The gauge is therefore calibrated so that 1/10 of an inch of rain in the funnel corresponds to 1 inch of rain in the tube and 1 inch of rainfall.

Runoff is measured by installing a device such as a weir over an open channel which raises the water level and measures the depths of water in the pool upstream and the depth above the device to determine a flow rate (Berner and Berner, 1987).

Applications

The use of these techniques and understanding has permitted several studies to estimate the magnitudes of water stored in major components of the hydrologic cycle. Oceans store the vast majority of Earth's water, followed by total groundwater and then glacial or polar ice (Brutsaert, 2005). Throughout Earth's history periods of hothouse and icehouse conditions have dictated all that takes place from evolution or extinction of life forms to the formation of landforms. During icehouse conditions storage of water in glacial ice meant sea levels would drop and cause transgressions, or periods of consistent erosion and during hothouse conditions higher sea levels caused deposition of sediments (Gornitz, 2009). The knowledge of the hydrologic cycle permits wide scale paleoclimatic investigations to further decipher Earth's history (Obrist-Farner and Yang, 2016). The hydrologic cycle is integral in applying stratigraphic principles, such as Walther's Law, in order to reconstruct the history of what has been the marvel of the human mind for over 3000 years: the Earth in all its aqueous sustenance.

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Figure 2.1 Copper engraving showing Lisbon in ruins and in flames. The Earthquake Engineering Online Archive – Jan Kozak Collection, 1755.

Figure 2.2 The women of the pleasure quarters blaming the catfish. Kawaraban namazu-e ni miru Edo Meiji no saigai joho – Ishimoto collection kara, 1855.

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Figure 2.18 Vitruvius' Conceptualization of the Water Cycle. Self-produced Graphic, based on the description by Pollio, 1826 pp. 234-235, 2020.Figure 3.24. A thin sheet of tar. https://www.flickr.com/photos/betsyweber/5301041172/, Betsy Weber, 2010.

Chapter 3. Prehistoric Life

Tyrannosaurus rex skeleton housed at the Manchester Museum.

Chapter 3.
Prehistoric Life

For as long as human civilization has existed, it has pondered what came before it. Initially in the form of myths and legends, humans have consistently conceived their own fascinating illustration or narrative of this ‘primeval’ world and the life inhabiting it. The appeal of prehistoric life is partially driven by its elusiveness. There is no chronicle or journal documenting prehistoric life, relying instead on more unconventional and creative study methods, and leaving room for imagination and curiosity to fill in the gaps.

The ambiguity of prehistoric life has led to an ever-changing portrayal of its nature across human history. Changing viewpoints on this topic have been driven by advances in technology and methodologies. Each new discovery adds a piece to the large mosaic representing prehistoric life. In recent decades, a large diversity of people from different disciplines have approached this topic collaboratively to provide further insight to the field, which has accelerated the rate of discovery.

However, humans are imperfect, and this is reflected in the scientific process responsible for our knowledge today. The introduction of novel ideas has often been met with an unusually large amount of resistance. Such ideas typically challenge societal preconceptions that have solidified over time, adding an additional degree of inertia before acceptance within a community. Conflict may even result from opposing ideologies, at the cost of scientific progress. This may occur if a scientist seeks to have their views overshadow that of another scientist or competes with another for prestige within the field.

This chapter will investigate the study of prehistoric life across history, including the associated highs and lows, and how modern study, while far from perfect, has learned from this and led to more productive, interdisciplinary research in the field.

Historical Perspectives on Amber

Amber has played a role that can be found throughout human history, but it was not until recently that humans have begun to explore the various ways through which amber can hint at the distant past. Amber is the resin of coniferous trees that over millions of years has fossilized and solidified. Before becoming true amber, a substance known as copal forms, which is distinct from amber in both its colour and hardness (Poinar, 1992). Copal is much softer, and has a lighter, more yellowish colour. The rate at which the change from copal to amber occurs is highly variable and depends on both the temperature and pressure of the environment, meaning that there is no set timeline for when the transition occurs. However, most copal represents resin that has been on the earth for less than 3-4 million years (Poinar, 1992), while most amber is found to be millions of years old, with the oldest known piece of amber having been dated at 320 million years.

Before its geological and paleontological significance were discovered, amber was used in a wide variety of applications ranging from medicine to jewelry (Duffin, 2015). Even in the modern day, amber has been ground up into a powder and used to treat many different ailments from drunkenness to halitosis. Amber was also prized for its use in jewelry and ornamentation, due to its relatively easy workability, its pretty colour, and relative abundance. The oldest discovered evidence of worked amber dates back to 13 000 years ago (Grimaldi, 2009), indicating that the use of amber in ornamentation is a very old practice among humanity.

The modern monetary value of amber fluctuates, and it is popular mainly in two communities: collectors and scientists. To collectors, the value of amber is derived from the colour, polish, and form, with little attention paid to the value of inclusions. In the scientific community, however, amber is appraised based on the inclusions found within (Poinar, 1992). Before the fossilization process, the resin of the trees would often catch small insects or animals within them, completely covering them and preserving the specimens. It is these specimens that further the discovery of scientific knowledge of the past. These inclusions consist of specimens of fungi, bacteria, algae, plants such as gymnosperms and angiosperms, and animals such as small insects, amphipods and isopods, and arthropods (Szwedo, 2002).

Along with all of these uses for amber, throughout history, it has been used as a valuable geological and paleontological tool that has helped us understand the past. Due to its unique qualities and mineral properties, it has been an early contributor to the discipline of mineralogy. The abundance of the mineral and the variety of theories as to its origins helped to develop the science of mineralogy to determine the truth behind amber. The inclusion of the variety of organisms that have been found in amber made its study a close parallel to paleontology and helped to tie the disciplines of paleontology and geology together to further our understanding of the history of the earth.

Origins of Amber

The first scientific account of the origin of amber is given by Theophrastus in the 4th century BCE, who in his treatise *On Stones* classified amber as a stone as it was dug from the ground (Caley and Richards, 1956). The next major advancement is given by the Roman historian Pliny the Elder, who in his work *Naturalis Historia* (77 CE) provides criticism of a wide range of historical accounts (Pliny the Elder, 77). He begins by disproving the ancient myth using knowledge of the geographical location of amber; since amber is not found in Italy, creationist myths rooted there must be false. He then cites the opinions of Pytheas (350-285 BCE) that amber was "an excretion of the sea in concrete form", of Demostratus that amber was the hardened urine of a lynx, of Sotacus that it exudes from British rocks, of Nicias (470-413 BCE) that amber was the result of a liquid produced by the rays of the sun and hardened by these same rays at sunset, and of various thinkers that it was the excretion of a tree. However, Pliny rejected all these explanations on the basis that such a common object must have a common origin. Instead, he provided his own explanation, which is incredibly advanced for the time. He postulated that: "Amber is produced from a marrow discharged by trees belonging to the pine genus, like gum from the cherry, and resin from the ordinary pine. It is a liquid at first, which issues forth in considerable quantities, and is gradually hardened by heat or cold, or else by the action of the sea…" (Pliny the Elder, 77). This explanation is remarkably close to the actual formation of amber and is determined from a few qualitative observations: that amber smells like pine when rubbed and like torch-pine wood when burned, as well as the name of amber in Latin (succinum, from the Latin for juice). As such, this can be regarded as the first scientific determination of the origins of amber.

With the fall of the Roman empire and the advent of the dark ages, not much research was conducted on amber for many centuries. By the mid 18th century amber had become an important revenue stream for many nations, which incited research into its origins. At this time there were several competing theories as to the origin of amber. The three major theories were that amber was a bituminous mineral generated under the surface of the Earth; that amber was produced in the ocean, possibly some excretion of sea-floor plants; or that amber was a mineralized resin or gum (Fothergill, 1744). Other theories were that it was solidified animal excrement which had been modified by wave action, that it was produced by insects as they were found in it, and that it was honey mineralized by vitriolic (sulphuric) acid (Chambers, 1851). While each theory had its supporters, the vegetal origin theory began to gain ground due to the emergence of scientific studies on the matter. One of the earliest such studies was performed by the influential English physician John Fothergill (Fothergill, 1744). A major argument that he made was that amber "hath the genuine characteristics of wood", noting that it had a similar fibrous texture to wood and that it floated and burned like wood. A more scientific argument he made was that amber must be from the surface of the Earth, rejecting the other major theories, as it contained animal inclusions that are not found in marine or subterranean environments. These three pieces of evidence were, he argued, irrefutable evidence that amber was the result of buried resin which had been fossilized. Typically of the time, he suggested that these trees may have been buried in the biblical Genesis flood, demonstrating the deep-set religious influences of the time. He then went on to suggest that time and "the acid of the earth, a vitriolic mineral acid" had changed the resin to amber since turpentine (a known vegetable resin) can be treated with sulphuric acid to make a material with many of the same characteristics as amber. This paper was incredibly advanced for the time, relying only on evidence that could be physically determined and on known facts to draw conclusions, while admitting ignorance where required.

By the mid-19th century a broad consensus had been reached that amber was formed from some sort of exuded vegetable juice, likely a resin from a coniferous tree (Lambert, 1867; Chambers, 1851), though there was still active debate as to the exact formation of amber, whether it was a single resin or a mix, whether it was even a resin at all or rather some form of dried wax (Lambert, 1867). A seminal driving force in this area was the work published by the famous Scottish physicist Sir David Brewster, who used polarized light to study the nature of numerous materials (Brewster, 1814, 1815). These experiments allowed him to determine that "the substance is undoubtably of vegetable origin" (Brewster, 1832) and that its structure is "produced by the same causes which influence the mechanical condition of gam-arabic, and other gums which are known to be formed by the successive deposition and induration of vegetable fluids" (Lambert, 1867). This marked a shift in the study of amber from taking qualitative observations and relating them to known material to making deductions based on discernable facts. Aside from light experiments, evidence was also gathered by examining insect inclusions in amber and fossil wood containing amber. The consistent appearance of insects in amber was taken as near irrefutable proof of its resinous origin, given that no other feasible method for their appearance could be made and that insects could be found similarly trapped in existing resins exuding from living trees (Culloch, 1824). By the mid-19th century, many fossilized trees containing amber veins had been found, which was used as evidence not only of the resinous nature of amber but also that it was mineralized over some time (Alessi, 1835). In 1838 H. R. Goppet used fossilized trees containing amber to determine which trees

Figure 3.1. Stratigraphic succession of Samland amber-bearing formation. Amber earth contained amber and was found to range from four to six feet deep.

could make amber. In a statement emblematic of uniformitarianism though of the time, he remarked that not only did amber come from numerous different tree genera, but also that most amber specimens were similar due to being formed under similar conditions (Goppet, 1838). By the time the mid-century came, the resin origin and old age of amber were nearly unquestioned, and the task had now become the identification of the specific tree species which produced it (Göppert, 1846). The exact mechanisms as to the mineralization of amber from resin continued to be a subject of avid debate into the end of the century, often studies using the geology of the amber-rich area of Samland. This was the period when geology began to truly define the field, with amber examined in relation to its surrounding strata (Thomas, 1848), the timeframe of surrounding deposits (Zaddach, 1868), and the supposed ancient environment of the region. At this point, chemical analysis could be performed to distinguish amber from other materials, such as Copal, and the main amber-bearing formation of Samland was described (Smith, 1880). At this point, the true nature of amber had been almost entirely revealed and today's more complete understanding has not changed greatly since.

Inclusions in Amber

To understand the context under which amber inclusions were studied, it is important to first understand the history of fossils. The earliest known deduction as to the true nature of fossils is by the Greek philosopher Xenophanes of Colophon (570-480 BCE) who wrote that some fossils were the remains of shellfish (De Klerk, 2017). This concept was also noted by the Greek philosopher Aristotle, who wrote that fossils were created by vaporous exhalations (Rudwick, 1985). This theory was modified by the Persian naturalist Ibn Sina then by the German philosopher Albert of Saxony in the 11th and 14th centuries respectively to state that living organisms are transformed into fossil by a "petrifying fluid", though the exact nature of this fluid was unclear. This remained the commonly accepted explanation of naturalists into the 16th century. Many natural processes were supposed to be evidence of this fluid, such as the growth of stalactites, the calcification of algae, and the presence of rocky organics such as corals, pearls, and gallstones. However, it was not until the 17th century that fossils began to be widely recognized as the remains of once-living organisms. Before this period natural philosophers followed either the Aristotelian school, which argued that seeds of living organisms entered the ground to generate objects resembling the organism, or the Neoplatonic school, which argued that the affinity between living and non-living things caused them to resemble each other, of philosophy (Rudwick, 1985).

In the 17th century new evidence caused scientific perceptions of fossils to change and the possibility of extinction began to arise. One early work is Athanasius Kircher's *Mundus subterraneus*, in which he attributes giant bones to an extinct race of giant humans (Kircher, 1665). Shortly afterwards Robert Hooke published the seminal *Micrographia*, in which he stated that some fossils may be of organic origin and their species may have died out (Hooke, 1665). Nicholas Steno then examined the common fossil objects known as "tongue stones" and determined that they had once been shark teeth, and that they had been brought to land by the biblical flood (Steno, 1667). However, many naturalists questioned this theory as the concept of extinction was contrary to the theological teachings of the time (Bowler, 2000).

In the late 18th century Georges Cuvier compared the skeletons of Indian and African elephants with the fossils of mammoths (Faria, 2012). Since mammoths differed significantly from both species and were not found alive, he inferred that they must have gone extinct. Late that same year he made a similar statement about a giant sloth by comparing it to two living species of tree sloth. The works of Cuvier laid the groundwork for widespread acceptance of extinction. As such, by the time research into amber began in earnest there was general acceptance of the existence of both fossils and extinct species.

One of the major reasons amber has been such a useful tool in geological and paleontological work is because of the inclusions that can be found fossilized and preserved in great detail within it. Over the years deposits of amber have been found to contain inclusions from a variety of life forms, including fungi, algae, arthropods, leaves, wood fragments, flowers from angiosperms, and many more. Some pieces of amber even contain larger animals such as amphibians and reptiles (Szwedo, 2002).

The study of these inclusions began in the early 18th century with Nathanael Sendelius, who lived from 1686-1757 (Penney, 2010). Sendelius was a physician by trade and worked as such for his entire life. However, on the side, he had a fascination with amber and was the first to study on a large scale the inclusions therein. The collection from which Sendelius received his amber was the royal *Naturalienkabinet zu Dresden*. This collection of amber at the time of Sendelius' study contained 600 samples of amber inclusions, having been built up since 1718 from the collections of August the Strong (1670-1733), the elector of Saxonia, the king of Poland, and his son Friedrich August I (1669-1763). While Sendelius only mentioned 600 pieces in his study, by the 1740s the collection was comprised of around 1500 pieces of amber and inclusions (Penney, 2010).

Sendelius classified the inclusions that he observed in the amber pieces into three categories based on the living environment of the organisms therein. The first was flying insects (insect volantia), the second was ground crawling articulate organisms (insect terrea renetia et apoda), and the third was aquatic animals (Penney, 2010). The plants that he found within the amber he summarized in a short chapter following the one on the animal inclusions. The product of his work was the *Historica succinorum corpora aliena involventium et nature poere pictorum et caaelatorum*, a 328-page volume on the selected amber inclusions that Sendelius chose to study. Even though Sendelius lacked proper preparation techniques and good microscopes, which would have made his work difficult, Sendelius pioneered the future of palaeoentomological amber research (Penney, 2010).

Almost 75 years after Sendelius died, a surgeon and geologist named John MacCulloch took an interest in amber, writing a short paper titled *On animals Preserved in Amber, with Remarks on the Nature and Origin of that substance*. In this paper, MacCulloch briefly remarks on the origins of amber, as well as the inclusions found within it. MacCulloch was one of the first to propose that since it is a reasonable conclusion that fossils belong to animals that are extinct, then so must the animals contained within amber also "have belonged to a former state of the globe" (Culloch, 1824).

In the 19th century, a physician named Carl Georg Berendt brought palaeoentomological amber research to its first major peak. He lived from 1790 to 1850 in Danzig, where he developed his father's amber collection in order to eventually publish his crowning work. Berendt studied his amber collection and worked to classify and categorize every inclusion using the binomial nomenclature of Karl von Linné (Penney, 2010). In order to complete this work, Berendt enlisted the help of several of his scientific co-workers: H.R. Goeppert, C.L. Koch, E.F. Germar, and F.J. Pictet and H. Hagen. With their help, Berendt established a new scientific standard for the study of inclusions found in amber. The final published work was edited in two volumes in 1845 and was titled *Die im Bernstein befindlighen organischen Reste der Vorwelt* (Penney, 2010). This work included and classified the entire diversity of all plants that were known to have been found in amber at that time.

Through the 20th century, there were fewer broad papers published, like those mentioned above, and geologists and entomologists began to publish more specific findings, such as the specific taxonomy of flora and fauna found within amber, and how they relate to modern extant organisms. One example of this more specific study was done by a man named Faustino Miranda in 1961. Looking at four pieces of amber, Miranda identified two species of plants that were similar to two species of extant plants (Acacia and Tapirira) (Miranda, 1963). By comparing the species of Acacia and Tapirira found in the amber to species of the same genus that are alive today, Miranda was able to draw conclusions regarding these specific species and their past. This was the first fossil species to be identified as Tapirira that was not a leaflet material, and these findings compared to modern day indicated a potential change in the environment that restricted the growth of these florae to one specific area.

There were many such discoveries occurring throughout the 20th century, and they have continued into the 21st century as technology becomes better and more and more amber deposits are discovered.

Figure 3.2. High quality sample of amber with butterfly inclusion. Note the level of detail with which the sample was preserved.

Modern Discoveries and Applications of Amber

In recent years, amber has become popularized in the media and popular culture, largely due to the writings of Michael Crichton and the Jurassic Park franchise. Crichton's science fiction novel about growing dinosaurs from the DNA extracted from the inclusions found in amber caught the public's eye, and since then this idea of bringing dinosaurs back from the past has been hugely popular. Based on both the morphological and biochemical preservation of materials seen in inclusions, amber was believed by many to be the best potential source for geologically ancient DNA, but unfortunately to date scientists have been unable to support these hopes.

Extracting Ancient DNA from Amber

Over the past several decades, there has been an increase in the search for geologically ancient DNA, particularly focused around extracting it from amber or fossils. The idea is fascinating and being able to extract and replicate DNA from these geologically ancient specimens would be a major breakthrough in science. However, while there have been studies that reported the extraction of replicable DNA from amber inclusions, more modern studies conclude that these results are erroneous.

One major reason why extracting ancient DNA from amber is not plausible at the current time is that the possibility for contamination is almost too high to comprehend. The scale on which contamination may occur in the lab with this kind of work is incredible. The way in which DNA is replicated once extracted from these specimens is Polymerase Chain Reaction (PCR), which can easily contain 10^{12}-10^{15} amplified molecules in a volume of less than 50μl (Jones, 2018). These samples, through just the act of opening a vial, can create microscopic aerosol droplets that contain millions of copies of a DNA template that would be spread throughout the lab (Jones, 2018). There is always the possibility that human DNA is mixed in with the ancient DNA that has been extracted, and even less likely to be noticed would be modern bacterial DNA contaminating these ancient samples. With bacteria being basically everywhere, it is very easy for a small amount of bacterial DNA to contaminate the samples and then be amplified over and over again by PCR (Jones, 2018).

However, the foremost reason as to why ancient DNA has not yet been successfully extracted from amber inclusions is the fragility of DNA itself. While organisms are alive, they are constantly regenerating and fixing their DNA, but once they die, this process stops. It is known that DNA is more likely to survive in cold temperatures, but the formation of amber requires both pressure and heat, therefore reducing the chance that any included DNA will remain intact. Put simply, it is very unlikely that any DNA will be preserved to extract from the amber.

Modern Discoveries

Despite being unable to grow extinct organisms from DNA preserved within its inclusions, there have been many new discoveries found within amber that have contributed to our knowledge of the past. New deposits of amber are constantly being discovered that contain novel organisms and in some cases even organisms that seem to have survived to the present day.

A discovery of a deposit of Triassic amber was found in 2006 and studied by a man named Alexander Schmidt. What Schmidt found within this amber, which was dated back to the Triassic period 220 million years ago, was a cornucopia of bacteria, fungi, algae, and protozoans (Schmidt et al., 2006). Among these were included a group of amoeboid organisms known as testaceans, making this the earliest evidence for terrestrial testaceans ever discovered. What is incredible about these findings is that one of the inclusions found by Schmidt is morphologically identical to the extant organism *Centropyxis hirsute* (Schmidt et al., 2006). This represents the earliest occurrence of a protozoan species that are extant today. The discovery of several species of these testaceans in the same drops of amber indicates that these organisms had become terrestrial and moved away from large bodies of water by the time of the Triassic. Schmidt believes that these organisms would have had to be living on the leaves of the trees or plants at the time, because there is no evidence of soil organisms within the amber, indicating that the amber solidified on leaves before falling to the ground (Schmidt et al., 2006).

Schmidt also published a paper in 2012 describing the preservation of arthropods in Triassic amber, which is dated back to 230 million years ago (Schmidt et al., 2012). These Triassic arthropods belong to a superfamily of herbivorous mites known as Eriophyoidea and the fossils found in the amber extend the lineage of these mites by approximately 185 million years. Additionally, these fossils definitively reveal that eriophyoids preceded angiosperms by at least 100 million years. This would mean that these mites fed on conifers and were most likely sheath dwellers or foliage feeders (Schmidt et al., 2012).

Novel Imaging Technology

In the world of imaging technologies, there have also been advancements in the recent past. Until 2004, it was impossible for inclusions within opaque amber to be identified, or even to know that they were there without destroying the sample. This poses a problem in areas where large portions of the amber retrieved are fully opaque, and nothing can be discerned about the interior of the piece of amber. Much of the Mesozoic amber that has been retrieved to date has been fully opaque. For example, fully opaque mid-Cretaceous ambers represented up to 80% of all amber retrieved from a site in Charentes, France—an amber-rich region whose amber commonly has biological inclusions (Lak et al., 2008).

Previously, semi-opaque ambers could be imaged using x-ray computed tomography, or microtomography, but this was only possible because of a vague idea of where the inclusion was in the amber, and what its general shape was. For fully opaque ambers, microtomography was nearly impossible without some prior knowledge of the inclusion (Lak et al., 2008). This inability to even know if there were inclusions in the amber of a certain region could lead to incorrect inferences as to the paleoenvironment of that time in that area. With the development of x-ray synchrotron imaging, relatively clear images can now be produced of previously unknown inclusions. In 2008, Lak et al. imaged 91 plates of fully opaque amber and found 356 fossil inclusions, all of which were nearly complete. These images were clear enough that the fossils could be identified up to the ordinal level in most cases, and in particularly exceptional cases were able to be identified to the family level (Lak et al., 2008). This ability to determine whether there are inclusions in opaque amber will be greatly beneficial to the furtherance of paleontological study as more amber deposits are found.

Amber is an old mineral that can be found in abundance, and has been incredibly useful in recent years in expanding the fossil record and increasing our knowledge of both extinct species that no longer roam the Earth as well as species that are very closely related or even the same as those that are extant today. Despite being unable to bring back organisms from the past, amber has become a particularly valuable paleontological tool in recent years.

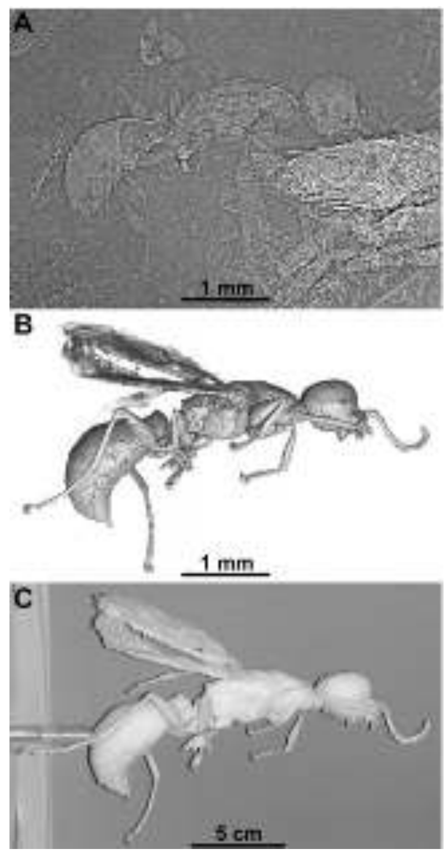


Figure 3.3. A: Image obtained from x-ray synchrotron of an inclusion in an opaque sample of amber. B: 3D image generated by a computer based on the x-ray image obtained of the amber. C: 3D printed model of the wasp to be used once the new species has been described in full.

A Sight for Saur Eyes: Representations of Dinosaurs in Paleoart Throughout History

For as long as people have collected fossils, they have tried to interpret them. The process of creating artistic interpretations of fossils based on scientific understanding is known as paleoart (Lescaze, Ford and Taschen, 2017), and it is intimately linked to paleontology, as it requires a careful analysis of fossils and their contexts. In this way, it is deeply a product of its time, reflecting changes in prevailing scientific theories and technological limits throughout history (Debus, 2003). If paleontology is, "the intrigues left by a vanished world imperfectly preserved," (Krishtalka, 1989, p.7) then paleoart is an attempt to understand and express these intrigues using only incomplete remains and human imagination – this challenge makes every work and subgenre of paleoart a uniquely immersive experience. However, perhaps no interpretation has intrigued paleoartists more than that of the dinosaur, whose depiction has undergone significant changes over the past 200 years (Lescaze, Ford and Taschen, 2017). Scientists and paleoartists such as Henry De la Beche, Richard Owens, Benjamin Waterhouse Hawkins, Joseph Leidy, Charles R. Knight, and John Ostrom have all aided in developing the rich imagery and understanding we have of dinosaurs today. Although it is by necessity a blend of fact and fiction, the potent reality that paleoart creates continues to fascinate people to this day.

Figure 3.4. A chaotic, vibrant, and violent scene, Duria Antiquior *(below) was the first full depiction of deep time. Over thirty ancient marine reptiles fight and feast on each other, brought to life in striking watercolour.*

Henry De la Beche – Fact and Fiction

The first known piece of paleoart appeared in England in 1830, with geologist Henry De la Beche's watercolour painting *Duria Antiquior* (Figure 3.4; Lescaze, Ford and Taschen, 2017). Based on clues from fossils themselves, as well as associated organisms and the rock substrate, De la Beche created a vibrant aquatic scene featuring his interpretations of prehistoric marine reptiles (Lescaze, Ford and Taschen, 2017). Three years later, as a director of the Geological Ordnance Survey and a strong proponent of geological literacy, De la Beche published a French version of *A Geological Manual*, a textbook outlining the geological practices of the time (Clary and Wandersee, 2009). This textbook contained three further pieces of paleoart (Clary and Wandersee, 2009). Due to the textbook's success and availability to the public, these initial illustrations are thought to have influenced paleoartists for years to come.

Owen and Hawkins – Creator of Clades, Drawer of Dinosaurs

The 14th of April, 1842, was an auspicious day in the history of paleontology – Richard Owen, a prominent British anatomist, had just published a paper that officially established dinosaurs as their own clade (Owen and Hawkins, 1854). This was largely based on evidence of a fused sacrum in the dinosaur genera *Iguanodon*, *Megalosaurus*, and *Hylaeosaurus* (Owen and Hawkins, 1854). Owen's view of these dinosaurs changed dramatically in the years before and after the creation of this new clade – at first, he and most of his contemporaries described dinosaurs as enormous, placing their length at around 200 feet, but this gradually changed to a more reasonable estimate of around 30 feet (Farlow and Brett-Surman, 1997). Owen described dinosaurs as highly advanced quadrupedal reptiles which behaved and looked somewhat like modern pachyderms (Farlow and Brett-Surman, 1997). As a vehement anti-Darwinist, it has been suggested that Owen's interpretations of dinosaurs as essentially the height of reptilian glory was an attempt to refute the idea that species became more sophisticated over time (Lescaze, Ford and Taschen, 2017).

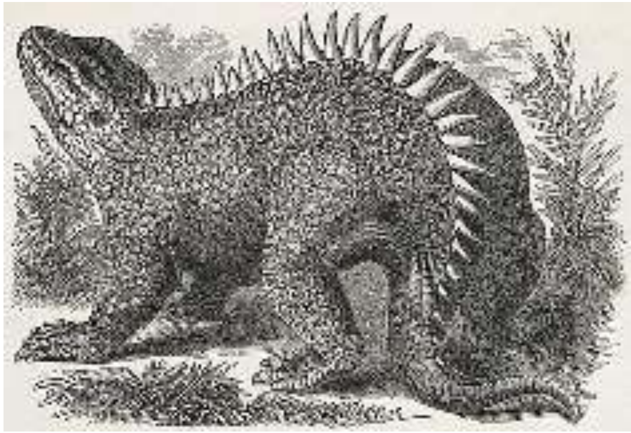


Figure 3.5. This Hylaeosaurus *drawn by Hawkins showcases the almost mammalian quality of his dinosaurs – rather than splayed lizard-like legs, these were stocky creatures with thick, straight limbs. Hawkins' distinct style influenced paleoart throughout Europe for years after his exhibition.*

Around this time, one of the first paleoartists, Benjamin Waterhouse Hawkins, was creating sculptures and illustrations based on Owen's descriptions (ex, Figure 3.5), which often depicted dinosaurs as large, unwieldy quadrupeds (Farlow and Brett-Surman, 1997). Owen and Hawkins collaborated to create a famous (now somewhat infamous) collection of enormous cement dinosaur sculptures as an exhibit in London's Crystal Palace Gardens (Waterhouse, 1854; MacDermott, 1854). The two hosted a high-profile New Year's Eve dinner in 1853, in which guests dined in the cement belly of a 30-foot-long *Iguanodon*, as an immense *Megalosaurus* looked on (Krishtalka, 1989). From a modern perspective, these sculptures may seem almost ridiculous, with their anatomical mistakes and fanciful interpretations; the sculptures have been described as looking, "about as nimble as cows in a cage. The *Iguanodon*, girded by four ponderous legs, had huge, clawed feet, a skin of diamond-shaped green scales, and a horn on its nose — a rhinoceros in lizard's clothing" (Krishtalka, 1989, p.254). However, Hawkins' Crystal Palace exhibition played a significant role in the history of paleoart by bringing to life what had previously been limited to small drawings, prints, and paintings, and presenting it to a broad audience (Lescaze, Ford and Taschen, 2017). The dinosaurs became hugely popular with the Victorian public, already in the midst of a kind of natural history renaissance – one captivated journalist working for the *London Quarterly Review* wrote of the spectacular dinner, "We are entering a mausoleum to the memory of ruined worlds; and that in the track of men, who, though like us, tremulous stones in the crumbling wall of time, are yet manifestly hewn in the rock of eternity," (Telford and Aquila Barber, 1854, p.238).

The scientific and societal concept of dinosaurs remained this way until the work of Joseph Leidy revealed its inaccuracies, but it remains immortalized in Hawkins' sculptures, many of which have been restored and are still on display in the Crystal Palace today (Friends of Crystal Palace Dinosaurs, 2020).

Joseph Leidy – Iguanados and Iguanadon'ts

Joseph Leidy, widely regarded as the founder of American paleontology, redefined the image of the dinosaur (Warren, 1998). During 1858, a series of marl pits were excavated in Haddonfield, New Jersey. In them, many fossils were discovered, including teeth and jawbone fragments of a new dinosaur species (Leidy, 1864; Academy of Natural Sciences, 1858). Leidy recognized the bones as being morphologically similar to *Iguanodon* and named the dinosaur *Hadrosaurus* (Leidy, 1864). *Hadrosaurus* had very distinct fore- and hind-limbs, leading Leidy to believe that dinosaurs, or at least relatives of *Hadrosaurus* and *Iguanodon*, had a significantly different morphology than those in Owen's depictions (Leidy, 1864). Rather than being quadrupeds, these dinosaurs would have stood in a semi-erect position, balancing on their back legs (Leidy, 1864). This had a fundamental impact on how these

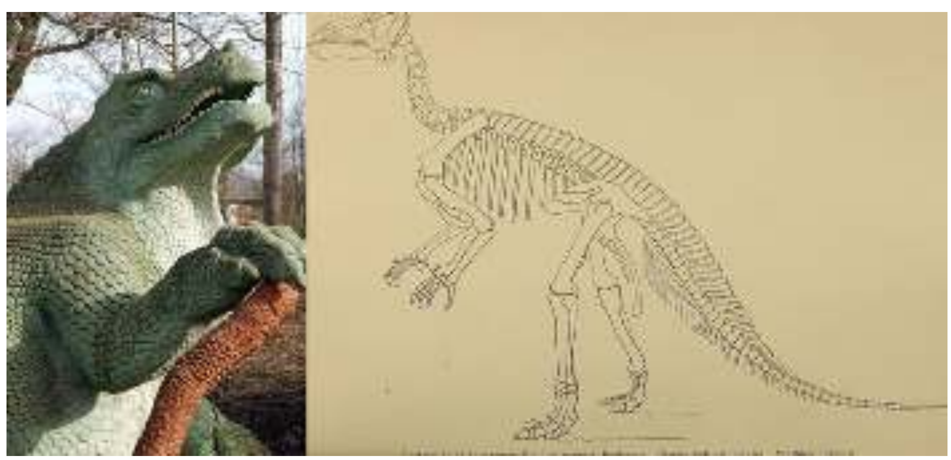


Figure 3.6. Left: A sculpture of an Iguanodon as Richard Owens envisioned it, as the peak evolutionary form of a reptile. Created by Benjamin Waterhouse Hawkins for the display at the Crystal Palace. Right: An updated drawing of an Iguanodon from the Transactions of the Connecticut Academy of Arts and Sciences, notably without its horned nose, which was a misinterpretation of the dinosaur's thumb spikes.

dinosaurs were illustrated (ex, Figure 3.6), shifting from very lizard-like quadrupeds to something not entirely divorced from our understanding of dinosaurs today.

The Bone Wars and Charles R. Knight – A *Bone* of Contention

The Bone Wars was a period in American paleontology characterized by a massive feud between palaeontologists Edward Cope and Othniel Marsh (Lanham, 1991). Edward Cope was a wealthy man born into a Quaker family. From a young age, he was fascinated with dinosaurs and studied under Joseph Leidy (Lanham, 1991). Othniel Marsh, on the other hand, was the son of a poor farming family (Lanham, 1991). Cope and Marsh struck up a bitter feud, each one racing against the other to find as many fossils and to name as many species as quickly as possible (Lanham, 1991). This feud meant that mistakes were often made. For instance, in 1868, Cope accidentally put the head on the wrong end of the aquatic reptile *Elasmosaurus* in his haste to complete the skeleton (Clary, Wandersee and Carpinelli, 2008). Similarly, Marsh accidentally put the head of a *Camarasaurus* onto the body of an *Apatosaurus*, creating one of the longest and furthest reaching mistakes in paleontology – the *Brontosaurus* (Clary, Wandersee and Carpinelli, 2008). The *Brontosaurus* was a hugely popular dinosaur, even though it technically didn't exist. Marsh first discovered the *Apatosaurus*, then, a short while later he discovered another skeleton and named it the *Brontosaurus* (Gould, 2010). As it turns out, these were the same dinosaur. Through a quirk of nomenclature, the older name is the one that is recognized by the scientific community, and thus, the *Brontosaurus* was no more (Gould, 2010). This led to an uproar amongst the general public who had grown to adore the *Brontosaurus* (Gould, 2010). The fossil assembly and cataloguing errors that were made by Cope and Marsh in their pursuit of fame led to mistakes that were preserved in paleoart in the years to come.

Charles R. Knight was born in 1874, just before the beginning of the Bone Wars (Milner, 2012). As a young child, he was fascinated with animals and drawing, which set him on a path to become one of the leading paleoartists of the 19th and 20th centuries (Milner, 2012). Knight's first foray into paleoart began in 1894 during a visit to the American Museum of Natural History, where he was asked to make a drawing of a prehistoric animal, and from there, Knight continued to produce paleoart (Milner, 2012). In 1897, shortly before Edward Cope's death, the two spent several weeks together, and Cope passed on many of his ideas about dinosaur anatomy and behaviour (Milner, 2012). It was during this period that Knight painted one of his most well-known paintings, *Leaping Laelaps* (Figure 3.8; Knight, 1935). Knight portrayed the dinosaurs as energetic and intelligent, at odds with the time period's common view of dinosaurs as stupid, slow moving beasts (Knight, 1935). Knight had a very particular way of creating these

Figure 3.7. Knight's 1897 painting depicts a group of 'Brontosaurus' *(really* Apatosaurus*), which were believed to be swamp-dwelling rather than terrestrial at the time, in his characteristic Impressionist style.*

Figure 3.8. Energetic and almost familiar, thanks to its inspiration from modern animals, Knight's Leaping Laelaps *has been suggested to represent the conflict between Marsh and Cope during the Bone Wars (Lescaze, Ford and Taschen, 2017).*

magnificent pieces of paleoart – to begin, he would observe a fossil, then create a miniature model and drawing of the dinosaur, before creating the extremely detailed finished painting (Milner, 2012). He also believed that in order to create images of the past, one must understand the animals of the present, so many of Knight's paintings drew insight from the behaviours and anatomical structures of extant animals (Milner, 2012). These beliefs came from his contact with Cope, who believed that the present can give context to the past and used extant animals to interpret fossils. In addition to this, he read extensively about past geological periods and their appropriate flora and fauna, so that each piece of paleoart was as historically accurate as possible (Milner, 2012). The careful consideration Knight put into creating these masterpieces was what made Knight one of the most influential paleoartists of his time, and why his work is still appreciated today.

Ostrom and the Archaeopteryx – A Paradigm Shift

The Dinosaur Renaissance, beginning in the early 1970s with a renewed public interest in palaeontology and fossils, marked a turning point in our understanding of dinosaurs (Oldham, 2018). This shift in understanding is largely credited to American paleontologist John Ostrom. Ostrom studied small carnivorous dinosaurs such as his first major discovery *Deinonychus*, the morphology of which suggested that birds are descended directly from dinosaurs (Ostrom, 2019). Another key piece of evidence for Ostrom's theory was fossilized remains of *Archaeopteryx* that had been discovered in the mid-1800s, which contained dinosaur-like bones with some bird-like characteristics, such as fused collar bones (necessary for flight muscles) and imprints of feathers (Krishtalka, 1989). This proposed link between birds and dinosaurs caused an uproar, as previous to this, it was widely believed that dinosaurs were most closely related to reptiles (Oldham, 2018). In addition to this, there was an uproar among creationists such as Sir Fred Hoyle, a British astronomer whose 'steady state' view of the universe was uprooted by Ostrom's delineation of birds as surviving dinosaurs (Krishtalka, 1989). In 1985, Hoyle called the feather imprints a hoax and theorized that Richard Owen, director of the British Museum of Natural History at the time of the fossil discoveries, had ordered the forgery and purchased *Archaeopteryx* for the museum in a scheme to embarrass Darwinians (Krishtalka, 1989). Hoyle was not the only creationist to cry hoax (Trop, 1983), potentially emboldened by the Piltdown Man scandal a few decades prior (Krishtalka, 1989) – but an investigation by the British Museum confirmed that the feather impressions were not a forgery (Charig et al., 1986).

Ostrom's theory that dinosaurs and modern birds are closely related called many of the reptilian characteristics previously associated with dinosaurs, such as exothermicity, into question (Ostrom, 1976; Oldham, 2018). The unintelligent, cold-blooded, slow-moving monsters of the past were transformed in a movement that Ostrom's protégé Robert T. Bakker himself proudly called heretical (Bakker, 1986, p.101). Bakker went on to create what some consider to be the first modern dinosaur restoration, in the form of a pencil drawing of a speedily running *Deinonychus* for Ostrom's 1969 monograph on the dinosaur (Benton, 2019). Despite their significance to our understanding and classification of dinosaurs, though, these discoveries took decades to become accepted among scientists and the general public (Oldham, 2018). This reluctance can be seen in the work of contemporary paleoartists, such as painter Jay Matternes – even while the Dinosaur Renaissance was taking place, none of his paintings depicted dinosaurs with feathers or other bird-like characteristics (Matternes, Carrano and Johnson, 2019). Although these theories would not be widely accepted for some time, the work of Ostrom, Bakker, and many others to challenge existing notions of dinosaurs forced paleobiologists to reconsider dinosaur physiology, behaviour, posture, locomotion, and ecology, and contributed to a renewed public interest in Dinosauria (Krishtalka, 1989).

Feathered Friends: Decoding Dinosaurs in the Modern Day

Years later, remarkable fossil discoveries finally confirmed Ostrom's theory that birds are living dinosaurs, descended directly from theropods (Benton, 2019). Possibly the most significant change in scientific understanding in the past few decades has been regarding feathers: direct and indirect fossil evidence suggests that not only were many dinosaurs feathered, but that feathers evolved much earlier than previously thought (Yang et al., 2019). Many theories surrounding feathered dinosaurs and the evolution of feathers and flight have been proposed and investigated using modern technology.

Figure 3.9. A remarkable Sinosauropteryx *fossil on display in the Inner Mongolia Museum. The well-preserved feathers and other soft tissues can be clearly seen.*

Much of the progress in recent dinosaur research can be attributed to rich fossil deposits discovered in the 1990s in Early Cretaceous rocks of the Liaoning Province in northeastern China (Norell and Xu, 2005). Dubbed the 'Jehol Biota,' these fossils are extraordinarily well-preserved by fine paper shales, allowing for the detailed preservation of soft tissues – such as skin, claw sheaths, and, of course, feathers – that are not normally accessible from the fossil record (ex, Figure 3.9; Zhou, Barrett and Hilton, 2003). The organisms preserved here, including many feathered theropods, are thought to have been buried quickly by volcanic ash in a low energy, potentially lacustrine, setting. This would have created an anoxic micro-environment allowing for the preservation of soft tissues (Norell and Xu, 2005). Microscopic analysis has indicated that the fossilized feathers have not undergone replacement, instead consisting of thin films that may represent the by-products of feather decomposition by bacteria (Norell and Xu, 2005).

Other important discoveries come in the form of feathers as inclusions in amber, which allows for extremely detailed preservation of three-dimensional structures. In 2011, several Mesozoic feather assemblages, from both early birds and non-avian dinosaurs, were found in Late Cretaceous amber inclusions from Grassy Lake, Alberta (McKellar et al., 2011). Five years later, the discovery of a 99 million-year-old dinosaur tail encased in amber at an amber market in Myanmar became the most reported fossil discovery of 2016 (Benton, 2019). Under a microscope, the tail bones, plumage, and even remnants of muscles and skin of a juvenile coelurosaurian theropod can be seen in extreme detail (Xing et al., 2016). This inclusion even contains ancient ticks that would have lived on these dinosaurs (Peñalver et al., 2017).

Indirect fossil evidence, such as anatomical and behavioural clues, has also suggested the presence of feathers in many species – quill knobs (anchor points for feathers) have been identified in velociraptors (Turner, Makovicky and Norell, 2007), and oviraptorosaurs may have exhibited nesting behaviour (Norell and Xu, 2005). Evidence in non-theropods, such as the recent discovery of feather-like pycnofibers in pterosaurs (Yang et al., 2019) suggests that feathers may have even evolved in early archosaurs.

Evolution Revolution

Much remains unknown about the evolutionary origin of feathers, but it has been proposed that they evolved from structures like hollow dorsal spines, essentially just modified scales (Prum and Brush, 2002). They would have begun as simple, flexible filaments similar to the protofeathers of *Sinosauropteryx*, before becoming more branched, and eventually evolving into the complex, asymmetrical flight feathers of *Archaeopteryx* (Switek, 2011). As the presence of true feathers in non-avian dinosaurs incapable of flight disproves the previously accepted theory that the origin of feathers was fundamentally linked to the origin of flight (Norell and Xu, 2005), the question of not just *how* these feathers originally evolved, but *why*, is hotly debated.

One theory is the visual display hypothesis: the idea that early feathers were coloured and increased reproductive success (Dimond, Cabin and Brooks, 2011). Discoveries of coloured (Zhang et al., 2010) and even iridescent (Li et al., 2012) plumage in various dinosaur species certainly supports this idea. Much of the research on feather colour is based on the analysis of melanosomes (tiny hollows in hairs or feathers that contain melanin and give them their colour) in fossils such as the Jehol Group (Benton, 2019). Since both mammals and modern birds share the same melanosome structure – spherical 'phaeomelanosomes' produce a ginger colour, while sausage-shaped 'eumelanosomes' produce black, brown, and grey – this can be assumed to be true for dinosaurs as well, based on extant phylogenetic bracketing (Benton, 2019). The shapes of these structures are observed using scanning electron microscopy and have led to discoveries such as a ginger-and-white striped tail in *Sinosauropteryx* (Benton, 2019). The feathers preserved in amber are too rare to break apart to study their melanosomes, but paleontologists are working on ways to use non-destructive X-ray imaging as an alternative (Switek, 2011). Patterns and colours like the ones seen in *Sinosauropteryx*, it has been argued, would have no camouflage benefits, and the costliness of evolving and maintaining these structures could only be explained by sexual selection (Knell and Sampson, 2011). The main argument against this theory is that there is little sexual dimorphism (a common result of sexual selection) seen in dinosaur fossils – although it has also been argued that this difference in sexes may be in feather colour rather than a noticeable structural skeletal difference, similar to modern birds like peacocks (Benton, 2019).

Other theories associate feather evolution with thermoregulation and insulation (Bock, 2000). The discovery of feather filaments in small Early Cretaceous basal tyrannosauroids, while none have been found in larger derived tyrannosauroids, could reflect a physiological strategy of losing filaments during maturity, when their large size is enough to aid in thermoregulation – in a similar manner to some of today's pachyderms (Xu et al., 2004). Still, others have proposed that early feathers evolved for metabolic benefits, serving as a sink for the sulphur waste produced by protein metabolism and preventing excess hydrogen sulphide production (Bock, 2000).

Overall, the strides made in our understanding of dinosaurs in recent years have been dinosaurian in size. New discoveries, along with technologies such as CT scanning, electron microscopy, and engineering and software techniques have given unprecedented insight into the lives of dinosaurs.

Roaring into the Future

Dinosaurs and their representations in paleoart have fascinated both the scientific community and the general public for centuries, and thanks to modern technology and incredible new discoveries we know more about them than ever before. This may be a mixed blessing for paleoart, though – with less room for imagination and artistic interpretation, recent paleoart has lost part of the romance of earlier works. However, the ancient world will always be up for some interpretation, and works of paleoart, past and future, will certainly continue to not only inspire and delight audiences, but also move us deeply with their "profound engagement with time." (Lescaze, Ford and Taschen, 2017, p.269).

Defining the Fossil

A Glimpse into the Past

The history of how modern palaeontology came to be is no simple tale. It is one with many twists and turns, including challenges of preconceptions and recurring cases of self-contradictory claims. Revisiting the birth, growth, and consequences of palaeontology throughout history is a way to remind oneself that science is continuously assembled by human beings that are imperfect, but they strive for a greater understanding of the world as it is, as it once was, and how it will inevitably change.

Figure 1. A line engraving of Aristotle, a philosopher whose prominence in the fourth century had a massive impact on the interpretations made by early *palaeontologists between the 16th and 18th centuries.*

It is difficult to say who was the first person to recognize a fossil; especially since the term "fossil" would not have been established in the context that it is used today. The earliest record of fossil recognition was in ancient Greece during the fourth century B.C. (Mukherjee and Ramaswamy, 1966). Aristotle was a philosopher that examined the world through the lens of a historian. He believed that knowledge passed down between generations was essential for the elucidation of the earth in its past form (Huxley, 1973). In other words, science is a process that relies on revisiting past studies. Aristotle recognized the significance of fossils but was unable to convince the public of the nature of the geological features (Fenton, 1933). The overwhelming cultural beliefs of the Greeks at the time tended towards the thought that a mysterious force of nature, in its various failed attempts to create life, left behind remains that were petrified in stone, never to truly exist as living beings. Due to the rejection of Aristotle's ideas, this idea of being able to determine the 'history of life' within stone laid dormant for centuries to come.

Aristotle was not the only person in ancient Greece to study fossils. Xenophanes of Colophon investigated the origins of Earth through observations of Earth's surface rock and fossils (Bicknell, 1967). Xenophanes' work in the 6th century was based on his belief that the land which he stood on was the product of the seas, or in other words, water was the substance that was transformed into earth (Fenton, 1933). This preconception is arguably what drove Xenophanes to investigate the nature of fossils. He recognized fossils as an avenue to discovering the history of previous lifeforms and interpreted the presence of marine fossils on land as evidence for the suggestion that land originated from water.

The views of Greek philosophers such as Aristotle and Plato had a huge influence on the interpretations of fossils between the 16th and 18th centuries (Simpson, 1983). One of the most famous interpretations of fossils that originated in ancient Greece, but still persisted in this time frame is the idea that some force known as *vis plastica* moulded the fossils, and that they were never alive (Simpson, 1983). These were considered Platonist ideas. Strong supporters of the theories of Aristotle argued that fossils never lived but were the result of seeds growing within the rock or were spontaneously formed underneath Earth's surface. This idea resembled the Aristotelian theories of life having a lithic origin. The ideologies of the ancient Greeks were not the only contributors to 'common knowledge' during this era, as Biblical literalists had their own unique interpretation of fossils (Simpson, 1983). They recognized the resemblance of fossils to extant organisms and thought them to be living organisms buried by the Noachian deluge, the catastrophic flood evaded by the survivors in Noah's Ark as described in the Old Testament of the Bible. This frame of thought was known as Diluvialism (Bowler, 1976). The Biblical interpretation had one implication that was a key distinction from Platonist or Aristotelian perspectives – that the organisms were once alive, as implied by the burial of these organisms by the great flood (Simpson, 1983). Diluvialism was of particular interest within the Arabic speaking nations, as it was there that people extrapolated that fossils were the remains of those that did not survive the Noachian flood due to their inherent sinfulness (Fenton, 1933). It is important to note that Diluvialism does not account for extinct species, as the Bible describes the conservation of pairs of each animal on Noah's Ark (Bowler, 1976). This would be a topic of intense debate many centuries later.

It was in 1565 when the more traditionally acknowledged "birth" of palaeontology took place (Solounias and Mayor, 2004), as this was when Konrad von Gesner first began collecting fossils that he encountered. He established himself as a palaeontologist in 1558, when he recognized the similarities between a common extant crab, and a "petrified crab" that he discovered (Simpson, 1983). It should be noted that von Gesner never made note of organisms that contrasted from the organisms that were extant in his time, nor did he ever indicate any notion of the fossil being a formerly living creature (Simpson, 1983). It could be inferred that the Platonist interpretation of fossils played a role in von Gesner's analyses.

It was not until the 17th and 18th centuries when scientists were able to establish these theories. Though Robert Hooke was an English scientist that is known widely for his contributions in mechanics (Hunter and Schaffer, 1989), it was Hooke that first theorized about the extinction of species, and the notion that fossils mark the ages of deposition and environmental conditions surrounding them (Fenton, 1933). The most important contribution of Hooke was arguably the most fundamental one, in which Hooke stated that fossils that appeared to be animals originated from animals themselves (Simpson, 1983). This perception was radically different than that of the early Platonists and Aristotelians; however, it was accepted in England, given that the belief of the Noachian deluge was not challenged by the introduction of this concept. However, Hooke also found that the biblical timeline was not long enough to account for all of the geological features observed in his time. This would not have been accepted by the general public, so Hooke was cognizant in regard to how he described geologic time, so that he would not exceed the Biblical timeline (Jackson and London, 2007).

Hooke understood that sediments lithified into rock layers that often had fossils within. One geologist that shared this is Nicholas Steno, who proposed that concept in 1667. These rules that describe the layering of rocks are described as the Laws of Superposition and the Principle of Original Horizontality (Jackson and London, 2007). It was Steno who first suggested that fossils originated from organic substances (Simpson, 1983). This was the result of his comparisons between fossilized and living animals (Fenton, 1933). He asserted that fossils originated from the Noachian Flood, which contrasted Hooke's belief that geologic time was much longer than Biblical history (Jackson and London, 2007).

In 1753, Ambrosio Soldani made a clear distinction between fossils originating from the deep sea, and those that were from regions along more shallow shorelines (Fenton, 1933). It is difficult to say whether these distinctions were based on the sedimentary structures in which the fossils were embedded, or if they were based on the appearances of the fossils themselves. However, this idea was supplemented by the work of a French evolutionist by the name of Georges-Louis Leclerc, Comte de Buffon, who claimed that sea levels often rise and fall (Fenton, 1933). Together, these ideas set the stage for future geologists to consider why there might have been a change from marine to land fossil types across different strata, as a local change in sea level would result in different organism types observed in adjacent strata. Buffon's investigations of natural history were influential for the next generation of naturalists, most evidently towards the end of the 18th century (Fenton, 1933). An evolutionist by the name of Jean-Baptiste Lamarck developed systematic methods for palaeontological studies in the context of invertebrates. This was accomplished through his investigations of marine fossils of the Paris basin (Fenton, 1933). It was at this time that a rivalry was brewing, as Georges Cuvier began to develop similar theories for the study of vertebrate fossils. Cuvier observed that some fossils had no similarities to any living organisms of his time, and so he constructed what is known as the Cuvierian Hypotheses to address this mystery (Simpson, 1983). First, Cuvier proposed that those organisms may have been from unexplored regions. Next, he stated that they may have metamorphosed into the living organisms observed in nature. Lastly, he hypothesized that extinction may have occurred. Cuvier never made observations that demonstrated evolution, so he maintained his extinction hypothesis, and framed it in the form of catastrophism – the theory that epochs of life are punctuated by catastrophic events that kill all present organisms, and that continents were repopulated from undiscovered regions, or by acts of divine creation (Fenton, 1933).

Figure 2. An oil and canvas painting by Edward Hicks depicting the pairs of animals chosen to be saved from the Noachian Deluge, as described in the Old Testament of the Bible. This story was paramount in many interpretations of fossils between the 16th and 18th centuries (Simpson, 1983).

Development of palaeontology in the 19th century could be characterized by a radiation of the study that was catalyzed by initiation of the work of William Smith, who began to distinguish Mesozoic rocks of England by their fossil types in 1801 (Fenton, 1933). Equipped with this knowledge, Smith created the first geological map of England (Winchester, 2001), and his methodologies were applied across Europe soon after (Fenton, 1933). Across Europe during the 1810s, William Smith, Giovanni Brocchi and Alexandre Brogniart demonstrated that fossil types arranged themselves in sequences (Simpson, 1983). Following this, subsequent fossil collections and reports regarding fossils were established by many individuals across the globe. But it was not until 1838 when Charles Lyell coined the term "Palaeontology", which means "science of ancient life" as derived from Greek roots.

Palaeontology co-developed with evolutionary biology, as exemplified in the discoveries of Heinrich Georg Bronn. Bronn demonstrated that some species could survive from one epoch to the next, which put an end to catastrophism as a major theory for fossil origin (Fenton, 1933). However, it was in 1857 that Bronn asserted that biological species do not evolve (Junker, 1991). This idea of biological constancy was contrasted by Charles Darwin's publication of *The Origin of Species*, which was a text that ultimately addressed debates pertaining to the Cuvierian hypotheses (Simpson, 1983). Darwin wrote of natural selection, and the concept of evolutionary change, both of which support the Cuvierian hypotheses, but not catastrophism. Interestingly, Bronn was a translator of Darwin's *The Origin of Species*. Despite his preconceptions and religious upbringing, Bronn felt that it was necessary to share Darwin's theories. Bronn added a post-scriptum that critiqued the text in accordance with his belief of biological constancy (Junker, 1991). Bronn was anything but typical in his time. Unlike what most religious scientists would have done in the 1800s, Bronn kept an open mind, not rejecting Darwin's ideas or trying to prevent the spread of his work. Instead, he shared Darwin's work and promoted discourse on the subject.

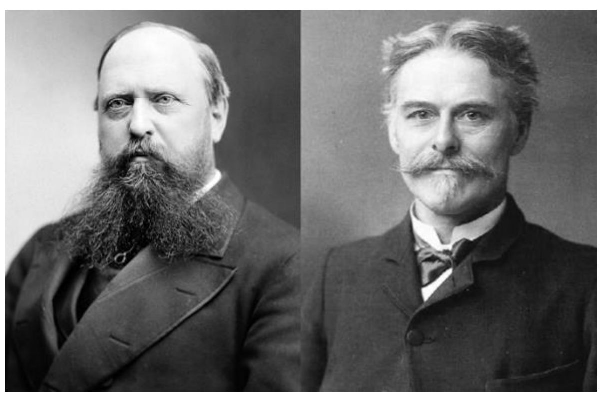


Figure 3. Othniel Charles Marsh is on the left, and Edward Drinker Cope is on the right. These are two prominent palaeontologists of the 19th century who were friends turned bitter rivals in an infamous feud known as the bone wars.

By the mid-1800s, many new fossils have been discovered. One of the most prominent discoveries was in 1847, when Joseph Leidy established the first account of fossilized American horses (Fenton, 1933). He began to describe the vertebrate fossils that were collected in government expeditions, but this work was ultimately inherited by Othniel Charles Marsh and Edward Drinker Cope, two scientists that would be the participants in one of the greatest conflicts in the history palaeontology as of yet.

The Bone Wars

While paleontology is a beautiful science, it has inspired some less-than-beautiful actions. An excellent example of this is what is now known as the "Bone Wars". Also called the "Great Dinosaur Rush", the bone wars was a 15 year period of intense and merciless competition between the two preeminent American Paleontologists Othniel Charles Marsh and Edward Drinker Cope.

Othniel Charles Marsh (1831-1899) grew up poor. His father was a farmer while his mother died when he was only two. Despite this however, due to the generosity of his uncle George Peabody, he was able to study at Yale College, completing a BA in 1860 and MA in 1863, both in geology. Following this, he moved to Europe to study paleontology, and upon his return in 1866, he was appointed professor of vertebrate paleontology at Yale, making him the first paleontology professor in the United States. To further establish his reputation, March worked with George Peabody to establish the Peabody Museum of Natural History, then becoming one of its curators and trustees (Schuchert, 1938).

On the other hand, Edward Drinker Cope (1840-1897) came from a very wealthy family, and while his mother also died when he was young, he and Marsh had few similarities. From a young age, Cope excelled in school, however, due to his wealth, he never completed a formal post-secondary degree. While Cope was an avid writer, publishing his first paper at the age of 19, his only education occurred at the University of Pennsylvania, which he attended for under two years, leaving early in 1863 to travel in Europe (Davidson, 1997).

It was in Europe that Cope, and Marsh first became acquainted. They met in Berlin while Marsh was studying at the University of Berlin, and while Marsh had two university degrees and Cope had zero, Cope had already published 37 papers to Marsh's two. Upon meeting, the two were quite jovial. Upon Cope's arrival, Marsh took him on a tour of the city, and the two stayed together for multiple days. In fact, after splitting they remained in contact, even exchanging photographs, fossils and manuscripts (Johnson, 2013). On top of this, they even named species after each other, Cope naming the Colosteus marshii for Marsh in 1867, and Marsh reciprocating with the Mosasaurus copeanus in 1969 (Dodson, 2011).

Their relationship went downhill from here, however. The first issue between the two was their difference of personalities. Cope was aggressive and extroverted, while Marsh was methodical and introverted (Osborn, 1930). Additionally, while Cope was a staunch proponent of Neo-Lamarckism, Marsh believed in Darwin's Theory of Natural Selection. This as well as personal egos led to great animosity between the two giants of paleontology, thus kickstarting a race to outshine and undermine the scientific discoveries of each other (Bowler, 1977).

The pair last worked together in 1868 when Cope invited Marsh to his marl (a carbonate sedimentary rock) pits. These pits were a wonder for both paleontologists, as they were incredibly fossil rich. Following their expedition however, Marsh bribed workers at the pit to send fossils found there to him instead of Cope. From here, their relationship exploded. They began attacking each other with their publications, making fun of each other's discoveries, ridiculing their mistakes, and hunting fossils on each other's turf (Johnson, 2013).

From here the two moved out West, where their feud continued. The two followed rumours of a wealth of fossils, and from the late 1870s through the early 1880s, the two worked tirelessly to discover new species and outdo each other, even paying large sums of money to those who could find fossils for them. The two employed militia-like groups of workers who were willing to assist in their efforts. The groups pillaged the West, digging up any fossils they could find, and destroying those they couldn't bring with them, or refilling their pits to prevent the other group from finding them. Both Marsh and Cope employed underhanded tactics, spying on the other's group, bribing rival workers to join their team, and sending in workers to steal fossils found by the other (Romer, 1964).

This continued for years, and even following their return to the East, the two continued to belittle and contradict each other. Their relationship never recovered, and while it isn't easy to declare a victor in the bone wars, Marsh discovered 80 new species while Cope discovered 56 (Colbert, 1984). However, both spent immense amounts of money and many years of their life pursuing this conflict, and in the end, the true winner was the general public, for all the knowledge they received.

Figure 4. Image taken at the Bone-Cabin Quarry, an important bone quarry which was excavated at during the bone wars.

As one could see, many of the conflicts in Early Palaeontology were related to public beliefs and philosophies. However, as the field further developed, disagreements became more materialistic. It was no longer a question of how life came to be, but a question of who is to gain the credit for discovering proof of Earth's history. The bone wars exemplified what happens when professionals grapple with deciding what is most important in life. In the case of Cope and Marsh, their friendship succumbed to the bone wars. However, not all scientists of the past have fallen into this trap. Bronn was an excellent role model for modern scientists, because of his acknowledgement and respect for Darwin's work, despite his belief in biologic constancy clashing with Darwin's theory of natural selection. Bronn shared Darwin's work, critiqued it, but never adulterated it or made any attempt at censoring Darwin's work. This is how modern science should be, as this facilitates discussion and debate in an orderly fashion. If scientists treat each other's research as Bronn treated Darwin's work, the frontier studies of tomorrow will go a lot more smoothly.

Modern Paleontology

Since its dawn in Ancient Greek philosophy, paleontology has evolved greatly. From a science of thought, to a science of exploration, to a science of technology, everything from the paleontologists to the equipment they use has changed drastically. In modern days, paleontology, much like science overall, is no longer a pass-time of the wealthy upper class. It is taught widely at universities in Canada, the United States, and across the world, and there are now hundreds of professional paleontologists uncovering the mystery that is ancient life.

Paleontology in the 21st Century

In fact, despite what one might think, more species of dinosaur are being discovered now than ever before. At a rate of one approximately one species per week, paleontologists are unearthing new pieces to the dinosaur puzzle (Brusatte, 2018). One person leading the way in this golden age of paleontology is Steve Brusatte. Despite being only 35, Dr. Brusatte has completed four degrees in vertebrate paleontology, including a PhD from Columbia University, and he has held a Chancellor's Fellowship in vertebrate paleontology at the University of Edinburgh since 2013. In addition to this, he has discovered over a dozen new fossils and has written many books (University of Edinburgh, 2018). One of these texts is a 2018 New York Times bestseller, "The Rise and Fall of the Dinosaurs: A New History of a Lost World". Brusatte has also starred in many documentaries, doing an excellent job of spreading the wonders of paleontology to the masses (Brusatte, 2018).

Figure 5. Steve Brusatte conducting fieldwork on the Isle of Skye in Scotland

While Brusatte may be more of the traditional field paleontologist, many of his colleagues are quite the opposite. Take Stephen Gatesy for example, a leading researcher at Brown University. Dr. Gatesy uses advanced computer software and x-ray technology to study the kinetics of movement in the clade Archosauria (Brown University, 2017). This stunning work is something that neither Charles Marsh nor Aristotle could have ever imagined. With this advanced technology, Gatesy has been able to delve into how bipedal motion changed throughout the 200 million year reign of theropods, and how these theropods developed flight. It is an incredibly complex and interdisciplinary process, which uses some innovative techniques, including XROMM, a software which was co-developed by Gatesy in 2006 (Brown University, 2017).

XROMM, or X-Ray Reconstruction of Moving Morphology, is a three-dimensional imaging software that is used to model in vivo skeletal movement of animals. While it is not exclusively for the study of dinosaurs, it is an incredibly useful tool for paleontologists, as they have no live specimens to study. XROMM works by first taking images of live animals from multiple different angles using CT imaging, laser scanning, or MRI machines (Hoogendyk, 2011). These images are then combined into one cohesive three-dimensional XROMM animation. From here, musculature and connective tissues can be added, and while these are rarely preserved in the dinosaur skeletons themselves, likely locations for these tissues can be inferred based on analogous species and assumed function. This gives scientists a complete view of how the dinosaurs would have moved, thus providing great insight into how they lived and interacted with other species (Hoogendyk, 2011).

One scientist using this cutting-edge technology, is Dr. John Hutchinson of the Royal Veterinary

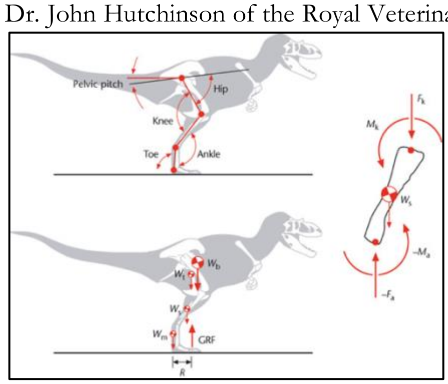


Figure 6. Image from "Tyrannosaurus was not a fast runner" showing the force profile of T. Rex movement.

College at the University of London. With a bachelor's degree in zoology, PhD. in integrative biology, and post-doctoral experience in biomechanical engineering, Hutchinson combines his plethora of experience in order to study the musculoskeletal structure and motion of both extinct and extant animals (Royal Veterinary College, 2020). Using XROMM, as well as other analytical techniques, such as force platforms (sensors which quantify the applied force to the ground below animals), motion analysis, and two and three-dimensional modeling, Hutchinson has answered many questions about the motion of many animals, from elephants to the *Tyrannosaurus rex* (Royal

Veterinary College, 2020). Even prior to the invention of XROMM, Dr. Hutchinson was doing incredible work in this field. In a pivotal 2002 paper titled "Tyrannosaurus was not a fast runner", which was published in the journal Nature, Hutchinson analyzed the joints and estimated muscle mass of the famous carnivore, coming to the conclusion that it was unlikely that the *T. Rex* was able to run, contrary to what is often depicted in the media (Hutchinson and Garcia, 2002). His work does not stop there however, as he has since completed countless studies on numerous species, incorporating new methods and technology into his research (Royal Veterinary College, 2020).

Conflict in Modern Paleontology

While one might think that new technology has erased ideological conflicts within paleontology, this is certainly not the case. In fact, there is an even greater divide in the field of paleontology than ever before thanks to the momentous rate of discovery seen today. An excellent example of this is something known as "The Nastiest Feud in Science". This feud originated in 1980, when Luis Alvarez posited the idea that the Late-Cretaceous extinction occurred due to a large meteor impact. He suggested that it caused a massive tsunami and great climatic change, thus wiping out an estimated 75 percent of life on Earth (Alverez et al., 1980). Evidence supporting his theory included the high prevalence of iridium in late-Cretaceous sediment. Iridium is a siderophile, meaning it is dense and tends to sink to Earth's core. Despite this however, levels of iridium well above what is usually seen in Earth's crust are found in these sediments. Coincidentally, these high levels of iridium are also seen in chondritic meteorites, suggesting that it was an impact of this type of meteor that provided the iridium that has now been observed (Alverez et al., 1980). Additionally, there is the Chicxulub crater, which despite being discovered many years later, provides great support to Alverez's theory, as it is the perfect to have caused this extinction. The Alvarez hypothesis was supported by impact deposits, as well as an impact site (Hildebrand et al., 1991). These pieces of evidence have convinced the majority of scientists, however, there are those who oppose it. Gerta Keller is one of those people. She suggests that this extinction occurred due to volcanism in the Deccan Plateau of India, and based on her evidence of cores from the Chicxulub crater, she deemed that the asteroid must have hit 200,000 years prior to the mass extinction, making it far too old to be the main cause (Schoene et al., 2015). However, coming to this consensus was not an easy path for her or others who opposed the Alvarez hypothesis. Many scientists were slandered by Alvarez, both publicly and in the world of academia, with Alvarez quickly shutting down any conversation or publication which went against his belief. Even after the death of Luis Alvarez in 1998, his son and other scientists continued to defend his ideas, in what is known as the "Dinosaur Wars". In fact, similar to the aforementioned bone wars, those on the side of Alvarez had purportedly resorted to the hiding and stealing of evidence, such as in 2002 when Jan Smit allegedly hid samples in his duffle bag to keep them away from Keller (Bosker, 2018). In the end, while paleontology may have changed in modern times, the human ego never will.

Figure 7. Image of the Deccan Traps in India, a large igneous provinces believed by some to be associated with the Late-Cretaceous extinction.

Not all conflicts are quite so grand, however. For the most part, they are cordial, academic arguments in which each side states its opinion and the evidence it has, without belittling those who purvey a different opinion. Most paleontologists tend to be professional and kind, simply using the evidence that they have to point out mistakes that others before them had made, such as in 2015 when a team of paleontologists reclassified the dinosaur Brontosaurus (Tschopp et al., 2015). Upon discovery of the Brontosaurus in the late 1800s, Charles Marsh believed it to be an entirely new genus and species. However, in 1903, Elmer Riggs reclassified it, believing it was not different enough to be a genus separate from *Apatosaurus.* It remained this way until 2015 when it was again reclassified, being given its own genus and being split into three different species (Tschopp et al., 2015). It is conflicts like these that are the vast majority of what we see in modern times.

All in all, while paleontology is a beautiful science with thousands of years of beautiful history, one cannot doubt that it has also had its sore spots. From destruction of property to slander, bitter rivalry and harsh conflict have always been a part of paleontology, and while they have, at times, halted progress, they have also pushed those in this field to work even harder, adding more tiles to this beautiful mosaic, and demonstrating that science really is a process. Paleontology has changed drastically over time, incorporating new ideas, new people and new technologies. But in the end, the goal has always been the same, to unravel the mystery that is prehistoric life, giving humans an enticing and intriguing look into Earth's magnificent past.

The Search for the Missing Link

The Piltdown Man

On December 18, 1912, Charles Dawson and Sir Arthur Smith Woodward announced their discovery of what appeared to be pieces from a hominin cranium and jaw from the Piltdown Common Region in Sussex (Lydekker, 1913) (Figure 3.17). In front of members of the Geological Society of London, Dawson and Woodward made a bold claim: this hominin represented a transitional species between man and ape (Keith, 1915). Darwin's theory of natural evolution had been published in 1858, and with it came significant efforts to uncover the supposed intermediate in the evolution between apes and humans (Kjærgaard, 2011). As a result, the Piltdown remains were hailed as the 'missing link' in evolutionary history (Goulden, 2009).

Woodward and Dawson supported their claim by pointing out that the cranium appeared to be very human-like, whereas the mandible was very similar to that possessed by apes, with the exception of two unique molar teeth (Straus, 1954). With the help of Professor Grafton Elliott Smith, they reconstructed the skull using these bones and the resulting structure suggested a transitional species in the human lineage. They declared it as a new species under a new genus: *Eoanthropus dawsoni*. *Eoanthropus* translates to 'Dawn man', thus named to signify its place in hominin history as the 'dawning' of modern humans. Approximately a year later, distinguished archaeologist Pierre Teilhard de Chardin discovered an ape-like canine tooth at the same site as the other remains that complemented Woodward's initial skull reconstruction. These remains were reconstructed to form an individual called Piltdown I, more popularly known as the Piltdown Man.

Figure 3.17. A drawing from 1915 that depicts key figures involved in the Piltdown Man discovery, including Charles Dawson, Arthur Smith Woodward, Arthur Keith, and Grafton Elliott Smith.

This discovery sparked exceptional interest in the British population, particularly because of the recent breakthroughs made by rival countries. In 1907, a *Homo heidelbergensis* mandible was discovered near the city of Heidelberg, Germany (Wagner et al., 2010). This was closely followed by the unearthing of a Neanderthal skull in France in 1908 (León and Zollikofer, 1999). Britain, on the other hand, did not have any discoveries of this prestige, which stirred a lot of discontent within the country (Tobias et al., 1992). With the discovery of the Piltdown Man, Britain was able to stake their claim in the study of human origins. Piltdown Man was readily welcomed as "the earliest Englishman" and quickly grew in fame (Woodward, 1948).

Sir Arthur Keith was a prominent figure in the field of human origins at this time. While he believed that *E. dawsoni* represented "the earliest specimen of true humanity yet discovered," after interpreting the remains, he had his own ideas about the reconstruction of Piltdown Man (Keith, 1915; Keith, 1913). Woodward and Dawson claimed that the Piltdown Man dated to the Lower Pleistocene epoch (2.58 mya - 773,000 ya). Sir Arthur Keith, on the other hand, believed that the Piltdown Man was much older, dating to the Pliocene epoch (5.33 - 2.58mya). Keith's proposed date would place the evolution of apes into modern humans much earlier than what Woodward and Dawson indicated. Additionally, while Woodward reconstructed the skull to such that it had a brain capacity of 1070cm^{-3}, halfway between that of modern apes and humans and thus existed outside of the genus Homo, Keith disagreed; he stated that Piltdown Man had a brain capacity of 1400cm^{-3}, the average amongst modern humans (Keith, 1915). Keith gave the specimen the name *Homo piltsdownensis* to reflect its modern characteristics (Goulden, 2009). Due to the ancient age attributed to Piltdown Man and the location of the find, it suggests that it was an early hominin who inhabited a nearby area to where our species originated, supporting the dominant idea of the time that humans originated in Eurasia.

Some scientists entirely disagreed with the initial assessment on the nature of the bone remnants and argued that the cranium belonged to a modern human while the jaw and mandible originated from an ape (Miller Junior, 1918). A year after the discovery, David Waterston, an anatomy professor at the University of London, showed that the mandible looked ape-like in appearance while the skull looked essentially human, and thus did not belong to the same individual (Waterston, 1913). Overseas, at the U.S. National Museum of Natural History, a zoologist named G.S. Miller was one of the strongest opponents of the Piltdown discovery, initially publishing a paper in 1915 supporting Waterston's claim (Smithsonian Institution, 1862). He claimed that it was more likely that this finding represented two species from separate genera that fell into this pit than a distinct intermediary species. Additionally, he noted in the beginning of his paper that 'deliberate malice could hardly have been more successful than the hazards of deposition in so breaking the fossils as to give free scope to individual judgement in fitting the parts together' (Smithsonian Institution, 1862). This highlights the way the fossils were broken at the site, allowing for a high degree of interpretation.

In 1915, Dawson informed Woodward of two pieces of a second human skull and a molar tooth that he claimed to have found around two miles away from the site that had contained the first Piltdown remains (Oakley, 1976). These remains resembled those of Piltdown I, and Dawson claimed that it represented a second individual from *Eoanthropus dawsoni*. However, he died from sepsis the following year, and Woodward presented the results individually in 1917, identifying the specimen as Piltdown II (Tobias et al., 1992).

The Piltdown II finding quelled much of the controversy surrounding the Piltdown Man and contributed to its acceptance by the scientific community, particularly within Britain (Osborn, 1922). The human-like cranium also complemented current evolutionary thoughts of the time that the development of the brain led the evolution of apes into humans (Smith, 1913). In the years following the discovery of Piltdown II, many of the supporters of the Piltdown discovery became leaders in the study of human evolution, contributing to the most significant discoveries of the time.

In 1921, Woodward became involved in the analysis of the Kabwe Skull, the first hominin discovery in Africa (The Rhodesian Skull, 1921). Woodward, working with Keith and Elliott Smith, theorized that it was from a new species that he named *Homo rhodesiensis* (Hrdlička, 1921). It was proposed to be a relatively modern but primitive hominin. Some of its defining features were compared by Elliott Smith to people of African and Aboriginal ancestry, but not those of Eurasian ancestry, highlighting racial beliefs of the time (Smith, 1922). Their interpretation of the find also supported the idea that the ancestors of modern humans originated in Eurasia and eventually migrated to Africa, which complements the Piltdown discovery. This discovery, as well as the mistaken analysis by Elliott Smith of an ancient pig tooth found in Nebraska that was believed to be from a hominin, led to a discussion in the media on the objectivity of hominin discoveries. An article in *The Times* from London commented that "the zeal for the discovery of ancestors, which is so often observed in the newly ennobled, has been carried to its highest pitch by the newcomer to the aristocracy of science, the anthropologist" (Hesperopithecus, 1928).

The Taung Child

Around seven years after the Piltdown discovery, Raymond Dart, an anatomy professor in his second year of teaching at the medical school in Johannesburg, South Africa, found something miraculous. In a crate full of fossilized remains from the nearby Taungs mine, he found a remarkably preserved skull that resembled an anthropoid ape (a classification of primates closely related to humans). However, due to his background in neurology, Dart immediately recognized that it was not an ordinary anthropoid skull. He hunted through the crate in search of a face, and located a stone into which the skull fit perfectly (Dart, 1959).

Dart published his analysis of the skull on February 7, 1925 (Dart, 1925). He announced that the find "was of importance because it exhibits an extinct race of apes intermediate between living anthropoids and man." In other words, Dart was describing his find as the missing link. Since only the first molar tooth had erupted on both sides of the jaw, he concluded that the specimen was juvenile, anatomically corresponding to a six-year-old human child. He further observed that the parabolic teeth arrangement and small size of the canines present in this fossil resembled humans rather than primates (Dart, 1925, 1959). He noted the absence of pronounced eyebrow ridges (a common anthropoid feature) and the presence of a steeply rising forehead (a human-like feature) in the cranium (Dart, 1925). Importantly, Dart also indicated a roundness in the brain and a high, narrow skull that greatly differed from living anthropoids (Dart, 1959, 1925). The brain capacity, when extrapolated to an adult creature, was expected to be nearly equal to a gorilla. Using these observations, he concluded that while the facial and cerebral characters were human in nature, a fossil with an anthropoid brain capacity could not be called a true human. He stated that the fossil represented a "man-like ape" and proposed a new species for this fossil: *Austrolopithecus africanus*. This fossil later became known as the "Taung Child" (Figure 3.18).

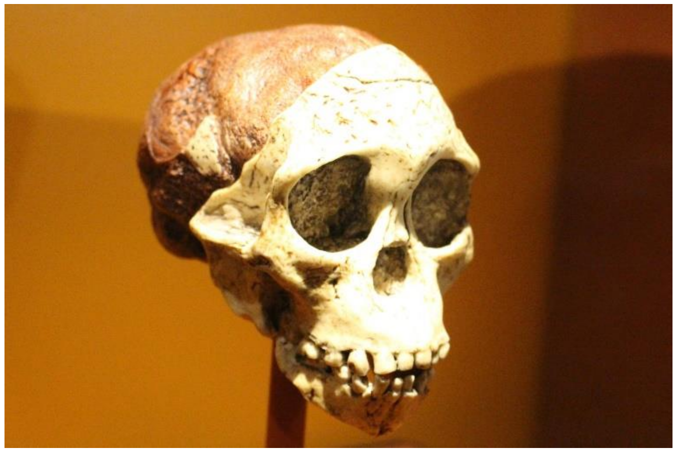


Figure 3.18. An image of the Taung Child, with the skull and face clearly depicted.

Criticism of the Taung Child

A week after Dart published his findings, a review was released by Arthur Keith, Grafton Elliot Smith, Arthur Smith Woodward, and Wynfrid Duckworth (Keith et al., 1925). Most of the researchers expressed their beliefs that the observed human-like characteristics could simply be attributed to the infantile nature of the specimen. Woodward was the most critical, dismissing the Taung Child from the study of the ancestral location of human origin altogether. All four researchers stressed the need for more evidence, particularly with regards to geological evidence and specific teeth morphology. It was evident that the discovery of the Taung Child was met with skepticism from many members of the scientific community. Interestingly, three of these same researchers readily accepted the Piltdown Man a decade earlier.

Over the next couple of months, the criticism of Taung Child became more fervent. Keith went on to call Dart's claim that the Taung Child represented the missing link "preposterous," stating that the Taung skull was simply that of a young ape (Keith, 1925). Smith closely followed with another scathing critique in a public lecture: "the [characteristics] upon which [Dart] relied for proof of his contention that Australopithecus was nearly akin to man, were essentially identical with the conditions met in the infant gorilla and chimpanzee" (Smith, 1925b). According to Smith, if Dart had had access to the resources available in London, he would have seen the 'obvious' similarities to young apes (Smith, 1925a). Keith continued to express his view that Taung Child was simply a young ape, and therefore did not have significance in human ancestry, in his 1931 book titled *New Discoveries Relating to the Antiquity of Man* (Keith, 1931). In this same book, he continued to accept the role of Piltdown Man in human lineage and proposed that in light of new discoveries, *E. dawsoni* could be considered the direct ancestor of modern humans. Less than a decade after its discovery, *A. africanus* had largely been disregarded from human lineage, while Piltdown Man remained widely accepted.

One researcher, however, had been quietly working to prove that Dart's claims about Australopithecus were correct. Robert Broom immediately supported Dart after his original publication, saying that Taung Child showed both human-like and ape-like characteristics, and proposed that it could be placed in the human lineage before *E. dawsoni* (Broom, 1929, 1925). As Dart began to recede from the study of human evolution, focusing on his career within the medical school, Broom undertook the task of upholding the place of *A. africanus* in human lineage. From 1936-1938, he unearthed two australopithecine fossil types in Africa, *Plesianthropus transvaalensis* and *Paranthropus robustus* (Broom, 1938, 1936).

Broom's findings won over the support of many people, including esteemed researcher William Gregory, who openly praised Broom and Dart for their work in the field (Dart, 1959; Gregory and Hellman, 1939). An important turning point in the perception of Australopithecus occurred when Wilfrid Le Gros Clark began to support the australopithecines after inspecting the fossils in Africa in 1946 (Richmond, 2012; Dart, 1973). After the 1946 publication of a monograph on the australopithecine discoveries, Clark stated his support in a review with the words "Australopithecines are extremely important for the study of human evolution, since they present an astounding assemblage of simian and human characters [...] it should be said that Dart's original interpretation of the Australopithecus material has in several respects been completely vindicated" (Le Gros Clark, 1946). Due to his prestige, his words quickly garnered support for the australopithecine fossils. Soon after this, Keith published a letter stating that he had been mistaken about Dart's discovery (Keith, 1947). Austrolopithecus had finally begun to receive recognition, more than twenty years after its discovery.

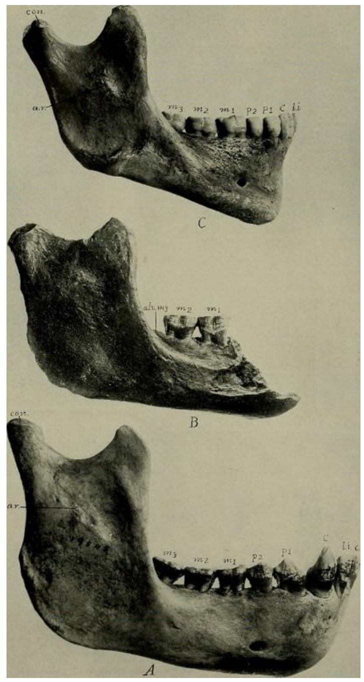


Figure 3.19. Depicted in the middle is the jaw of the Piltdown Man. The jaw on top is of an ape and the jaw on the bottom is of a modern human. The Piltdown Jaw is actually the jaw of an ape that has had its teeth artificially filed down to look more human-like.

Piltdown: a Hoax?

While australopithecines began to become accepted, the age and the place of Piltdown Man within the hominin lineage became more unclear and controversial (Washburn, 1953). Discoveries from the 1930s and 40s, including the australopithecines, had presented a completely different view of what Lower Pleistocene hominins looked like, leaving the Piltdown Man in a state of uncertainty (Oakley and Hoskins, 1950). For example, the Peking Man had recently been discovered in China, whose features contrasted the Piltdown's Man ape-like jaw and human-like cranium (Weiner, 2004).

Prior to the advent of the fluorine dating technique, methods of dating the Piltdown Man had largely been limited to analyzing the fossils of fauna found near the Piltdown site. This method was applied by Dr. Kenneth Oakley, from the British Museum of Natural History, and chemist Dr. Hoskins in 1950 and surprisingly revealed that the Piltdown Man was from, at oldest, the Middle Pleistocene (770,000 - 126,000ya) and was potentially from the Upper Pleistocene (126,000-11,700ya). This created a conundrum; the date suggested that the Piltdown Man lived at the same time as *Homo sapiens*. This also conflicted with Waterston and Miller's view that it comes from an ape and a human, since no ape fossils have been discovered from this time period (Oakley and Hoskins, 1950).

To solve this conundrum, Oakley, along with Le Gros Clark and Joseph Weiner, conducted a follow-up study. They found that the cranial bones were from an ancient hominin, but the jawbone and teeth were from a modern ape (Figure 3.19). They also discovered that the jawbone had been artificially coloured with iron to match the cranial bones. Observation of the teeth revealed that the teeth had been ground down evenly, suggesting it was caused by artificial filing rather than natural causes (Oakley and Weiner, 1955). They then moved to study Piltdown II and they found that it was made up of a piece from the skull in Piltdown Man and an artificially ground molar tooth from an orangutan. Piltdown Man was nothing more than an elaborate hoax.

Repercussions

With this startling discovery, it came to light that for more than forty years, the scientific community had been fooled by a skilled hoaxer. While the hoax would have been a source of embarrassment for the researchers heavily involved in studying the Piltdown remains, the repercussions on the study of human evolution were even more far-reaching.

The Piltdown Man had been a large barrier for the acceptance of the Taung Child when it was initially revealed. This is predominantly because while Piltdown Man complemented current evolutionary views, Taung Child did not. The consensus within the scientific community in the beginning of the 20th century was that the brain had evolved into a human-like form before all other features (Smith, 1931). The Piltdown Man's ape-like mandible and a human-like brain greatly supported this theory. The Taung Child, with an ape-like brain and human-like teeth, contradicted this belief. Since the Piltdown Man discovery was believed by many prominent researchers, *Australopithecus africanus* conflicted too much to be seen as the ancestor of modern humans (Leakey and Goodall, 1969). Furthermore, Keith had gained a lot of recognition from his support of the Piltdown Man; due to this, he may have felt an obligatory need to reject Taung Child (Tobias et al., 1992). His rejection of the Taung skull, due to his prominence in the field, significantly impacted the way it was perceived. As a result, the scientific community dismissed the Taung Child based on their preconceived notions on human evolution. The general acceptance of the Piltdown Man discovery therefore had major repercussions for the acceptance of the Taung Child, and significantly hindered progress in the study of human evolution for years.

Many of the societal biases that greatly influenced the criticism and consequent rejection of Taung Child were also responsible for the acceptance of the Piltdown Man as a significant finding in hominin evolution.

As mentioned previously, Piltdown Man fit pre-existing evolutionary beliefs that the brain was the first anatomical feature to evolve in the transition from apes to humans. In addition, England was searching for a discovery in human evolution to respond to the significant findings in France and Germany at the time. The 'discovery' of the Piltdown Man fulfilled this need and placed British scientists such as Woodward and Keith as leaders in the field of hominin evolution. The proposed age of the Piltdown Man also contributed to the belief that humans originated in Eurasia, which originated in part from racial beliefs that Europeans led the world in all aspects. These racial beliefs were also used to justify primitive features of Piltdown Man, which were compared to features of people of African and Aboriginal ancestry.

These historical events demonstrate that the search for the 'missing link' was riddled with bias, which led to the acceptance of a hoax and the rejection of a real discovery. This tale is therefore one of caution, as though scientific discoveries are regularly scrutinized, it is important to recognize when scrutiny borders on blatant criticism and when one's personal worldview can influence the analysis of a new finding.

Genetic Analysis: Studying Archaic and Modern Humans

Today, *Homo sapiens* is the only hominin species roaming the Earth. However, this is a relatively new phenomenon, since anatomically modern humans (AMH) coexisted with other hominin species as recently as 30 000 years ago (Vattathil and Akey, 2015). Though the specific dispersion model of humans throughout the world is a topic of much debate, it is generally believed that AMH emerged from Africa and spread throughout the world (Garcea, 2012). As they expanded throughout Africa and Eurasia, AMH would have frequently encountered archaic human groups, such as Neanderthals, throughout many parts of the world (Stewart and Stringer, 2012). Due to the spatial and temporal overlap of hominin groups, there would have been opportunities for hybridization; however, this was initially heavily debated (Hammer et al., 2011; Stewart and Stringer, 2012). Some early work suggested that hybrid individuals existed based on morphological comparisons between various fossils (Trinkaus, 2007), but this technique could not be applied to elucidate complex relationships between hominin species. In the early 2000s, the ability to sequence mtDNA and nuclear genomes created a revolution in this field; the sequencing of archaic and modern genomes provided the evidence that AMH had interbred with archaic hominins (Wolf and Akey, 2018). With this revelation, these new techniques began to be applied to determine the presence of admixtures (genetic material from archaic hominins) within modern populations.

Neanderthals

Homo sapiens neanderthalensis, more commonly referred to as the Neanderthals, are believed to have inhabited Eurasia until around 40,000 years ago before they seemingly disappeared. This notably corresponds to an overlap period with modern humans (Higham et al., 2014).

Recent research indicates that their culture and way of life was relatively complex. Their evolution from *Homo heidelbergensis* led to increased technological diversity, and the ability to control fire (Carrión, Lalueza-Fox and Stewart, 2019). This allowed them to collect a diverse array of food and utilise health care practices to care for their ill and injured. There are various theories for their extinction, and some of these are related to humans, stemming from their temporal overlap in Eurasia. The two predominant theories are competitive exclusion from AMHs or assimilation into the human gene pool through interbreeding (Carrión, Lalueza-Fox and Stewart, 2019).

Over the last decade, the use of ancient DNA has opened our eyes to the presence and extent of interbreeding between humans and Neanderthals (Gross, 2019). The first Neanderthal genome was presented in 2010, revealing that around 2-4% of the genome of non-African populations is derived from Neanderthals. This suggested that humans interbred with Neanderthals following their migration out of Africa, probably in the Middle East before the different non-African populations diverged.

Figure 3.20. An artist's depiction of a Neanderthal individual. Notice the heavy brow ridges, much different than the facial anatomy of modern humans.

Starting in 2015, researchers began to use population genome records to utilise larger sample sizes when studying Neanderthal DNA in human genomes (Gross, 2019). Recently, it has been found that genes that produce the high sphericity in the braincase of humans compared to Neanderthals are also involved in the regulation of nearby genes that affect brain development, increasing the intelligence of AMH compared to Neanderthals. Since then, multiple different phenotypes have been linked to Neanderthal ancestry. Many of these phenotypes influence the risk of having certain disorders, such as autoimmune diseases and depression. These phenotypes probably would have aided Neanderthals, but changes in our culture and lifestyle have made these more detrimental. For example, alleles that increase blood coagulation would have potentially have saved Neanderthals from excessive bleeding, but now contribute to disorders such as stroke. Neanderthal DNA also influences physical features such as our hair and skin colour.

Neanderthal-AMH admixture events also have evolutionary significance. As modern humans began to migrate out of Africa, interbreeding with acclimated Neanderthals would have introduced beneficial alleles into the gene pool (Ségurel and Quintana-Murci, 2014). For example, some advantageous alleles present in human toll-like receptor genes, a key component of the immune system, are a result of admixture with archaic humans (Dannemann, Andrés and Kelso, 2016). As seen in these examples, using genetic analysis provides novel insights into archaic and modern human interactions.

This field is progressing rapidly and in January 2020, a groundbreaking article was published that utilised a novel genetic technique, which uniquely did not use a modern human reference population (Chen et al., 2020). This technique was used to identify that around 0.5% of the African genome is from Neanderthal heritage. To explore why this is the case, the researchers tested two simulated models, one involving a back-migration of humans from the Middle East to Africa after interbreeding with Neanderthals, and the other involving a smaller migration before the big 'Out of Africa' dispersal of modern humans. They found that the combination of these two models produced the most fitting results, suggesting that both situations are responsible.

In summary, the technological advancement and increased use of ancient DNA to study hominin lineages has led to multiple advancements in our understanding. One particularly important breakthrough has been the discovery of interbreeding between AMH and Neanderthals. While this technique has illuminated much on this topic, it has also created exciting new questions relating to the circumstances behind the interaction between these hominin groups and the resulting consequences both in hominin evolution and in our everyday life.

Discovering the La Brea Tar Pits

Figure 3.21. The interior of the George C. Page Museum in the heart of Los Angeles Miracle Mile. Shown are few of the many collection on display of late Pleistocene megafauna fossils.

Situated in the heart of Los Angeles, the Rancho La Brea deposit is one of the world's richest repositories of late Pleistocene fossils. With over 660 species recorded in these asphalt-rich sediments, these "Ice Age" era fossils have provided a detailed record of plant and animal life in southern California between 40,000 and 80,000 years ago (UCMP, 2020). The abundance and quality of specimens uncovered at the La Brea Tar Pits allow for a near-complete reconstruction of this paleoenvironment (Harris and Jefferson, 1985). Over 100 different excavations have been conducted at the Rancho La Brea site since the early 1900s, recovering millions of fossilized flora and fauna. Most of these are now stored and displayed at the George C. Page Museum of La Brea Discoveries on site (Figure 3.21), where they remain available for public viewing and academic research today (Harris and Jefferson, 1985).

This chapter will be discussing the historical and geological records of Rancho La Brea, as well as its contributions to the understanding of the local environment during the late Pleistocene. Emerging techniques for paleoenvironmental reconstruction with the fossil data from the tar pits will also be examined.

The Mystery of the Tar Pits

The story begins with the thorough journal descriptions by Friar Juan Crespi during the Spanish expedition, led by the explorer Gaspar de Portola from 1769-1770 (Piper, 2009). The journal speaks of his missionary work with the natives, as well as provides honest and accurate observations of the uncharted land and environment. He also made a record of locations he deemed appropriate for future missions.

When they arrived in the Los Angeles Basin on August 3, 1769, Crespi was the first to make note of the tar springs in the middle of a plain at the foot of Santa Monica Mountains (Wood, 1971, 215). He wrote that they came across "some geysers of tar, issuing from the ground like springs; it boils up molten, and the water runs to one side and the tar to the other. The scouts reported that they had come across many of these springs and had seen large swamps of them" (Wood, 1971, 214). They christened these tar springs 'Los Bolcanes de Brea de la Porciúncula'. The land was an unassuming part of a Mexican land grant known as Rancho La Brea, before eventually being passed down to the Hancock family (Piper, 2009).

In the nineteenth century, the tar from Rancho La Brea was being mined commercially and while the occasional bones found were assumed to be the remains of cattle and birds (Figure 3.22), but the importance of the fossils was not noticed until later. In fact, the course of events that started the paleontological frenzy at the La Brea Tar Pits was initiated by Henry Hancock, who owned the land in 1875 (Harris and Jefferson, 1985). He showed a large canine tooth of what was later found to be a European saber-toothed cat to William Denton from the Boston Society of Natural History. He proposed to take some of the bones for further study and write a report on his findings, but the scientific

Figure 3.22. Excavation in the Los Angeles Museum Pit 4, Rancho La Brea, demonstrating the array of skulls and bones of Pleistocene animals preserved in the asphalt. Of note here are the wolf skull at the top, the camel skull with teeth exposed in the middle and the bison skull at the bottom, though they were not recognized as important fossils until later.

community was not interested (Weston, 2002).

This changed in 1901, when William Orcutt, a petroleum geologist whom, upon examining Rancho La Brea for petroleum resources, was the first to recognize the bones as fossils (Merriam, 1911). He noted that "on the surface of the asphalt, a mosaic of beautiful white bones, uniform in shape, lying in an exact pattern" (Orcutt, 1924). This would mark the first of many excavations, and in this process, he was able to uncover several skulls, many bones and vertebrae of these late Pleistocene fauna (W. W. Orcutt, 1924).

The Fossil Rush

The veritable fossil frenzy would begin in 1905, when Dr. John C. Merriam, a vertebrate paleontologist from the University of California, Berkeley, joined the fray. Merriam was extremely interested in Orcutt's work, agreeing that the fossils were scientifically significant and thus, striking up a correspondence (Orcutt, 1924). Shortly after Merriam secured a lease from the Hancock estate to begin his excavation, news of this discovery spread quickly throughout the United States and Europe. Within three months, numerous institutions, with the permission of Allen Hancock, were working to uncover other specimens. After about two years, it was clear that the number of fossils extracted would be huge; almost three hundred complete skeletons of saber-toothed cats, many mastodons, condors, wolves and numerous small animals were discovered during this time (Orcutt, 1924). The extraction process was not without its difficulties however, as retrieving the delicate bones from the rocky asphalt was laborious and time-consuming (Weston, 2002).

It was unclear exactly who made one of the key discoveries of this fossil rush: a small pocket of densely packed fossils that was loose enough to be broken through. Due to the matrix of tar and sand that composed the sediment, the location was ideal for fossils since the preparation process was relatively straightforward (Weston, 2002). This really was the first indication that the Rancho La Brea was special, housing a paleontological treasure trove that would find "no parallel among the great records of the past life of the Earth brought to light by the paleontologist and geologist" (Stock, 1930).

The prime reason why the La Brea fossils were so significant to paleontology at the time was due to the volume and grade of preservation on the bones retrieved. Though the fossils overall appeared ravaged and damaged, they were still remarkably well-preserved (Weston, 2002).

Figure 3.23 John Merriam's sketches of a Canis dirus skull (no. 10834) extracted from Rancho La Brea, California during the excavations (Merriam, 1911 pg.224).

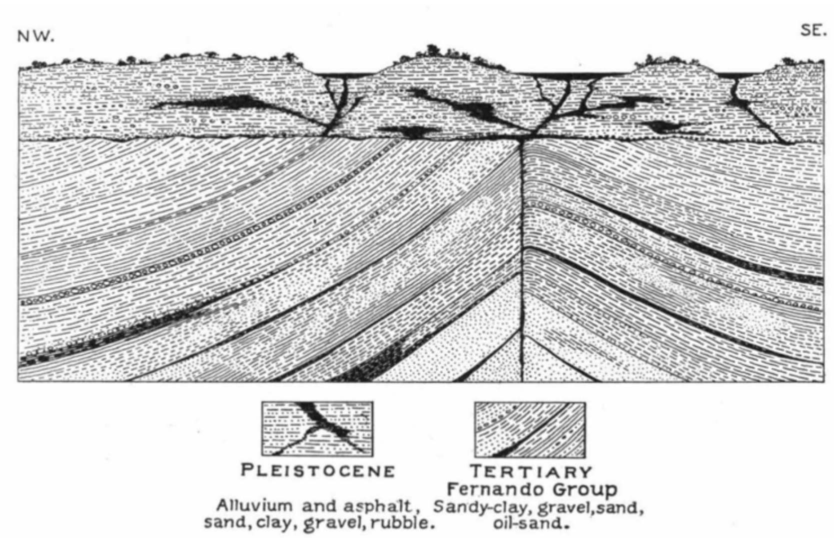
John C. Merriam kept meticulous, detailed notes throughout the bulk of the excavation process and ended up publishing them. He made sketches (Figure 3.23) of the fossils uncovered and would make thorough observations and measurements comparing the bones to extant species by closely examining bone anatomy. His work characterizing many of the vertebrates from the excavation sites was influential, though only marked the beginning of a long process to better appreciate the biotic and environmental conditions from an earlier time. This is one that continues there today.

The Geology of Rancho La Brea

The site of the La Brea Tar Pits has a unique geography that allows for the excellent preservation of fossils. For fossilization to occur, the specimen often requires rapid burial by sediments to protect it from environmental decomposition and scavenger activity. These environments tend to mostly occur in marine, fluvial or lacustrine – underwater – conditions. The sticky tar from La Brea is thus, a rare site that combines both the rapid sedimentation and the unique added benefit of asphalt impregnation – an invaluable asset that increases the fossil's structural integrity (Harris, 1985).

Rancho La Brea is located on the modern-day Santa Monica plain, at the edge of the Los Angeles basin of Southern California (Akersten et al., 1983). However, no more than one hundred thousand years ago from today, the basin is completely submerged by the Pacific Ocean (Harris, 1985). With the last glaciation event of the Pleistocene, the sea level retreated and the water from the basin dried. Rancho La Brea is now situated on a flat plain of marine sediment encircled by mountains all around the horizon. This claim is supported by a layer of early Pleistocene and Miocene marine mudstone

Figure 3.24. Cross-section of the geologic structures and relationships of formations at Rancho La Brea, recording Pleistocene life in California (USGS, 1907).



(left) that covered the region at this time (Harris, 1985). This layer of sediment later gained another key role; it would act as the large reservoir of petroleum that would become the source for the La Brea Tar Pits (Akersten et al., 1983).

The layer of mudstone is overlain by a "fining up" sequence of sediment (Figure 3.24) which is understood to be characteristic of alluvial fans. The canyons that surrounded the plain were eroded and the stream carrying these sediments dropped from a steep angle, spreading out across the flat plain in the shape of a fan. As these fans extend further and further, the basin is built up gradually by sediment layers of sands and gravel (Harris, 1985). It just so happens that alluvial fans are also known to be hydrocarbon traps, making the region ideal for the formation of tar pits (Haldar and Tišljar, 2014).

The dominant theory explaining the formation of the tar pits and their development into a rich mine of fossils is as follows: during the warm dry summer, crude oils and other hydrocarbons seep through fissures and vents until they reach the ground surface. Subsequently, the more volatile elements evaporate, leaving behind a thin blanket of residue natural asphalt (Harris, 1985). Instead of being like a deep pit of swallowing quicksand, the tar "pits" of La Brea is more akin to sticky flypaper (Akersten et al., 1983). To add to the deceptive nature of this trap, it is believed to be concealed by a layer of fine dust and leaves (Figure 3.25).

Unwary animals, therefore, could be easily trapped, luring other scavengers and predators to the same fate with their cries. As their body decayed and bones rotted freely, their remains were saturated by asphalt as their bones sank below the mire. Come winter, the cool temperatures would solidify and harden the asphalt just as fresh rain brought fresh sediment from nearby canyons to bury any exposed bones. This yearly cycle likely continued as the warmth of summer dried the streambed and liquified the asphalt, resetting the trap for its next batch of unfortunate victims (Harris, 1985).

Figure 3.25. A thin sheet of tar concealed by a blanket of leaves and dust. It's a trap for any unsuspecting individuals.

The Contributions of La Brea Tar Pits

The Rancho La Brea Tar Pits are a key and significant contributor to our current scientific understanding of the Pleistocene ecosystem and environmental conditions. Between the years of 1906 and 1915 alone, over two million specimens of large animals were excavated from the pits, not including the substantial collection of algae, vascular plants, mollusks, arthropods and birds (Akersten et al., 1983). The sheer bulk of the samples (left) was astronomically helpful for paleontologists, as they possessed large enough sample size for cross comparison of the same element – a luxury typically rare in the study of prehistoric fossils.

Figure 3.26. The large, yet incredibly well-preserved collection unearthed from the La Brea Tar Pits.

The asphalt of the tar pits was an excellent preservation medium and it allowed the fossils of La Brea to maintain its surface and internal structural detail. Many delicate skeletal structures that were seldom preserved elsewhere were found in abundance at La Brea (Akersten et al., 1983). The courses for nerves and blood vessels of some specimens were still visible, as well as the wings and antennae of certain individual insect fossils (Weston, 2002). These details allowed scientists to understand, in depth, the functional morphology of these ancient biotas and be led one step closer to understand the evolution of those that came before.

Indeed, the preservation of insects was novel and profound, as the sticky tar substance allowed for their preservation, though this was rare. Their remains are often fragile and thus, scarcely conserved, but the insect guild can serve as great bioindicator species for their environment (Akersten et al., 1983). One study that emerged from the La Brea collection used the radiocarbon dated insect fragments of the past 50,000 years to infer the paleoenvironment and climate. The idea is to use sensitive species of beetles as a proxy for past climate change and ecological trends. Through La Brea's insect collection, they are able to predict the late Pleistocene climate of Los Angeles is similar to its present day demitarian climate (Holden et al, 2017).

The excellent preservation of surface features on the La Brea teeth collection allowed for a complete and comprehensive study into the diet of numerous herbivore species. Although rare in most fossils, many La Brea teeth contain plant matter trapped within cavities called fossettes (Akersten et al., 1983). This, along with detail on the microwear and mesowear on the teeth, gave insight into the diet of these Ice Age giants. The abundance of specimens in the La Brea Tar Pits even allowed paleontologists to observe an adaptive trend on how the herbivores altered their diet to cope with the changing climate (Jones and Desantis, 2017).

No other fossil site has recorded as complete a representation of the ancient ecosystem and environment as the La Brea Tar Pits. These findings are but a sliver of the site's potential. Today, the site is protected under a park and museum, educating the public about the amazing discovery and contribution of a simple pit of pitch to humanity's understanding of the lives that came before us. With the development of subways and architectural foundations around the booming heart of LA, more and more fossils are unearthed in La Brea – a constant reminder of the inevitable tie between archaeological discovery and human economic growth.

Developments in Paleoenvironment Technique

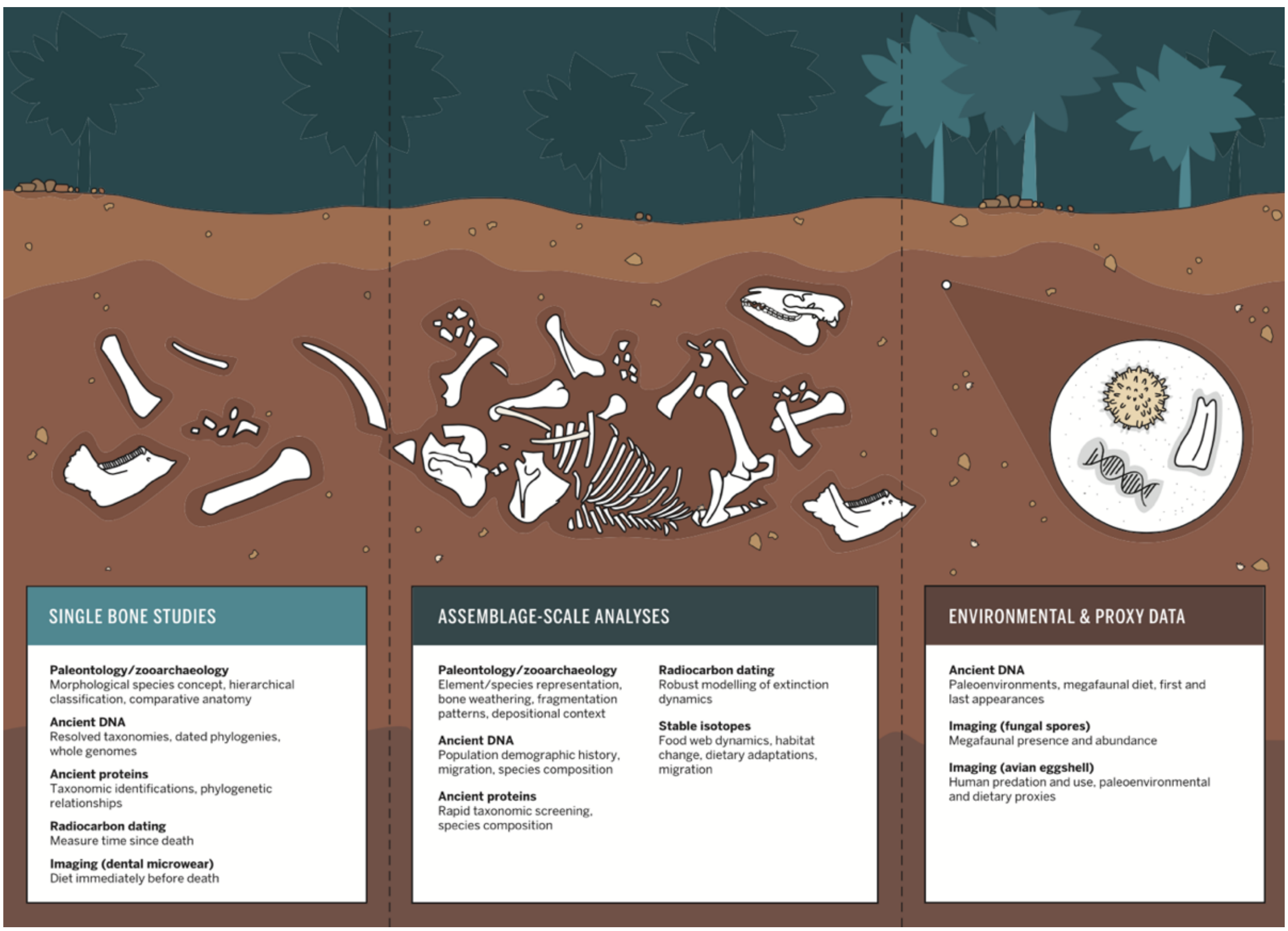
Figure 3.27. Higher-resolution technology can complement existing strategies to study paleoenvironments to gain new insights into a single megafaunal bone, complete assemblages or the paleoenvironmental context (Swift et al., 2019).

Fossil evidence from the La Brea Tar Pits has greatly contributed to our understanding of the late Pleistocene environment due to the sheer volume of well-preserved material. There are, however, shortcomings with the traditional taxon-based approaches to fossil analysis, particularly in regions with limited or missing data (Swift et al., 2019). The development of new scientific technologies (Figure 3.27), including more robust compound analysis and high-resolution imaging, have allowed for more fine-grained investigations of paleoenvironments using the samples from Rancho La Brea, including details such as population dynamics and extinction chronology (Swift et al., 2019).

Radiocarbon Dating

Radiometric dating provides direct age estimates for the age of a specimen and is helpful for determining a chronology of historical events and processes (Richter and Wagner, 2015). Recent developments in mass spectrometry and pre-treatment filtration techniques have allowed for more reliable chronologies to be developed, particularly in the study of the late Pleistocene megafauna extinctions. The efficient elimination of contaminants from bone collagen by ultrafiltration pre-treatment procedure has improved existing radiocarbon methods. This is because samples contaminated with younger carbon can result in erroneous dating and less reliable results (Swift et al., 2019).

Furthermore, specific amino acids are now being targeted for radiocarbon dating as a way to understand the extinction chronologies of the giants of the late Pleistocene. Though analyzing single amino acids can involve only a small



proportion of datable material, multiple amino acids are also able to be dated simultaneously. This is done by hydrolyzing the bone collagen and passing it through a hydrophobic resin (Swift et al., 2019). Even though radiometric analysis has a set range through which it is most effective, developments in refined radiocarbon dating techniques have been used in conjunction with stratigraphy for an improved understanding of paleoenvironments (Richter and Wagner, 2015).

Isotope analysis and paleoecology

Interpretations of environmental preferences and ecological interactions are often hindered by a poor understanding of the ecology of these extinct species, particularly when there is no modern analogue. As a result, stable isotope analysis of animal tissues can be valuable, as they contribute evidence that allows for the reconstruction of paleoecology and trophic interactions (Lee-Thorp and Sponheimer, 2015). For instance, stable carbon, oxygen and nitrogen isotopes in bone collagen can be used to find differences in dietary and environmental preferences of various extinct species (Swift et al., 2019). This is because the compositions of animal tissues are determined by the proportions of nutrients consumed, meaning that the amount of various available foods consumed over parts of their lifetime can be calculated (Schwarcz and Schoeninger, 2011). Along with information from coprolites and intestinal contents, Pleistocene food webs, competition dynamics and carnivore habits can be reconstructed. Relationships can thus be found between these trophic interactions and the longer-term persistence of certain species and the extinction of others. Additionally, specific amino acids more closely associated with certain trophic level positions, such as glutamic acid, can be used to support certain trophic level statuses (Swift et al., 2019).

Stable isotope ratios derived from inorganic tissues at various times in history, like tooth enamel, can also be used to track paleoenvironmental changes (Swift et al., 2019). Correlations between these values and paleoenvironmental information, such as sediment cores, can indicate periods of relative climatic stability or the disappearance of other key species. Moreover, certain isotopes, including stable carbon, oxygen and strontium ratios, can also track mobility and ranging, as different isotopic signatures can be linked to migrations between regions or hunting ranges of populations (Swift et al., 2019).

Ancient DNA and proteins

Ancient DNA (aDNA) analysis has been used to identify megafaunal species from the Pleistocene and provide a more reliable method to distinguish between taxa than visual analysis of fossils (Hummel, 2015). Developments in aDNA sequencing have allowed for the entire nuclear genome of megafaunal fossils to be mapped, providing insights into the demographic history of generations. Bulk-bone metabarcoding is another example of emergent molecular technology that has allowed for the rapid analysis of fossil assemblages, by grinding the bone fragments into a mixture and determining the species composition. This has allowed for a broad sense of the biodiversity at the time and has helped to both identify several distinct species or revealed sexual dimorphisms within a species (Swift et al., 2019).

Paleoproteomics, the retrieval and analysis of proteins from degraded biological sources, has also been promising because proteins can be preserved even longer than DNA. This is because typically, DNA can be preserved for weeks or thousands of weeks, depending on chemical or biological factors that are not well-understood or predictable (Hummel, 2015). Collagen peptide mass fingerprinting, in particular, is an efficient tool that uses MALDI-TOF mass spectrometry to identify the sources of bone collagen (Swift et al., 2019). This technique is minimally destructive and rapid, which allows for more diverse and numerous samples to be sequenced, providing insight into the faunal community structure and biodiversity. It is also able to identify ancient human remains, and therefore could play a role in determining the degree of correlation between human dispersal and the extinction of late Pleistocene megafauna (Swift et al., 2019.

History of Paleontology

The history of paleontology dates back to the Greek philosopher, Aristotle (384-322 BC). He believed fossils were produced *via plastica,* an extraordinary force within the Earth that tried to reproduce life inside rocks (Shourd, 1970). His ideas dominated the Middle Ages and continued into the Renaissance; influencing several theories, including those used to explain the discovery of petrified shells (mollusk fossils) on mountains (Baucon, 2010). The inorganic theory states that these shells are natural curiosities that emerged beneath the ground spontaneously, whereas the biblical flood theory identifies them to be living organisms brought to the mountains by a flood. These theories were refuted by Leonardo da Vinci, a polymath and paleontology pioneer of the Renaissance, who used an empirical method to analyze natural phenomena (Baucon, 2010).

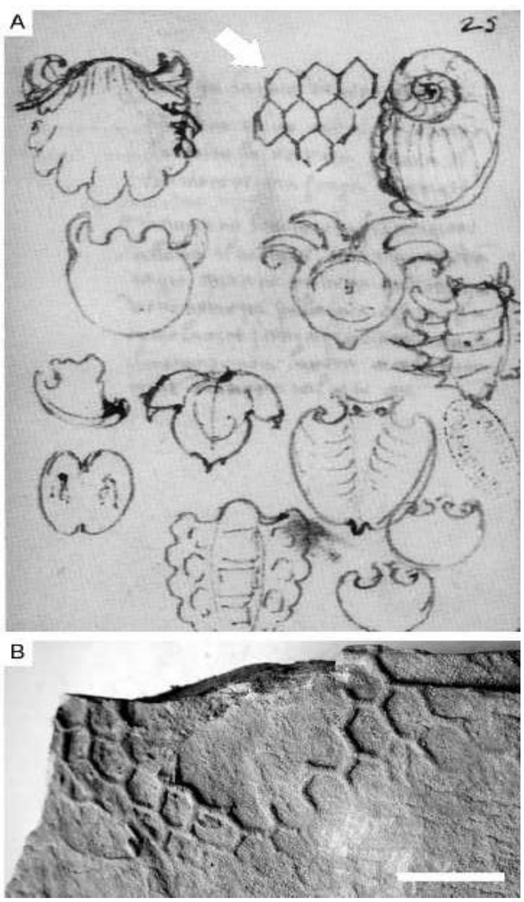


Figure 2.28: A) Leonardo da Vinci's drawings of the petrified shells discovered on the mountains. B) A close up of the borings found on the mollusk fossils Leonardo da Vinci studied.

Da Vinci had three contradicting arguments. Firstly, the strata containing petrified shells are of sedimentary origin. Secondly, the petrified shells are analogous to existing marine mollusks. Thirdly, the evidence on hand showed that there have been several transgressive events. He suspected that petrified shells were once living organisms of the ancient sea and studied trace fossils of these shells and other corals to prove his ideas surrounding the nature of fossils. He found indications of living organisms being perforated into rock, and questioned why "forces" would produce such borings on a shell (Baucon, 2010). Moreover, he observed signs of movement of fossils between different strata (known as bioturbation today) which he interpreted as evidence that fossils were the remains of entombed prehistoric animals. Da Vinci's use of trace fossils to support his hypothesis regarding the relationship of body fossils and the host sediment united the two main branches of paleontology: trace and body fossils (Baucon, 2010). His conclusions surpassed three centuries of paleontological research on the nature of fossils.

Paleontology in the Age of Enlightenment

The seventeenth century marks the beginning of the Age of Enlightenment, which is an intellectual movement centered around the use and celebration of reason to understand the universe. This period promoted the scientific method and led to revolutionary advancements in art, philosophy, and nature (Duignan, 2019). Agostino Scilla, a naturalist at the time, was one of the first to attempt sedimentological interpretation of rocks. This allowed him to collect evidence to prove fossils were former living marine organisms (Romano, 2014).

Nicolaus Steno, a geologist and anatomist (Drake and Komar, 1981), expressed similar ideas to da Vinci regarding the origin and nature of body fossils. During his work, he recognized that shark teeth looked like stony objects called glossopetrae. He wondered whether this resemblance was due to the possibility of shark teeth from ancient individuals being deposited there when land was covered by oceans. Steno did not believe in the *via plastica* theory (Bek-Thomsen, 2013). He argued that if shells grew inside rocks, like Aristotle suggested, then rocks should crack, but they did not. Not to mention, that there is no current evidence of fossils growing in rocks. Therefore, his alternative was that rocks were once fluid, which then solidified around and on top of older strata and fossils overtime. This was used to explain how horizontal strata throughout the Earth was created, building fundamental concepts of geology (Bek-Thomsen, 2013).

In 1665, Robert Hooke published *Micrographia* in which he featured illustrations of the plants and animals he saw from examining fossils under his microscope. Hooke reported similarities between petrified and living wood, as well as, between living mollusk and fossil shells (Woodruff, 1919). He deduced that petrified wood is living wood that was soaked up with "water impregnated with stoney and earthy particles". Likewise, he suggested that fossil shells were ordinary shells that had been "fill'd with some kind of mud or clay, or petrifying water" (Hooke, 1665). He disagreed with Aristotle's *via plastica* theory as he believed that nature did nothing in vain (Woodruff, 1919). Hooke studied fossils for the rest of his life, and postulated three stages that fossils undergo during formation. In the first stage, organic remains are deposited in beds of peat, moss, and mud. In the next stage, remains transmute within lignites and brown coals but are not fossils yet. In the final stage, organic remains are trapped within layers of coal and are fossilized. These ideas were a topic of debate and did not get accepted until the beginning of the eighteenth century (Winchester, 2001). Robert Hooke declared fossils to be petrified exuviae of animals deposited within the layers of the Earth by natural occurrences like earthquakes (Kusukawa, 2013). In addition, his work involved comparing fossils to existing organisms, through which he observed that many did not have living analogs. As a result, he concluded that species alive today did not exist in the past and fossils are the key to understanding the history of life on Earth (Woodruff, 1919).

Paleontology in the Eighteenth Century

In the eighteenth century, fossils of elephants were uncovered in Europe despite them no longer residing there. However, elephants do live in Africa which made naturalists wonder whether other fossils had living counterparts in remote parts of the world (Thomson, 2008).

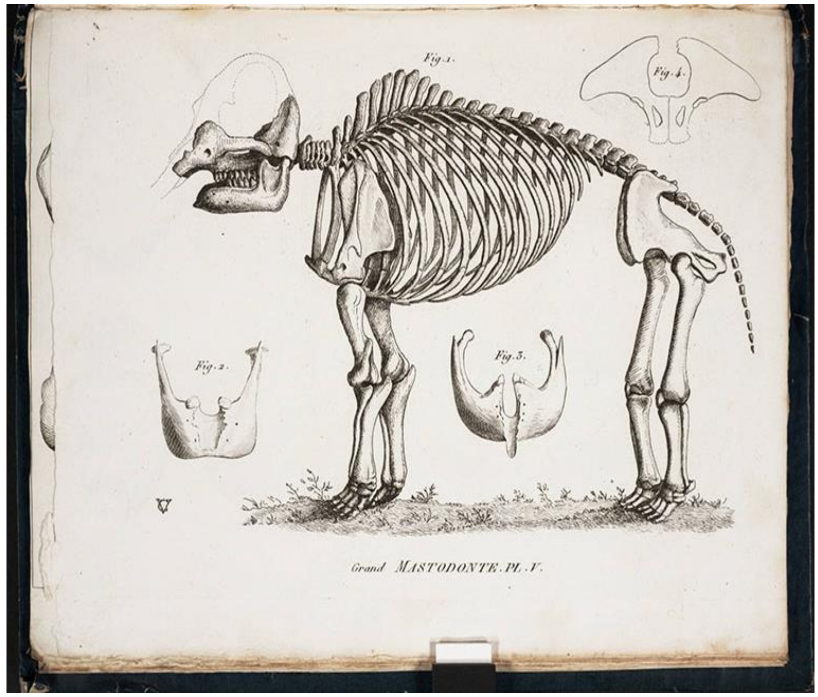


Figure 3.29: George Cuvier's reconstruction of the Mastodon skeleton in 1812.

French zoologist, George Cuvier, studied the elephant fossils in Europe by reconstructing their complete skeletons. By doing so, he realized that they were undeniably distinct from living elephants in Africa as they were far too large in comparison. As a result, he declared them to be a separate species that had become extinct and named it Mastodon (Thomson, 2008). Similarly, this was seen among many fossils of large mammals. The deep, more remote strata contained fossils distinct from living organisms than those found within recent strata. Thus, Cuvier proposed the geological theory of catastrophism that claims the planet went through sudden, short-lived, violent events that wiped out several species. Today, these "events" are known as mass extinctions. The theory of catastrophism explained the succession of organisms seen in the fossil record (LaFreniere, 2007). Cuvier established the connection between comparative anatomy and paleontology by introducing fossils into zoological classification. He demonstrated the importance of functional and anatomical relationships by using his knowledge of comparative anatomy to reconstruct fossil skeletons (Rudwick and Cuvier, 1998).

Near the end of the century, a surveyor and mining engineer by the name of William Smith made extensive use of fossils to correlate rock strata found at different areas (Winchester, 2001). He faced difficulty distinguishing between strata of fine-grained sediments like sandstones, which led him to seek a natural measure of dating, fossils. He noticed that different species of fossils were present in different sediment layers depending on which species were alive when the beds were formed (Winchester, 2001). These observations coincided with the principle of faunal succession proposed by Cuvier, which states that each strata of sedimentary rock contains fossilized flora and fauna that succeed each other in a predictable manner which can be observed over wide distances (Winchester, 2001).

Debates of the Nineteenth Century

Henri Marie Ducrotay de Blainville and Gotthelf Fischer von Waldheim were paleontologists of the nineteenth century who independently coined the term "paleontology" to describe the study of ancient life (Shourd, 1970). Scientific debates within the field of paleontology led to major advancements during this period.

John D. Godman, a physician and naturalist, discussed a mastodon animal preserved from the Pleistocene. This specimen contained small tusks in the lower jaw and an elongated jaw which were not common with the Mastodons reconstructed by Cuvier. Hence, Godman assigned the specimen to a new genus called Tetracaulodon. The classification of this specimen became a controversial debate among the American fossil devotees of the century (Gerstner, 1970). Both sides of the debate contributed to the development of paleontology making the dispute well known across the globe. American paleontologist, Richard Harlan, viewed paleontology as an international study and would share American information with Europeans. On one of his trips to Europe, Harlen worked in a cooperative study with European paleontologists to compose evidence that proved giant reptiles lived on Earth in the past (Gerstner, 1970).

In addition, fossils were used to develop the geological time scale. Members of the Geological Society of London engaged in the debate of The Great Devonian in which uniformitarianism was rebutted against catastrophism (Rudwick, 1985). This led to identification of geological periods by observing succession of strata containing preserved fossil fauna. The coherent sets of strata determined by fossils correspond to four geological periods of the Earth: The Cambrian, Silurian, Devonian and Permian (Rudwick, 1985).

Use of Paleontology in Wegener's Theory for Continental Drift

In the twentieth century, fossils were used to substantiate a number of theories regarding the geology and formation of the Earth. The presence of the same fossils on different continents raised the question of how prehistoric organisms were able to travel across seas. Alfred Wegner, a German geophysicist and meteorologist, responded with his theory of continental drift. Wegener first proposed his theory that all the continents were once connected in 1912. However, he faced several contradictions and did not gain recognition for his ideas until 50 years later. During this time, he did not possess the credentials as a geologist to make such controversial claims (Hallam,

Figure 3.30: A photograph of Alfred Wegener, the German geophysicist and meteorologist, who created the idea of continental drift.

1975). It is unclear how Wegener first conceived the idea of continental drift, although it can be assumed that the complementary Atlantic coastlines on the map likely lead to the development of his theory as inferred from in his published work, *The Origins of Continents and Oceans* (Wegener, 1966). His idea was first presented publicly in January 1912 and was published in two German journals later that year. The geographically disjunctive distribution of similar life forms on separate continents also played a large role in the development of the continental drift theory (Frankel, 1985). The fossil distribution of *Mesosaurus* is evidence Wegener used to support his continental drift theory. The *Mesosaurus* is a small reptile species that lived during the Paleozoic era. Its fossils were found in both Brazil and South Africa, but nowhere else in the world (Hallam, 1972). The *Mesosaurus* was 18 inches from the tail to snout and was predicted to have lived in swampy areas. Judging by its stature, it would not have been able to swim large distances, including swimming across the ocean to another continent (Tasch, 1967). If the *Mesosaurus* was able to swim across the ocean, then it should have dispersed more widely to other areas. However, since the fossils are distributed in a disjunct endemism pattern, it suggests that South America and South Africa were once connected.

There are four principles used to describe the distribution of fossils; the first is "convergence." As time passes the degree of resemblance between faunas from distinct regions increases (Hallam, 1972). Early in the Miocene era, records of mammals from Eurasia were found entering Africa through one or more land connections. This migration led to the extinction of some indigenous African fauna. This connection allowed a substantial degree of convergence between Africa and Eurasia and can be attributed to the continental drift theory. The second principle is "divergence," the opposite of convergence. During the Cenozoic era, fossil faunas from various continents differed from one another. The pattern of divergence in this era is the consequence of the break-up of Pangea. The third principle is "complementarity" (Hallam, 1972). The faunas in adjacent areas of shore and ocean shelf react to changes in the environment complementary to one another. When a new land connection is formed, the land faunas tend to converge whereas the divided marine fauna diverge. When a land connection separates it has the opposite effect. The fourth principle is "disjunct endemism." This occurs when a group of fossil organisms appears in two or more parts of the Earth that are separated by geological barriers (Hallam, 1972).

There were debates regarding the explanation of these fossil distribution patterns. Many biogeographers refused to believe Wegener's ideas and supported alternative explanations such as the theory of sunken land bridges. This theory, hypothesized by Eduard Suess, states that there once existed former continental land bridges that extended across the ocean from continent to continent and sunk to the ocean floor leaving behind a stratification of sedimentary deposits. The presence of these land bridges would provide a migratory route for life forms hence accounting for the fossils of different flora and fauna on multiple continents (Frankel, 1985). Wegner rejected this model as many of the distinctive features on the Earth could not be explained unless by coincidence. As well the sinking of land bridges violates the theory of isostasy, which states that lighter crust floats on denser underlying mantle (Hallam, 1975). Wegner believed that the theory of continental drift offered a more complete view of both paleontological and geophysical evidence. His theory also accounted for the fact that fossils of similar life forms were present on separate land masses with different climates and latitudes. In his supporting points he discusses the *Glossopteris flora*, a late Paleozoic flora founded in the southern hemisphere and peninsular India. Deposits of *Glossopteris* is often associated with glacial deposits, however, deposits of the flora were found across southern continents, as well as India. This correlation was used as evidence for continental drift as it is impossible to assume that the flora would have experienced the same climate at every period of the Earth's history in separate continents (Frankel, 1985). Although Wegener's theory was premature at

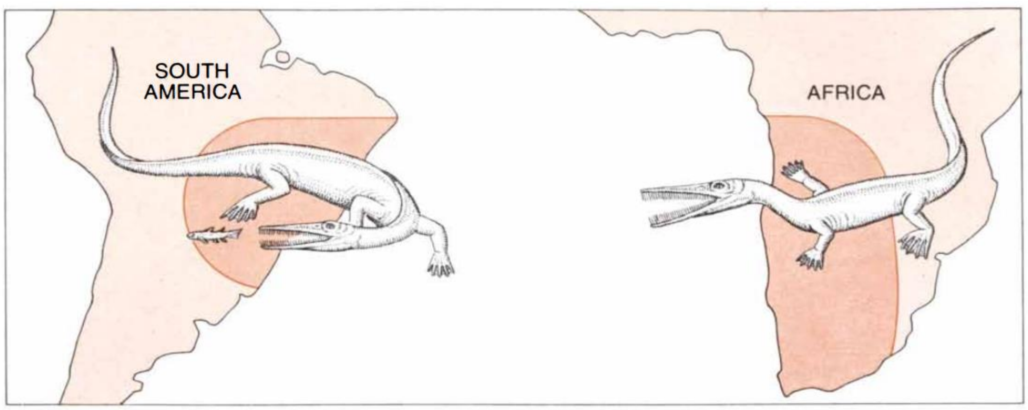


Figure 3.31: Fossils of the Mesosaurus are found on both sides of the South Atlantic but nowhere else in the world.

the time, he was one of the first geologists to use a multidisciplinary approach to study fossils and use it as evidence to support his theory of continental drift. Today, his theory is one of the fundamental ideas in the field of geology.

Reconstruction and Dating of Fossils

The surface of the Earth is constantly changing and has been for the past 4.6 billion years. Throughout all of these changes, fossils provide a record of the past, both chronological and spatial, that we can study. This record gives us an insight into events that have occurred in the Earth's past that can then be used to predict future changes. These include climatic changes, previous life forms, tectonic plate movements and oceanographic events (Rosen, 1988). Fossil sites are a valuable and non-renewable resource that have scientific significance, economic values for local tourism, as well as, cultural significance when fossils sites coincide with places of historical value (Briggs, 1991).

Fossils can be dated to determine the temporal living conditions of a specimen and how it was preserved. There are two general approaches to dating fossils: absolute dating and relative dating. Relative dating methods determine the age of fossils and rocks by comparing them to others of a known age. This method of dating puts the fossils in chronological order relative to one another but does not take into account the exact age of the specimen (Michels, 1972). There are two aspects of relative dating; one of which is sequence dating whereby the relative chronological position is used to determine the age of the rocks relative to one another. The other method is cross-dating which assumes that a sequence of archaeological units has been established and the relative age of the new component can be determined when compared to a similar component that has already been dated. Different principles like original horizontality, superposition, and cross-cutting relationships are also used to determine the relative age of the strata (Michels, 1972). When dating rocks and fossils, the principle of faunal succession can be used. Fossils only occur for a distinct interval of time from the first occurrence of the fossil to the last. Through the application of the principle of faunal succession, it is observed that fossil assemblages found in the same rock layer were deposited at the same time (Peppe, 2013). This makes it possible to correlate fossil sites and other characteristics of the rocks.

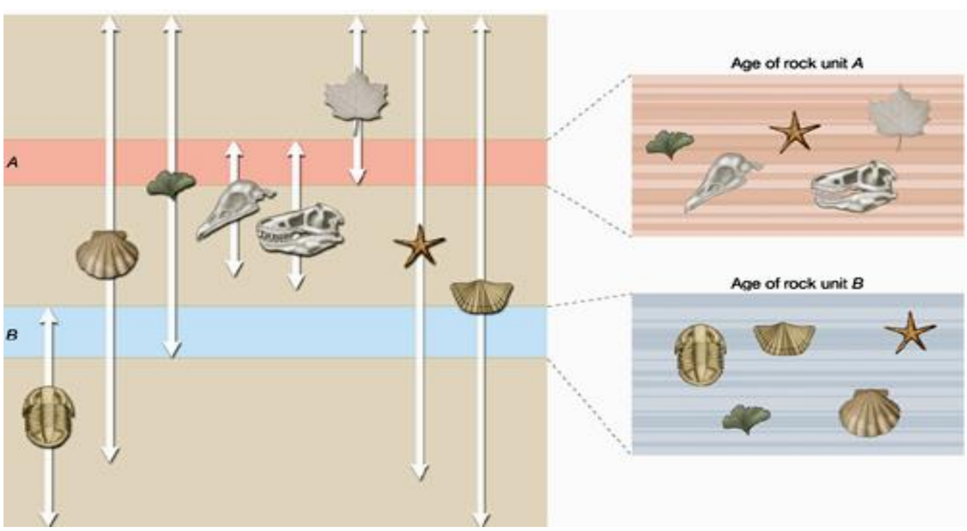


Figure 3.32: The principle of faunal succession, used to study the correlation between fossil deposits and characteristics of the rocks to better understand the past.

Absolute dating is a more precise method that uses radiometric dating techniques to measure the decay of isotopes in the rock or fossil. Sedimentary rock contains fragments and grains of pre-existing rocks of different ages making it less ideal for dating. Igneous and metamorphic rock have radioactive minerals trapped within them that start to decay upon cooling at a predicted rate (Deline et al, 2015).

Radioisotopes are a good indicator for dating fossils. One radiometric dating technique is radiocarbon dating. Carbon is one of the most common organic compounds and occurs naturally in living organisms and the environment on Earth. Living organisms consume carbon-14 (C-14) and once they die, the C-14 begins to break down to form carbon-13 (C-13), a more stable form or daughter isotope of carbon. Measuring the amount of C-14 in the fossil using a mass spectrometer can provide information regarding the age of the sample. However, there are some disadvantages of radiometric dating, the main being that carbon has a short half life of 5730 years (Michels, 1972). Therefore, if the fossil is older than 60,000 years this dating method will not be effective. This method of radiometric dating also assumes that there was a uniform amount of C-14 in the atmosphere during the past 50,000, although variables like cosmic ray intensity, variation of magnetic field and sunspot activities may have influenced the amount of C-14 in the atmosphere (Michels, 1972). Other isotopes that occur naturally in the environment and living organisms but have longer half lives are potassium-40 and uranium-234. The potassium-argon (K-Ar) isotopic decay method can be applied to specimens to the order of a billion years, and uranium up to 500,000.

Another radiometric dating method is fission track. Uranium-238 is present in rocks and minerals and naturally decays. This process can also occur due to fission whereby the uranium atom splits due to its sensitivity to heat. The atoms of the isotopes move at high speeds inflicting damage to the rock or mineral. When volcanic rocks form, there are no fission marks present but overtime the number of tracks increases depending on the amount of uranium in the rock. Analyzing the content of uranium and the density of fission markings can be a useful method to determine the age of a rock (Michels, 1972). The absolute dating methods discussed can be used to measure the decay of isotopes found within the fossil or the rocks associated with it.

Reconstruction of Fossils

Other advancements in technology can provide visual reconstructions of fossil specimens. X-Ray Computed Tomography (CT) datasets used in modern medicine can be used to analyze fossil samples by creating highly accurate three-dimensional imagery (Rowe et al., 2016). CT has been used for over 30 years by paleontological researchers because the technology can interpret the 3D form of the specimen more accurately than humans. Visualizing a specimen provides researchers with a high definition forensic interpretation of samples with an incredible level of detail beyond just the outline of the specimen. It illustrates the composition of internal bones and soft tissues, revealing details that may be overlooked by the naked eye. For example, it is possible to view the endocast of the brain and inner ear. Another benefit of this technology is that it is non-destructive. It is common for vertebrate fossils to break upon discovery and during excavation. Especially on bedding planes that are thin and have laminated layers (Rowe et al., 2016). The CT dataset separates the fossilized bone from the surrounding sediment matrix to make a 3D print by which paleontologists can interpret and have a better understanding of the appearance of the specimen (Schilling et al., 2013).

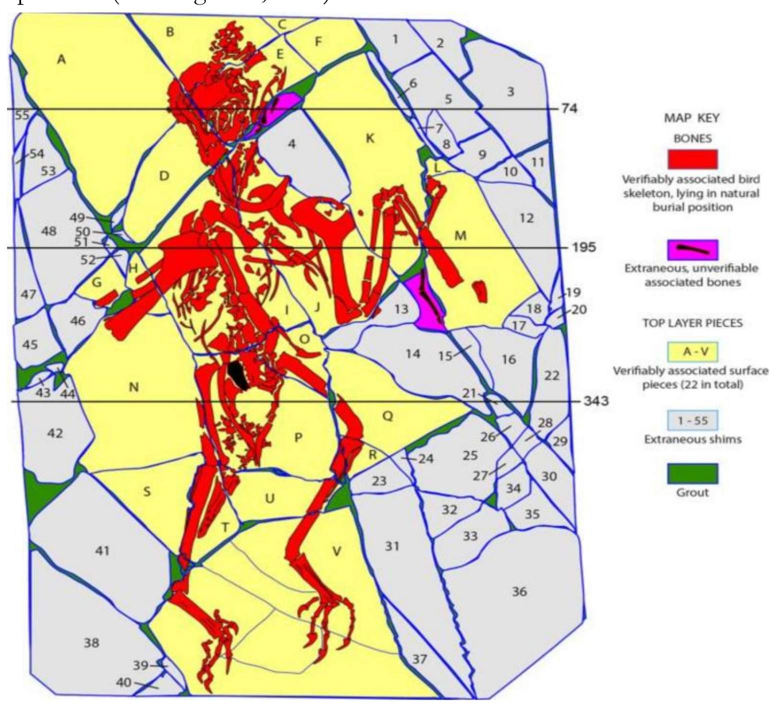


Figure 3.33: Image of Confuciusornis derived from high-resolution X-ray CT data. The skeleton shown in red and yellow is shale.

Some paleontological methods for dating fossils are not as accurate, hence fossil identification must be taken from a multidisciplinary approach (Balaram, 2009). To obtain a better understanding, more than one method should be applied (Taylor, 2000). The development of absolute dating methods can give relatively accurate estimates of a fossil's age compared to relative dating. Overall, the study of paleontology is more than just empirical, and when combined with relative methods, it can give researchers insight into past life and geological events on Earth.

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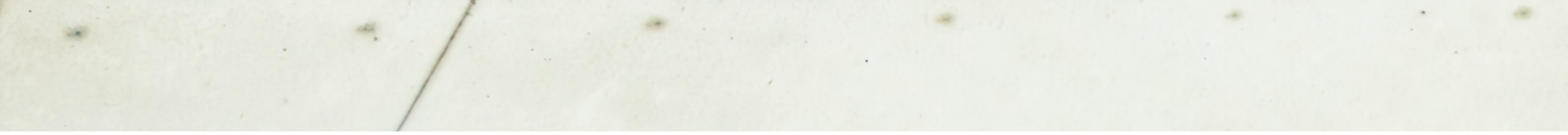
Chapter 4.
Mapping & Exploration

Photograph from the second BANZARE Voyage to Antarctica, 1930-1931.



Chapter 4.
Mapping and Exploration

The articles in this chapter consider the history of mapping and exploration in mankind's quest to understand the world we live in. But beyond this thematic thread, the following articles demonstrate the value of "seeing" in the quest for knowledge. "Seeing is believing" is a trite and overused saying. And yet, perhaps it holds some truth…

From a historical perspective, maps represent a snapshot of how humans interpreted the world at various points in time. Although many maps resemble works of art, accurate mapmaking is highly technical. To portray a curved area thousands of kilometers wide on a small two-dimensional surface requires skill and sophisticated mathematical knowledge. Moreover, mapping is itself a scientific tool. It is a means of visually synthesizing vast amounts of data and observations. When information is presented in a map, patterns are revealed and discoveries are made. Seeing is believing.

While historical maps captured wider and wider horizons over time, they also spurred a natural human curiosity about what lay "unseen" beyond their borders. Exploration takes a hypothesis, a dream, a suspicion of something more and transforms it into reality. It latches onto a shadow and searches for its true cause. Exploration is a mission to discover something new and to see what has never been seen before. And when the sailor cries "land, ho!" or the discovery is made, it becomes apparent that seeing is believing.

While the thread of mapping and exploration runs through this chapter, each article approaches the topic from a different perspective. As you read through the following pages, you will be introduced to the role of Islam in promoting cartography in the Middle Ages and the uses of mapping for agriculture, tourism, taxation, or travel. You will learn how brave individuals persevered and continued to probe the unknown in the face of dangers and prejudice. You will understand how the technologies of mapping have evolved into what they are today. Finally, you will come to realize that in some cases seeing truly is believing.

Geography and Cartography in the Islamic Golden Age

It is a common misconception that religion is something that defies the concepts of science, discovery, and rationality. When one thinks of religion, the first thing that comes to mind is often a belief in a god, or multiple gods. In fact, surveys done in 2014 showed that almost 59% of Americans believe that religion conflicts with science and scientific thought (Funk and Alper, 2015). However, throughout history, religion has often been observed to be a strong driving force for research, and the development of the sciences. Indeed, religion has had an active role to play in the sciences, and religious beliefs have often been the motivation behind research in specific fields (Al-Monaes, 1991). In particular, the religion of Islam has time and again shown its support for scientific research and discovery. Evidence of this is seen in many of the religious texts and scriptures such as the Qur'an. In the Qur'an, it is commanded of Muslims:

"He it is who hath made the Earth subservient unto you, so walk in the paths thereof and ear of its providence" (Khan and Khanam, 2011).

It is this very verse, among many others in the Qur'an, that would have likely sowed the seed of curiosity that sprouted in the hearts of every cartographer, and geographer of the Muslim world (Al-Monaes, 1991). Over 1200 years ago, such fields of geographic science were just being born, and the commandments of Islam were the driving factor.

Caliph Al-Ma'mun: The King Who Loved Science

Every scientific revolution starts somewhere. In the case of the science of cartography and geography, it is often debated as to who really catalyzed it during the Islamic golden age. Between all these debates, there is one thing that is agreed upon: The Caliphs (or Kings) of the Islamic golden age were among the most influential factors for the evolution of cartography and geography in the Islamic world. However, one man stands out the most out of all these leaders. Caliph Al-Ma'mun, who lived from 786 to 833 AD, was a king who not only ruled with justice and compassion, but also showed great interest in science and philosophy (Al-Monaes, 1991).

While the Islamic golden age saw great prosperity and major advancements in all aspects of society, there were still some ruinous conflicts and disagreements. Throughout his life leading up to becoming a Caliph, Al-Ma'mun was witness to constant conflict between various denominations of Islam. People from different denominations often rebelled against each other or oppressed other groups. As a compassionate and just leader, it was only natural that Al-Ma'mun would attempt to unify the Islamic population (Sourdel, 2020).

His first attempt at trying to unify the people involved a more political stance. He tried to hire people from as many denominations as he could, to emphasize that fact that at the end of the day, they were all Muslims (Sourdel, 2020). He even changed the colour of the flag of his region in support of some of the oppressed groups. However, this failed as it was not enough to pacify some of the minorities who were trying to rebel, and incited further bitterness from the majority groups (Sourdel, 2020). Despite this initial setback, Al-Ma'mun was still determined to unite his people. After observing some of the other denominations in his kingdom, he realized that there were many denominations that had a more rationalist view of the religion and were trying to use science and philosophy to explain the religious teachings of Islam. This movement was called the Mu'tazilah movement (Sourdel, 2020). Through more research, Al-Ma'mun grew interested in science as well, and thought that this would be a wonderful way to unite the people of his kingdom. The idea of taking science and applying it to religion was, in fact, the whole basis behind this Mu'tazilah movement, and was adopted by Al-Ma'mun, who at once instilled this in his people (Hourani, 1976; Sourdel, 2020).

The Mu'tazilah doctrine has been described as one that combines religion, philosophy, and science. It requires one to not only believe in all that is told in the Qur'an and act on the commandments of Islam, but to think rationally as well (Hourani, 1976). In terms of its implications on Caliph Al-Ma'mun's kingdom, it would demand the highest religious and moral qualities from the caliph and would allow an unjust caliph to be rebelled against (Sourdel, 2020).

However, it is arguable that the most important impact of the legislation of this Mu'tazilah movement is the strong impact it had on scientific and philosophical thought in the Islamic world. With this more progressive religious movement, many doors were thrown open for the Islamic population. Caliph Al-Ma'mun strongly encouraged the translation of many of the Greek philosophical and scientific works that were extant during that era. In order to further support the Muslim scientific communities, he founded an academy called Bait-al-Hikmah, or "The House of Wisdom" (Sourdel, 2020).

Thus, through one King who was determined to achieve his goals, great change was brought to the Islamic world. He catalyzed the spread of rational thought in Islam and introduced new religiously inclined legislations that would benefit many of the future scientific and philosophical giants of the Islamic golden age.

Al-Biruni: The Critic and Innovator

As the Islamic empire continued to evolve, the seed of rationality and scientific thought began to sprout and grow. Over a century after the rule of Caliph Al-Ma'mun, science continued to flourish throughout the Muslim world. Among many of the distinguished scientists, Abu Raihan Al-Biruni is considered one of the intellectual giants of mankind. He was not only a geographer, but also a distinguished astronomer, physicist, linguist and historian as well. Al-Biruni was born in 973AD in the district of Kath, a town located near the Aral Sea (Saliba, 2019).

During his youth, Al-Biruni was educated by his foster father who was a member of the royal family and was himself a distinguished mathematician and astronomer. Specifically, he introduced Al-Biruni to Euclidean geometry and Ptolemaic astronomy. As Al-Biruni grew older, he became highly skilled in the fields of astronomy, geometry, mineralogy, geography and cartography.

During much of Al-Biruni's life, political turmoil and conflict between kingdoms was commonplace. Everywhere he went, he was witness to rebellions and civil wars caused by unjust leadership. It is believed that for this reason, Al-Biruni travelled a significant amount, often having to look for a new prince to be his patron, while escaping such violent conditions (Adel, 2016). However, despite these setbacks, opportunity presented itself to Al-Biruni. He used his proficiency working with latitude, longitude and compasses to collect geographic information during his travels made to escape from the turmoil and strife (Sparavigna, 2014).

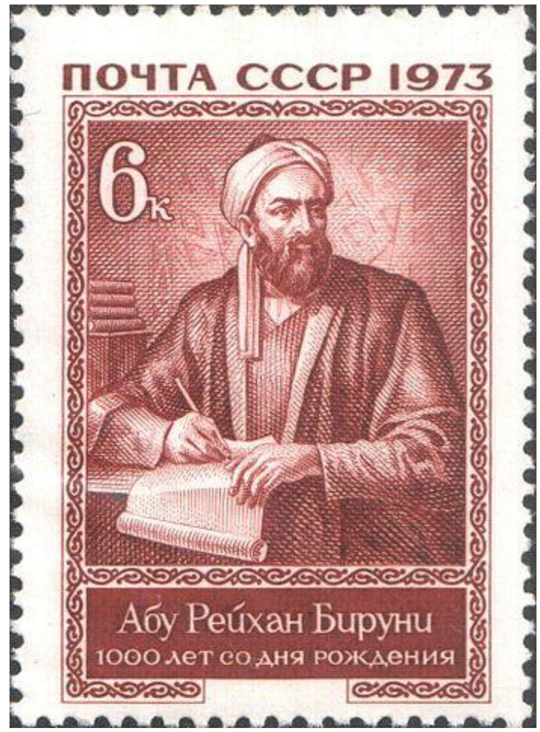


Figure 4.1 A postage stamp from the USSR depicting the well-known Muslim scientist, Abu Raihan Al-Biruni.

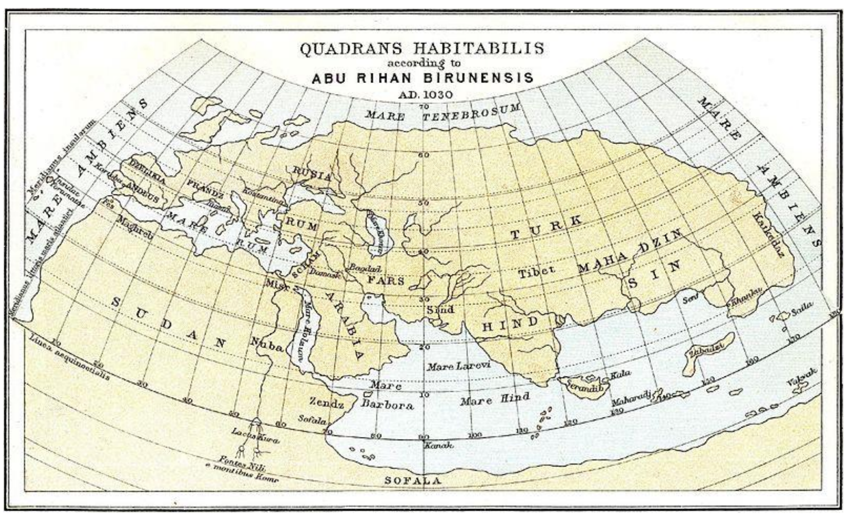
Despite the unstable conditions, Al-Biruni made many major contributions to the field of cartography, one of which was the length of the meridian arc, which is the distance between two points with the same longitude (Saliba, 2019). It is believed that through his journeys or from his studies in geography and cartography, Al-Biruni likely came across the measures of the meridian arcs calculated by the geographers commissioned by Al-Ma'mun a century prior (Schoy, 1924).

Looking back at the reign of Caliph Al-Ma'mun, it is believed that he commissioned many geographers to measure these distances, making geography and cartography an integral part of the Mu'tazilah movement that he introduced to the general population. The measurement of distances and determining longitudes and latitudes was a crucial aspect of geography and cartography for the Muslims, as it was necessary for the creation of sundials to accurately tell the time for prayer. It was also extremely important for some of the larger-scale religious traditions, such as being able to accurately point mosques in the direction of the Kaaba, the main center of worship for Muslims, located in the city of Mecca (Al-Monaes, 1991).

For a geographical concept with such powerful implications on the religious traditions of the Muslims, it would only be natural for a distinguished geographer such as Al-Biruni to have concerns about the methods used for such measurements. It has been hypothesized that Al-Biruni did not completely agree with the method that Al-Ma'mun used for his calculation, which required stretching several ropes over a very long path. Instead of physically measuring the lengths, Al-Biruni proposed to measure the angles (Schoy, 1924). His method began by measuring the elevation of a hill. He then climbed the hill, where he measured the angle of the dip with respect to the horizon. With the obtained angles, Al-Biruni used the law of sines to accurately and efficiently calculate the arc length. Al-Biruni's calculation was extremely accurate, with only a two percent difference from the radius of curvature measured through modern methods (Sparavigna, 2014).

Additionally, Al-Biruni proposed a mathematical method for calculating the difference of longitude between two points. Specifically, he used the mathematical concepts entailing Ptolemy's theorem, and the chord function. Chords were the preferred objects of early trigonometry and were essentially secant lines to circles, used in calculating angles. To obtain the values necessary for these types of calculations, Al-Biruni used the lengths of caravan routes, renormalized by means of a certain coefficient depending on whether the route was direct or difficult. To calculate the difference of longitude between Baghdad and Ghazni in Afghanistan, Al-Biruni applied his own method using three different paths. The final value of longitude had an accuracy of about 1.5%, between Baghdad and Ghazni, and with a difference of longitude of about 24 degrees (Sparavigna, 2014).

Figure 4.2 A map of the known world produced by Al-Biruni. It is titled "Quadrans Habitilis".



The results of such research, in conjunction with the length of the meridian arc, would prove useful for some of Al-Biruni's most notable achievements, such as mapping the globe.

Around the year 1005, Al-Biruni did some work on the mapping of the globe, which he called 'The Flat Projection of Figures and Balls'. In this written work, Al-Biruni discussed several types of map projections. One is the azimuthal equidistant projection, today used for polar projections, which shows all meridians as straight lines (Sparavigna, 2014).

Maps and locational information were crucial parts of geography and cartography in the Islamic world. Not only were they useful for recording the locations of resources and towns, but were also useful for locating the Kaaba, which is important for prayer direction as well as for the Hajj pilgrimage done once a year (Sparavigna, 2014).

Muhammad Al-Idrisi: The Travelling Geographer

Muhammad Al-Idrisi was born sometime in 1100 ca in Sabtah, a Spanish exclave in Morocco. The family of Al-Idrisi held ruling positions in Sabtah for over three centuries. In his youth, Al-Idrisi completed most of his education in the small city Cordoba, located in Al-Andalus. While studying at the University of Cordoba, Al-Idrisi had access to documents on foreign lands that were collected at the institution (Selin, 2008). As a young man at the age of 16, Al-Idrisi completed his formal education and began to travel the world.

He embarked on this journey visiting places in Europe such as England and France. Additionally, his adventures landed him in more remote locations like North Africa and Anatolia.

Figure 4.3 A statue of Muhammed Al-Idrisi

It was through these travels where Al-Idrisi gained a unique perspective through his experiences. It was these perspectives and experiences which influenced his work compared and differentiated him from many other Muslim scholars. In fact, it was during these travels where Al-Idrisi discovered his true passions: geography and cartography (Jwaideh, 2020).

During his travels through Europe, Al-Idrisi began cultivated a strong relationship with King Roger II of Sicily. This King would greatly influence the work of Al-Idrisi. For instance, in 1138, King Roger instructed Al-Idrisi to compose a map in which the locations of all known foreign lands were accurately marked. In addition, the map also had to depict the lands' population, resources, economic makeup, cultures, and customs. It would be the first map of its kind (Masood, 2017). During the same time period, King Roger formed a group of geographers where he appointed himself to the highest position and gave the second highest position to Al-Idrisi. Many of the Muslim geographers that were members of this group were known for their creations of "road books" which were typically used for trade purposes. Furthermore, these works often described routes, cities, and other information useful for travelers (Selin, 2008).

Al-Idrisi's service in Sicily resulted in the completion of three major geographic works. The first being a silver planisphere on which was depicted a map of the world. Second, a world map which consisted of 70 sections formed by dividing the Earth north of the Equator into 7 climatic zones. Lastly, he produced geographic text intended as a key to the planisphere (Jwaideh, 2020). Although King Roger greatly influenced Al-Idrisi, the greatest influence may have been non-Muslim scholars from the group, such as Ptolemy. Throughout his career, Al-Idrisi drew heavily from Ptolemy's Geography in particular (Jwaideh, 2020).

Nearing the end of King Roger's life, he instructed Al-Idrisi to make one final book for him since he was extremely impressed by his previous works. This book would include world geography that displayed the summary of findings of the commission's fifteen-year efforts. It was to be called Al-Kitab Al-Rujari or "Roger's Book" in English. Al-Idrisi gave this book to Roger a few weeks before the king's death in 1154. There are very few details known about the last years of Al-Idrisi's life; however, it is speculated that he continued to follow his passions (Selin, 2008).

Figure 4.4 One of the world maps Al-Idrisi made for King Roger, which consisted of 70 sections. The map was titled Tabula Rogeriana or "Map of Roger".

Modern Methods in GIS and Geodesy

Throughout the Islamic golden age, Muslim geographers like Al-Ma'mun, Al-Biruni, and Al-Idrisi all used physical maps to display data. The process of making these maps was often very tedious and time consuming. The basic components needed to make these maps often had to be derived by hand.

For example, measurements of the shape of the earth had to be made based on various assumptions. During the golden age of Islam, various methods were employed to make these measurements, including surveying (measurements done in the field), as well as computations using mathematical laws (as Al-Biruni did). This was all an early form of what we now call Geodesy, which is the science of studying the size and shape of the Earth (Maling, 1993). However, this tool would not be useful on its own when creating maps. In order to produce maps on paper, or flat surfaces, projections needed to be used. Projections are how the three-dimensional shape of the Earth is mapped onto a two-dimensional surface. Although it may involve some deformities to the actual areas, shapes or distances in the real world, it can still be useful for producing maps for specific purposes (Maling, 1993). Scientists such as Al-Biruni aided in the production of various coordinate systems that would allow for map projections to be made.

Another thing to note was the fact that the scientists mentioned earlier all carried out their work in similar manners. They were travelers, recording everything they could about many of the notable locations they came across in their travels, and summarizing all of it in impressive maps (Al-Monaes, 1991). This process of collecting information and producing maps that reference information based on such locations is essentially the basis of many of the modern methods in cartography geography.

Thus, through measuring the shape of the Earth, projecting that three-dimensional image onto a two-dimensional plane, and assigning information to various locations, highly detailed and accurate maps were able to be produced. Arguably, the former two aspects of cartography and geography are more important to understand in order to make maps. How have such methods of geodesy and making map projections improved and evolved over time? Modern methods, cartography and geography employ many new tools and techniques to create extremely accurate maps.

Geographic Information Systems

Today, a popular and powerful tool used by many in the field of geography and Earth sciences is Geographic Information Systems, or GIS for short. GIS is a collection of computer hardware, software, geographic data, and personnel designed to effectively capture, store, manipulate, analyze, and display all forms of geographically referenced information (Clarke, 1986). This is a tool that builds on what many of the geographers and cartographers of ancient history, such as Al-Idrisi and Al-Biruni, accomplished by hand. Through GIS, all the tools and methodologies such as geodesy, map projections, and georeferencing (assigning information to a location) are integrated. Making maps in GIS involves taking geographic coordinate systems, projected coordinate systems, and georeferencing (University of Wisconsin-Madison Libraries, 2020).

Geographic Coordinate System

A geographic coordinate system (GCS) is essentially a three-dimensional visualization of the Earth and is a reference system that can be used to locate points on the Earth's surface. Due to the three-dimensional nature of the GCS, the units of measurement are angular, hence why locations are referenced in terms of decimal degrees (ARCGIS, 2020). As a consequence of using the angular units, the coordinates of a location can be stated in decimal degrees of Longitude and Latitude. The construction of a complete grid system using Longitude and latitude (called a geographic graticule) is essential in the map-making process, as it provides a starting point from which projections and other manipulations can occur (ARCGIS, 2020). A geographic coordinate system tends to have three main components:

1. An angular unit of measurement, as mentioned above.
2. A prime meridian, which is some line of longitude used as the origin.
3. A datum based on an ellipsoid.

While the first two components are relatively simple to produce, the datum based on an ellipsoid is much more difficult. As seen throughout history, and especially in the Islamic golden age, these datums had to be produced by hand. However, through modern methods in geodesy, the Earth's shape can be accurately measured and used for the purposes of creating these geographic coordinate systems.

Specifically, the use of satellites in modern geodesy is something that has greatly improved the ability to accurately measure not only the general shape of the Earth, but to accurately measure changes in the shape of the Earth caused by various internal or external factors as well. As such, satellite geodesy consists mainly of observational and computational techniques which allow one to solve geodetic problems using precise measurements done between near-Earth satellites (Seeber, 1993). Thus, the datums used in GIS are extremely accurate, and the technological advancements involving satellites has allowed for much better measurements than those seen throughout history. However, datums and measurements of the Earth are only part of a geographic coordinate system in GIS. Other pieces of the overall product have been improved over time as well.

Projected Coordinate Systems

Using the geographic coordinate system, as well as the datum based on the measured shape of the Earth, maps are able to be produced. However, the three-dimensional coordinate system must be projected onto a two-dimensional surface before a proper map can be produced. Projections have been made using various mathematical methods throughout history, such as in Al-Biruni's work 'The Flat Projection of Figures and Balls' where he discussed various projections such as the azimuthal equidistant projection (Sparavigna, 2014).

As explained with geodesy, methods throughout history involved computations done by hand based on surveying and observational data. However, modern methods in making map projections has allowed for better map projections to be made. Unlike geographic coordinate systems, the projected coordinate systems used in GIS involve linear units of measurement (ARCGIS, 2016). These projected coordinate systems result in some deformation or deviation from the actual layout and shape of the Earth's surface (ARCGIS, 2016).

As opposed to the methods employed by the scientists of the Islamic golden age, modern methods in making map projections have been optimized to have the least amount of deviation from true values observed in the real world (ARCGIS, 2016).

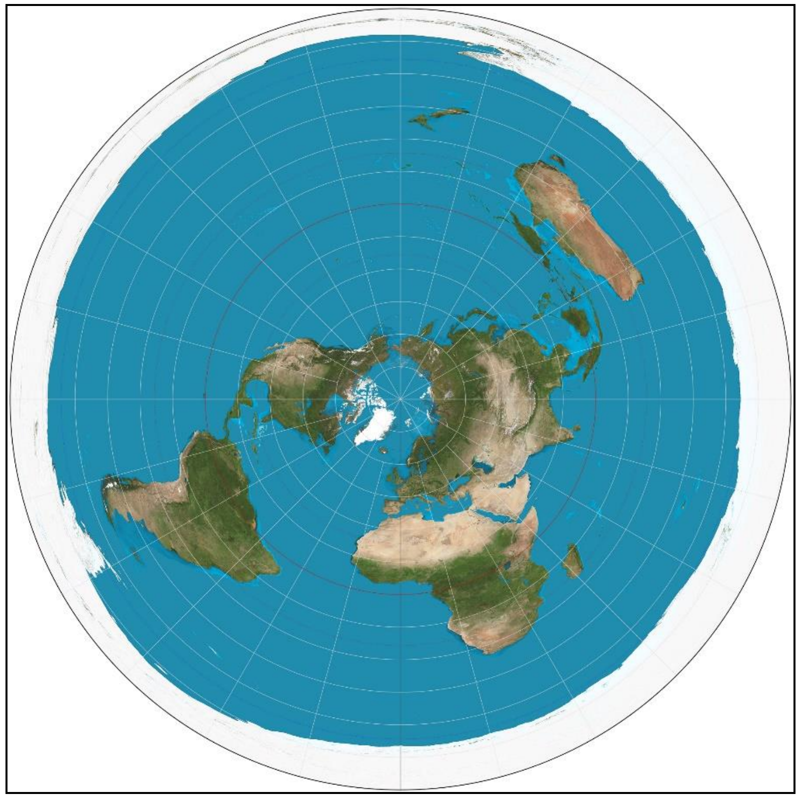


Figure 4.5 A modern version of the azimuthal equidistant projection, as originally described by scientists of the Islamic golden age such as Al-Biruni.

While some projections will cause marginal distortions of area, shape, and direction, other projections may be designed to completely minimize or mitigate the distortion in one or two aspects, such as maps that preserve direction for navigational purposes (ARCGIS, 2016).

As such, from the Islamic golden age to present day, the developments in scientific thought, technology, and methodology can be observed. As a seed sprouts into a sapling, and finally into a tree, geography and cartography were both sciences that came from small beginnings. Their seeds were sown during the medieval atmosphere of the ancient Muslim world, and their influence grew rapidly, resulting in the many branches of geodesy, cartography, and geography that tower over the field of Earth sciences today. All this catalyzed by a religion with a love for science and discover.

Taking Shape: Antarctica from Aristotle to Wegener

Antarctica is the most recently discovered continent. The mainland was not sighted until 1820 yet, prior to its discovery the existence of Antarctica was hypothesized and hotly debated. Cosmologists, explorers and geologists from across the globe have contributed to our current understanding of Antarctica since pre-Hellenic Ancient Greece. Here we hope to bring together Antarctic exploration and the importance of these discoveries to the development of continental drift and our understanding of the history of Earth's surface.

Figure 4.6 An interpretation of Crates' globe. In addition to considering land in the southern hemisphere, Crates' interpreted Homer's description on the sun rise/sun set as two separate populations of Ethiopians in the southern hemisphere. However, Strabo's Geography, in passages unrelated to Crates formulates this image of four land masses separated by Oceanus (Stallard, 2016; Strabo, 1917).

Terra Australis Incognita

In the times of Aristotelian Ancient Greece (384 - 322 BCE), the Earth was generally accepted to be a sphere. The acknowledgement of a spherical Earth was essential to the early conceptions of hemispheres and therefore, the existence of a southern landmass (McClymont, 1892; Stallard, 2016). Philosophers of fourth century BCE recognized landmasses in the Northern Hemisphere known as *oikoumene* (the known or habitable world). The early hypothesis of a southern landmass is largely attributed to Aristotle, due to his recognition of *klimata*, or climate zones, that determined Earth's habitability (Aristotle, 1952). In *Meterologica* (written c. 340 BCE), Aristotle writes that the two habitable zones are the "one, in which we live, towards the upper pole, the other towards the other, that is the south pole" (Aristotle, 1952, p. 179).

Another important figure in the postulate of a southern landmass is Crates of Mallos (c. 180-150 BCE), the creator of the first globe (Figure 4.6). Though there are no records of Crates' writing, Strabo (1917) writes of Crates' recognition of an inhabited southern continent, opposite to and separated from the northern inhabited lands by *Oceanus*. Crates' idea is described as being based on his inability to explain a passage in Homer's *Odyssey* (written ca. 800 BCE) that tells of Ethiopians, that live where the Sun rises, and some others where the Sun sets—before Earth was accepted to be spherical (Homer, ca. 800 B.C.E.).

The symmetry involved in these early theories of a southern continent developed into the idea of *Antipodes*, the belief in principles such as symmetry and balance that govern the Earth; by this logic, a southern landmass must exist for there to be order (Stallard, 2016). The idea of *Antipodes* was not well received in Medieval Times (beginning in the 5th century), a period primarily governed by Christian and Pagan ideologies. This refutation of early Greek philosophers' cosmological theories is exemplified by St. Augustine in *The City of God*: "But as to the fable that there are Antipodes, that is to say, men on the opposite side of the earth…that is on no ground credible" (St. Augustine, 426 C.E., p. 118). However, St. Augustine's problem with the idea of Antipodes, like many others', stems from the presence of Man on a southern continent—which would suggest a second act of Genesis—rather than the possibility of a southern landmass (Hiatt, 2002). The hypotheses of a southern continent persisted through the Dark Ages into the 15th century, which brought about significant changes in the visualization of a southern continent.

Claudius Ptolemy (c. 100-165 CE), the writer of the *Geographia*, revolutionized cartography when it was rediscovered to people in the 15th century, around the same time modern printing was developing, allowing for greater map accessibility (Murray, 2005). It contained a record of known locations organized according to a mathematical grid system, resembling current latitude and longitude. Despite there being no known copies of the original *Geographia*, its popularity in 15th century Europe ensured there were many copies of Ptolemy's work. Early Ptolemaic maps display a southern continent, whose name has evolved to be *Terra Australis Incognita*—the unknown land—as well as a land bridge that connects Southern Africa and East Asia (Figure 4.7) (Stallard, 2016).

Figure 4.7 *One of the earliest known copies of a Ptolemaic map created by Jacopo d'Angelo (interpreter) and Nicolaus Germanus (artist) in Ulm, Germany, 1482 (Stallard, 2016).*

The land bridge proposed by Ptolemy and represented in 15th century Ptolemaic maps was later proven to be false through the 1488 and 1498 explorations of Dias and da Gama (Stallard, 2016). Around this same time, Christopher Columbus embarked on his voyage west, in search of a passage to the East. In 1492, Columbus believed he had reached Japan and discovered a passage to the East Indies but had actually discovered the Americas (Irving, 1878).

Entering the early 16th century, the rapid evolution of the notion of a southern continent is displayed by early modern maps. At this time, followers of Antipodean thought had to reconcile their knowledge with the new discovery of the Americas, and later, the Cape of Good Hope in South Africa. Cartographers such as Duarte Pereira did this by conceptualizing a map in which all landmasses are linked. The next major development is a map created by Francesco Rosselli in 1508 (Figure 4.8). This map displays a southern continent—now detached from South America—alike in shape to Antarctica today (Stallard, 2016).

The enigmatic southern continent did not remain unknown for much longer. Its discovery later in the 16th century is an extension of the transformation of scientific thought from pure theorization to the necessity of ocular verification as demonstrated by Columbus, and the cartographic developments since the Ancient Greeks.

Circumnavigation and the Search for the Southern Continent

Of the early voyageurs involved in the discovery of Antarctica, among the two most notable are Magellan and Drake—both ascribed with the discovery of passages to the South Seas.

Upon hearing of Columbus' discoveries and the voyage across the Atlantic, the Spanish and Portuguese entered a battle to claim ownership of the New World. Magellan (born 1480), a Portuguese-born exile in Spain, pledged allegiance to the King of Spain, Charles V. This

Figure 4.8 Rosselli's world map of 1508 that displays a southern continent with defined magnitude and shape, unlike previous maps. Upon close inspection, C. Antarcticus is inscribed over the small southern landmass, likely representing the current Antarctic Circle (Stallard, 2016).

was largely due to his fervent belief that the Spice Islands to the East could be reached through a passage in the West (Heawood, 1921). Magellan set sail around 1519 and came to discover *Tierra del Fuego*—the newest name of the hypothesized southern continent—and Magellan's Strait around October 1520. This was a breakthrough in circumnavigation: Magellan achieved what Christopher Columbus originally sought to accomplish. This new passage was essential to the trade of riches from the East (Simpkin and Marshall, 1836).

Sir Francis Drake of Britain followed Magellan in 1577, setting sail from Plymouth. Due to a storm, Drake was separated from the rest of his fleet who re-sailed back through Magellan's Strait to England. Drake, however, was pushed south by the waves towards the South Coast of *Tierra del Fuego*. From this deduced that *Tierra del Fuego* was not the *Terra Australis* that people continued to place on maps but was not yet discovered. This changed cartography; the connection between *Tierra del Fuego* and a southern continent was gradually removed. His discovery altered trade patterns significantly; there was now an alternate passage to Magellan's Strait—controlled by the Spanish—that allowed more direct entrance to Asia (Simpkin and Marshall, 1836).

A few hundred years later, Captain James Cook began his voyages of discovery. During his second voyage (1772-1775) he was under order from the British Royal Navy to search for the unknown southern continent. This was mostly prompted by British Admiralty member Alexander Dalrymple, an ardent believer in the existence of the southern continent. Cook, aboard the *HMS Resolution*, accompanied by the *Adventure,* sailed southward, and in January of 1773, Cook and his men crossed the Antarctic Circle—the first in history to do so (Herdman, 1958; Low, 1876). There, the two ships became separated and looked to rendezvous at Good Charlotte Sound, New Zealand. This rendezvous never occurred, as a storm pushed *Adventure* off course. Done waiting, *Resolution* set sail once again towards the South. Cook was met with an impenetrable barrier of ice when crossing the Antarctic Circle for the second time and turned around. From this Cook concluded that no southern continent existed, being only ice, or that the southern continent was much smaller than thought, not at all the expanse of land that people imagined (Simpkin and Marshall, 1836; Low, 1876; Cook, 1777).

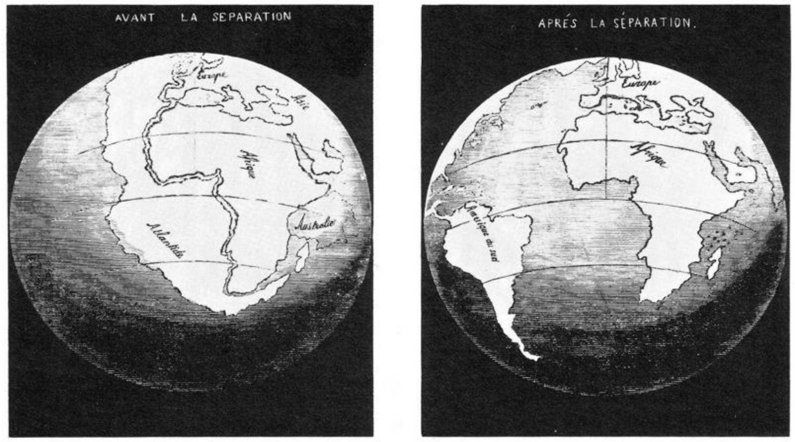


Figure 4.9 The early-Carboniferous supercontinent proposed by Snider-Pellegrini in La création et ses mystères dévoilés. On the right, the inscription reads "Après la séparation" (after the separation) and on the left it reads "Avant la séparation" (before the separation) (Holmes, 1944; Snider-Pellegrini, 1859).

The next major expedition to the unknown southern continent was by Russian, Fabian Gottlieb Thaddeus von Bellinghausen in 1820. This was prompted by Tsar Alexander I, in a display of his Navy's strength (Cook, 1901). The Russian Antarctic expedition (1819-1821) brought Bellinghausen towards land; however, ice prevented them from anchoring on land. Despite this, Bellingshausen is recognized for being the first to catch of glimpse of the continent (Gould, 1948).

The Russians were not alone in this discovery; though Bellinghausen was the first to sight the continent, the British and the Americans had also sent ships to search the South Seas. William Smith, discoverer of the South Shetland Islands, and Eduard Bransfield of England were the first to touch land on what is known today as the Antarctic Peninsula. The British, headed by Nathaniel Palmer happened upon Trinity Island—sometimes known as Palmer Land—off the coast of the Peninsula much later (Tammiksaar, 2016).

Changing Views of the Earth and its Movement

Around the same time Magellan and Drake neared the Antarctic Peninsula, that Abraham Ortelius created the first world atlas. It is believed that he was the first to recognize the similar shapes of the Eastern South American and Western African coasts. However, he described the process that separated the two continents as a great flood or earthquake. Other early theories on the movement, or rather the immobility of continents in some cases, stem from stories of Genesis in the Bible. These explanations fit a catastrophist point of view; the dominant geological ideology proposed by Baron Georges Cuvier (1769-1832). Catastrophism—the idea that the Earth's surface changed due to sudden, violent events— went unchallenged until the 18th century. James Hutton then proposed that the Earth has been changing and continues to change in the present saying: "we find no vestige of a beginning, —no prospect of an end" (Hutton, 1795, p. 248). Charles Lyell's *The Principles of Geology* (1830) furthered this idea, by proposing what is commonly known as uniformitarianism. This revealed the massive rift among members of the geology world; despite this, uniformitarianism was generally accepted as the primary ideology by the late 1800s. Recognition that the Earth was old and could have changed slowly over a long period of time was essential to future developments in geology.

In 1859, French geographer Antonio Snider-Pellegrini published *La création et ses mystères dévoilés,* which saw the return of the cartographic idea that all the continents were fused (Figure 4.9). However, Snider-Pellegrini attributed the continental split to a flood of Biblical proportions.

The publication of *Das Antlitz der Erde (The Face of the Earth),* by Austrian geologist Eduard Suess was a tipping point for the understanding of continental movements. He aimed to describe the origins of mountains, the oceans, and continents. In it, Suess uses the term Gondwana —originally coined by Medlicott in 1879 when describing the stratigraphic Gondwána system of India (Medlicott, 1879). Suess' Gondwana was a combination of three continents: Africa, Europe and Asia and was defined by the similar *Glossopteris* flora found in each of these regions. He attributed this to past land bridges between these landmasses that were subsequently infilled by ocean (Suess, 1904; Torsvik and Cocks, 2013). Suess, unable to explain the later movement of continents, continued to subscribe to contractionism—the idea that Earth was continually shrinking as Earth's molten surface cooled (Frankel, 2017). Though the process Suess describes was incorrect, his concept of Gondwana is essential to later developments by Wegener.

Figure 4.10 The division of Antarctica plotted by Markham – the Weddell and Enderby Quadrants were given to the Germans, while Britain received the Ross and Victoria Quadrants (Lüdecke, 2003).

Frank Taylor's paper (1910) focused on the origins of the Tertiary mountain belt, something poorly explained by Suess through contractionist theory. Instead, he came up with the idea that the large continents began far apart at the poles and when brought together caused the land to crumple, forming the mountains. The fault in his ideas was the assertion that the movement of the continents was of astronomical origin—due to the pull of the Moon (Laudan, 1985; Taylor, 1910). Unlike Suess' proposition of Gondwana, Taylor included the Antarctic lands in his discussion on drift, stating that unlike South America and Australia, the Antarctic land "held fast" (Taylor, 1910).

The Heroic Age of Exploration

The importance of Abraham Ortelius' atlas was not lost on later generations. In 1869, his home country of Belgium had plans to erect statues of him and fellow geographer Gerardus Mercator. The Belgian intellectual and geography enthusiast Charles Ruelens was inspired by this to propose an international meeting, dedicated towards the pursuit of geography and peace. This gathering, the first International Geographical Congresses, took place in 1871 (Shimazu, 2015).

Subsequent congresses garnered international anticipation for multinational polar expeditions

(Royal Geographical Society, 1896). However, The Seventh International Geographical Congress saw a shift in peoples' ambitions: countries began expressing their desire to plan independent expeditions. Englishman Clements R. Markham proposed splitting Antarctica into four quadrants: two free for the Germans to explore, and the other two for his homeland (Figure 4.10) (Luedtke, 2011). The planning of these expeditions marks the beginning of the Heroic Age of Antarctica Exploration (Larson, 2011).

Markham, a member of the Royal Navy, was primarily interested in Antarctic exploration because of the possibility of new land and for the opportunity it provided young naval officers. Markham had several candidates in mind, including the young officer Robert Scott (Day, 2013). In 1900, the young Scott was put in charge of the British National Antarctic Expedition, despite his complete lack of interest in polar science and experience The expedition, which lasted from 1901-1904, was a success for several fields of science, despite the lack of experience of many of the crew members. One of these crew members was Ernest Shackleton, who later led his own Antarctic expedition in 1907. Ending in 1909, the expedition saw one of Shackleton's leading men, Frank Wild, being the first to locate coal in the southern continent (Rose and MacElroy, 1987; Stonehouse, 2002). These closely matched coal-bearing rocks of Australia, India, and southern Africa, fitting neatly with the recent hypothesis of Gondwana (Harley, Fitzsimons and Zhao, 2013).

Perhaps the most important discovery of this era was made by Scott on his second and final expedition to the southern continent. The story of this expedition is now famous: hoping to claim the South Pole for Britain, Scott and his crew eventually reached the Earth's southernmost point, only to find that a Norwegian team led by Roald Amundsen had beaten them to it. Returning from the South Pole, the team was met with bad weather, taking the lives of Scott and four of his men (Stonehouse, 2002). While he may not have achieved his greatest ambition, he located fossilized leaves that were later determined to belong to the plant *Glossopteris*. As fossils of this plant had been identified in South America, South Africa, Australia, and New Zealand, Scott's discovery would profoundly influence future theories on the origin and history of Earth's continents (Tewari et al., 2015).

Alfred Wegener's Theory of Continental Drift

The German Antarctic Expedition of 1901-1903, another undeniable success for scientific data collection (Lüdecke, 2006), inspired the young German scientist Alfred Wegener to pursue polar expeditions. Having just received a Ph.D., Wegener managed to get a spot as a meteorologist on a 1906-1908 expedition to Greenland. In 1910, two years into his role as a professor in Germany, he was gifted an atlas. It was poring through the atlas that he came upon an observation that many had before: the striking similarities between the shapes of the coasts of South America and Antarctica. This led Wegener to believe that they were, at one time, connected (Greene, 1984).

Wegener, a member of the German army, was called to fight in the First World War. He was sent home after receiving a shot to the neck, allowing him to work on his theory of continental drift. This theory was revealed in *Die Entstehung der Kontinente und Ozeane (The Origin of Continents and Oceans),* published in 1915 (McCoy, 2006). Likely foreseeing the controversy with which his ideas would be received, the work devoted five chapters to a different type of evidence each: geophysical, geological, paleontological/biological, paleoclimatic, and geodetic. Scott's *Glossopteris* discovery is mentioned as evidence that the continents moved; there is no way, argued Wegener, that a plant could grow in the modern climates of the locations on which it was found fossilized (Wegener, 1924). While scientifically rigorous, Wegener made the book more accessible for broader audiences. He gave his readers a gentle introduction to his postulates by discussing the striking pattern that he and so many more before him noticed by simply looking at a world map: "He who examines the opposite coasts of the South Atlantic Ocean must be somewhat struck by the similarity of the shapes of the coast-lines [sic] of Brazil and Africa" (Wegener, 1924, p.1). Wegener was not particularly clear on the mechanism by which continental drift occurred, perhaps regrettably, as the lack of a mechanism became one of his critics' favourite talking points (Powell, 2015). He attributed it to "the displacing forces" (Wegener, 1924, p.190), which he thought may have been caused by the Earth's gravity, the gravitational pull of the Sun and Moon, or convection currents. The ideas regarding these forces, he wrote, were "too much in a state of flux" for a satisfactory answer to exist (Wegener, 1924, p.5).

While Wegener was not the first scientist to propose a theory of continental movement, his book was the first that, due to its range of evidence, could not be dismantled easily. Because of the complexity of Wegener's arguments, rebutting each individual point became a multinational effort, and Wegener was highly criticized at conferences in the years following. In spite of this scorn, Wegener undeniably influenced the geology in the 90 years following (McCoy, 2006).

Post-WWII Exploration and the Acceptance of Continental Drift

The tensions of the Cold War produced some of the most influential mapmaking since the time of Ortelius. Made nervous by the encroaching risk of submarine warfare, the United States Navy sent out geologists such as Bruce Heezen to collect bathymetric data (Dierssen and Theberge Jr., 2013). His colleague, Marie Tharp, painstakingly sifted through Heezen and others' data, with the goal of crafting a seafloor map (North, 2010). The map produced—the Heezen-Tharp map— revealed a massive chain of large mountains running across the Atlantic called the Mid-Atlantic Ridge (Figure 4.11), whose length and height was a surprise to the scientific community (Powell, 2015).

In the 1950s it was also discovered that cooled magnetic rocks contain a record of the direction of the North Pole at their time of cooling, with the electrons in iron atoms pointing North. This new field of study, named paleomagnetism, was a breakthrough—if Wegener's theories were correct and the continents moved, then magnetic rocks would contain an archive. A team led by Nobel Prize winner P.M.S. Blackett performed a paleomagnetic examination of British rocks and found incongruences between the rocks' record of the North Pole and its current location—evidence that the continents had moved. However, there was a dilemma, as there was another explanation: The North Pole could have been moving, not the continents. Ted Irving noted that this could be tested by finding rocks from the same time period at different locations. If the rocks pointed towards a different pole, then it was clear that at least some of the movement was of the continents themselves (Powell, 2015).

It was not long after that a breakthrough was made by geologist Ken Creer. After extensively mapping the paleomagnetic properties of British rocks, Creer compared his findings to paleomagnetic findings from rocks in the United States in 1954. Mapping it out, his conclusion seemed certain: neither the continents nor the North Pole had stayed still throughout the Earth's history (Powell, 2015). 11 years

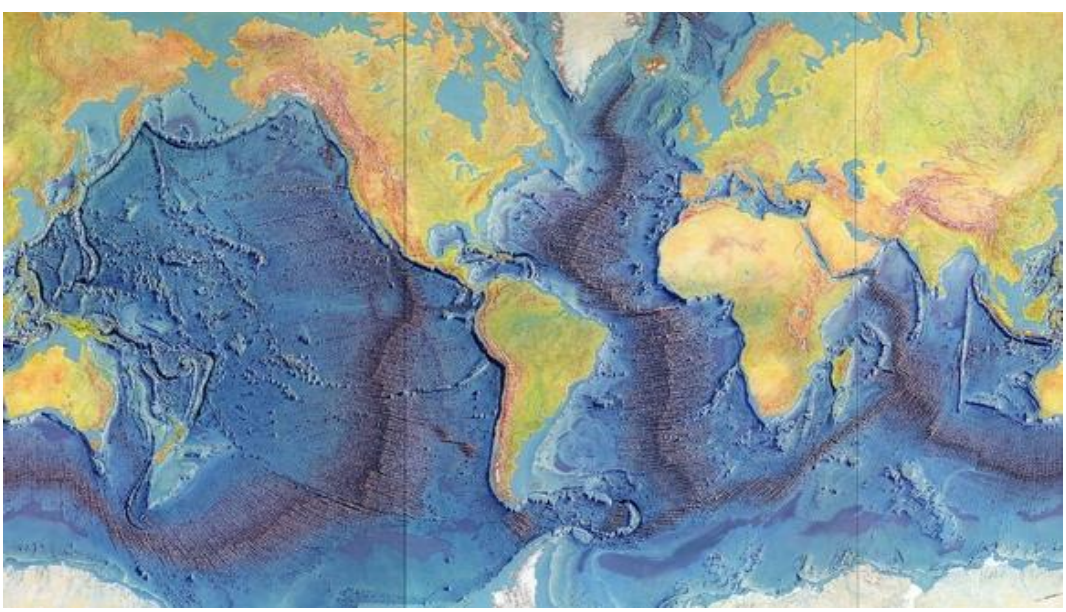


Figure 4.11 The now-famous map showing the exaggerated seafloor (Dierssen and Theberge Jr, 2013), painted by Austrian cartographer Heinrich Berann.

later, Creer used paleomagnetic evidence from the continents that formerly made up Gondwana—Africa, India, South America, Australia, and Antarctica—as support for continental drift (1965).

It was at a similar time that American geologist Harry Hess described his theory that later became known as "seafloor spreading" (Powell, 2015). Noting that mid-ocean ridges (such as the Mid-Atlantic Ridge) often appeared at the midpoint between two continental basins, he suggested that oceanic crust is formed at ridges and then flows outwardly in either direction. Crust then disappears in deep-sea trenches at depths of over 10 km, explaining why oceanic crust was always dated at no older than 300-400 million years old. Before, opponents of continental drift had questioned how continents could have been able to move through oceanic crust; now, it was clear that they moved with it (Stanley and Luczaj, 2015).

In 1965, Canadian geologist J. Tuzo Wilson noted that movements of the Earth's crust seemed to suggest the existence of what he referred to as "mobile belts". He suggested the existence of a "continuous network" of these belts underneath the Earth's surface, dividing it into "several large rigid plates" (Wilson, 1965, pg. 1). This theory, later named plate tectonics, has massive implications. A review of seismologic data supported this theory by showing the link between plate boundaries and earthquake activity. Finally, the elusive mechanism for continental drift had been found, and Wegener's hypothesis was no longer the laughingstock of geologists (Powell, 2015). Still, geophysicist Harold Jeffreys, along with several paleontologists, found this magnetic and physical evidence insufficient and refused to change their minds until fossil evidence was provided. Although Jeffreys never truly accepted the theory (Powell, 2015), additional Antarctic exploration in the 1960s provided the fossil evidence he claimed to want. In 1967, Peter J. Barrett found an amphibian lower jaw fossil, making Antarctica the last large landmass in which ancient fossils of terrestrial vertebrates had been found (Figure 4.12). In 1969, more vertebrate fossils were found in Antarctica, including *Lystrosaurus*, a Triassic genus also found in southern Africa, India and China (Elliot et al., 1970). Elliott et al., wrote that "the present position of Antarctica, with its assemblage of Triassic land-living amphibians and reptiles, can be explained only by continental drift from a former position contiguous to Africa" (1970, p.1200). Other fossils found around this time included Jurassic-era ammonites (Quilty, 1970), trails and burrows thought to be traces of Devonian organisms (Webby, 1968), woody gymnosperm plant fragments resembling those found in the other southern continents (Plumstead, 1975), and Devonian bivalves (McAlester and Doumani, 1966). This more recent fossil evidence, like Scott's *Glossopteris* fossils and Wild's coal, suggests that Antarctica once had a temperate climate (Cracraft, 1973). During this period, stratigraphic sequences in Antarctica were shown to have strong correlations to South America, India, South Africa (Doumani and Long, 1962), and Australia (Hamilton, 1963).

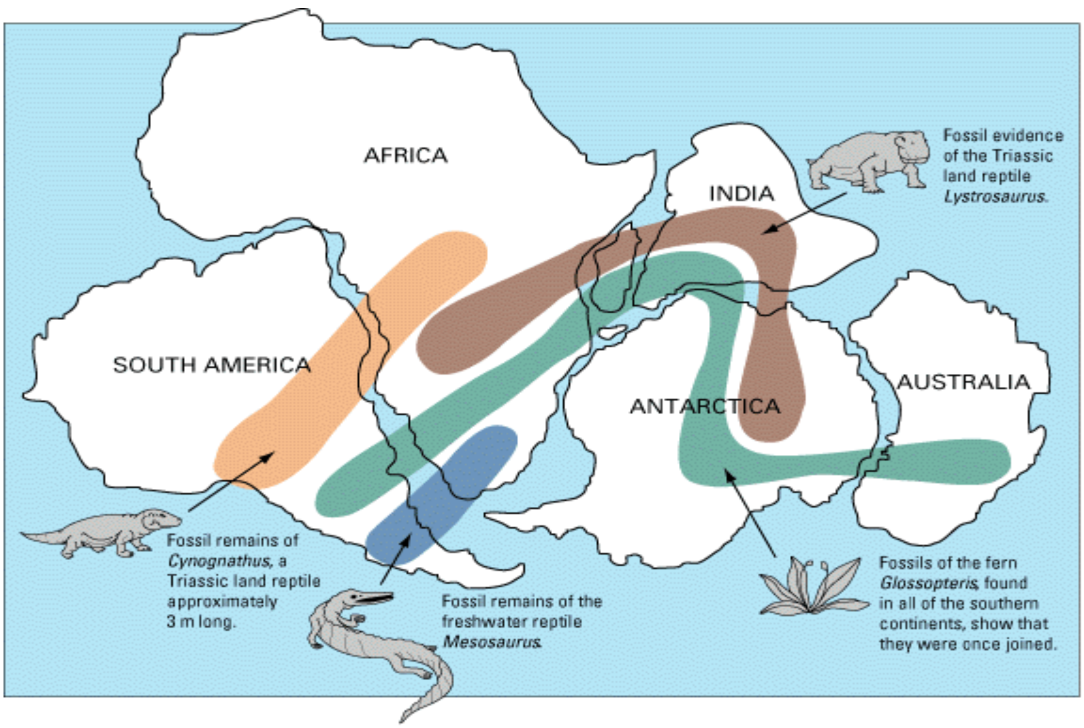


Figure 4.12 The distributions of various plant and animal fossil taxa compared to the proposed position of continents at the time of the supercontinent Gondwana.

Present Inquiries into the Past

Modern Antarctic research is fueled by both recent technological advances and a better understanding of geological processes. However, these advancements are based on ideas of the past. Evidence of Wegener's continental drift continues to be examined in Antarctica through further examination of rocks on the surface. Studying these rocks with modern technology allows scientists to discover specific properties of the rocks, with one of the most relevant being age.

U-Pb Dating

One of the most important technological advances in the field of geochronology is Uranium-Lead (U-Pb) dating. This form of dating is primarily used for igneous rocks and uses the radioactive decay of Uranium-238 (^{238}U), which has a half-life of approximately 4.468 billion years (Holden, 1981). The final product of this decay is Lead-206 (^{206}Pb). Using mainly the relative abundances of ^{238}U and ^{206}Pb, as well as the half-life equation, the approximate age of a given material can be calculated. However, other factors, such as initial leads present at the time of formation, and the loss of lead due to radiation damage must be factored in when calculating the age of a rock (Parrish, 2014). While this method was first applied early in the twentieth century, new tools continue to be built that help to increase measuring capabilities and precision.

SHRIMP Analysis

Sensitive high-resolution ion microprobe (SHRIMP) analysis is commonly used for U-Pb dating and is frequently used in modern Antarctic studies. Created between 1975 and 1980 by Stephen Clement, a Ph.D. graduate from the Australian National University, this technology was created out of a need to analyze higher mass resolutions with higher sensitivity (Compston, 1996; Ireland et al., 2008). SHRIMP can perform multiple *in situ* analyses of Zircon crystals. Additionally, SHRIMP analyses have the benefit of being close to non-destructive, as they only consume a few nanograms of the material (Ireland et al., 2008). This technology functions with the use of Secondary-Ion Mass Spectrometry (SIMS). In SIMS, a primary ion beam is aimed at a surface, eroding it. This ejects a fraction of atoms from the surface, which are then ionized, forming secondary ions. These secondary ions are then analyzed using mass spectrometry. The secondary ions that are emitted from a surface are determined by the type of primary ion beam used (Compston, 1996; Ireland et al., 2008). For example, if an oxygen primary beam is used, alkali metals are almost completely extracted (Ireland et al., 2008). As a result, SIMS can analyze a variety of different surface materials. The larger size of the SHRIMP machinery allows for wider slits that can accept a higher number of ejected ions (Compston, 1996; Ireland et al., 2008; Parrish, 2014). This leads to the higher sensitivity of SHRIMP devices, which is essential for geochronology, as slight errors in measurement could be representative of millions of years in geologic time. The first iteration of SHRIMP found success, as it was capable of dating Hadean rocks in Western Australia over 4 billion years old (Ireland et al., 2008; Parrish, 2014). After this, further research was put into refining the system and SHRIMP was developed for commercial use. SHRIMP analysis became a primary tool soon after and has since been responsible for major discoveries in Antarctica and around the world.

The Breakup of Gondwana

In the early 1990s, research on the Gondwanan supercontinent began to shift towards investigating the mechanisms behind its breakup. One group, called the South Pacific Rim International Tectonic Expedition (SPRITE), investigated the Pacific margin of Western Antarctica in the summers between 1990 and 1993 (DiVenere, Kent and Dalziel, 1995; Weaver et al., 1994). This expedition was performed with the purpose of investigating the breakup mechanism between Antarctica and New Zealand in the mid-Cretaceous period. The study focused on the information obtained from the various igneous rocks present in Marie Byrd Land (Figure 4.13). Based on the chemical composition of the rocks, the researchers were able to classify them into three possible suites. Suite 1 rocks consist of igneous-type (I-type) granitoids, which are granite rocks from an igneous source. This type of rock is associated with the melting of crust, and as a result, are indicative of a once present subduction zone (Weaver et al., 1994). These rocks were dated to be between 108 and 124 million years old. Suite 2 rocks consist of anorogenic-type (A-type) granitoids, which are more commonly found at continental rifts (Weaver et al., 1994). These A-type rocks were dated to be between 95 and 102 million years old and comprised 75% of the surface of the study area (Weaver et al., 1994). This information led to the formation of a hypothesis that the separation between Antarctica and New Zealand began approximately 105 million years ago (Weaver et al., 1994). At this time, the once-existent Phoenix plate was completely subducted and melted at the New Zealand-Antarctica boundary, leaving behind traces in the older I-type granitoids. Following this, a continental rift between these two bodies began to form, as New Zealand and Antarctica were separated (Weaver et al., 1994). The evidence for this is in the younger, A-type granitoids, which suggest that continental rifting occurred after subduction.

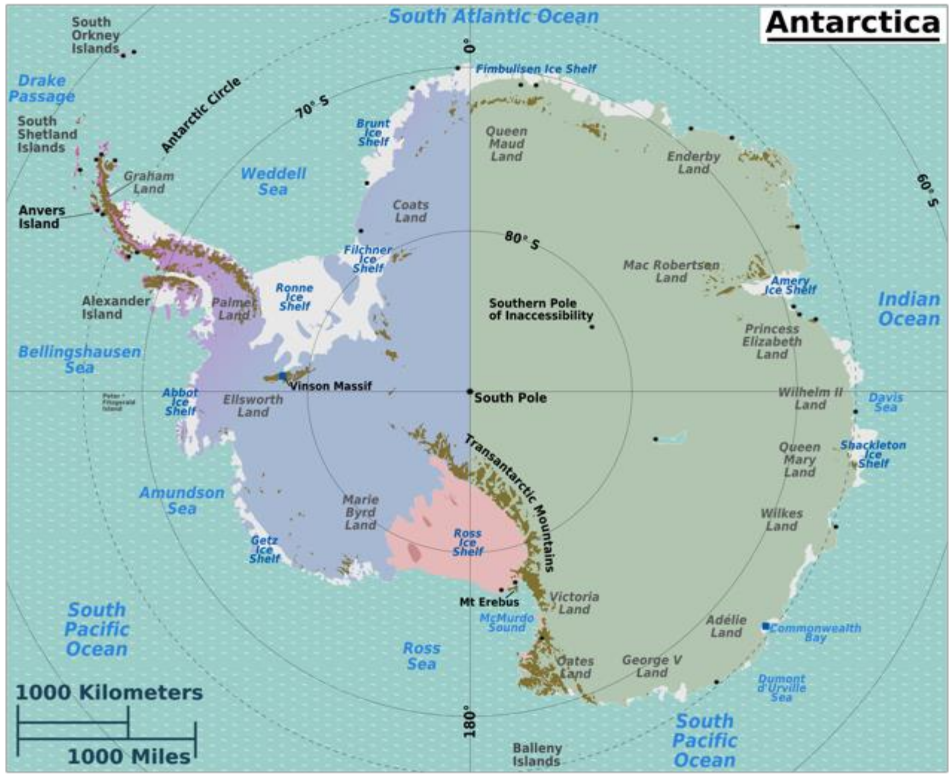


Figure 4.13 Labelled map of modern Antarctica showing regions of the continent. Marie Byrd Land and Queen Maud Land are both locations that were studied for tectonic information (Grantham et al., 2008; Weaver et al., 1994).

Applications of SHRIMP to Gondwana

In more recent years, SHRIMP has been applied to investigate the tectonic processes of Gondwana. One study from Grantham et al. in 2008 investigated the correlation between rocks found in Antarctica, Mozambique, and Sri Lanka, and its applications to the geology of Gondwana. SHRIMP was used to date zircon crystals in both Mozambique and Queen Maud Land with respect to both the crystallization age and the age of metamorphic events (Grantham et al., 2008). It was found that between these two locations, the ages of both crystallization (470-500 Ma and 950-1000 Ma) and metamorphosis (450-650 Ma and 950-1200 Ma) were close to identical. Sri Lanka, despite having an overall lack of data, also had rocks that approximately match the ages found in Mozambique and Antarctica (Grantham et al., 2008). In addition, the exposed rocks in both Mozambique, East Antarctica, and Sri Lanka were highly sheared in certain regions. The higher level of shearing is indicative of a thrust fault, which, given the age of the metamorphic events, occurred between 590 and 550 million years ago (Grantham et al., 2008). It was formulated that the terranes in Antarctica, Sri Lanka, and Mozambique were once part of a mega-nappe, which is a large section of crust that is thrust-faulted over another section of crust (Grantham et al., 2008). This nappe, part of Northern Gondwana, was thrusted 600 km over Southern Gondwana during this time. The exact barriers of this mega-nappe are unknown due to high levels of erosion that destroyed evidence in Africa; however, evidence of this thrust fault remains in Antarctica in the form of zircons deposited in the Transantarctic Mountain Range (Grantham et al., 2008).

Despite the difficulties of exploring such a remote area, Antarctica harbours information that is well worth the search. Throughout history, Antarctic expeditions have been among the most dangerous, leading to several casualties. However, the information obtained from the southern continent is vital towards our understanding of the underlying mechanisms that change the Earth

History of Exploration and Speleology in Mammoth Cave

The Mammoth Cave in Kentucky, USA has long inspired and captured the attention of the world. This cave system is currently the longest in the world with 667 kilometres of discovered cave passages; however, active exploration of the cave continues to grow this number as new passages and connections are discovered (Sutton, 2017).

Mammoth Cave has been established as a National Park since 1941, with over 200 square kilometers of land on the property (Palmer, 2004). Due to the cave's geological, biological, and archaeological significance, the system was designated as a World Heritage Site in 1981 and

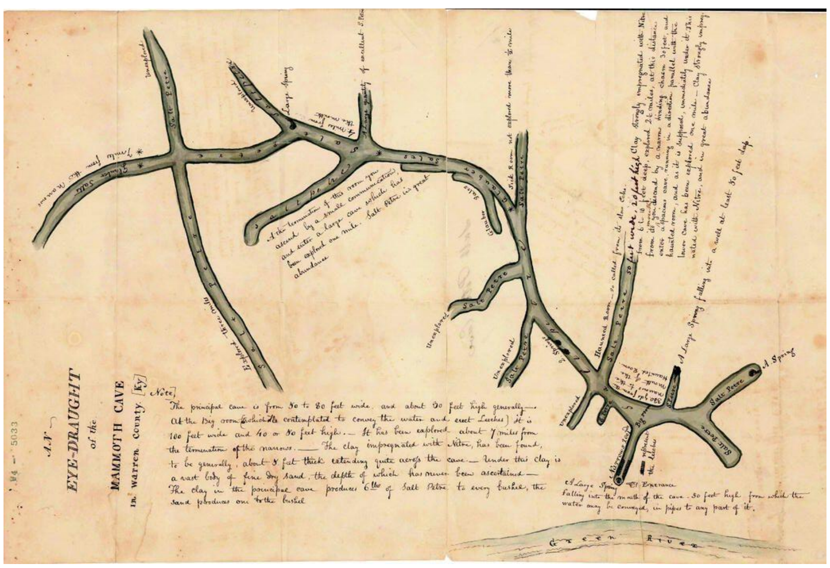


Figure 4.14 The Eye-Draught Map of 1811, published in the 1853 edition of Jefferson's Notes on the State of Virginia. The map covers the Main Cave and junctions with major side passages.

an International Biosphere Reserve in 1990 (Palmer, 2004). Although 1.7 million annual visitors to the cave are permitted to walk 15 kilometres of passageways with tour groups, the majority of the cave system is restricted to ongoing mapping and research (Palmer, 2004).

Exploration and use of the cave go back 4000 years to when Archaic indigenous peoples used reed torches to travel the cave passages, discovering and systematically mining multiple kilometres of the passageway for the gypsum crusts and flowers on the walls and ceiling of the caves (Palmer, 2004; Watson, 2005).

Detailed mapping of the Mammoth Cave began in the early 19th century and is ongoing today. Cartography and surveying work was especially important because it set a new standard for mapping and was an anomaly. In the past, explorers would discover new lands and map these areas for further reference and orientation purposes. However, cartography fueled exploration at the Mammoth Cave, as explorers used early maps to make more discoveries.

"Mapping is never the innocent process it first seems [...] for it works hand in hand with exploration to first intrigue, then inform, and ultimately seduce."

–Dr. Francaviglia (Brucker, 2008).

The Eye-Draught Map

The Mammoth Cave was mapped parallel to the mapping of North America, starting around the early 17th century with rudimentary maps (Sutton, 2017). The first recorded map of the Mammoth Cave was the Eye-Draught Map of 1811, which was more of a sketch than a survey (Hovey, 1899). The map had three different versions, the most prominent being a published version in the 1853 edition of Jefferson's *Notes on the State of Virginia*. The so-called Jefferson map shows the entire Main Cave area, as well as junctions with the major side passages. It specifically outlines the locations of calcium nitrate and salt deposits in Mammoth Cave, which are the cave's main industrial products (Meloy, 1975). Since these products are clearly outlined, the maps are thought to have been made to tempt potential buyers of the cave land. For example, with the War of 1812 on the horizon, Jefferson would be interested in the potential of acquiring war supplies, so calcium nitrate could be used to manufacture gunpowder. Although its purpose was increasing profits, this map did have a significant impact on exploring the cave system. It was responsible for naming some of the places inside the Mammoth Cave, as well as coining the name of the cave itself. The map's author is anonymous; however, the most likely candidate is Fleming Gatewood Sr., who co-purchased the cave in 1810.

The Foundational Map

By the winter of 1834, Mammoth Cave was an established tourist site, complete with a small guide force and a hotel (Sutton, 2017). During this time, the 24-year-old civil engineer Edmund F. Lee was hired to conduct the first survey of the cave (Meloy, 1975). He used specific-length chains, markers, and compasses for three months to create an extremely comprehensive map. The masterpiece revealed 13 kilometres of the caves, using colours to indicate the lower levels and many cave rooms including the Main Cave and the Bottomless Pit. Although the map was slightly incorrect when it came to pit dimensions, it was very accurate for its time and set the basis for the maps to come. Furthermore, Lee's map included survey notes that showed the cross-sections of passages, as well as the vertical profiles of the tunnels, which was innovative for his time (Lee, 1835). Although it was speleologically significant and a beautiful example of early cave cartography, the Lee map was most likely used for commercial purposes to sell the Mammoth Cave to Franklin Gorin in 1838. However, this was still a cartographic masterpiece, and it would be around forty years before another map with this much detail would be produced.

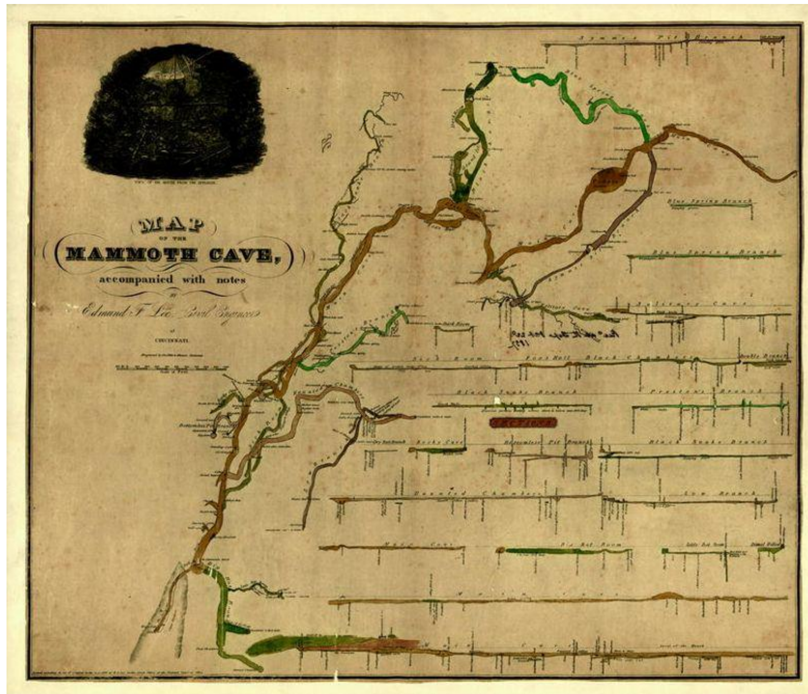


Figure 4.15 The 1835 Edmund Lee map shows 13 kilometres of Mammoth Cave and uses colours to indicate the lower levels and cave rooms, including the Main Cave and the Bottomless Pit.

The Bishop Map

Lee's map was highly celebrated and was in print for sixty years after it was made. However, three years after Lee published his map, Stephen Bishop, a black slave cave guide, crossed the Bottomless Pit and suddenly Lee's map became outdated (Sutton, 2017). This made a large part of the cave accessible to exploration, and Bishop then became the leading expert on the geography of the passages

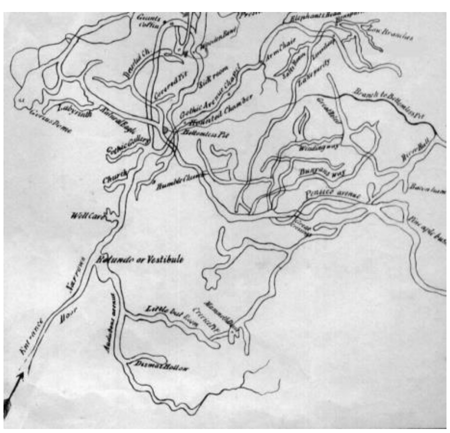


Figure 4.16 Stephen Bishop's 1842 Map of the Explored Parts of the Mammoth Cave of Ky, published in the Rambles in the 1845 Mammoth Cave guidebook.

beyond the rivers. Even when the ownership of Mammoth Cave was changed, Bishop was sold as a part of the land package due to his vast geographical knowledge (Sutton, 2017). In 1842, Bishop convinced his slaveholder to publish a map with the newly discovered passages, spending weeks to create an up-to-date map, consulting the Lee map for certain portions of the cave. The final product was well below standard for the maps of the time, lacking scales, compass directions, and colours. However, it was a huge advance in geographic coverage (Bullitt and Croghan, 1845). It also changed societal norms considering a self-educated slave became the published author of a popular map.

The motivation of this map was tourism potential, and was published in *Rambles in the Mammoth Cave*, the standard guidebook for several decades (Bullitt and Croghan, 1845). However, as tourism grew for the cave, managers of the estate became worried that the maps being produced would show that the cave runs beyond their estate, creating potential competition for their tourism business. In 1849, no surveys of the new passages discovered by Bishop were permitted, and many maps were hidden away from the public so that explorers would not discover the vastness of the cave (Sutton, 2017). These restrictions continued for the next few decades, and maps that were created were suppressed and unpublished until many were brought to the light by Horace Hovey's Mammoth Cave guidebooks.

The Hovey Era

Hovey created many different Mammoth Cave guidebooks between 1882 and 1912, many with versions of the earlier maps, including the Bishop sketch for newly discovered passages. He also included details such as profile views of pits around the Bottomless Pit, with depths measured by plumb line and the heights by balloon (Hovey, 1899). Hovey's guidebooks are the earliest account of the Mammoth Cave's cartographic history, and he is credited with being one of the greatest promoters of the Mammoth Cave. He brought the spotlight back to the cave even after survey restrictions from the estate managers, allowing explorers and scientists to regain interest in the cave, including Max Kämper (Sutton, 2017).

The Famed Map

Max Kämper's 1908 map of the Mammoth Cave was the one that eventually became the best known (Daunt-Mergens, 1981). Kämper was a mining practices student who visited the cave in 1908 and was inspired by its vastness. He proposed a survey of the cave, and the manager of the estate finally allowed the survey to be conducted, seeing the advantage of having an accurate map for his own use, with no intention of publishing the map to the general public (Daunt-Mergens, 1981). Kämper spent eight months using a good surveyor's compass, a measuring chain, and a journal to describe his daily activities (Olson, Kliebhan and Toomey, 2013). On the first day, the journal outlined that Kämper's first discovery was Gerta's Grotto, named after his lover, Gerta Luyken. He continued to survey the cave and proceeded to conduct the most comprehensive cave survey at the time.

The final product lacks an explicit scale and north arrow; however, this information was encrypted into the map through an entrance arrow that pointed to the southeast, and seven circles that showed the scale of 1:4000 (Olson, Kliebhan and Toomey, 2013). Kämper's map was innovative not only for its details and accuracy but also because it used different colours to show distinct level passages, making the map three-dimensional. Furthermore, the map is a large source of information regarding the names of the places in the Mammoth Cave, with a total of 340 different place names, around 100 named by Kämper.

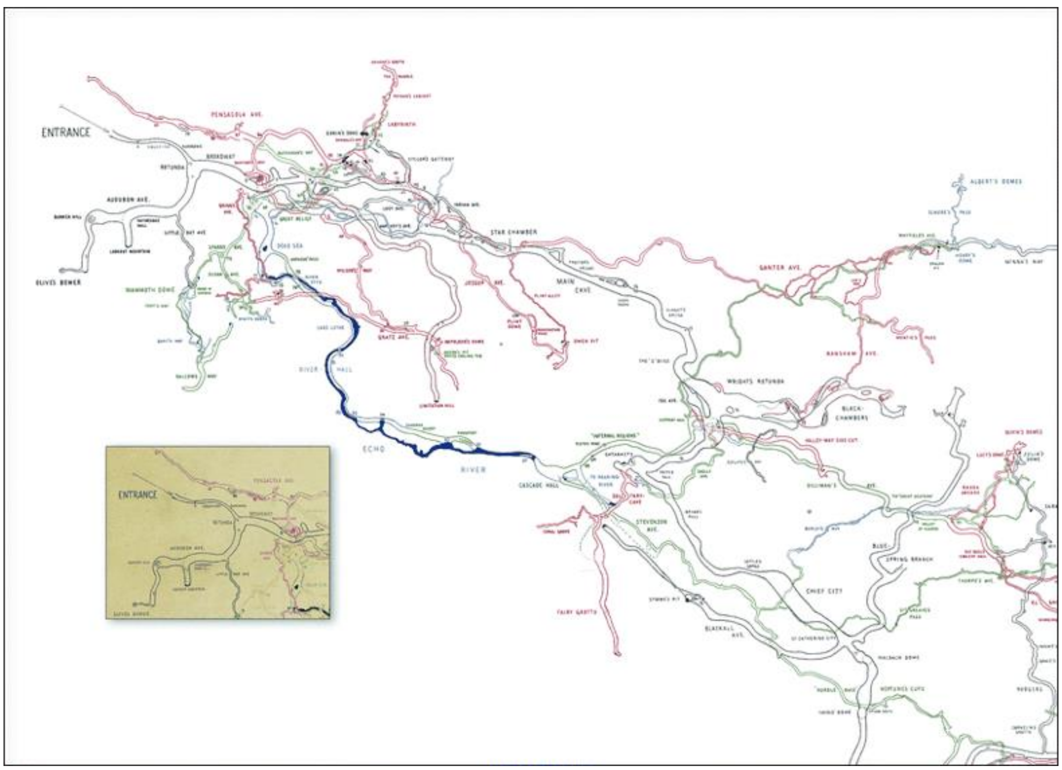


Figure 4.17 An inset of Kämper's 1908 original map, shown in the digitally restored map by Seymour (2016). The original map is badly deteriorated due to earlier preservation attempts.

The Battle of the Cave

As maps continued to be produced over the next years and Kämper's survey became known to the public. Even without clear scales, it became increasingly obvious that Mammoth Cave extended beyond the estate (Sutton, 2017). Around 1915, George Morrison, an oil prospector, decided that he would open another entrance to the Mammoth Cave and compete with the tourism at the estate. He leased land near the estate and unsuccessfully tried to drill holes to find the cave. He then decided to get a Mammoth Cave guide to give him a copy of the key to the cave entrance and would spend the nights wandering around the cave to find an alternate entrance. After many failed attempts and being caught red-handed several times, Morrison ended up narrowing his search to a specific area, which he then blasted to create another entrance to the Mammoth Cave (Sutton, 2017).

A map of the newly opened section was created by a local civil engineer, Roger Parrish (Sutton, 2017). This map included a scale and a north arrow, property boundaries, and passages connecting new and old entrances. However, this map was biased because the map shows the estate's historic end in a very simplified and distorted manner to undermine the estate's tourist offerings. In contrast, the new entrance was very realistic and accurate. Finally, the cave wars were brought to an end in 1936, when the Mammoth Cave Association bought the rival properties to include them in the Mammoth Cave National Park (Brucker, 2008).

The Trapped Man

Perhaps one of the most foundational events that brought light to the extensive cave systems in Kentucky was the death of farmer and cave explorer William Floyd Collins (1887-1925). The following account is based on research on the event by Crothers (1983), who gives a relatively unbiased perspective, unlike most newspaper accounts at the time. The third of eight children, Collins was born and raised on Flint Ridge in Kentucky where he spent his childhood running around and exploring caves with some of his siblings.

In 1917, Floyd Collins discovered Crystal Cave on his father's property and developed it with his father for tourism. However, the entrance to the cave on their property was far from any major roads, so most tourists in the area would be side-tracked by other closer and better-marketed caves before making it there. Floyd began exploring neighbouring properties closer to main roads in the hopes of finding an entrance to a cave that could prove more profitable, successfully finding an entrance to Sand Cave that he began working to expand in 1925.

The entrance passage was very narrow and full of break down, so on January 26, Collins used dynamite to loosen some of the rocks to better navigate. On January 30, Collins took a bit of rope and a single kerosene lantern with him down into the narrow crevasse, without telling anyone, as was his norm. He made it down a narrow, almost vertical crawl way and to the bottom of a six-metre pit, before making his way back towards the surface. His lantern went out, but Collins had been in many caves and pushed on. On his way up however, a rock dislodged and trapped his left leg. Collins was unable to dislodge it or turn around to see it, becoming trapped. The following day, the estate owner went looking for him, beginning rescue parties led primarily by Collins's youngest brother Homer Collins and a reporter named William "Skeets" Miller.

When Collins was found, volunteers were sent down to give him food and blankets. A few unsuccessful attempts to free Collins were made. On February 4, two collapses of the passageway discouraged rescuers and trapped Collins further. National Guardsmen soon took over the scene and on February 16 the shaft they dug finally broke through to the passageway. After 18 days of entrapment in the cold, damp darkness, Floyd Collins was found dead. Coroners estimated that he had died of starvation and hypothermia on February 13.

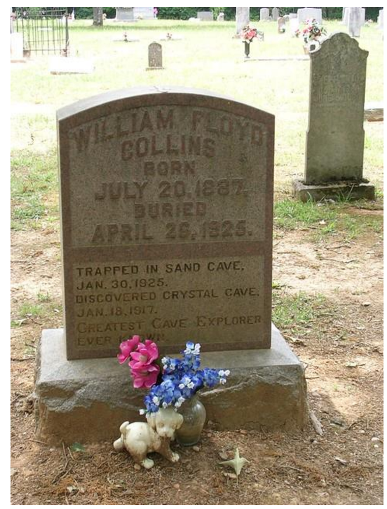


Figure 4.18 Photo of Collins's gravestone with the inscription "Greatest Cave Explorer Ever Known". Collins's body was initially buried on Flint Ridge on April 26, 1925 but was dug up and placed in a coffin in Crystal Cave as a tourist attraction in 1927 where it would remain for many years until family descendants reinterred him at Flint Ridge.

Meanwhile, news of the attempted rescues and death of Floyd Collins swept the country by storm. Major newspapers wrote articles of the daring and brave attempts while radios broadcasted the news. The story even had an international reach. Embellished and romanticized accounts brought caving to a new light and encouraged many to take up a newfound interest in caving.

Speleogenetic Evolution of the Cave

After Collins's death, research of the Mammoth Cave system took off with foundational papers by James Marvin Weller and William Morse Davis, in 1927 and 1930 respectively. Davis's paper was titled *Origin of Limestone Caverns* and included a few dozen pages on the geology and speleogenesis of Mammoth Cave and its surroundings, building upon Weller's *The Geology of Edmonson County*. In this paper, Davis contradicted Weller's hypothesis that the formation of Mammoth Cave depended on the downcutting of the Green River through its valley. According to

Weller, five main galleries in the cave likely formed when the river paused in downcutting and eroded the stone, or where the layer of stone forming the floor was resistant to erosion (Davis, 1930). However, Davis pointed out several pieces of geological evidence that suggested this was not how the cave formed, as nearby caves and the Green River valley did not show evidence of pauses in downcutting. Davis proposed that a "two-cycle" formation occurred where galleries were carved out by ground-water solution and then dripstone deposition created the final structures.

Davis referenced Hovey's maps multiple times in his description of the formation of Mammoth Cave, as the structure can reveal clues about passageway formation, such as along dips, faults, or peneplanes in the rock. Hovey's descriptions of pits and domes in the cave, which accompanied his maps, also allowed for Davis to postulate as to their origins. Exploration and mapping of the Mammoth Cave system were very important for not only performing research, but also for forming ideas about how the greater cave structure was formed.

Modern Speleogenesis and Mapping Techniques

Speleogenesis

The understanding of how various caves have come to form in all their shapes and sizes has grown over the last century and particularly since the 1980s. One of the leading geologists studying caves in the USA is Arthur Palmer, who has studied the Mammoth Cave, among others. The description of the speleogenesis of Mammoth Cave in this section is based on Palmer's book section *The Mammoth Cave Region, Kentucky* in *Caves and Karst of the USA* (2009).

Mammoth Cave is covered by a resistant caprock made of Mississippian sandstones, shales, and interbedded limestones, as well as Pennsylvanian sandstones and conglomerates. This caprock has protected the upper levels of the cave from erosion. Mammoth Cave itself consists of approximately 120 metres of limestone. Without the caprock, the cave would likely be much smaller due to erosion of the upper levels.

The drainage basin of the area surrounding Mammoth Cave is extensive, with water coming in from the Green River and draining through sinkholes and streams (both above surface and subsurface). Stream erosion formed the passages in Mammoth Cave and the surrounding cave systems during the late Tertiary Period. The water generally followed

Figure 4.19 Broadway, one of the larger passages in Mammoth Cave, likely formed during a pause in water base level. Tourists are guided along a boardwalk in the cave by a tour leader.

natural faults and bedding in the limestone, forming a network of passages that is extensive due to thin bedding.

Many of the passages in Mammoth Cave are narrow, vadose canyons that follow the dip of the rock layers, about 0.3° northwest overall with some local variations. Clusters of tubular passages were formed during pauses in the base-level lowering of the Green River. This is the idea that Weller first postulated for the formation of the five main galleries in the Mammoth Cave and that Davis later dismissed (Davis, 1930). New evidence has shown that these passages are independent of stratigraphic control, meaning that the water base level exerted control on their development. This demonstrates how thought on cave formation has changed over time as more evidence is found and interpreted.

Upper-level passages in the Mammoth Cave are filled partially or completely with sand and gravel up to 20 m deep from between 2.6-3.5 million years ago when sediments accumulated in the surface rivers and drained into the cave.

Lower passages, generally smaller than the upper passages, formed as the drainage patterns of the area changed with glaciation which created the historical Teays River, now a dried riverbed covered by glacial deposits. The Teays River increased flow into the Ohio River and in turn the Green River, causing rapid erosion in the valley and lowering the rivers' base levels, which eroded the lower passages.

Vertical shafts tend to deepen in stages as opposed to singular drops and are major water drains. Shafts such as the Bottomless Pit connect horizontal passageways in the cave.

The Modern Survey of Caves

In 1964, the Cave Research Foundation (CRF) published a map that was the end product of an expedition that showed the Mammoth Cave connected to Crystal Cave, Unknown Cave, Colossal Cave, Salts Cave, and Flint Ridge Cave, making the 232-kilometre-long Mammoth Cave the longest cave in the world (Brucker, 2008). In 1977, the CRF published a total surveyed Mammoth Cave system that could be printed on a sheet of paper. The purpose of this was to set straight the growing number of contradicting maps of the cave (Sutton, 2017). The map shows distinctive cave levels in different colours and overlays topography. Then in 2007, on the CRF's 50th anniversary, all the Mammoth Cave maps were digitized and overlapped, showing 587 kilometres of cave passages.

The cave is surveyed today with many volunteer cave surveyors, data analysts, and cartographers. Nowadays, Suunto precision instruments, calibrating compasses, cave radios, and laser rangefinders are used to refine locations of points and accurately measure dimensions. Second order level nets and the Geometer's Sketchpad (GSP) are used to control and adjust the loops of surveys due to magnetic declination. Computer processing is also used to create cave survey-processing programs that input distances and angles to create coordinate points, through the use of trigonometry, allowing for line plots with scales to be created easily. Furthermore, CRF cartographers are assigned sections of the cave to map. The maps must fit the cartographic standards and exhibit uniformity. This provides information to make explorers aware of where passages are "missing" or undiscovered, and those are the sections of high priority. This system follows the CRF motto: "No exploration without survey".

Figure 4.20 The Bottomless Pit in Mammoth Cave, a deep vertical shaft.

The current length of Mammoth Cave is 667 kilometres, with around 2800 place names in the cave (Sutton, 2017). It is believed that some of the nearby caves could connect to the Mammoth Cave system, totalling around 1600 kilometres, however these caves will probably not be a part of the Mammoth Cave story in the near future. Research on the Mammoth Cave continues as geologists' hearts and minds are captured by the longest cave in the world. Exploration, mapping, and speleological study of the Mammoth Cave system have driven the field forward in the USA and around the world due to the cave's spectacular beauty, haunting stories, and competition for the discovery of new cave passages.

Historical Evolution of Scientific Soil Mapping and Taxonomy

The evolution of our knowledge of soils is inherently linked to the development of agricultural practices. Our first interactions with soil began with the initiation of agricultural activity approximately 10,000 years ago with the neolithic agricultural revolution, marking our transition from hunting and gathering to farming and housing livestock, as agriculturalists (McNeill and Winiwarter 2004; Yaalon, 1997). It is thought that this was done on the soils of large alluvial fans and semi-arid regions due to the easy to clear land and accessible irrigation from nearby springs (Yaalon, 1997). The transition to agriculture meant a heavy dependence on soils, and thus an advanced knowledge of its properties was required (Hartemink, Krasilnikov, and Bockheim, 2013; Yaalon, 1997). Over centuries, our dependence on soils has increased due to multiple large population growths leading to higher agricultural and industrial soil-related consumption. This includes food, lumber, mining, architecture, and other natural and anthropogenic activities on or with soils. A major paradigm shift occurred in the early 19th century when Vasily V. Dokuchaev led the world into a period of modern soil science, where the development of soil taxonomy, chemistry, biology, physics, and geology was henceforth explored (Yaalon, 1997). This review of historical advances in soil will focus on our historical knowledge of soil taxonomy and mapping, which are foundational in the field of soil science. In recent years, the practices of soil conservation and management have been explored and improved due to the vital yet simple fact that soil is a non-renewable resource. The field of soil science is becoming increasingly integrated with new developments in technology including Artificial Intelligence and spectroscopy.

Early Soil Knowledge

The earliest known advances in the knowledge of soils began around 5000 BC with the Mesopotamians, who were able to recognize differences in soil fertility (Brevik, 2005). As early as 2000 BC, the Greeks and Romans were able to characterize and describe soil (Brevik, 2005; McNeill and Winiwarter, 2004). The philosopher Xenophon put forth that life begins and ends in soil, a nod to the nutrient supplying capabilities of soil, which is home to many organisms (Brevik, 2005). Theophrastus wrote the first agronomic literature which classified soil according to the tools used to reap it (Brevik, 2005). Due to the lack of experimentation and testing of these observations and theories, these developments were not considered to be a 'soil science' until the early 19th century (Brevik, 2005).

Agriculture and Soil Erosion

The uplift of soils for farming promotes erosion and depletion of nutrients through the physical actions of the farmer and the removal of nutrients by plant life. There were three major waves of erosion associated with agricultural activity, described in terms of technological advances and transitions into different geographic regions (McNeill and Winiwarter, 2004). The first wave of erosion was in 2000 BCE, when river-basin civilizations in Yellow River, Indus River, and around Maya lowlands moved to higher elevations (McNeill and Winiwarter, 2004). The newly exposed slopes were then further prone to erosion from rainfall (McNeill and Winiwarter, 2004). Many of the world's forests were converted to farmland subsequently (McNeill and Winiwarter, 2004). The second wave of erosion took place in the 16th to 19th centuries where the rise of stronger plows occured in North America, Eurasia, and South America (McNeill and Winiwarter, 2004). As Europeans took to colonized lands, their stronger plows went with them and increased rates of soil erosion there (McNeill and Winiwarter, 2004). The third wave of erosion occurred following 1945 as great population growth encouraged the move into tropical rainforests for the collection of lumber and other resources (McNeill and Winiwarter, 2004).

Soil Management

Soil erosion must be met with soil management and conservation in order to reduce the rate at which fertility is lost. Terrace building is quite possibly the earliest form of soil management and occurred in many places around the world (McNeill and Winiwarter, 2004; NRCS, 2001).

The earliest known instances of this are in Arabia 4000 years ago, and 1000 years later in China (McNeill and Winiwarter, 2004; Yaalon, 1997). Terrace building is one of the most widespread soil management techniques and reduces runoff to allow soil particles to settle before the cleaner water is carried off the field (NRSC, 2001). An example of the structure and application of terrace building is shown in Figure 4.21.

Figure 4.21 Terrace building for mountainous erosion control.

Development of Soil Science

The early beginnings of the classification of soils stemmed from declines in fertility. An early technique developed by Columella in Rome, first century AD, tested soil fertility by digging a hole in the soil and filling it with the loose soil (McNeill and Winiwarter, 2004). The soil was deemed fertile if the mound rose above the ground, and infertile if the mound was level with the ground (McNeill and Winiwarter, 2004). A more thorough classification was developed earlier in China, 500 BCE (Hartemink, Krasilnikov, and Bockheim, 2013; McNeill and Winiwarter, 2004). This was written in the book Yugong, and classified soil according to fertility, colour, texture, moisture, and vegetation (McNeill and Winiwarter, 2004). This was further developed by Guan Zi in 200 BCE, with 90 recognized soil types (McNeill and Winiwarter, 2004). Later developments arose in ancient India and Rome, 1000 CE with the addition of factors like landforms, erosion, flooding, sedimentation, land use, and human health (McNeill and Winiwarter, 2004).

Development of Soil Taxonomy and Pedology

Pedology, the study of soils in their natural environment, is a term coined by Friedrich A. Fallou in 1862 (Yaalon, 1997). Subsequently, the first investigation of soils in the field was conducted by Vasily V. Dokuchaev in 1877, involving the development of soil profiles and horizons (Yaalon, 1997). These soil profiles were centred around 5 independent soil forming factors: climate, biota, relief, parent material, and age (Yaalon, 1997). These were published in volume of Russian Chernozem in 1883, due to their collection from the Russian steppe (Yaalon, 1997).

Soil Formation and Taxonomy

The process of creating soil is an evergoing, two-fold system, the first step being the weathering, or splitting up of existing rock, minerals, and other matter. Weathering can occur in one of three manners: physical, chemical, and biological (Queensland, 2013). Physical weathering occurs when rocks are broken due to disaggregation, the most common form being abrasion (collision from ice, water, wind, and other sediments) (Queensland, 2013). Other forms of disaggregation are due to temperature, pressure and frost (Queensland, 2013). Chemical weathering is a chemical alteration of minerals within a rock, weakening its structural integrity (Queensland, 2013). This occurs primarily when water, air or some form of chemical interacts with the minerals, producing a chemical reaction where a new or secondary mineral is developed (Queensland, 2013). Hydrolysis and oxidation are the main contributors, as chemical weathering occurs best when water, oxygen, or acids produced by biological agents are present (Queensland, 2013). The final form of weathering occurs when biological specimens interact with the rock, this can be through the process of burrowing, scratching, or the transportation of material (Queensland, 2013). These interactions allow for physical and chemical weathering to occur in an easier fashion. A primary example would be the allowance of water and air to permeate the rocks easily due to burrowing, allowing for further weathering to occur (Queensland, 2013).

The acronym CLORPT (Climate, Organisms, Relief, Parent Rock, and Time) is used when deriving which taxon a particular plot of soil can be classified as (Jenny, 2012). This can be used as a checklist of attributes to classify plots of soil, as each letter represents a soil forming factor (Jenny, 2012). The climate dictates the rate at which weathering and organic decomposition occur. Organisms are the biological species that occupy the substrate (Jenny, 2012). Relief is the difference between the highest and lowest vertically elevated points and influences the amount of drainage, erosion and deposition that will occur (Jenny, 2012). Knowing the parent material of the soil helps to understand the composition of the soil; different combinations of clays, silts, and sands from this parent material allow for the understanding of how the soil will function in the environment (Jenny, 2012). Time is valuable in the creation of soil, as it is considered a non-renewable substance. This is due to the amount of time that it takes to create soil, as well as how many changes the soil can go through over time (Jenny, 2012). Due to the many factors that play a role in the creation of soil, a clear understanding of how long soil generally takes to form is not fully agreed upon. Yet, it is agreed that the formation does not readily occur in one lifetime (Jenny, 2012). The variation in interactions between the climate, organisms, relief, parent material, and time alludes to the large diversity of taxon of soil (Jenny, 2012).

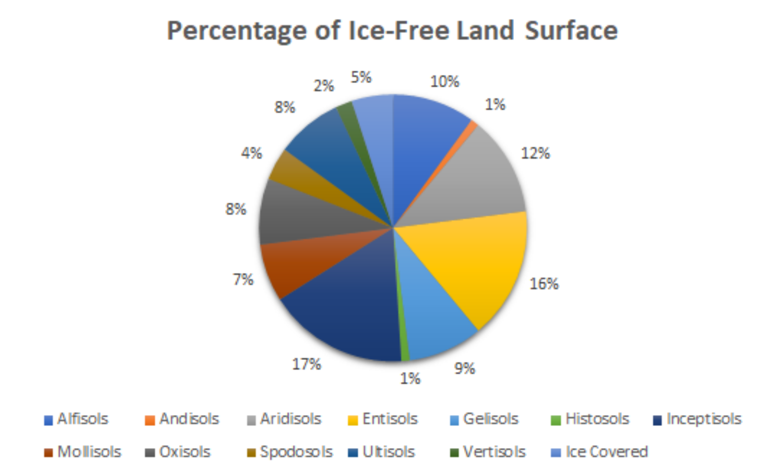


Figure 4.22 A pie chart displaying the proportions of the Ice-Free land occupied by the different taxa.

Soil Mapping

Soil maps depict the distribution of different soil taxa and types and have been used for a variety of purposes ranging from taxation to military intelligence.

Early Soil Maps

The first soil map was produced 4000 years ago in China. This map was produced for taxation purposes, to determine tax rates based on the qualities of soil for agriculture (Hartemink, Krasilnikov, and Bockheim, 2013). Soil fertility, color, texture, and moisture were mapped across 9 provinces (Hartemink, Krasilnikov, and Bockheim, 2013). Subsequent maps depicting soil qualities in terms of productivity were constructed by the Aztecs as early as 1345 CE, with their own developed classification with 132 glyphs (Hartemink, Krasilnikov, and Bockheim, 2013).

Scientific Soil Maps

Early scientific soil maps were developed in the 1850s and 1860s using agrogeologic knowledge (Hartemink, Krasilnikov, and Bockheim, 2013). These maps were based on soil textures and contents in Germany, France, Austria, Netherlands, and Belgium (Hartemink, Krasilnikov, and Bockheim, 2013). However, a greater demand for soil mapping was present in countries like Russia and the USA, where a greater prevalence of unmapped land existed (Hartemink, Krasilnikov, and Bockheim, 2013). Much of the need for soil mapping in Russia was fueled by the Russian military, for relevant soil knowledge like fertility (Hartemink, Krasilnikov, and Bockheim, 2013).

Dokuchaev, an important figure in Russian soil mapping, was able to form the connection between soil taxonomy and soil formation factors (Hartemink, Krasilnikov, and Bockheim, 2013; Yaalon 1997). Much of this work was inspired by A. von Humboldt and A. Fallou for their work on biogeographical zoning and soil horizon classification respectively (Hartemink, Krasilnikov, and Bockheim, 2013). In 1899, Dokuchaev completed a large-scale map of the soils in the northern hemisphere to be published later in the World Exhibition in Paris, 1900 (Hartemink, Krasilnikov, and Bockheim, 2013). This publication included 11 soil types (Hartemink, Krasilnikov, and Bockheim, 2013). Due to his limited knowledge of the southern hemisphere's soils, he had insufficient data to produce a large-scale world map of soils with enough resolution (Hartemink, Krasilnikov, and Bockheim, 2013).

World Soil Maps

While to-date many world soil maps of different types have been created, the first large scale world soil map was constructed in 1908 by K. D. Glinka, one of Dokuchaev's students (Hartemink, Krasilnikov, and Bockheim, 2013; Yaalon 1997). This map had a scale of 1:80 million and depicted the correlation between the spatial distribution of soils and their climatic distributions (Hartemink, Krasilnikov, and Bockheim, 2013). This map included 18 soil types and information on relevant bodies of water (Hartemink, Krasilnikov, and Bockheim, 2013). Glinka's success with this world map was due to his extensive knowledge of soil science and his involvement in the

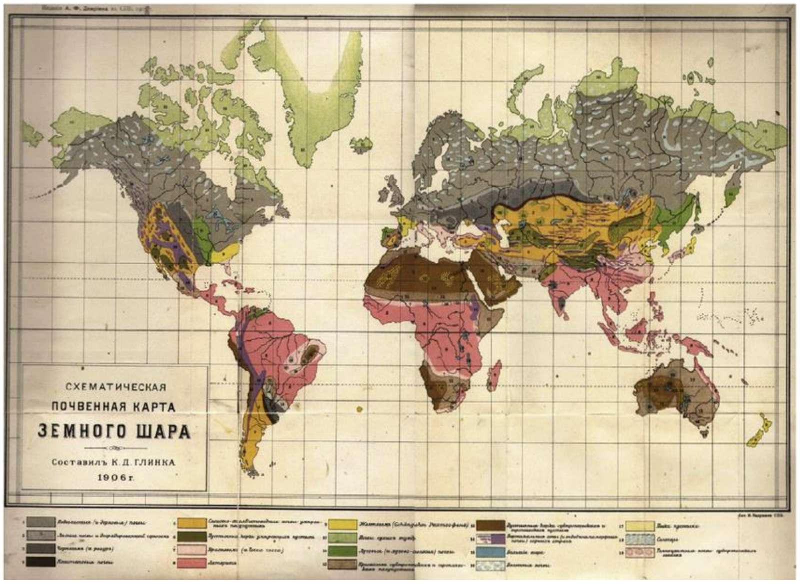


Figure 4.23 A schematic soil map showing the distribution of soils worldwide at a scale of 1:80 million.

international community of soil scientists (Hartemink, Krasilnikov, and Bockheim, 2013).

Evolution of Soil Maps

Early soil maps, much like those of China, were focused on communicating simple information about the land for purposes like taxation and land development (Gong, et al., 2003; Hartemink, Krasilnikov, and Bockheim, 2013). This form of map making did not need a high degree of spatial resolution, and much extrapolation from theory was used. Early scientific soil maps continued with heavy use of extrapolation with minimal field data, but were led by Dokuchaev to a shift toward mapping groups of soils rather than basic soil properties (Hartemink, Krasilnikov, and Bockheim, 2013). This came from the realization made during his commission project on desertification that soils and their climate are linked (Brevik, 2005; Hartemink, Krasilnikov, and Bockheim, 2013). At the beginning of the 20th century, an attempt was made by G. F. Nefedov to shift toward overlaying multiple soil maps, each showing a different property (Hartemink, Krasilnikov, and Bockheim, 2013; Savin, Zhogolev, and Prudnikova, 2018). According to Nefedov, the clearest picture of soil distributions would form from an overlay of these individual properties to show where regions are similar, as individual soil properties vary in such a wide range to mitigate any real utility (Hartemink, Krasilnikov, and Bockheim, 2013; Savin, Zhogolev, and Prudnikova, 2018). This attempt, however, was rejected by his colleagues and contemporaries, as he did not have enough knowledge nor data to link individual properties in such a manner. Instead, maps could only be made from actual field measurements (Hartemink, Krasilnikov, and Bockheim, 2013; Savin, Zhogolev, and Prudnikova, 2018).

The transition toward electronic soil mapping is currently underway. An electronic soil map could not only allow for greater spatial resolution and clarity, but allow for a more realistic picture based on large compilations of actual field data rather than extrapolation.

Pressures that contribute to this transition are environmental, social, and economic. As soil fertility is greatly sensitive and can be depleted easily, soil is a non-renewable resource and must be treated accordingly. Soil management techniques rely on accurate visualization of soil property distributions. Historically, soil fertility depletion, population growth, and the dependence on soil for natural resources like food and lumber have driven the need to improve these visualizations. With modern electronic models, it is possible to improve the resolution of these maps in order to predict soil properties for easier soil management.

Current Advances in Scientific Soil Mapping

The current focus of today's society in the study and development of soil science is on-site surveying and how we can utilize tools such as Geographic Information System (GIS) mapping, and other mapping software to create an in-depth picture of the soil topography. In the United States, the process of soil surveying has drastically evolved from 1899 (Golden and Hempel, 2008). As technology has improved, the pressure to perfect soil maps has increased as it endows a greater economic value due to the use of currently outdated maps (Golden and Hempel, 2008). Current surveys have mapped 90% of American soil alongside 96% of non-federal land, which are readily available through public domains such as the Web Soil Survey (Golden and Hempel, 2008). The current goal is to develop updated maps to allow for a better understanding of what lies beneath our farmlands, our construction sites, and our globe. The techniques for mapping that were previously in use were unable to account for the changes that occur due to the time and management of the land (Golden and Hempel, 2008). The United States Department of Agriculture developed a soil survey program with the goal to update the currently outdated maps by utilizing GIS, remote sensing, landscape modelling, and branching out to more federal agencies (Golden and Hempel, 2008). The program's goals in advancing soil mapping are tripartite. The first part is to create a survey program that is able to change and enhance with time (Golden and Hempel, 2008). The second is to increase the funding for mapping Non-Federal land (Golden and Hempel, 2008). Finally, the third is to utilize online databases and become completely paperless (Golden and Hempel, 2008).

Another goal is being achieved through technologies such as reflectance spectrometry (RS) and artificial neural networks (ANN) (Leone, et al. 2008). This research was conducted by Leone, et al., 2008 in 3 environments in Italy. Their study aims to predict the compositions of clays, silts, sands, organic carbons, and calcium carbonates of these pedological environments using RS with wavelengths between 300 and 2500 nm, and an ANN (Leone et al., 2008). Utilizing an ANN means that with more data collected with RS, the better the system is with its predictions (Leone, et al. 2008). The RS measures the spectral reflectance (of wavelengths 350-2500 nm), which is the amount of electromagnetic energy reflected by the soil surface (Leone, et al. 2008). However, lab-based studies tend to be costly to conduct. To alleviate some of this cost, some information is collected through etho-knowledge, the process of asking farmers about their land through generational knowledge (Leone, et al. 2008). Analyzed samples, however, are measured with extreme precision, but the smaller the grain, the longer it takes to analyze the sample (Leone, et al. 2008). However, even modern systems can't predict everything to the utmost efficiency; while the presence of clays and organic matter are predicted with high accuracy, sands and calcium carbonates can only be predicted with moderate accuracy, and it struggles to predict the presence of silts accurately (Leone, et al. 2008).

Since the dawn of the neolithic agricultural revolution, humankind has developed its knowledge of soils, their properties, and formation. From documenting basic soil properties for taxation to predicting soil fertility for soil management and conservation, soil science has become an interdisciplinary field. Ancient agricultural practices have allowed farmers and philosophers alike to learn about the ground beneath them and the biota it is home to. Early soil science began with simple observations and extrapolations about regions in order to determine which lands were most profitable. As it developed, we learned more about the global diversity of soil properties, and how to group these according to the five independent soil forming factors. In the 19th and 20th centuries, soil mapping began to advance in terms of spatial resolution but lacked the ability to relate independent properties to each other. With modern electronic and digital technology, a dramatic increase in mapping efficiency and clarity is seen. Nefedov's push to map independent soil properties separately predicted the beginning of increased mapping utility. Currently, we are able to collect field data digitally through spectroscopy and GIS in order to create a larger, more thorough soil database. The use of algorithmic systems like neural networks has allowed for the prediction of soil properties to a high degree of accuracy. Future steps in this field include broadening the scope of the science to further include microbiology and soil-plant biochemistry, and to better our understanding of soil conservation. As our population grows, our environmental and agricultural needs intensify. Thus, it is increasingly important to recognize how impermanent our soil fertility is, and to find novel, interdisciplinary ways to prevent the loss of this resource.

The Overlooked Contributions of Marie Tharp to Oceanography

The ocean covers the majority of the Earth's surface; however, it has always been a subject of mystery. The study of the ocean's surface topography is still a relatively new field starting in the late 19th century. This is because the bottom of the ocean reaches extreme depths, presenting a great difficulty to map and research (Wölfl et al., 2019). Even today, much of our oceans have not been studied, explored or precisely mapped. Studying the seafloor is essential to learning about continental drift, past climate change, benthic organisms, mineral resources and more (Wölfl et al., 2019).

Many scientists have contributed to our current understanding of the seafloor, but one person stands out in particular: Marie Tharp. As a woman in the 20th century, she faced prejudice at every point in her career and her accomplishments were barely even acknowledged. She confronted the male dominated scientific community and took on the difficult task of mapping the seafloor when there was little technology to help ease this process, tediously interpreting data using her hand and a pencil (Felt, 2012). Nonetheless, to truly comprehend the magnitude of her contributions, it is important to first examine the predecessors that came before her and the general understanding of the seafloor before she entered the field.

Understanding the Seafloor Before the 20th Century

Although the seafloor has presented a challenge to study, this minor obstacle did not stop the curious humankind. Tomb paintings in ancient Egypt dating to 1800 B.C.E. demonstrated that humans had been attempting to acquire more knowledge of the seafloor characteristics for years (Theberge, 1989). These images depicted Egyptians using sounding poles and weighted lines to measure the depths of the Mediterranean Sea. They would insert a pole into the ocean until they reached the seafloor to quantify the depth. Weights were attached for deeper soundings. This method was simple and although it was a great start, it resulted in very limited data. However, in subsequent years, there was no real advancement in analyzing the seafloor (Theberge, 1989).

The earliest modern oceanographic researchers began with the Challenger expedition in 1872 to 1876, which was the first international marine research expedition (Adler, 2013). Prior to this, there was no data to suggest that the ocean floor

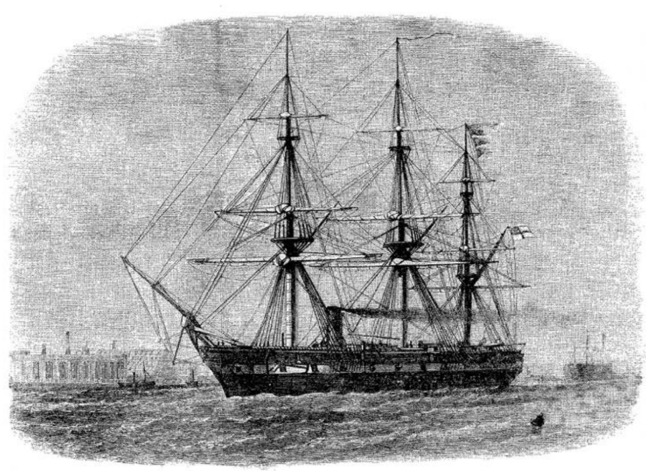


Figure 4.24 An illustration of the H.M.S. Challenger *in 1858.*

was nothing more than a flat plain filled by sediments from land, which was the general consensus (Tharp, 1999). The expedition consisted of the vessel, *H.M.S. Challenger*, and was led by Captain George Nares. It contained many scientists onboard, with laboratories, specimen jars, and various equipment. Similar to the ancient Egyptians, they used a weighted rope to record the depths of the ocean floor (Lyman, 1954). Using this data, they produced bathymetric maps. However, this technique only allowed scientists to measure one singular point of depth (Dierssen and Theberge, 2014). Although the maps were not entirely accurate, the different depths indicated a more dynamic seafloor than once thought and sparked intrigue from other scientists, demonstrating the untapped knowledge in this field.

The Challenger expedition contributed greatly to the understanding of the ocean, however, there was still no way to visualize the changing landscape of the seafloor on a global scale and with more detail (Dierssen and Theberge, 2014). With these challenges, it was not until the 20th century that humanity began to understand more of the seafloor topography and Marie

Tharp, unconventionally, was crucial in this evolution.

The Early Life of Marie Tharp

Born on July 30, 1920, in Ypsilanti, Michigan, Tharp quickly began to discover her passion for geology and science. Her father, William Tharp, was a soil surveyor for the United States Department of Agriculture (Felt, 2012). Growing up, Tharp helped her father with his work, giving her early exposure to the field of research. As a woman, Tharp did not believe she could follow in the footsteps of her father (Tharp, 1999). At this time, it was rare for women to work in science and female occupations were limited to teacher, secretary or nurse. Originally, Tharp's plan was to become a schoolteacher, similar to her mother, Bertha Tharp (Tharp, 1999).

Figure 4.25 A picture of Marie Tharpe (left) and Bruce C. Heezen (right) as they look at a map.

Tharp used her academic career to search for a job that she found interesting, rewarding and challenging. She found herself changing her major often and taking a range of courses (Tharp, 1999). Tharp quickly realized that she would not enjoy any of the occupations dictated for women, she did not even really like teaching. In these years, she took a couple of geology classes and really liked it. On her professor's recommendation, Tharp learned drafting, as it could increase her chances of finding work in the field. Women were unlikely to do fieldwork, but she could work in an office (Felt, 2012). She proceeded to graduate with a Music and English degree and multiple minors, at the same time as World War II (Tharp, 1999).

World War II presented a time when most of the males were sent to war. As a result, there was an opening in the scientific field for women, as they needed to fill the jobs that were suddenly left open (Barton, 2002). A year after the war began, the University of Michigan began to accept women in the geology faculty. In 1943, Tharp was recruited to earn a degree in geology at the university, with the promise of a job in the petroleum industry (Barton, 2002). After earning her master's degree, she worked with Stanolind Oil Co. in Tulsa, Oklahoma and then went to the University of Tulsa for a degree in math (Tharp, 1999).

In 1948, she became one of the first women employed at the Lamont Geological Observatory of Columbia University in New York, working as an assistant with Maurice Ewing, the founder of the Observatory and a pioneer of geophysics, and her future collaborator, Bruce C. Heezen (Barton, 2002). Initially, she worked as a drafter for anyone who needed help. However, this proved to be too difficult and she temporarily ran away to her family's home. Due to her gender, she was unable to run her own projects and she was forced to complete a multitude of impossible tasks for all of the men. After she returned and set aside her frustrations, Ewing gave Heezen the task of delegating her time and she eventually progressed to working exclusively for Heezen (Tharp, 1999).

Mapping the Seafloor

The beginning of the 20th century marked a change in gathering information from ocean environments, as scientists began to use sound waves. In the past, sounding has always referred to measuring the depth of the ocean. The word comes from the Old English *sund*, which meant to water or sea (Fulk, 2005). It was not related to sound at all, but ironically, we began to measure these depths with sound.

This development of underwater acoustic techniques was triggered by the need to detect underwater objects, such as the titanic that sank in 1912, as well as for submarine warfare in World War I (Wölfl et al., 2019). Furthermore, seafloor mapping was a topic of interest for many reasons, including the safety of navigation, hazard studies (identifying potential risks such as slope failures and turbidity currents), modeling of ocean circulation, seafloor installations (such as cable laying), marine conservation, and more (Wölfl et al., 2019).

The US Navy was particularly interested in seafloor mapping at its emergence since detailed information about the ocean floor was thought to be invaluable to naval defence operations (Wölfl et al., 2019). This newfound need to explore the ocean sparked more scientific research funding and interest, resulting in the natural advancement of this field. Before the 1920s, the Coast and Geodetic Survey used a sonar technique to map deep waters and make one of the first detailed maps of the ocean floor (National Oceanic and Atmospheric Administration, 2010). The sonar that was used for the mapping consisted of a transducer that was used to transmit and receive sound waves.

This transducer would transmit sound waves from the boat to the bottom of the ocean. When the sound waves hit the bottom of the ocean or any other structure, they would echo back to the transducer, which would collect the depth data.

In earlier days, this sonar mapping focused on a very small area of the seafloor. However, as technology improved, so did the methods for sonar mapping, and the area surveyed by each sonar pulse widened as a result (Wölfl et al., 2019).

One of the advancements made was the capability for non-stop echo sounding, where depth measurements could be made continuously. A sound such as an electronic ping would be sent out periodically, with a microphone in the ship's hull to pick up the echo (Tharp, 1999). In order to collect data with this mapping method, a stylus would be set in motion on a paper when the electronic ping was sent out, and would mark the paper with an electric spark when the echo returned, resulting in an uninterrupted log of seafloor depths (Tharp, 1999).

It was at this time of technological development and American interest in the field that Tharp joined Heezen and together, they worked to interpret data from echo soundings to understand more of the structural landscape of the seafloor (Barton, 2002). Heezen worked for 18 years on the research ship called Vema, which used a precision depth recorder to produce bathymetric data. The precision depth recorder was a more advanced echo sounder that provided more accuracy when differentiating between smoother- and rougher-textured areas. It also detected more subtle features on the seafloor. This level of accuracy was essential to Tharp's work (Tharp, 1999). However, due to her gender, Tharp was not allowed to go out on the ship. She instead drew maps from the data that Heezen collected on Vema. She worked before the emergence of computers; therefore, she had to compile the pages of seafloor logs and plot out the readings with contour lines on navigational charts to visualize the changing water depths. This process was tedious and done only with pencils and rulers (Wölfl et al., 2019). In spaces with limited data, Tharp had to use her geological knowledge to fill in the gaps, which we now know was mostly correct (Tharp, 1997).

In 1957, Tharp and Heezen's first map was published, an impressive feat, considering Tharp

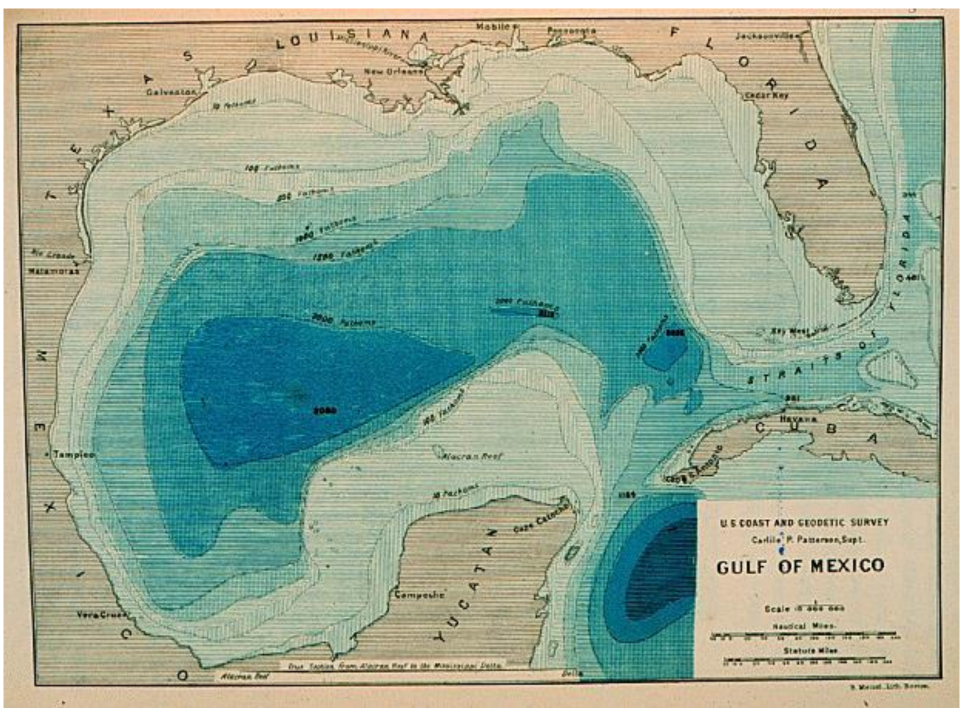


Figure 4.26 The first realistic bathymetric map, created by the U.S. Coast and Geodetic Survey.

only used her hands (Wolfe, 2012). They chose to publish their work as physiographic maps, as the U.S. Navy classified any detailed contour maps of the ocean (Tharpe, 1999). Tharp used the information that she received from Heezen to draw out a map of the entire North Atlantic Ocean. They then decided to map the entirety of the world's oceans and used more data from Vema, along with data from other past expeditions. They collaborated with the artist, Heinrich Berran, and together, their map of the world's oceans was published by the Office of Naval Research in 1977 (Wolfe, 2012).

Contributions and Controversies

Tharp has made large contributions to our understanding of the ocean floor and the ongoing processes of the Earth. She systematically completed a global ocean map, proving that the ocean floor had various landforms and features. As a woman, her work was largely unrecognized and overlooked (Tharp, 1999).

at this time, most scientists rejected the validity of this theory and it was more or less scientific heresy. When Tharp first mapped the rift valley, she showed Heezen and he dismissed her work as "girl talk". He forced her to redo her drawing, which she did. And again, she found that there was a mid-ocean rift to Heezen's discontent (Tharp, 1999).

Heezen still refused to accept Tharp's interpretation of the data. However, she was not deterred and sought out to prove the existence of the valley, she continued to remap the sounding data and correlated it with new information. It was not until a year later that Heezen began to accept the rift when Heezen was simultaneously working on a different project with Ewing. This project focused on seismology and using their data, they mapped out earthquake epicentres and found that they fell within a continuous line down the center of the Mid-Atlantic Ridge (Tharp, 1999).

When Tharp made this discovery, her mind naturally went to the theory of continental drift.

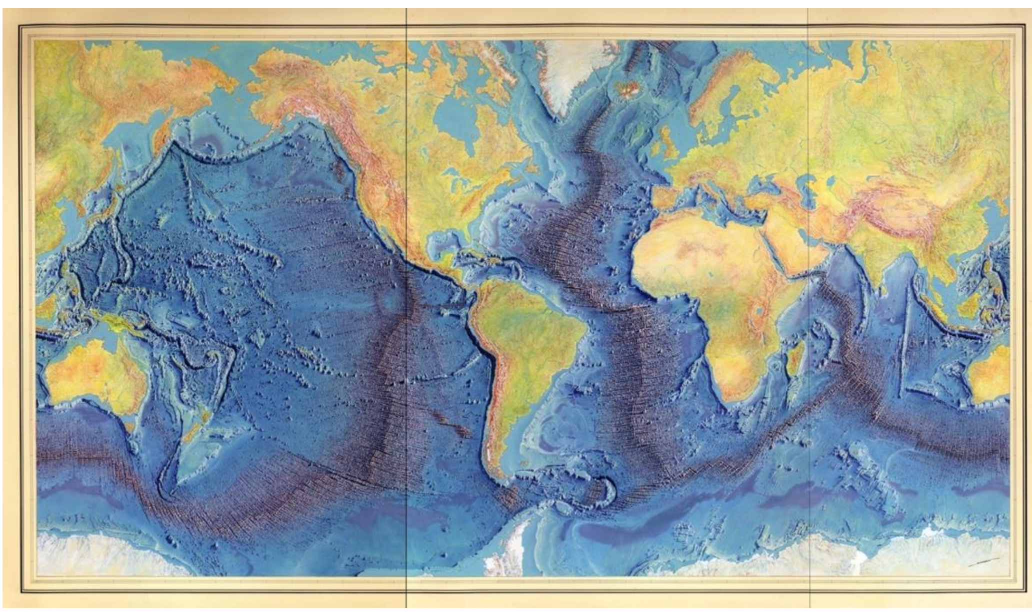


Figure 4.27 Physiographic diagram of the world's oceans published in 1977 by the Office of Naval Research created by Tharp and Heezen.

One of her major contributions to Earth Science was the discovery of a mid-ocean rift valley when she was mapping the topography of the oceans, providing more evidence for continental drift and igniting the shift towards accepting the theory. Continental drift theory was originally developed by Alfred Wegener in the year of 1912. The theory stated that over time, Earth's continents have drifted and moved. The discovery of a rift valley would help support the theory, as it represents an area where the tectonic plates diverge (Yount, 2009). However,

In her experience with geology courses, she was taught to look at current landforms and use them to understand the past processes (Felt, 2012). She applied this logic to the rift, and she came to the conclusion that continental drift may not be so far-fetched, especially with the seismological correlations (Felt, 2012). However, even after confirming the discovery of such a rift, many scientists, including Heezen, did not believe in the theory (Tharp, 1997).

When they first published their physiographic maps, many scientists believed the rift to be a lie made up from limited data (Felt, 2012). One could theorize that this was due to the politics of the scientific community, as almost everyone in America refused to accept continental drift, including their boss, Ewing. Even Tharp stated that it was very difficult to oppose the rest of the

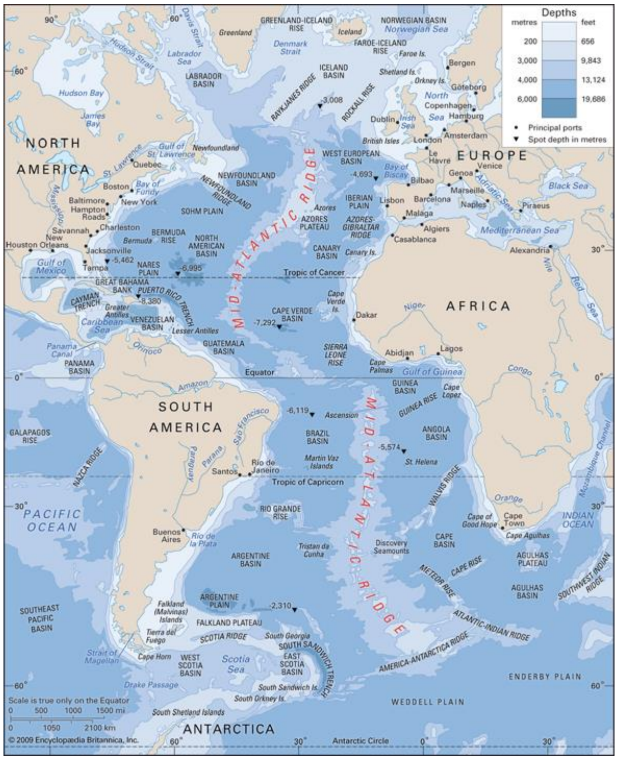


Figure 4.28 A modern map of the Atlantic Ocean, including the Mid-Atlantic Ridge in red, demonstrating that Tharp's rift is now well accepted.

scientific world (Tharp, 1999). This opposition of continental drift was not peaceful or quiet. In fact, Tharp even describes it as violent (Tharp, 1997). At this time, mentioning continental drift in academic papers could cause one to be ostracized and thus, Heezen found his work was being censored by Ewing. In one paper published, he had to use the words "continental displacement", as saying the word "drift" was a fireable offence (Tharp, 1997). As a result, Heezen incorrectly interpreted the discovery by relating the rift to a crack caused by tensional stress in the expansion of the Earth's crust (Felt, 2012). Tharp, on the other hand, with no position of power, decided not to take part in the debates and simply let the others argue while she made more maps of the rift (Tharp, 1999).

Beyond not being taken seriously, Tharp also faced the obstacle of being left out of publications. Tharp played a major role in mapping the rift valley and understanding where it came from (Felt, 2012). However, numerous papers published by Heezen and Ewing on this subject omit her name. After Heezen's death, Tharp did not have the academic status to fund her work and she was forced into an early retirement (Felt, 2012). It was not until substantial time had passed that Tharp finally received some of the credit that she was due. When asked about being left out of the limelight, Tharp stated that she was simply lucky enough to find a job that was so interesting and contribute to something so important (Tharp, 1999).

Marie Tharp was born at just the right time, when technology allowed humanity to glimpse into the ocean depths and women were allowed in scientific careers. She persevered through gender bias to use her geological, mathematical, and topographical knowledge and creativity to create a physiographic map of the global ocean and discover a continuous rift valley (Felt, 2012). Her discoveries eventually led to the acceptance of continental drift and allowed us to learn more about the seafloor. Due to societal circumstances, she was never properly acknowledged; however, this did not prevent her from pursuing her goals and contributing to oceanography. Tharp's love for her work outweighed her need to be recognized and allowed her to become one of the formidable female scientists of the 20th century (Felt, 2012).

Modern Approaches to Seafloor Mapping

In the 20th century, Marie Tharp made an impression on the scientific community by successfully mapping the ocean floor by hand. Her accomplishments set the scene for more development and discoveries to be made in the field. We now have multiple ways of gathering information from the ocean, as well as many maps already created of the entire ocean floor (Wolfe, 2012). However, there is still a lot left to learn about the ocean, and the resolution of many of these maps are very poor. Researchers are constantly looking for higher quality assessment and a newer field has even been looking at the ocean's subsurface geology (Makowski and Finkl, 2016).

Recently, there has been an increasing importance placed on seafloor mapping. Past motivations consisted of the World Wars; however, newer reasons have surfaced. In the 21st century, there have been tragic disappearances of flights that have led people to address the need of mapping more of the ocean floor. Natural disasters, environmental degradation, habitat loss and the desire for offshore energy and marine resources have caused investors to fund scientific research in this field (Wölfl et al., 2019).

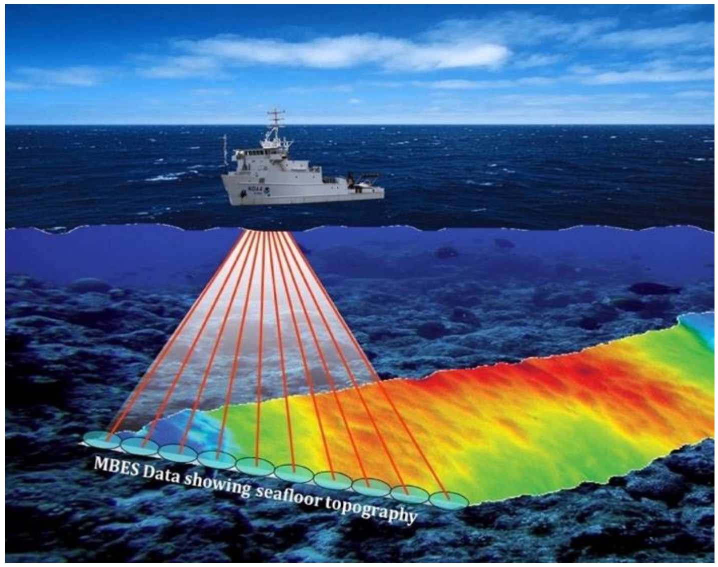


Figure 4.29 Multibeam echo sounders being used to survey the ocean floor.

None of this is possible without Tharp's initial map of the world's ocean. Tharp and Heezen's map helped demonstrate the significant lack of understanding of the ocean floor and established the basis for more scientific research.

Technological Developments

Since the push to gather more information from the water, there have been multiple other methods developed for surveying and collecting data in the underwater environment. Single beam echo-sounders (SBES) use a ceramic based transducer to send and receive acoustic signals (EL-Hattab, 2014). Multibeam echo-sounders (MBES), made publicly available in the 1970's, improved the area surveyed by radiating a fan of sound instead of a line (Mohmmadloo, Snellen and Simons, 2018). Satellite derived bathymetry (SDB) and light detection and ranging (LIDAR), both developed in the 1970's, are used for surveying shallower areas (Traganos et al., 2018). And satellite altimetry, first launched in the 1970's, is used not to measure the depth of the ocean, but instead to measure the height of the ocean's surface (Egbert and Ray, 2000).

Many of these mapping techniques are used today, with the addition of some new and more advanced techniques. Some advancements in mapping technology include using new transducer materials for sonar mapping, and the use of Remotely Operated Vehicles (ROV's) for more detailed and reliable seafloor mapping (Mayer, 2006). One trend in the recent developments has moved towards autonomous mapping, with ships being designed for unpiloted exploration of the seafloor in mind. This automation would eliminate the human resources needed and would also allow for a quicker turnaround of the gathered information being interpreted and distributed (Wölfl et al., 2019).

Seabed 2030

Building off of the work started by Tharp and Heezen, one major advancement that is expected to take place in the near future is the Seabed 2030 project. The goal of this project is to create a comprehensive map of all the world's oceans (Smithsonian, 2017). The project is currently recruiting around 100 ships that will circle the globe for 13 years to map approximately 140 million square miles of seafloor that has never been extensively surveyed before. The project intends to collect all bathymetric data available, in order to produce a definitive map of the world ocean floor (Smithsonian, 2017). It is essentially a modern version of what Tharp and Heezen sought to complete.

The project will use multibeam echo-sounders that will allow a single ship to collect and analyse thousands of square kilometers of data in a single expedition. However, even at this rate, it would take way too long for a single ship to do this mapping, but 100 ships doing this mapping makes the project seem a lot more manageable. The illumination of the seafloor will be a great feat involving many disciplines of science, and will provide long-awaited information that will be helpful and informative to many people and lifesaving to others (Smithsonian, 2017).

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Chapter 5. Contention & THEORIES

Lava from the Kilauea volcano flowing into the ocean.

Chapter 5.
Contention & Theories

Within any scientific field, there exists a single constant that holds true to the scope of our knowledge. We are constantly learning, and thus our understanding of certain topics is ever evolving, and as a result, scientific theories are seldom stagnant. With respect to the earth sciences and geology, there have been many past theories developed that have furthered our current understanding of geological processes.

The course of scientific advancement is one that guides us towards the pursuit of what is most true at any given moment. In retrospect, it may be easy for us to critique theories developed centuries ago, that have since been refuted. However, we must consider the limited knowledge available at the time. After all, these theories were the foundation for our current understanding of the Earth. Moreover, it is not unlikely that our current knowledge will be challenged in years to come as new information comes out.

A significant proponent to change the way science is communicated and accepted by others is related to the influence of external factors. In the past, religion played a vast role in the creation of theories, many of which were linked to Biblical events. Similarly, one's reputation could play a key role in the acceptance of their theories by others.

Another vital component of the scientific process lies within contention and dispute between key figures in a field. The desire to be correct and the best in a field is simply human nature. However, does this necessarily have to be a bad thing? While this can result in intense feuds where the sole purpose is to stain someone else's reputation, this is not always the case. Historically, there have been instances of contention that drive both parties forward, leading to the proposal of new research and a constant drive to advance knowledge in the field.

This chapter delves deeper into the world of scientific theories, from their creation to their rebuttal, and everything in between. It will also investigate key disagreements between scientists and how these instances of contention have led to what is known today.

Abraham Werner's Road to Failure Through Success

When discussing the history of science, one tends to focus on the major breakthroughs that changed humanity's way of thinking, especially ideas greatly contributing to the current knowledge within science. Be that as it may, sometimes a wrong idea can act as a stepping stone towards the right one. Abraham Gottlob Werner (1749-1817) is a famous geologist, most notably remembered for popularizing the theory of Neptunism which was eventually proven wrong in favour of Hutton's theory. Despite this, his work within the field of geology is largely regarded as not only necessary, but crucial for the advancements seen in nineteenth century geology and beyond. Werner demonstrated the power that an individual character has on the field of geology, bringing forth new knowledge despite a critically flawed theory.

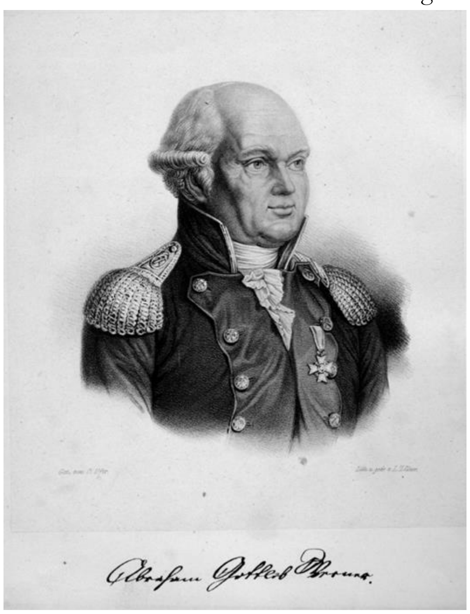


Figure 5.1. An artist's portrait of Abraham Gottlob Werner (1848).

Eighteenth Century Freiberg, Germany

The climate of eighteenth-century Freiberg, Germany (modern day Freiberg, Germany), into which Werner was born, gives context to the thoughts, actions, and proposals he put forth. At the time, a strong religious driving force throughout Germany was Pietism, an ideology to which Werner was heavily exposed throughout his secondary education (Sengor, 2001). This religious reform movement combined the importance of Biblical teaching from Lutheranism with the Puritan view of an individual piety, and placed a strong emphasis on practical learning (Sengor, 2001). As a result, it is thought to have influenced Werner throughout his life.

As a lecturer, Werner focused on preaching what he regarded as true, rather than fostering a learning environment which sought to discover new truths. The inevitable religious influence of Pietism within Germany can be attributed in part to his success as a lecturer and his ability to popularize the theory of Neptunism. Some also argue that Werner's theories were based on common stories found in the Bible; specifically, the great flood of Noah. However, there is no definitive indication that the universal ocean Werner described was attributed to or related to this Biblical event. It must be noted that the theory was theologically acceptable as it explained Earth's creation in a relatively short time frame, which conformed to the religious views of Earth's creation popular in the eighteenth century. Since the German mining community was strongly influenced by Christianity, the traditions and practices therein also served as a large influence on Werner.

The history of geology and observations made within and by the mining community were restricted by the Bible and its teachings (Sengor, 2001). In other words, the mining community of Germany accepted the biblical interpretation of Earth's creation, making it difficult for the development of new scientific theories. This traditional mindset was not only more familiar but also more teachable than the new geological developments nearing the end of the eighteenth century, which incorporated more dynamic processes, such as the Huttonian theory of uniformitarianism. It is through these strong influences that bring forth the largely accepted idea that Werner set out as both a miner and teacher to verify his truth rather than to discover it.

Abraham Werner's Source of Inspiration

Werner was the German geologist responsible for developing a theory for Earth stratification, as well as for popularizing the theory of Neptunism. Born and raised in Saxony (modern eastern Germany), Werner descended from a long family history of miners. His exposure to the techniques of mining from a young age, as well as knowledge regarding this craft, provided the outline for his success as a professor (Newcomb, 1990; Sengor, 2002). His father, Abraham David Werner, worked as an inspector for the Duke of Solm's ironworks in Wehrau and Lorendorf, Germany. He forced his son to quit school at a young age after deciding that his son would learn best under his personal tutelage. By the time Abraham G. Werner had reached the age of nine, he was already heavily educated in the ways of the mining industry and received the basics of mineralogy from his father by working in his iron foundry (Newcomb, 1990; Oakes, 2007). Working in the iron works industry gave him the requisite platform required to venture into what was considered a novel topic at the time. As he grew older, he took his basic skills and applied them to university level concepts, popularizing the field of geology (Newcomb, 1990; Oakes, 2007). He studied at the University of Freiberg and Leipzig, where he continued to pursue his passion of geology.

The Development of a Competent Mineral Identification System

Werner's initial works were a result of his strong interest in mineralogy. In the third year of his studies, he took courses on foreign languages, philosophy and medicine, but he always had a deep underlying passion for mineralogy and the natural branch of science (Carozzi, 1960). As a student studying at the University of Leipzig, he quickly realized the lack of a structural system in place to both classify and identify minerals. Prior to Werner, the classification system was based on the ideas of Georgius Agricola (1494-1555) and his book *De Natura Fossilium*, which separated minerals based on simple categories (i.e. earths, stones metals, etc.) (Newcomb, 2009; Staples, 1983). Agricola was widely considered to be the father of modern mineralogy, but Werner found his approach in direct conflict with his own as he was convinced that both chemical composition and physical characteristics could be used in conjunction with each other. In spite of Werner's criticism of Agricola's work, Werner credited Agricola for giving him partial inspiration, stating, "He was the first to introduce the real use of external characters in the description of minerals" (Newcomb, 2009, 11). Inspired by Johann Carl Gehler's mineralogical treatise *De characteribus fossilium externis* (1732-1796), Werner was determined to study this topic in hopes of creating a new method for classifying minerals. Within the following year, he published the textbook *Vonden äusserlichen Kennzeichen der Fossilien* (On the External Characteristics of Fossils, or of Minerals) (Carozzi, 1960; Staples, 1983). His textbook was the first in the world to outline a new scientific description of minerals, a system that has continually been refined as geologists discover new knowledge. He stated that minerals should be classified based on their chemical composition, in addition to their external characteristics and physical properties. Almost immediately, his published work generated much excitement around Europe, based on his position as a professor and the amount of respect given by his fellow scholars and future students. Many young scientists quickly developed a passion for the field of geology and became inspired to pursue a career in a similar field of work (Guntau, 2009; Newcomb, 1990).

Although his works were initially written in German, they have been translated into various languages, including English and French, over the years. Controversially, the English and French translations were not exactly identical. Specifically, within the English version, there were found to be slight modifications in the sections of crystallography. The modest differences per translation were indicative of his progressive ideas; as it appeared, he gave different sets of notes to various translators (Carozzi, 1960). Furthermore, after the Library of the University of Illinois acquired Werner's personal copy of the 1774 original text, it was discovered to be heavily annotated, meaning that any translations published near the time period of his research were not a holistic representation of his original ideas (Carozzi, 1960). Only recently published copies of his works were able to appropriately showcase the progressive thinking and evolution of Werner's mineralogical ideas. Chorley (1993) wrote, "As a mineralogist Werner's repute is not questioned. While still a student at Leipzig he wrote a description of mineral characteristics which introduced descriptive methods then unknown to practitioners of the science. He was certainly no armchair theorist for he sought his information both from the hills and down the mines, even at times indulging in the ordinary work of a miner in order to glean first-hand material" (Chorley, 1993, 27), demonstrating the true nature of Werner's abilities as a mineralogist and a theorist. His discovery and methods of conducting research provided a stepping stone for the development of his infamous Neptunism theory.

The Evolution of Neptunism

The development of the theory of Neptunism began with initial studies of plate tectonics. By the 1700s, plate tectonics data still had not been well documented, leading many to speculate about the formation of the Earth. One prominent philosopher, Robert Hooke (1635-1703), was the first to recognize that earthquakes came from land movements (Drake & Komar, 1983; Rappaport, 2011). Hooke primarily supported the ideas of Diluvialism, which states that Earth had been flooded more than once. Although modern Diluvialism and Neptunism are now fundamentally different, in the 1600s and 1700s they were seen to be comparatively similar (Allaby, 2009). As Hooke was never heavily influenced by the teachings of the Bible, he did not see the immediate need to correlate it with observable phenomena in nature. Hooke believed that earthquakes were the result of the Earth's uneven surface and his intention was to explain the movement of the terrestrial crust, through the mechanisms of faulting and volcanic eruptions. Additionally, these initial ideas on earthquakes led him to develop his concept of cycles in nature. He believed that these cyclic processes were the driving force behind the formation of fossils (Drake & Komar, 1983). Moreover, he continued to use this belief to explain the nature of fossils and how they were composed of petrified organic remains, insisting that marine species must have come from the bottom of the ocean (Drake & Komar, 1983).

Some years later, French naturalist Georges-Louis Leclerc, Comte de Buffon (1707-1788), built upon Hooke's work and insisted that all landforms had originated on the seafloor. Georges-Louis Leclerc did not know of Robert Hooke or much of his teachings, but their combined theories provided the necessary stepping stone for the development of Neptunism (Bednarczyk, 2007). Although he was unable to explain the reason behind the emergence of land from the depths of the ocean, it became even harder for the scientists and scholars at the time to rely on the explanation surrounding a central heat source found within the Earth. The unimaginable idea of a heat source existing deep within the Earth gave Neptunism its initial advantage, which started gaining traction around 1790 through the work of Nicholas Steno (1638-1686) (Ospovat, 1980). Although the theory of Neptunism had existed long before Werner, it was Werner who gave the theory scientific credibility at a time in history when the previously provided reasoning was no longer enough to support the theory in the eyes of the scientific community (Ospovat, 1980). He used geological observations as a guide to inductively reason that all the rocks of Earth's crust aligned with his proposal (Ospovat, 1980). Werner's personal mineralogical experience was limited to the confines of Germany, from which he rarely ventured beyond. Based on the scientific discoveries available to researchers in the time period, it was more reasonable to believe the ocean was the answer to the formation of the Earth. Neptunism is the belief that rocks were formed from the waters of a primeval ocean, by the process of crystallization. This apparent discovery led to the development of Werner's theory, which states that the Earth could be divided into five categories including 1) primitive, 2) flots, 3) alluvial, 4) volcanic, and 5) transitional (Ospovat, 1960). It is believed that Werner followed his ideas to the very end of his life.

The Spread of Neptunism

Werner spent the majority of his career at Freiberg Academy as a lecturer (Chorley, 1993). The dissemination of his theory and ideology was largely due to his students, as Werner did not travel much outside of Germany. His students were mostly studying to become practical miners, and thus required knowledge on mineral identification and ore bodies opposed to Earth dynamism theories, such as that proposed by Hutton, which made it extremely difficult to correlate rock bodies over large distances (Sengor, 2001). In other words, the theory of Neptunism provided a one-dimensional layout of the depositional processes of all rock bodies on Earth, and was a simpler, more comprehensible theory to assist in the work of a miner. Werner's theory fueled his teaching and allowed him to describe, from a few pieces of rock, a clear, orderly pattern that explained what was seen and observed at the time (Chorley, 1993). He could guide students through the strata sequence, embarking on a story about the mighty ocean that assisted in the deposition of each layer, describing the fossil deposition of each strata, while painting a picture of the aqueous solution responsible for the rock evidence he collected (Chorley, 1993).

However, many of Werner's students initially accepted, and then later rejected, the Neptunism theory. For instance, Jean Francois Aubuisson de Voisins (1769-1841) studied under Werner and was a proponent of Neptunism, but in 1819 published his two-volume *Traite de Geognoise*, which put forth arguments against Neptunism through discussion of the similarities of igneous rocks and surface lava flows (Aubuisson de Voisins, 2011). Despite his student's eventual transition of beliefs, he mentored and inspired his students greatly, many of whom went on to make great contributions to the field of geology. For instance, Friedrich Mohs (1773-1839) was a student at Freiberg Academy who studied under Abraham Werner. Friedrich went on to develop a classification system for rock hardness known as the Mohs Scale of Hardness. In this case, Werner's teaching of strata classification is thought to have influenced Mohs, who went on to create a different rock classification system based on rock hardness. Although his teaching methods may have prioritized educating his students on his truth rather than creating an environment of discussion, he became so well known for his teaching abilities that when word of Werner's passing spread, the enrolment rate at Freiberg Academy plummeted, demonstrating his true impact as a teacher (Chorley, 1993).

The Debate: Plutonism and Neptunism

Despite the popularity of Neptunism at the time, some scholars did not conform to the common belief system. The best example came from a man known as James Hutton (1726-1797), a Scottish geologist responsible for popularizing the theory of Plutonism, which directly contradicted Werner's theory of Neptunism. Followers and believers of Neptunism strictly believed that all rocks had precipitated from a global ocean, including igneous rocks, which James Hutton had vehemently opposed (O'Hara, 2018). Followers of Neptunism firmly believed in a global menstruum, where humans lived in a world where the ocean advanced and receded globally multiple times throughout the course of geologic history. This theory helped them to explain the extraordinary phenomena of volcanoes, which were thought of as accidents (Rappaport, 2011). Neptunism followed the belief that volcanic eruptions were an unimportant aspect of Earth's geology, as they were classified as unpredictable accidents. This completely differed from the Plutonism point of view, as they believed intrusive igneous rock was formed through the solidification of magma underneath the Earth's surface (Rappaport, 2011).

However, the biggest controversy between the theories of Neptunism and Plutonism revolved around basalt. Neptunism insisted that basalts were sedimentary rocks composed of fossils which could not have originated from volcanoes. On the other hand, this differed greatly from James Hutton's (1726-1797) idea of Plutonism, who believed that lava flows were a direct result of volcanic eruptions, while igneous activity could be seen as a force which countered the forces of erosion (Rappaport, 2011). Followers of Plutonism believed that basalt came from solidified molten magma. Although there are no credible documents proving Hutton and Werner ever met in person, it was clear they were contemporaries who strongly disagreed with the other's theories (Mutch, 2015). Unfortunately for Hutton, his ideas spread slowly due to a lack of a respected academic teaching position. In addition, he was a lousy writer who was well known for a lack of clear communication (O'Hara, 2018). These factors, coupled with Werner's prestigious stature, delayed the development of Hutton's true theory. The debate between these two theories lasted until the early nineteenth century, until the works of Charles Lyell (1797-1875) confirmed the plutonism theory of James Hutton (Sengor, 2002).

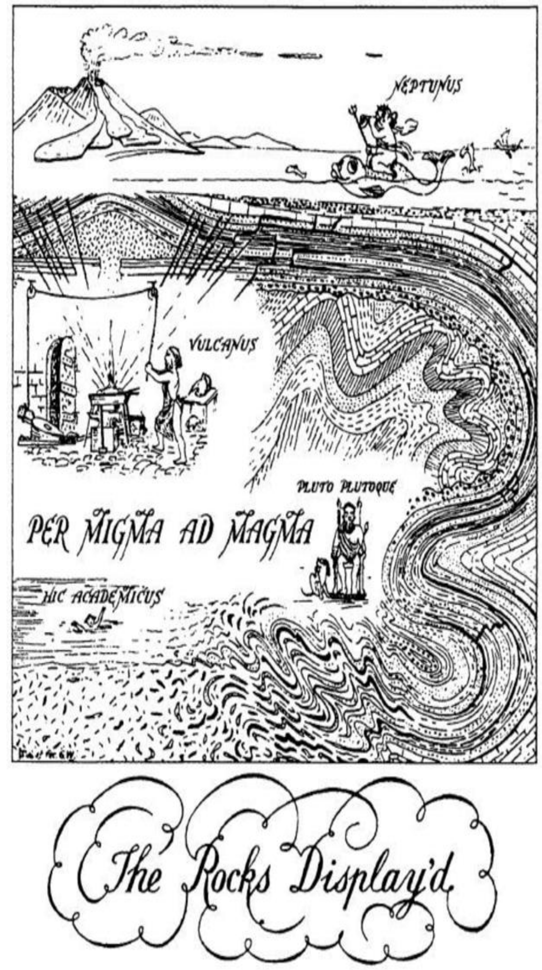


Figure 5.2. A cartoon fitting to the Neptunism and Plutonism debate of the nineteenth century drawn by D.A. Walton (1957).

Interestingly, evidence in the form of silica exists to prove Werner's theories. It is theorized that Werner may have examined the properties of silica within a water solution from his experiments, although Werner had an unknown name for the modern-day rock. For rocks to be deposited under a water-based solution, both a mechanism and precipitation of silica needed to be present (Newcomb, 1986). Surprisingly, the process that occurs today is not vastly different than what was observed before, making it somewhat plausible that Werner's theory made logical sense to a certain degree. This was proven using laboratory chemistry evidence and quantitative analysis techniques (Newcomb, 1986). It is also thought that Werner was strongly supportive of his ideas because he deemed the theory to be most reasonable at the time (Guntau, 2009; Newcomb, 1986). In Werner's time period, it would have been logical to agree with Neptunism as common, geological phenomena were not clearly understood. Nevertheless, critics still rightfully pointed out that Werner should have been more careful with his observations.

Criticisms of Werner's Work

It can be said that Werner's limited scope and early discoveries led him to dedicate his life to Neptunism. Although it is generally accepted that the regional geology of Saxony, Germany played a large role in Werner's universal ocean theory, an article written by Alexander M. Ospovat, a Historian of Geology at the University of Oklahoma, claimed otherwise. He argued that scientific theories "rarely, if ever, rest only on empirical evidence", and that this was a "far too simplistic approach to deduce the thought process of Werner" (Ospovat, 1980). While the true impact of regional geology on Werner may be lost in history, it is evident he failed to acknowledge the rock structures that did not conform to his theory of Neptunism. He was consistent throughout his life with the belief that failure to explain a phenomenon does not override or erase all evidence that proved its existence (Ospovat, 1980). In the case of Werner, his inability to explain how the mountain-covering universal ocean shrunk to its current sea level did not cause for self-doubt. Rather, he fought criticism of the theory with the exact argument stated above: that lack of evidence does not correlate with implausibility. However, his inspiration and adoration for this specific field inspired thousands of new geologists to venture into the new space, a subject still scarcely understood. A primary example was seen through the works of William Maclure (1763-1840), a famous American geologist who used Werner's classification system and nomenclature to publish the first geological map of the United States of America (Newcomb, 1990; Ospovat, 1960).

Currently, new technology is being developed for a better understanding of Earth's stratigraphy. Abraham Gottlob Werner's creation of a mineral identification system, coupled with his failed theory of Neptunism, has paved a realistic path for new scientists to traverse in discovering the true mysterious origin of Earth, with less fear of failure.

Spectrometric Applications for Dating and Composition

The theory of Neptunism, although eventually disproven, was the first theory that systematically classified minerals. It also acknowledged the chronological succession of rock strata, providing a link between stratification and geological time. As the science of geology has progressed and technology has advanced, mechanisms to more accurately predict the age and geochemical makeup of rock samples were invented. In modern times, there are various techniques and methods used to determine rock strata origins, in addition to their depositional environment and age. As a miner, Werner relied heavily on visual observation, a technique still used today. Without knowing it, Werner was practicing the techniques of biostratigraphy.

Radiometric Dating Methods

Radiometric dating methods for igneous, metamorphic and sedimentary rocks are based off the idea that rocks, or the minerals therein, contain unstable isotopes which decay at a constant rate through geological time (Earle, 2015). It also assumes that during elemental decay, no atoms escape from the rock into the surroundings. For igneous and metamorphic rocks containing a potassium-bearing mineral, the K-Ar dating technique is commonly used through mass spectrometry to determine the difference between the masses of atoms (Earle, 2015). Once the masses of the parent and daughter element are determined, these values are used along with the half life of the parent element to determine the age of the rock. Although radiometric dating enables igneous and metamorphic rocks to be dated, this technique is not usually sufficient to date sedimentary rocks, particularly those with lack of volcanic interbedding. Furthermore, sedimentary rocks with low organism presence makes it difficult to date works using biostratigraphy. Sedimentary rocks are difficult to date because of their older composition and the assumption that no daughter product is present at the time of formation. Recent technologies have furthered our ability to date and examine sedimentary rocks, examples of which are discussed in this section.

Diagenetic Xenotime Geochronology

A new technology called diagenetic xenotime geochronology is advancing the field of radiometric dating for sedimentary rocks, particularly those from Precambrian time that are low on biodiversity (Rasmussen, 2005). Xenotime (YPO4) is a phosphate mineral that has been identified as a trace constituent capable of early growth on detrital zircon during diagenesis in siliciclastic sedimentary rocks (Rasmussen, 2005). Xenotime occurs in sandstone, conglomerate, shale, siltstone, and volcaniclastic rocks that can range in age from the Archaean to the Mesozoic (Rasmussen, 2005). Xenotime diagenesis results in euhedral-shaped overgrowths, which are believed to form shortly after sediment deposition, allowing for it to be used as a dating chronometer (McNaughton, Rasmussen and Fletcher, 1999). In situ isotopic analysis of these overgrowths utilizes SHRIMP II (Sensitive High-Resolution Ion Microprobe) mass spectrometer analysis (McNaughton, Rasmussen and Fletcher, 1999). This technology works by using a high-energy ion beam to ionize sample material which can then be electrostatically extracted into the mass spectrometer. Analysis consists of U-Pb geochronology to estimate the age of the rock, as well as element geochemistry. This process is very similar to radiometric dating of igneous and metamorphic rocks. For example, it uses isotopic analysis of uranium and lead (^{203}Pb forms from ^{238}U) concentrations within the sample to estimate the age of the rock. A study conducted by Rasmussen (2005) found the U-Pb dating of xenotime (high content of U but low content of Pb) to be similar in precision to U-Pb dating of igneous zircon, demonstrating its potential within the field of geochronology.

X-ray Fluorescence Spectroscopy

A similar approach to investigating minerals is through the investigation of trace elements. The International Union of Pure and Applied Chemistry defines a trace element as "any element having an average concentration of less than about 100 parts per million atoms or less than 100 μg/g." (Brown and Milton, 2005). X-ray fluorescence spectroscopy is a well-established method of investigating the composition of rocks. It uses X-ray radiation to analyse solid samples based on the principle that X--ray photons of energy are emitted from individual atoms, which can then be estimated to predict its sample composition (Oyedotun, 2018). Its widespread use can also be attributed to the simple, non-destructive nature of sample preparation (Oyedotun, 2018). On the XRF spectrum, each element has a fixed position, making it simple to identify the elements present in a sample (Oyedotun, 2018). This technology provides a quantitative breakdown of elements present in a sample in a non-destructive manner, playing an integral role in our understanding of Earth material composition.

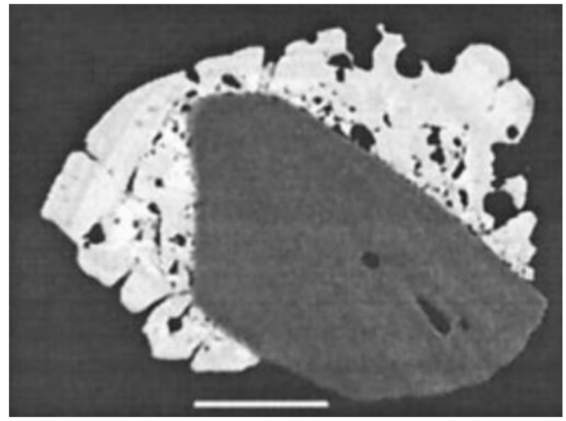


Figure 5.3. A scanning electron microscopy image of a siliciclastic sedimentary rock showing zircon (grey) with xenotime overgrowths (white), from McNaughton, Rasmussen and Fletcher (1999).

Future Applications: Thermal Emission Spectroscopy for use on Mars

Thermal emission spectroscopy is a type of vibrational spectroscopy that has been proven accurate in determining the mineralogy of metamorphic and igneous rocks; although the technology for use on sedimentary rocks has been limited (Thorpe et al., 2015). Molecular stretching and bending of the vibrational modes that are present in any material are sensed by this form of spectroscopy, and the frequencies of the vibrations of minerals in a sample rock are then related to the structure and composition of a sample (Thorpe et al., 2015). While this technology has demonstrated success with igneous rocks, research on its application for sedimentary rocks is limited, as thermal emission spectra is influenced by particle size and compaction (Thorpe et al., 2015). This technology is currently being utilized by NASA to locate clays on the surface of Mars that could contain carbonate minerals. It fundamentally works off the notion that when different materials or minerals are exposed to the same amount of thermal energy, they will have different temperatures.

Overall, advancements in rock dating and identification have furthered our ability to understand the processes of geology. However, the processes needed to gather the structure of Earth, its environment, and its creation began centuries ago, when individuals such as Abraham Gottlob Werner started embarking on a journey to discover and share their truths.

The Bone Wars

Nineteenth Century Paleontology

The mid-nineteenth century, a period commonly coined as the Great Dinosaur Rush, was a time in which paleontology was taking the Western world by storm. It was a time of broad scientific discoveries as well as a time of political conflict and personal bias. The ending of the Renaissance period brought with it a surge of interest in the study of paleontology and the natural world. Various discoveries regarding past life were accumulating rapidly but were disorganized and inconclusive.

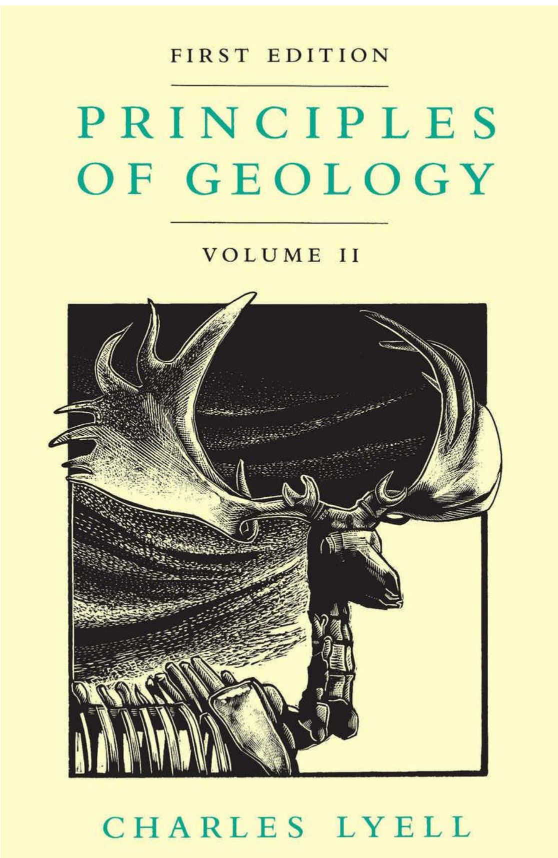


Figure 5.4. Cover of the second volume of Lyell's "Principles of Geology", with hand-drawn image of skeletal remains of an Irish Elk (Lyell, 1991).

Charles Lyell was a renowned Englishman at the time, who aimed to organize and compartmentalize current scientific discoveries. In 1830, Lyell published his book *Principles of Geology*, which consisted of three volumes and was continually revised throughout the next 42 years as scientific discoveries changed (Lanham, 2012, 8). At the time of publication of his initial version, Lyell was critical of the concept of evolution. He believed that animals that existed in the past still existed in the same way today and that any evidence of physical differences were due to degradation of fossils over time. As scientific discoveries advanced, and as Darwin's discoveries were confirmed, Lyell rethought his initial hypothesis and revised his book to better reflect the concept of evolution (Lanham, 2012, 11).

Lyell also showed a significant amount of interest in the processes that shaped the world, ranging from sedimentary processes to the complexities of climate change (Lanham, 2012, 14). He was a pioneer for future scientific discoveries and coined the concept that "the present is the key to the past."

Europe was quite advanced at the time in regards to various paleontological findings. The United States was not as well versed in regards to scientific methods and the accuracy of obtaining fossils (Jaffe, 2000, 22). American paleontology at the time was heavily fixated on results and less focused on methods. This resulted in scientists resorting to many unethical and inaccurate approaches. The study of paleontology had a vast opportunity for growth that only few would deem as advantageous.

Paleontology: A Field of Opportunity

Two individuals that did take advantage of such a field of opportunity were Edward Drinker Cope and Othniel Charles Marsh who were notable paleontologists of the nineteenth century. To discuss their life and history, three main sources of literature have been chosen to be referenced. The first is the 2000 book *The Gilded Dinosaur: The Fossil War between E.D. Cope and O.C. Marsh and the Rise of American Science* by Mark Jaffe. The second is the 1999 publication *The Bonehunters' Revenge: Dinosaurs, Greed, and the Greatest Scientific Feud of the Gilded Age* by David Rains Wallace. The third is the 2012 book *The Bone Hunters: The Heroic Age of Paleontology in the American West* by Url Lanham.

The first book pieces together a biography of the two men, while providing a strong account of their respective emotions and personal motivations. Jaffe utilises many letters and correspondences that were written to and from their colleagues and families to aid his writing. Wallace follows a more linear writing style, as opposed to Jaffe's sporadic excerpts. Wallace also provides additional emphasis on the background of key characters and locations, which assists in understanding implicit personal motivations for the various characters. Both of these works were received well, with Scientific American (2000) reviewing the first with "The early years and troubled maturation of American paleontology are Jaffe's subject, which he...makes a rich tale of...describing not only the tense relationship...but also what it was like to hunt for fossils on the frontier". Professor John McIntosh says of *The Bonehunters' Revenge* (1999) "Wallace's...book is sure to become the definitive work on the Marsh-Cope feud". For the third book, Lanham provides a description of the early life of both men, and the beginnings of paleontology. He emphasises the inherent differences between them and the quality of work that they produced. The three pieces are diverse, well-written and comprehensive sources, critical to recounting this chapter of history.

Edward Drinker Cope

Edward Cope was born to a wealthy Philadelphia family and spent the majority of his childhood exposed to a vast extent of opportunity. He was often described as "spoiled" and "entitled" as a child (Lanham, 2012, 61). Cope entered the field of academia because of the reputation carried by his family name. His work and areas of interest led him to the Academy of Natural Sciences in Philadelphia where he worked on classifying various biological specimens (Lanham, 2012, 63).

Due to the small size of the university, and the weight that his family name carried, Cope was able to secure a teaching position at Haverford College. However, in order to teach at an American university, Cope required an academic degree, and one was bestowed upon him as a formality (Wallace, 1999, 21). Since his obtained master's degree was only honorary, he lacked any formal education (Wallace, 1999, 22). As a result, Cope's entire reputation relied on the success of his work. He focused more on quantity over quality and thus published as many findings as he could, to create and maintain a stellar reputation.

Cope reached the height of his career in the 1870s when he made several critical discoveries that were revolutionary for paleontology at the time. One such discovery was of the sauropod *Amphicoelias* which was the largest dinosaur ever discovered at that time (Lanham, 2012, 65). These bones were discovered in Colorado rock outcrops and were eventually classified as belonging to an entirely new taxon. That same year Cope published an additional 76 papers that thoroughly described and analyzed his findings (Lanham, 2012, 60). These papers included findings from his travels to New Mexico and Colorado, and the qualitative observations he made. These discoveries led him to an inevitable encounter with Marsh in the 1870s when their paths crossed.

Othniel Charles Marsh

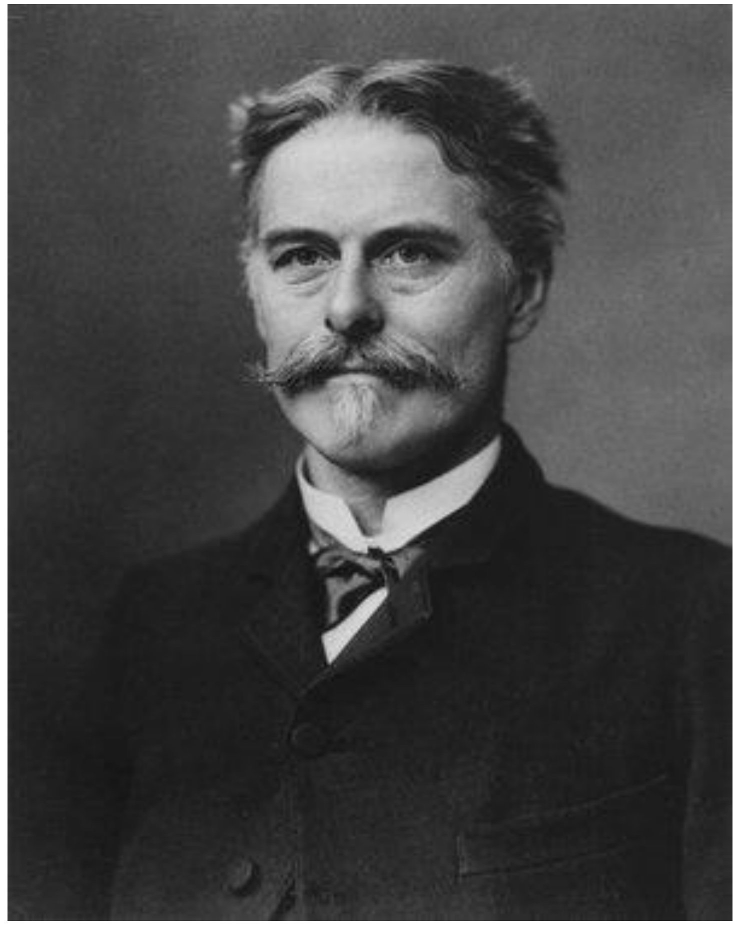


Figure 5.5. Portrait of E. D. Cope at age 55 in 1895 (Yale Peabody Museum, 1895).

Othniel Charles Marsh was another well-known paleontologist during the nineteenth century and was the other significant figure involved in the well renowned Bone Wars. Marsh was born to a simple, modest American family. With the academic support of Marsh's wealthy uncle and an academic scholarship, he was able to attend Yale college at which he studied geology and mineralogy. Marsh's uncle, George Peabody, was a significant figure in the life of Marsh, as he provided financial support for most of Marsh's education (Wallace, 1999, 28). This allowed Marsh to continue to make scientific discoveries in addition to receiving formal schooling.

In the years to follow, Marsh studied paleontology at a number of European academic institutions. Specifically, Marsh spent time in Berlin, Heidelberg, and Breslau, focusing on anatomy in addition to paleontology (Lanham, 2012, 48). Upon returning back to Yale, Marsh was appointed as the first American professor of vertebrate paleontology. Within that same year, he was able to persuade his uncle to donate a significant amount of money to finance the Peabody Museum of Natural History (Jaffe, 2000, 24), of which Marsh became one of three curators. Due to the additional wealthy donations made by various academic dignitaries, Marsh was able to finance his various upcoming paleontological expeditions (Wallace, 1999, 31).

Marsh had certain areas of interest regarding paleontology. Specifically, Marsh described dozens of new species and fixated on the evolution and origins of various bird species. Throughout his work, Marsh discovered fossils that substantiated the evolution of the horse (Lanham, 2012, 51). These findings were significant as they backed Darwin's earlier postulates regarding evolution.

Cope and Marsh First Meeting

Cope and Marsh first met one another in the winter of 1863 in Berlin, Germany (Jaffe, p. 47). Cope had relocated himself to Berlin in an attempt to escape being drafted into the American Civil War. Additionally, through residing in Berlin, he was able to continue his studies pertaining to natural history. Marsh was a graduate student, also pursuing additional studies in Germany at the time (Jaffe, 2000, 47).

The two men differed significantly in both education and experience. Marsh had a notable amount of academic experience, while Cope compensated for what he lacked academically with practical experience. At the time of their first encounter, Cope currently had 37 papers published, sharply contrasting Marsh's two.

Additionally, the quality of work between the two men differed significantly. Cope was a quick worker and was capable of producing many manuscripts in a short period of time. However, this speed led to an increase in the number of mistakes, which led to a lack of confidence in his published work (Lanham, 2012, 62). On the contrary, Marsh's work was often quite intensive, and well thought out, although it took much longer to be produced.

Upon their first interaction, Cope and Marsh appeared to enjoy one another's company and seemed as though they might be companions. They engaged in many activities together throughout their time spent in Berlin. Upon returning to America a year later, Cope named a dinosaur after Marsh, the *Pytonius marshii*, an amphibian-like fossil (Wallace, 1999, 42). The next year, Marsh named a recently discovered giant serpent *Mosasaurus copeanus* after Cope. The beginnings of their interactions appeared amicable, and it wasn't until seven years later in 1870 when the beginnings of dispute began to arise (Jaffe, 2000, 27).

The Feud

As time progressed, more significant differences became apparent between the two men. Cope had a short temper and was often loose-lipped, particularly regarding his opinions of others. Marsh tended to be much more introverted and kept his opinions to himself (Wallace, 1999, 42).

The first conflict occurred when both Cope and Marsh ventured to Cope's marl pits in New Jersey. Marl pits are fossil sites rich in calcium carbonate or mudstone with significant amounts of silt and/or clay. This pit was a fairly new excavation site (Jaffe, 2000, 51) and was rich with a multitude of undiscovered fossils. After parting, Marsh bribed several of the pit operators to send him the fossils, unbeknownst to Cope (Jaffe, 2000, 51).

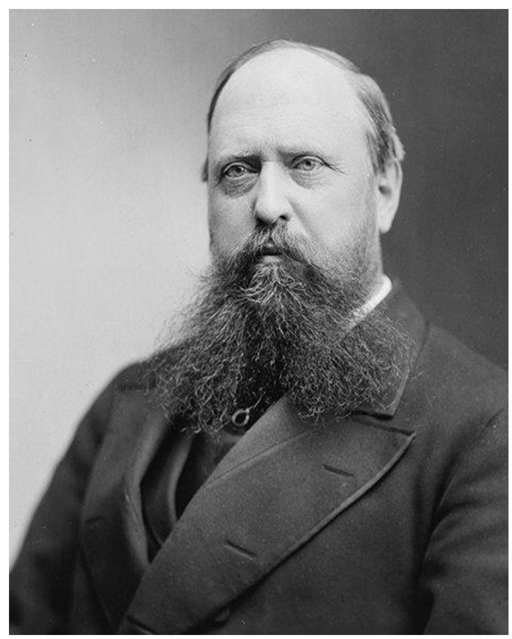


Figure 5.6. Portrait of O. C. Marsh (right) at age 47 in 1880 (Brady, 1880).

The next significant conflict occurred in 1868, when Cope discovered and restored the remains of the giant marine *Elasmosaurus*. In doing so he accidentally placed the skull of the creature on the end of its tail. When Cope invited Marsh to see, Marsh was ecstatic to point out the mistake, especially in front of fellow colleague Joseph Leidy (Jaffe, 2000, 52). This act filled Cope with indignation and was later believed to mark the distinct beginning of the feud.

Shortly after this event, Marsh put together a summer expedition to the Midwest, in which he brought a handful of Yale students to assist him. Over those weeks he uncovered copious amounts of fossils (Jaffe, 2000, 53), which included a pterodactyl that was at least twenty-times larger than anything found in Europe at the time. In addition, Marsh was able to publish five papers, which was a substantial number for him at the time. This success made Cope envious, and he began to make plans to travel out to the plains to take part in the action.

The subsequent travels that occurred in 1871-82 revealed the friction between the two men. Cope would arrive later than Marsh, and many a time would hire those who Marsh had left behind, discarded, or treated poorly (Jaffe, 2000, 53). Marsh's rejects would be very willing to gift Cope with the knowledge of locations that Marsh had already covered, increasing Cope's successes.

Marsh was extremely territorial in regards to all aspects of his work; he would not even let the president of his own university into his private study (Jaffe, 2000, 28). Therefore, it was no surprise that he would have trouble sharing any piece of the Midwestern United States with other paleontologists. With the arrival of Cope as well as other notable colleagues such as Leidy, Marsh grew increasingly aggravated at every fossil find, and every paper written by someone other than himself. In that time, Cope managed to find a pterodactyl that was even larger than Marsh's. Additionally, he and Marsh managed to find fossils of the same species on the same day, and then published papers with their own distinct names for the creature (Wallace, 1999, 73). This speed was unprecedented in the scientific community and caused a huge commotion with the now outdated methods (in the end it was discovered that Leidy had published a paper about the same species two weeks before, and therefore was credited with the discovery) (Jaffe, 2000, 90). Eventually, Marsh came to the realization that Cope was explicitly watching his expedition group, and visiting the sites that they had left, to scrounge for bits. In response, Marsh devised a trap, in which he planted bones from different animals at a site, to make it seem as though they were related. As predicted, Cope took these bones and soon published a paper proclaiming the discovery of a new species, a mistake that would not be corrected for two decades (Jaffe, 2000, 81).

It was in 1873 when the feud between the men escalated. After a couple of snide personal letters to each other about fossil theft, Marsh took to the *Naturalist* and the *American Journal of Science* to add comments to his own papers, essentially calling Cope a cheat. Cope and Marsh began to print rebuttals to each other, escalating to the point where the journal had to cease printing the attacks, and said if they wished to continue they would have to buy appendix papers. Buy them they did, spending copious amounts of money to buy tens of pages in which to publish their accusations (Jaffe, 2000, 97).

Throughout the rest of their lives, each man utilised every single opportunity to sabotage the other. The goal was no longer to elevate their own stature but rather to destroy the reputation of the other. Marsh used his connections within the newly created U.S. Geological Survey and copious bribes to both slow the publication of Cope's papers, and to keep secret the location of newly discovered boneyards (Jaffe, 2000, 226). Cope's reputation was being damaged at every turn, yet he gave no indication of giving up. He began to experience massive financial burdens, which he had no way of paying (Wallace, 1999, 190). Cope's final attack on Marsh came in the form of one pinnacle accusation piece in the *New York Herald* in 1890. It brought the decades-

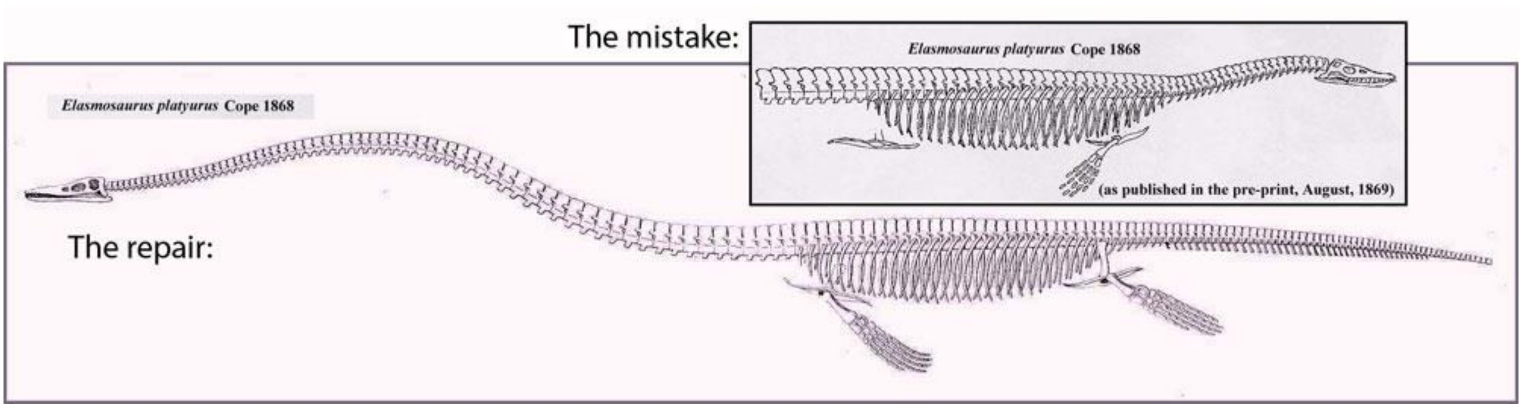


Figure 5.7. Image of Cope's drawing of Elasmosaurus *before and after the discovery of the skull placement mistake (Cope, 1869).*

long feud that had remained solely within the inner circles of academics and government into the eyes of the general public (Wallace, 1999, 217). After a few weeks of circulation, the commotion finished with little change to the situation and stature of both men. After that, Cope withdrew his attacks on Marsh as his health began to deteriorate (Wallace, 1999, 270). His death in 1897 marked the end of the public dispute, but Marsh held on to his disdain until his own death in 1899. After nearly three decades, the feud was finally over.

Modern Paleontology

Scientific Process and Modern Paleontology

The complexities of the Bone Wars and the feud affiliated with them taught present day scientists much not only about paleontology, but the scientific process as well. Science prior to the nineteenth century was heavily dominated by religion and spiritual beliefs. A key figure at the time was Aristotle, who believed that science and religion were one and that natural processes could be explained by God's actions rather than natural phenomena. At the time science had not yet evolved to be secular. The coming of the nineteenth century brought with it seemingly controversial topics, such as that of evolution and, later in the twentieth century, ideas about the Big Bang. These topics brought with them a new process of thought, one that could only be supported through a vast amount of scientific evidence.

At the time of the Bone Wars, Cope and Marsh's methods of scientific analysis and critical thinking skills were inherently defective and inaccurate. Their execution of the scientific process was riddled with critical flaws. For one, the work was sloppy and often inaccurate. Both men were fixated on how fast they could accomplish work rather than the quality of the work. In addition, their version of the scientific method consisted of bribery, coercion and competition. In comparison to former scientific methods, science should aim to be free of personal bias and should be as impartial as possible. It is difficult for science to advance when personal issues interfere.

For Marsh and Cope, their inevitable feud ruined the relationship that they had not only with one another, but with the scientific community. Repeated conflict discredited their work and taught fellow peers within the scope of academia that research must be impartial.

When individuals debate who won the Bone Wars, the common answer is paleontology itself. Although the constant conflict destroyed both Cope and Marsh's reputations and careers, the field of paleontology flourished. Prior to Cope and Marsh, there were nine identified dinosaur species in North America. At the end of the Bone Wars there were over 130 identified species (Lanham, 2012, 62). This period of conflict allowed for science to progress, albeit unethically. However, despite the vast number of discoveries by these scientists, a significant

Figure 5.8. Portrait of Marsh and his Yale graduate students preparing to go on another digging expedition (Ostrom, 1872).

number of fossils were destroyed in the process. These fossils may have contributed to even more discoveries had they not been ruined through reckless actions. The lesson that can be taken from the actions of Cope and Marsh is that in the field of science, most individuals have an ego. However, it is integral that such an ego does not interfere with the completion of one's scientific discoveries.

Paleontology: A Tool of the Twenty-First Century

In what is now the twenty-first century, paleontology is still flourishing. Scientists from all around the world are continuously working to discover the various origins and complexities of life as it exists today. With the current global climate crisis, many are turning to paleontology as a possible key to survival (Louys, 2012, 22).

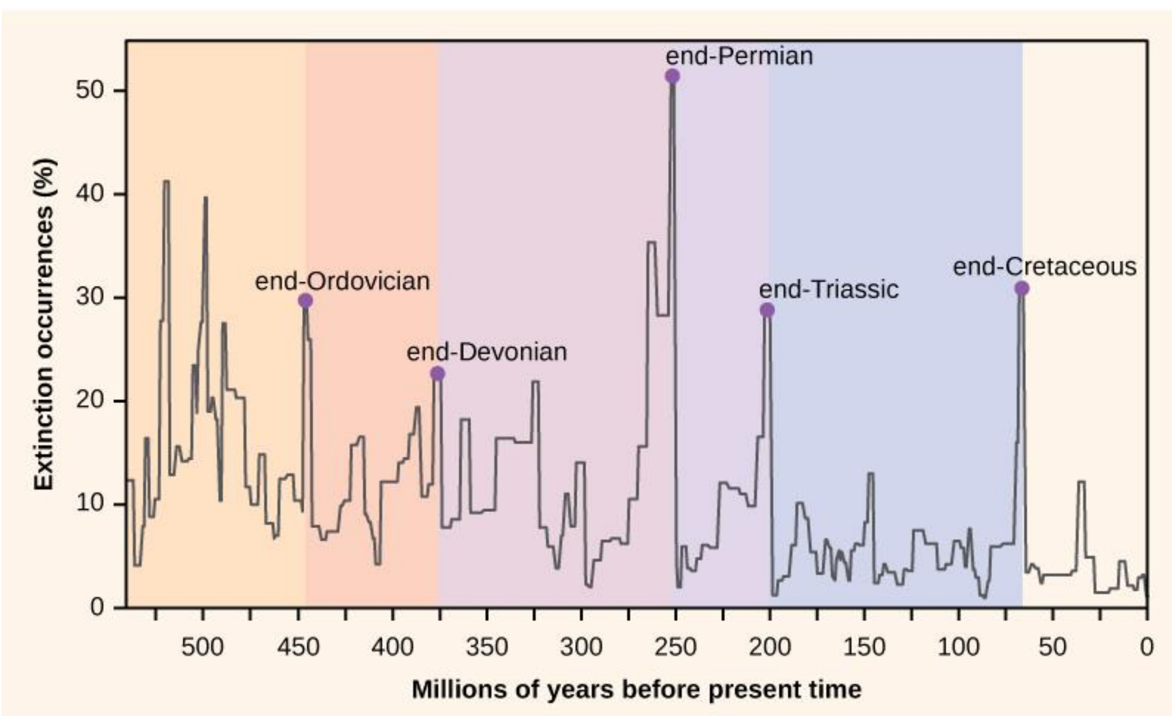
In geological history, the Earth has experienced five key mass extinctions in which life on Earth has been decimated. With the sudden increase in fossil fuel emissions and climate change, scientists fear that our Earth may be at risk of the sixth mass extinction. Studying past life can provide insight into preventative measures that can be adapted to current situations. The fossil record explains how various global climate systems are interconnected. Past carbon release events are often evident in fossil records and indicate how flora and fauna at the recorded time responded to significant atmospheric conditions.

Scientists and paleontologists are studying remains of animals during said mass extinction periods to better understand extinction sensitivity. These studies allow biologists to make more accurate predictions regarding the extinction possibility of organisms that have no fossil record (Louys, 2012, 52). One critical realization that fossil records have provided is that the combination of heating and oxygen deprivation is particularly dangerous. This is valuable insight for researchers as to what the extraction and utilization of fossil fuels are doing to the Earth (Louys, 2012, 56).

Paleontology's Future

As the Earth continues to develop and evolve, so does the scientific process and the study of the past. Just as paleontology has evolved from the time of Cope and Marsh, so it will continue to evolve. In understanding how to interpret the data collected by fossil records paleontologists can continue to advance and search for answers to some of science's biggest questions.

Figure 5.9: Graph depicting all of the last five major extinction events in occurrence percentages and time (CNX OpenStax, 2016).



The Development of Extinction Theories Through History

Taking a look at the living beings that walk on Earth today, it can be said that these creatures are definitively distinct from those that existed millions of years ago as a result of evolution. While older species fade away and new ones arise over time to fill the emerging ecological niches, the rate of extinction throughout Earth's history has not been constant. In the last 500 million years or so, life on Earth has recovered from five different major mass extinctions during which 75% to more than 90% of the species existing at any given period became extinct in a geologic instant (Elewa, 2008). While the existence of mass extinction events may seem obvious today, the development of the idea of mass extinction alone is the cumulation of nearly two decades of scientific development. Through extensive research into the stratigraphy of the Earth, the mechanism at which these mass extinctions occurred has been theorized, however there is still an ongoing debate on the severity and the main contributors to what caused the mass extinctions.

Enlightenment and the Great Chain of Being

Since ancient times, Europeans assumed that the species observed in the present were all brought to existence around the same time by God (Lovejoy, 1936). Due to His goodness and perfection, it was assumed that the natural world was full, complete, and perfect, containing as much variety as possible. This concept, known as the 'principle of plenitude' as coined by Arthur Lovejoy in 1936, can be traced to Aristotle and was the worldview of many Europeans and Americans in the eighteenth century during the Age of Enlightenment, a social and intellectual movement (Rowland, 2009). With this worldview, it was also presumed that God constructed all life in the natural world within an ordered structure called *scala naturae* or the 'Great Chain of Beings' (Lovejoy, 1936). Within this hierarchical chain, all species were viewed as a link in which God, angels, and humans composed the three highest links (Rowland, 2009). This metaphor peaked in popularity during this time and was a recurring theme for many philosophers and poets whose imagery exemplified the importance of the existence of each living thing (Lovejoy, 1936). In a passage from Alexander Pope's poem titled *An Essay on Man*, it states "Vast Chain of Being! Which from God began;/…Where, one step broken, the great scale's destroyed:/ From nature's chain whatever link you strike,/ Tenth or ten thousandth, breaks the chain alike". Here it was evident that the modern idea of extinction was equivalent to the loss of a link in the Great Chain of Beings. This was an unimaginable event that would destroy the Lord's perfect order; thus, it was logical to the people of this time that God would not allow for extinction to occur (Rowland, 2009).

Nature, Fossils, and Extinction: Shifting Views in the Late Eighteenth Century

Among the belief in a benevolent Creator, for the Europeans of the eighteenth century it was seen that the universe crafted by God's hand behaved according to natural laws which science could reveal (Lovejoy, 1936). This aligned well with Enlightenment philosophy in which the core belief was that that natural world was better understood through the mental faculties of man rather than just through faith and tradition (Rowland, 2009). Unlike the fields of chemistry and physics, understanding the laws that governed the world of living things was difficult to understand and consisted of a historical aspect due to the geographic occurrence of past living creatures. The study of strata, fossil record and general recognition of the field of Earth history was just beginning in the eighteenth century. It was during this time that more fossil evidence such as nautilus-like fossils and unidentifiable quadrupeds arose, and the idea of extinction became increasingly controversial (Rowland, 2009).

However, the idea of extinction was not a novel one and its beginnings can be traced back as early as sixth century BCE (Gregory, 1984). Into medieval times and the seventeenth century, the origin and depositional history of fossils was increasingly explored. In the late sixteenth century, Leonardo da Vinci interpreted fossils to have come from biological origin rather than the common view that they were created by God and brought to their present place through biblical Deluge (Gregory, 1984). More than a century later in 1664, Athanasius Kircher interpreted fossils to be the product of non-biological processes (Rudwick, 1976). In 1667, Nicolaus Steno rose as a strong defender that fossils were biological in origin (Rowland, 2009). He compared the teeth of a modern shark with the nearly identical fossils called "tongue stones" and made an inductive leap towards the idea that fossils were the remains of previously living organisms. His work was published by the newly arisen *Philosophical Transactions of the Royal Society of London* and agreed upon by Robert Hooke who was the Society's Curator of Experiments and a prominent natural philosopher (Rudwick, 1976). In 1686, Hooke presented a fossil to the Royal Society that was two feet in diameter and similar to a nautilus, yet still morphologically different from any live species (Inwood, 2005). Along with the discovery of this shell in a location the species could not have possibly survived in, Hooke believed that the species no longer existed. Despite many of Hooke's other fossil discoveries indicating the same thing, much of the Royal Society held strongly to creationist views and rejected Hooke's proposal (Saunders and Landman, 2009).

However, by the late seventeenth century, conclusions like those of Steno and Hooke became widely accepted by European naturalists and by the eighteenth century, these naturalists started to explore why some fossils such as ammonites and belemnites did not have living counterparts (Rowland, 2009). New world quadruped fossils also became invaluable to the discussion about extinction in the late eighteenth century. As early as 1739, fossil bones and tusks were found by European travelers in an area termed the Big Bone Lick near the Ohio River. These fossils belonged to a quadruped named the 'Ohio animal' which is now known as the mastodon, a species part of the proboscidean family. While evolutionarily related to elephants and mammoths, their molars are distinct with flatter chewing surfaces more akin to that of hippos (Rowland, 2009). Thus, when the fossils of the jaw and molars were found separated from one another, the French naturalist Louis Jean Marie Daudenton concluded that two species of quadrupeds were present at the Big Bone Lick assemblage (Rudwick, 1976).

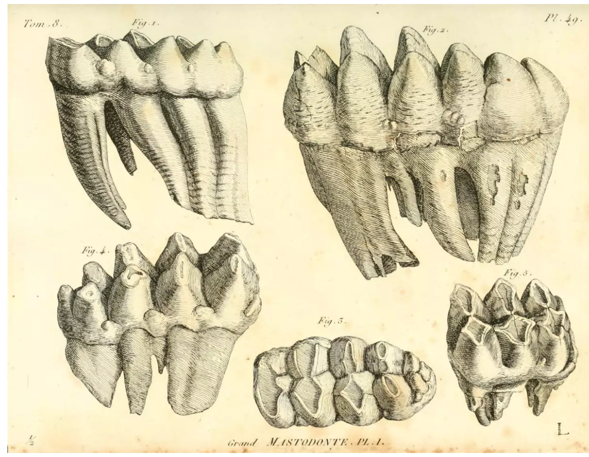


Figure 5.10: Drawings Cuvier drew of fossilized mastodon teeth from the Big Bone Lick. These drawings exhibit how the mastodon teeth were flat-surfaced and cusp-shaped, which are different from mammoth and elephant teeth that are more highly evolved and more suited for breaking down leaves and branches (Cuvier, 1806).

However, in the 1760s, a mastodon jaw with intact teeth was brought to the British Museum where the anatomist William Hunter declared the Ohio animal was an extinct species, never before having been described among modern species (Rowland, 2009). In 1812, Cuvier published *Recherches sur les Ossemens Fossiles de Quadrupèdes* or 'Research on the Fossil Bones of Quadrupeds', a compendium of his work identifying and discussing over 49 different extinct species including the mastodon, the giant sloth and the Irish elk (Kolbert, 2014). Using his exceptional skills in comparative anatomy, he was able to support his theory of extinction as the fossils showed no anatomical relation to any extant species.

Emerging Perspectives: Former Worlds Paradigm

With the increasing volume of emerging fossil evidence, the intellectual movement towards extinction had gained a great deal of momentum. In 1778, naturalist Georges-Louis Leclerc, Comte de Buffon published *Les Époques de la Nature* which was a highly influential work during that time (Rowland, 2009). In it, he examines the differences between animals of the Old World and New World. He concludes that the quadrupeds of the New World were diminished in appearance, weak and inferior to those of the Old World, often with no equivalent counterparts for the largest creatures found in the New World (Leclerc, 2018). With evidence such as that of the Ohio animal, he proposed this theory of New World degeneracy as the mechanism with which extinction occurs, thus solidifying the idea among prominent naturalists in Europe that extinction was a real occurrence (Leclerc, 2018).

With the conclusion of the eighteenth century and the movement into the nineteenth century, Buffon's work laid the foundation for future notable works including those of Georges Cuvier which would catalyze the emergence of a new paradigm in Earth history (Rowland, 2009). Within it, rather than extinction being seen as a rare event that threatened God's creation of the Great Chain, it was a recurring set of catastrophic events. Global ecosystems were said to have lived in 'former worlds' that were periodically, but abruptly, ended. This would come to be known as the former-worlds worldview which brought the end to the completeness-of-nature worldview centered around principle of plenitude and the Great Chain of Being (Rowland, 2009).

This transition could be attributed to several social and scientific factors. The first, and perhaps most significant, factor was the continual discovery of fossil species with which no extant counterpart could be found (Rowland, 2009). Secondly, there became a decreasing amount of unexplored land on Earth that could house undiscovered large mammals (Molyneux, 1695). Until the Lewis and Clark expedition from 1804-1806, the North American Interior had not yet been explored by Europeans and Americans and thus it was plausible that living creatures to the unmatched fossils could still be found (Rowland, 2009). Finally, during this period of transition, the influence of Enlightenment was waning among the social transformation as a product of the French Revolution. In the wake of the rising Romantic movement, there was a greater rejection of the rationality of Enlightenment with greater acceptance towards understanding untamed worlds of the past and present (Rowland, 2009). The factors allowed for the easier acceptance of former-worlds worldview among the public in Europe and America, setting the stage for Cuvier and his theory of catastrophism.

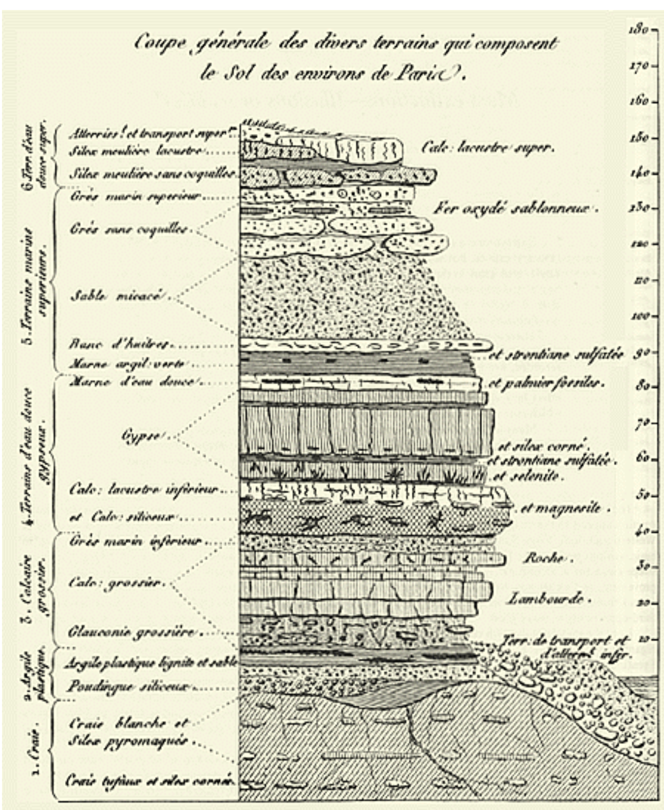


Figure 5.11: Drawing of the Paris Basin drawn by Cuvier himself. The different layers of strata have distinctly different fossils within different layers with very little overlap as well as sudden disappearances of a large amount of species at once. This indicated to Cuvier that a catastrophic event, such as a great flood, must have occurred to cause the disappearance of so many species at once (Cuvier, 1831).

Cuvier and Catastrophism

Into the nineteenth century, it was now generally accepted that extinction of certain species occurred throughout Earth's history, but it still remained uncertain within the community how it occurred and with what rapidity. Perhaps more than any other figure, Georges Cuvier was the one to bring the concept of mass extinction to modern Earth history (Rowland, 2009). Cuvier was a talented French zoologist and was highly established in the sciences of comparative anatomy and paleontology (Rampino, 2017). With his colleague Alexandre Brongniart, they both studied and mapped the rocky strata of the Paris Basin in which they made several key observations as summarized in their 1811 joint publication titled *Essai sur la géographie minéralogique des environs de Paris* (Kolbert, 2014).

Within the strata they first noticed alternating layers of saltwater to freshwater or marine to terrestrial deposits. Cuvier determined that these shifts did not occur slowly and were rather sudden "revolutions on the surface of the earth" (Rampino, 2017). Similarly, the two observed unconformities in the fossil records within the strata (Palmer, 2010). They found that although different strata contained specific and particular fauna, the presence of biological disruptions meant that entire worlds of life would suddenly disappear before reappearing once more as new fauna after a length of time (Courtillot, 2002). The flora and fauna that they observed did not exist in their time and thus were determined to have gone extinct. He believed that their disappearance could be attributed to a terrible catastrophic event such as a great flood from the sea and concluded that no modern event "would have sufficed to produce its ancient works". He summarized and analyzed these findings in *Théorie de la terre* or 'Essay on the Theory of the Earth' published in 1812 (Courtillot, 2002). This essay provided the basis for the catastrophism paradigm which was taken up by many geologists of the time but was also met with strong opposition.

Although Cuvier's work was largely based off of stratigraphic observations and secular conclusions, there was still some difficulty among the public with accepting the notion of possible mass extinctions (Kolbert, 2014). Thus, many of his ideas and publications became inevitably tied to religious topics to support theological views and conclusions. For example, in the 1650s, Bishop James Ussher calculated the approximate age of the Earth based on information in the Bible and approximated Creation to have occurred only 6000 years ago (Rampino, 2017). This implied that the Earth lacked deep history and any major geographical changes must have been quick and catastrophic in nature which aligned well with Cuvier's catastrophism theory (Rampino, 2017). Other naturalists such as William Buckland, a supporter of catastrophism, attempted to use Cuvier's concept of catastrophic flood as evidence for Noah's flood (Miller, 1990).

The Stifling of Catastrophism: Opposition in the Nineteenth Century

Despite the initial widespread acceptance of Cuvier's catastrophism, opposition still existed among academics who continued to debate on the exact mechanism by which extinction occurred (Rowland, 2009). Among the naturalists, Jean-Baptise Lamarck was a prominent gradualist thinker with the central belief that geologic processes were slow (Courtillot, 2002). Although he did not call it evolution, he conceived the idea of slow changing species in response to a changing environment (Courtillot, 2002). According to Lamarck, organisms had a force within them known as the 'power of life' which pushed them into becoming increasingly complex with time (Kolbert, 2014). By acquiring new 'habits' in response to changing environments, they would acquire physical modifications in their lifetime which could be passed down to their offspring. While Cuvier only saw fixity of a species, Lamarck believed that species transformed through direct descent and thus extinction did not occur (Courtillot, 2002). Lamarck was a strong proponent of *transformisme* or 'transformation theory' and was overall skeptical in the idea of catastrophic events (Kolbert, 2014).

At the core of modern geology was Charles Lyell who was not only a large and powerful figure, but also a proponent of uniformitarianism (Courtillot, 2002). His magnum opus, *Principles of Geology,* which was published in three separate volumes from 1830-1833 provided the core principles to the science of geology, but was also a strong piece of opposition to catastrophism (Courtillot, 2002). His most well-known postulate proposed that geologic change was a slow and gradual process (Rampino, 2017). It was a force that could be observed in the modern day and acted over long periods of time to create change in the natural world. With it, he mocked the idea of catastrophism and the idea of alternating periods of calm and disorder on Earth. However Lyell and the *Principles of Geology* eventually became so widely accepted within scientific opinion that Lyell himself proclaimed that "all theories are rejected which involve the assumption of sudden and violent catastrophes and revolutions of the whole Earth, and its inhabitants" (Rampino, 2017). However, Lyell's theories of uniformitarianism and the arguments supporting this school of thought relied heavily on assumptions rooted in theology (Rampino, 2017). Lyell first assumed that the Earth was designed and molded by the hands of God for human occupancy. He assumed that what was achieved in global geology was the result of calm, order, and gradual change as per God's plan. He stated, "in whatever direction we pursue our research, whether in time or space, we discover everywhere the clear proofs of a Creative Intelligence and of His foresight, wisdom and power." Rather than originating from an impartial analysis of geologic records like Cuvier, Lyell often fell back to theological roots that supported his theories (Rampino, 2017).

Modern knowledge now shows that both Cuvier and Lyell were both partially correct in their theories. The current concept of extinction and mass extinction is the cumulated product of many great minds of the eighteenth and nineteenth century during a time of great change and deeper exploration of geologic strata to better explain natural origin.

Figure 5.12: Painted portrait of Georges Cuvier, the 'Father of Paleontology'. Using his extensive skills in comparative anatomy, he was central in the creation of extinction theory and catastrophism. (Vincent, n.d.).

The Weapons of Mass Destruction

In the modern-day, extinction and more specifically mass extinction are both considered as fact and not theory. However, the mechanism by which mass extinction occurs has been debated for the last 50 years and is still currently being argued. In 1982 two paleontologists, Jack Sepkoski and David Raup from the University of Chicago brought evidence using the marine record that five mass extinctions have occurred throughout Earth's history (Raup and Sepkoski, 1982). Once Sepkoski and Raup identified five mass extinctions, people had to find out what caused them and how severe each extinction was. The five extinctions include the late Ordovician (57% of marine genera disappeared), late Devonian (75% of all species disappeared), late Permian (also known as 'The Great Dying'; 95% of marine life, 80% of amphibian life, and 75% of reptilian life disappeared), late Triassic (48% of all genera disappeared), and the late Cretaceous (17% of all families disappeared) (Elewa, 2008).

Asteroids Killed the Dinosaurs

Asteroid theory being used to explain mass extinction has been debated in recent history from the 1970s to the 1980s. However, in 1982 Luis Alvarez, a professor at the University of California, gathered experimental evidence from both himself and his colleagues and concluded that an asteroid was the largest contributing factor to the most recent mass extinction, the Late Cretaceous extinction (Alvarez, 1983). His most indisputable evidence lay in the identification of high concentrations of iridium (an element common in asteroids) in a layer of clay that was present worldwide. He believed that after the asteroid hit the planet's surface a "great dust cloud" covered the globe creating the iridium-rich clay layer. He presented evidence of fora-miniferas (small-shelled creatures) and other small ocean organisms dying in a limestone layer almost simultaneously after the asteroid impact. Similarly, he brought up evidence that pollen counts dropped by nearly 300-fold or even entirely in coincidence with the iridium presence. With extinctions at the base of the food chain in both the ocean and land occurring almost instantly after the asteroid impact, he hypothesized that this must have been the cause of the late Cretaceous extinction. Alvarez even went as far as to state that if this asteroid did not hit, dinosaurs would be the dominant species right now or present humans would have obvious reptilian features because they would have descended from reptiles instead of mammals (Alvarez, 1983). The asteroid that Alvarez was referring to has been named Chicxulub, and even in as recent as 2017, 1.4 million dollars has been granted for research led by a group of scientists at the University of Texas Institute of Geophysics (UTIG). They are trying to answer questions such as, "did this event also cause massive cooling and climate change?", "were there extensive wildfires that decimated habitats?", etc.

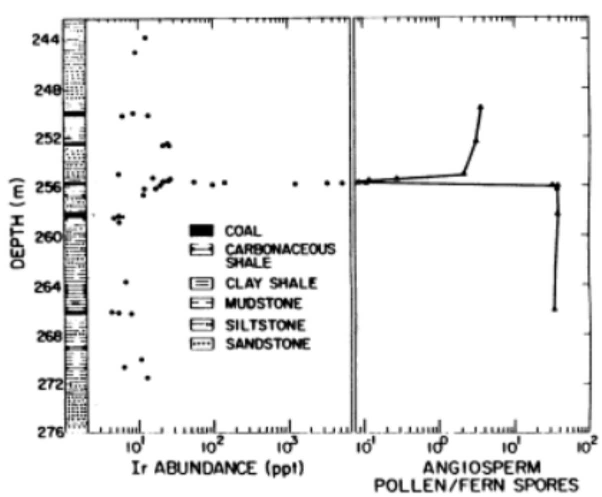


Figure 5.13: Correlation between iridium concentration and angiosperm pollen/fern spores. This segmented graph shows that around a depth of 256 m, iridium concentrations spike positively in coincidence with angiosperm pollen and fern spore concentration spiking negatively. This exhibits that angiosperm and fern spores decreased at geologically the same time as when the asteroid hit during the late cretaceous extinction (Alvarez, 1983).

Change but Not for the Better

Sea level change theory has been one of the lesser argued topics, due to its strong evidence through rock stratigraphy, however we will still discuss it as it has great importance in mass extinction theory. In 1999, Tony Hallam from the University of Birmingham and Paul Wignall from the University of Leeds published a paper on how sea-level changes were one of the leading causes of mass extinctions (Hallam and Wignall, 1999). They were able to correlate large rapid eustatic inflexions with several of the mass extinctions. The late Ordovician and late Cretaceous extinctions were associated with unequivocal major regressions that can be seen worldwide. Similarly, the late Permian extinction can be correlated with a first order lowstand of sea level based on the latest Permian ammonoid markers. They could not determine what caused the transgressions and regressions, however they determined that the late Ordovician, late Devonian and late Cretaceous extinctions could be clearly correlated with glacial eustatic changes as the main driving force behind them.

Molten Earth

Once again in 2001, Wignall wrote another paper discussing how flood basalt events leading to the formation of large igneous provinces was a large contributor to almost all mass extinctions (Wignall, 2001). Similarly, this topic is widely disputed and is crucial in the understanding of how mass extinctions occur. He explained that flood basalt events would emit particulates and aerosols in large amounts, which would inhibit photosynthesis for long periods of time. Similarly, emission of sulphur oxides would produce acid rain and release of large amount of carbon dioxide which would kill both large and small organisms. These two factors would greatly affect the bottom of the food chain causing the collapse of the entire food chain. To no surprise in 2005, Wignall wrote a paper tagging anoxic conditions caused by these flood basalt event as being a factor contributing to the late Ordovician, late Devonian, late Permian and late Triassic extinctions (Wignall, 2005). Anoxic conditions at the ocean's surface to mid-depth were determined to range from being oxygen deficient to being entirely lacking in oxygen killing most marine life.

Global Warming of the Past

In 2003 a hypothesis that would have high controversy arose. This hypothesis was the Clathrate Gun Hypothesis made by Kennett et. al (Kennett et al., 2003). Their hypothesis states that a contributing factor to the late Permian extinction was the rapid release of methane. This rapid release would be caused by earthquakes and global warming that would break or release pressure from methane clathrates (rocks that form a lattice that traps methane). Methane is a stronger greenhouse gas than carbon dioxide and therefore Kennett et. al thought that this would greatly increase the magnitude of global warming during that time. They backed their hypothesis with evidence of methane in ice cores, however a lot of new evidence both backing up or discrediting the hypothesis has come out (Kennett et al., 2003). In 2007, D. Archer indicated that most methane hydrates (methane clathrates) are currently far too deep for global warming to have affected them and that if these releases were to occur they would be chronic and not catastrophic and rapid (Archer, 2007). In 2016, a paper by John Kessler and Carolyn Ruppel indicates that methane from methane clathrates in the upper continental slope cannot properly get to the surface before dissociating or decomposing in the ocean water, meaning that release of methane from methane clathrates would most likely not cause a catastrophic event (Kessler and Ruppel, 2016). This debate has evidence springing up even in 2019 and there might not be a conclusion anytime soon.

These theories are only a snippet of the wide variety of theories trying to explain mass extinctions. While these theories appear to be catastrophic by themselves, many of these events are not mutually exclusive and most likely occurred in tandem with one another. Evidence for many of these theories cannot be entirely proven or disproven, however with the future of technology one day we might have a definitive answer to what could kill 90% of life on Earth at a given time.

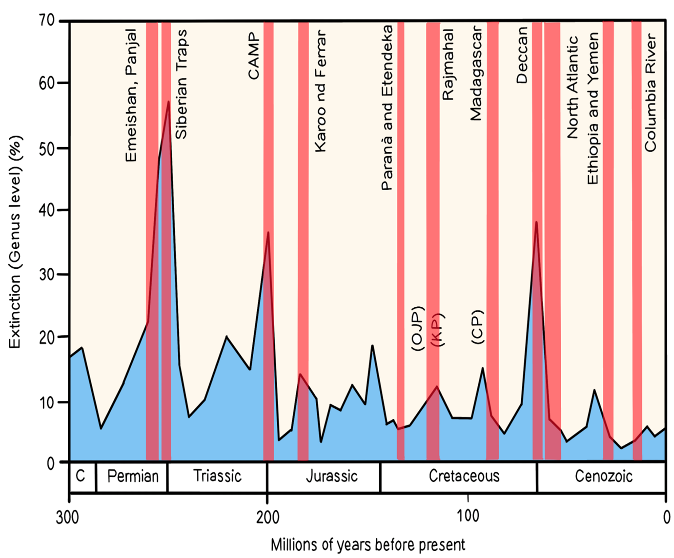


Figure 5.14: Correlation between flood basalt events and mass extinction events. Graph demonstrating the correlation between continental flood basalts (red bars) and large decreases in genus (mass extinction events) (Adapted from Reichow and Saunders, 2008).

Jean Baptiste-Lamarck vs. Georges Cuvier

The theory of evolution and its own evolution as discussed in modern curricula often begets a narrative in which its conception and advancement is single-handedly catalyzed by Charles Darwin himself. A one-man show. Yet this discounts pre-Darwinian pioneering in the field of evolution. Two figures, Jean Baptiste-Lamarck (1744-1829) and Georges Cuvier (1769-1832), dredged up the debate concerning the origin of all species in French academia (Rudwick, 1997). Among the many academics studying natural philosophy during the late eighteenth and early nineteenth centuries remembered in the shadow of Darwin, the rivalry of Lamarck and Cuvier marked the arrival of particularly avant-garde theories such as catastrophism and adaptive forcing, a distant relative to the idea of modern selective pressures for speciation (Rudwick, 1997). The success of Lamarck and Cuvier's theories, which are closely tied to the study of fossils and stratigraphy, warranted unique circumstances. They required an educational background that provided access to study materials, a difficult requisite considering their humble backgrounds which were a stark contrast to those of their predecessors and peers (Chen, 2018). France in the eighteenth century was, rather famously, politically precarious. The French Revolution in 1789 was instrumental to the dismantling of socio-political institutions, providing Lamarck and Cuvier subsequent opportunity to rise in academia (Rudwick, 1997). Due to the political climate and ideology of reigning leaders of France, such as Napoleon, unique advantages were presented to Cuvier whose findings were found preferential to those of Lamarck (Gershenowitz, 1980). In spite of this, it is the legacy of Lamarck which is often more readily noted in modern academia.

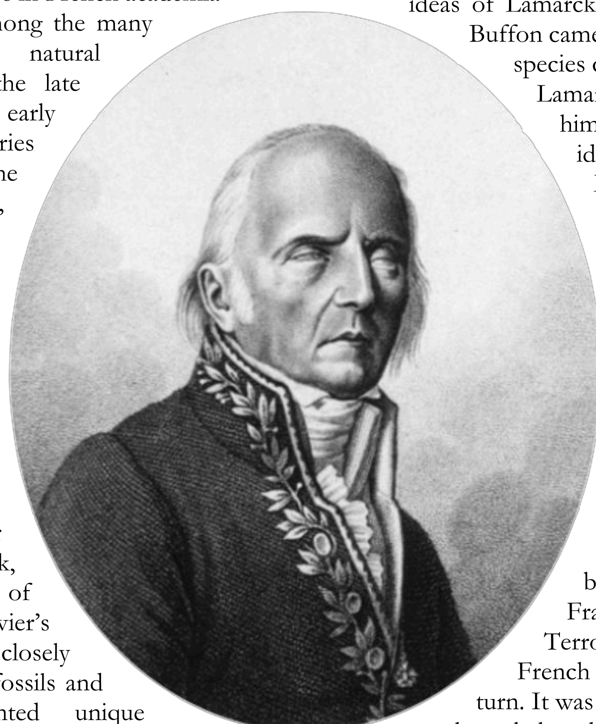


Figure 5.15. Portrait of Jean-Baptiste Lamarck (1744-1829) when old and blind, by Ambroise Tardieu in 1824.

Early Life of Lamarck

Jean-Baptiste Pierre Antoine de Monet, chevalier de Lamarck, or as most people knew him, Lamarck, was born in 1744 in a small village in northern France (shown in Figure 5.15). As the youngest son of eleven with a family history of soldiers, he joined the French army, which at the time was campaigning against Germany. However, he later left due to injuries and acquired a job tutoring Count Buffon's son (Packard, 1901). It is at this point in his life when Lamarck first began exploring botany and medicine, along with some of the cornerstone ideas of Lamarckian evolution. Count Buffon came up with the idea that species change over time, and Lamarck having idolized him drew from these ideas later on in his life. However, Buffon also had a major role in Lamarck's life, playing patronage, and helping him get appointed as assistant botanist at Jardin des Plantes (Royal Botanical Garden) in 1781 (Packard, 1901).

In 1793 things really began to change in France, as the Reign of Terror began and the French Revolution took a turn. It was during these times of upheaval that the Jardin du Roi was renamed the Jardin des Plantes of the Museum National d'Histoire (Botanical Garden of the National Museum of History). It was decided then that the museum would be run by twelve professors, Lamarck being offered a position as a professor of invertebrates (Packard, 1901). It is speculated that although Lamarck had no previous knowledge on invertebrates, and that a professor of such was considered the lowest out of all scientific disciplines, he took this in stride driven by his curiosity and thirst for knowledge. During his time at the museum he was able to publish several books and articles on his findings, talking about everything from meteorology, physics, chemistry and biology (which is a term he coined). His work with the invertebrates was a cornerstone in his life, allowing him to explore an ignored niche in science (Packard, 1901).

Early Life of Cuvier

Georges Léopold Chrétien Frédéric Dagobert Cuvier, also known as Georges Cuvier, was a French zoologist in the late eighteenth and nineteenth centuries (shown in Figure 5.16). He was born in 1769, in a small town originally part of Germany but later a part of France. His father, a retired officer, had wanted Cuvier to become a Lutherian minister; however, after being denied a scholarship to theology school, Cuvier had to consider other options (Chen, 2018). Little is known about the years between his rejection from theology school and 1784, when he was able to find a patron and attend Academie Caroline (Caroline University). From 1784 to 1788, Cuvier attended the university and was able to fine-tune his abilities and skills. His original studies were in the legal and administrative department, but after befriending a zoologist professor, he began studying comparative anatomy and dissections (Chen, 2018). It was during this time that Cuvier developed his skills in dissection and his keen eye for details that were integral to his success later on in his life.

Following his time at Caroline, he became a private tutor to a wealthy family in Normandy. Living in the countryside, he had access to various marine organisms including mollusks, which were the centre of his work (Chen, 2018). For the next six years, from 1788 to 1794, Cuvier spent his time dissecting and analyzing said marine invertebrates, culminating in an unpublished comparative anatomy paper. It was this paper that launched his career in science, as they were sent to Étienne Geoffroy Saint-Hilaire, a prominent scientist at that time (Chen, 2018).

Figure 5.16. A portrait of Georges Cuvier (1769-1832) painted in 1831 by W.H. Pickersgill, and later engraved by George T. Doo in 1840.

The Sacred Ibis Debate

The year 1795 marked when Cuvier would join Geoffrey at the Museum of Natural History in Paris (Chen, 2018). In the subsequent years, Napoleon's army returned to France with a vast amount of spoils after invading Egypt in 1798, among which were mummies of cats, jackals, dogs, ibis, and humans (Curtis, Millar and Lambert, 2018). The flux of resources was partitioned amongst 150 chosen individuals, one of whom was Geoffrey, and sparked the establishment of the Egyptian Institution, an organization dedicated to documenting the ancient Egyptian remains (Curtis, Millar and Lambert, 2018). Cuvier was then exposed to the mummified remains of ancient Egypt through his then close colleague, and then embarked to use this evidence to support his evolutionary speculations. Organisms, Cuvier opined, were fixed beings, whose anatomy was such that should a single feature change, the organism would fail to survive the environment it was created to live in (Chen, 2018). Cuvier would continue to firmly support his theory for the duration of his life and time in academia. Certainly, such obstinate beliefs would clash with those of another academic theorizing species' mutability through time. Lamarck, amongst the majority, subscribed to belief in "The Great Chain of Being" and with it, believed that organisms were ordered from simple to complex as per the divine order of the universe (Curtis, Millar and Lambert, 2018). Furthermore, he speculated that organisms could change and adapt to new environments, gradually.

Initially, the mummified Sacred Ibis, a beloved Egyptian bird, were mistakenly believed to be yellow-billed storks with a smaller stature and curved beak. What appeared at first to be inclined towards evidence for a speciation event was examined critically by Cuvier with copious measurements and detailing of their being (Curtis, Millar and Lambert, 2018). Cuvier searched for species which would comply with the anatomy of the specimen, such as its curved beak, and found relief in the unnamed avian fossils held within the Museum of Natural History (Curtis, Millar and Lambert, 2018). Further comparison between the fossilized museum remains and Egyptian specimen placated Cuvier, for neither he nor Lamarck believed there to be remarkable phenotypical changes in the 2,000-3,000 years they were separated by (Curtis, Millar and Lambert, 2018). Simultaneous to their work regarding the Egyptian remains, Cuvier and Geoffrey devised methods of comparative anatomy to identify key differences between elephants residing in Asia and Africa. Their findings would go on to be published in 1801 (Rudwick, 1997). In their paper, "Memoirs on the Species of Elephants, Both Living and Fossil", Cuvier and Geoffrey featured the at-the-time famed "Ohio Animal", which through their analysis they determined to be an altogether separate but related species to present elephants (Rudwick, 1997). Cuvier averred from the discovery that there were no presently living creatures of its kind, that the "Ohio Animal" species was extinct. This spurred Cuvier to postulate, with further evidence from available fossil records, that throughout Earth's history, there had been periods of mass extinction (Rudwick, 1997). Furthermore, he believed that they were cyclic in nature, paired with periods of creation. The conformity of this novel hypothesis to the fixity of species served to solidify Cuvier's belief in his theories regarding the natural world. Much later, Cuvier would continue his postulations regarding the fossil, the species from whence it came, or the *Grand Mastadonte,* as he referred to it as, and its origins (depiction shown in Figure 5.17). When Lamarck and Cuvier would present their findings to the French Academy in 1802, it marked a public exposé of the two academics' opposing theories (Curtis, Millar and Lambert, 2018). Lamarck maintained that evolution would occur in longer instances, where a change in the environment could create selective pressures that would force the species to adapt; however, Cuvier insisted that the Sacred Ibis were evidence for immutability of species through time (Curtis, Millar and Lambert, 2018). The debate is often recalled as a prime example of Cuvier's sabotage of science, by once again obstructing the developing theory of gradual evolution and speciation of organisms from acceptance in the academic domain.

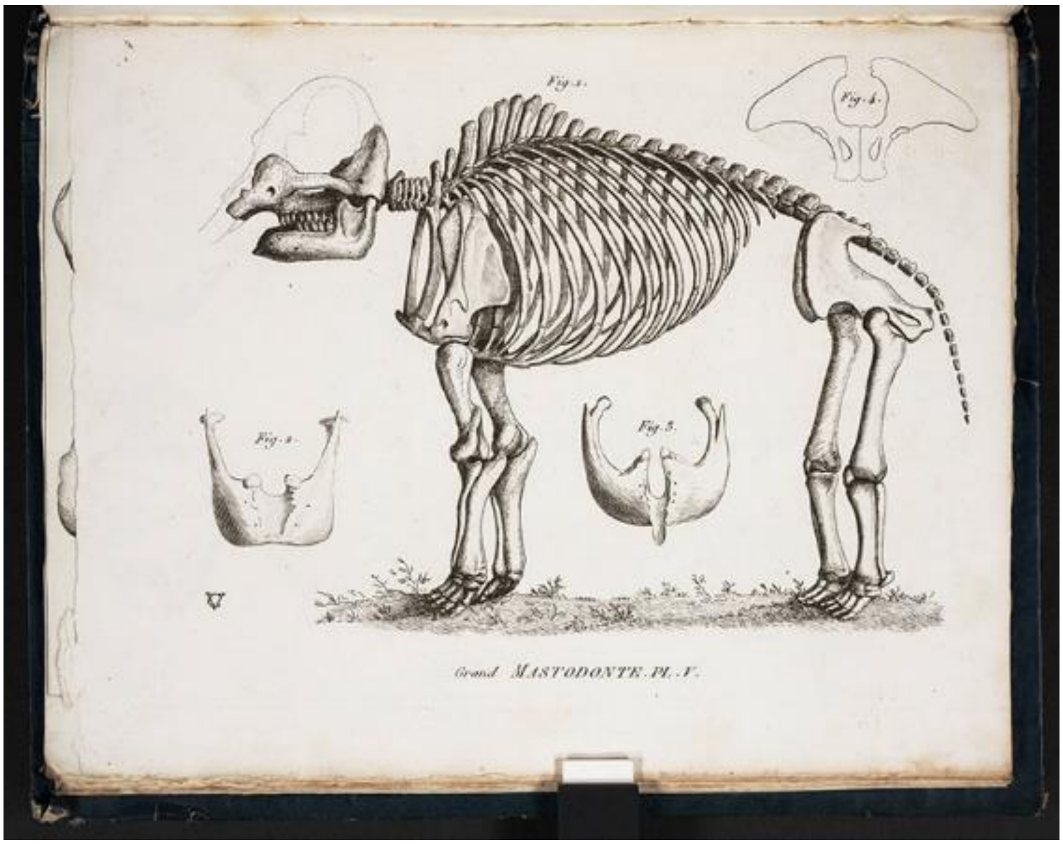


Figure 5.17. Cuvier's drawings of the Mastadonte skeleton from his paper "Recherches sur les ossemens fossils" published in 1812.

Philosophie Zoologique

In 1800, Lamarck presented a lecture, Floreal, where he first outlined his theory of evolution. As a botanist and professor of invertebrates he came to observe the influence of environment on different species, both plant and animals. Many argue that his work classifying molluscs and invertebrates allowed him to recognize the variation between different species, and start the development of his theories. By 1809, Lamarck had a fully fleshed out theory which he published in his Philosophie Zoologique (Lamarck, 1809). In his book he had developed two major laws, the first one stating that the use or disuse of structures can cause them to enlarge or shrink. In order to explain this, he many times referenced giraffes, stating that their long necks could be the result of extended extension of their necks in order to reach upper branches of leaves (Lamarck, 1809). His second law was about the heritability of such changes, and the idea that these changes can be passed on through lineages. These laws led to his overall deduction that evolution was a process of increasing complexity and "perfection", which he states towards the end of his book (Lamarck, 1809) . This idea of increasing perfection meant that, to Lamarck, species did not just disappear or go extinct, they instead evolved into other more complex and perfect beings (Lamarck, 1809). Here is where Lamarck's conflict with Cuvier really escalated, as this directly contradicted Cuvier's theories on mass extinctions due to global catastrophes.

After 1809, Lamarck started receiving quite a bit of backlash for ideas, mainly from scientists who believed in catastrophism, the main proponent of this being Cuvier. Not many newspaper articles or journal articles can be found at this time talking about Lamarck's works, showing how invalid and unacceptable they were considered to be at the time of his publishing. By this point Cuvier was a well known paleontologist due to his previous work on mammoths and mastodons, and had significant influence over the scientific community (Gershenowitz, 1979). He particularly disagreed with Lamarck's theories, primarily due to a firm belief in catastrophism and opposition to evolution. It is thought that Cuvier publicly debased Lamarck's works plenty of times, and due to his standing in society Lamarck had very few followers and believers who agreed with his theories (Lenoir, 1924). However, it was not just the resistance from fellow professors, but also the shifting political climate at the time (Gershenowitz, 1979). Napoleon, a military leader who came to power during the revolution, had rejected Lamarck's ideas, choosing instead to back Cuvier who had curried for his attention. Cuvier had a political and administrative ability that Lamarck lacked, he was able to sway people to his favour not just through his scientific works (Gershenowitz, 1979). It is thought that, although the Napoleonic era was short (1801-1841), it had a large impact on how the political and scientific communities viewed Lamarck's works (Gershenowitz, 1979). However, regardless of such external pressures, Lamarck was able to publish two other works later on in his life, exploring the two different evolutionary paths of invertebrates (Histoire Naturelle des Animaux sans Vertèbres - 1815 Vol 1, 1822 Vol 2) (Gershenowitz, 1979).

Le Règne Animal

Arguably Cuvier's most famous work, the publication of "The Animal Kingdom" in 1817 marked the beginning of classifying and arranging organisms (Cuvier, 1849). The book organizes all animals into four distinct Divisions: vertebrate animals, molluscous animals, articular animals and radiate animals (Cuvier, 1849). These divisions were further subdivided into Classes, Orders, and then Families. The publication featured both known extinct and extant animals and was remarkably the first of its kind in the field of phylogeny. The work consisted of several editions, the first of which had four volumes, a second with five, of which he wrote all but an edition on insects (Cuvier, 1849). The publication does not, however, feature speculation concerning further species either extant or extinct (Cuvier, 1849). It is certainly possible that this was a symptom of Cuvier's methodological personality, which sought to adhere to the physical evidence which was accessible to him during this time. In 1819, he was designated a peer of France, a rather respectable distinction, for his contributions in French Academia, and was henceforth Baron Cuvier (Rudwick, 1997). A third edition followed in the years subsequent of his passing in 1832 during an epidemic of cholera (Rudwick, 1997).

The Death of Lamarck

At this point, due in part to Cuvier's constant opposition, Lamarck had reached quite a low in his career, where most if not all of his works were discredited. Among these already hard times, in 1818, Lamarck began to lose his eyesight, further hindering his status (Packard, 1901). His inability to do further research and solidify his stance with evolution led to a greater deviation of power to Cuvier. In fact, even in such trying times for his colleague, Cuvier was

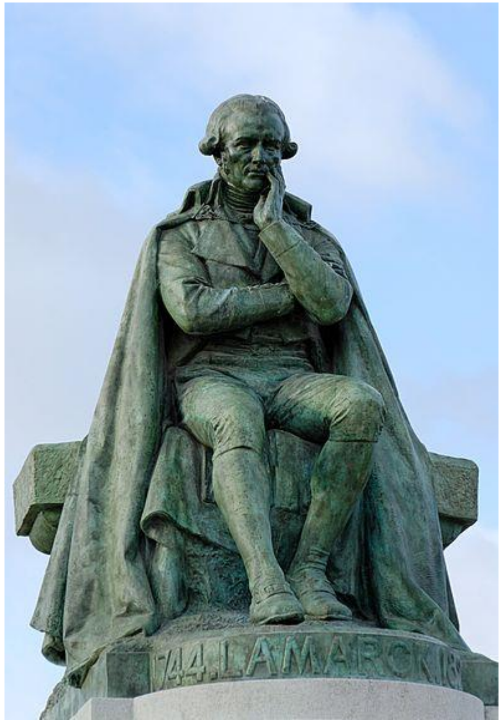


Figure 5.18: A statue of Jean-Baptiste Lamarck, in front of le Jardin des Plantes, by Leon Faget in 1908.

relentless, critiquing both his theories and Lamarck himself (Cuvier, 1832). Some have mentioned Cuvier using Lamarck's wasting eyesight as a jibe, asking him whether it was his disuse of his eye that lead to his blindness, indicating Lamarck's shortcomings in both science and life (Lenoir, 1924). Lamarck died in 1829, poor and blind, with several of his colleagues at the museum providing eulogies at his funeral (Lenoir, 1924). Surprisingly, Cuvier was one such colleague, and even after his death Cuvier, through his eulogy, was sure to enforce how wrong Lamarck's theories of evolution were (Cuvier, 1832). It is thought that the eulogy was quite chilling, and many newspapers and journals refused to publish it, thinking it wrong to talk ill of the dead. At several points in his eulogy, Cuvier mentions how Lamarck was a dreamer, and as such had fantastical ideas that were not necessarily true nor could be proven (Cuvier, 1832). He mentions Lamarck's great works involving classifications of both living and fossilized invertebrates. But, he is keen to mention that without his work on molluscs and marine invertebrates that started his career, Lamarck would have never come up with his classification systems (Cuvier, 1832).

Cuvier and Lamarck, although different, have both had a major impact on science as we know it. Regardless of which one was right and which one was wrong, these were two scientists that helped shape the political and scientific climate of the eighteenth and nineteenth centuries (Lenoir, 1924). Even centuries later, their works are still celebrated and recognized. In fact, Lamarck's works were later recognized by Charles Darwin, and since his time various statues have been erected in his name, including one at the Jardin des Plantes in Paris (Figure 5.18) (Packard, 1901). Their feud helped develop biology, paleontology, Earth history and science as it is known today. Without the rigorous questioning from Cuvier, Lamarck might not have delved deeper, and without contesting theories to catastrophism Cuvier would not have developed his theory further. And through these two scientists, the history of science was explored and seen.

Interactions Between Molecular Phylogeny and the Fossil Record

Molecular phylogeny employs the use of genome sequencing in identifying phylogenetic relationships between organisms, extant and extinct. The application of molecular sequencing has allowed scientists to quantify relatedness, and thus identify phylogenetic groups (Olsen and Woese, 1993). Conversely, this also allows them to understand more concretely the fine line between genetic diversity and speciation. Within the study of phylogeny are a plethora of terms to describe traits by their evolutionary history. A plesiomorphy is a trait characteristic to a phylogenetic group and can be integral to their identity as a group, as opposed to an apomorphy which describes a derived or novel trait which can suggest speciation. Phenotypic plesiomorphies can be scrutinized at the genetic level, which has been imperitive to realizing a true definition for homologous features (Olsen and Woese, 1993). A homologous feature is a physical characteristic shared between two or more organisms due to having a common

Figure 5.19: An illustration of the geologic timescale, depicting ancient biota discovered through the fossil record.

ancestor. Archaea were mistaken for Bacteria for a significant period of scientific history, for which the appearance of ribosomal RNA (rRNA) in phylogenetic study proved particularly useful, resulting in the understanding of prokaryotes as two distinct domains (Olsen and Woese, 1993). However, much molecular genetics was an advantage to the task of devising a historically accurate phylogenetic tree of life, the intersection between paleontological data and molecular phylogenies has been a subject of increasing academic attention. Phylogeny has been a useful tool to study the evolution of species with poor or non-existent presence within current fossil records (illustration in Figure 5.19). Where the fossil record lacks, phylogenetic trees could compensate. However, phylogeny generally makes use of generous assumptions regarding rapid diversity loss, let alone mass extinctions (Morlon, Parsons and Plotkin, 2011). Constrained diversity is theorized to be key in the observed, relative neutrality of genotype evolution. Furthermore, the fossil record suggests mass extinctions and periods of biotic stress which compromise the confidence scientists have in current phylogenetic models (Morlon, Parsons and Plotkin, 2011). For example, current phylogenetic models for cetaceans, in particular, appear to conflict with fossil record data (Morlon, Parsons and Plotkin, 2011). To reconcile geological and genetic data at scientists' disposal, a number of computational techniques have been employed. These studies seek to incorporate rates of speciation and extinction to model a realistic change of diversity over time. Experimentation with variation in the homogeneity or heterogeneity of diversification rates across lineages, has resulted in more advanced birth-death models that can demonstrate cladogenesis, loss of diversity, and increased conformity to the fossil record (Morlon, Parsons and Plotkin, 2011). This incites another methodology to study macroevolution from an interdisciplanry perspective: to use paleontological data in a phylogenetic framework (Slater and Harmon, 2013). For example, to increase correlation of phylogenetic trees to the fossil record, the use of fossil data to estimate diversification rates of species has proven helpful. This is a method better employed for species with richer fossil records. Emphasis on the identification of patterns in diversification across time in this field results from the identification of diversity-dependence, a term used to describe how diversity has demonstrated a negative feedback loop effect on diversification rates (Etienne et al., 2012). Some existing models which incorporate diversity dependence, however, demonstrate zero extinction. Analysis of these models, and their resulting phylogenetic trees then demands the assumption that clades demonstrating relatively low branching, or speciation events, suggest extinction of lineages (Etienne et al., 2012). Understanding macroevolution and its mechanisms is a continuous study which involves the integration and intersection of a multitude of disciplines, not limited to phylogeny, paleontology, computer modelling and genetics. The discourse and introduction of novel techniques in each of these fields has helped facilitate a greater understanding of the Earth's history and the organisms which have lived on it.

How the Unbelievable Became Truth: The Story of Meteorites

Meteorites have fascinated human civilization for centuries, and for good reason. There are very few things more fantastical than massive fiery stones hurtling through the skies. Throughout history, they have been the inspiration for cults and myths in ancient Greece and Rome (McBeath and Gheorghe, 2005), while in ancient Egypt iron meteorites were forged into swords and jewelry for the ruling class (Gannon, 2013). Even now, with a scientific understanding of what causes this phenomenon, people continue to make wishes on "falling stars", or as they are officially known, meteorites.


Ueber den
Ursprung
der von Pallas gefundenen
und anderer ihr ähnlicher
Eisenmassen,
und über einige damit in Verbindung stehende
Naturerscheinungen.
von
Ernst Florens Friedrich Chladni,
in Wittenberg, der Phil. und Rechte Doctor, der Berliner Gesellschaft Naturf. Freunde Mitgliede, und der königl. Societät der Wissenschaften zu Göttingen Correspondenten.
Leipzig,
bey Georg Joachim Göschen.
1794.

Figure 5.20. The title page of Ernst Chladni's book on meteorites, translated to English as "On the Origin of the Iron Masses Found by Pallas and Others Similar to it, and on Some Associated Natural Phenomena".

Ernst Chladni, Recognizing That Meteorites Are Extraterrestrial

The field of meteorite research is relatively young when compared to geology as a whole. Interestingly enough, possibly the most influential scientist in this field was not a geologist but a physicist. Ernst Chladni, known best as the father of acoustics, primarily studied waves, however, he also delved into another topic that was hotly debated in the late 1700s. That topic was the study of fireballs that seemed to appear and disappear in the night sky (Marvin, 2007). A well-respected source of this period of his life is titled *Ernst Florens Friedrich Chladni (1756-1827) and the origins of modern meteorite research*, written by Ursula B. Marvin, and is the major source for this chapter.

It is believed that Chladni's interest in meteorites was sparked by conversation with his mentor Georg Christoph Lichtenberg when on a trip to visit him in Gottingen in 1793. At the Gottingen library, Chladni compiled 24 reports of fireballs and 18 reports of the falls of masses of stone and iron. The stories were all so similar that Chladni began to wonder if perhaps these ideas were not the folk tales that most logical thinkers considered them to be at this time (Marvin, 2007). Chladni correlated these eyewitness accounts with locations of "native iron" which were located far from volcanoes and smelters. Chladni finished a book on iron masses only a year later in 1794. The book was titled *Über den Ursprung der von Pallas gefundenen und anderer ihr ähnlicher Eisenmassen und über einige damit in Verbindung stehende Naturerscheinungen* (Figure 5.20), which when translated from his native German to English reads "On the Origin of the Iron Masses Found by Pallas and Others Similar to it, and on Some Associated Natural Phenomena" (Marvin, 2007). There was some scientific thought at the time on falling masses, but this book established the branch of science and validated meteorites as a true phenomenon. Chladni believed these stones were cosmic in origin because they had been witnessed coming from multiple directions and at much higher velocities than could be explained by gravity alone (Marvin, 2007).

In his book Chladni discussed five postulates. Firstly, that masses of stone and iron fall from the sky. Second, that these stones form fireballs as they plunge through the atmosphere.

He also proposed that these bodies originate in cosmic space, either from primordial masses that never aggregated into planets or fragments of planets created by explosions or collisions (Marvin, 2007). These three postulates are currently considered to be correct, however there was some knowledge that was unavailable at the time that caused Chladni to propose ideas that modern scientists know to be incorrect. Chladni believed that high-altitude shooting stars were caused by small bodies entering the atmosphere and then shooting back into space. He also thought that some meteorites that were low altitude came from Earth, a more conventional hypothesis for the time (Marvin, 2007).

Fireballs appear to move very fast and be extremely large. At the time that Chladni was researching this topic the only form of combustion was classical combustion, where the fire's size is proportional to that of the burning object. Based on knowledge of the physical properties of the universe available to Chladni he postulated that friction in the upper atmosphere caused these solid masses to heat up, melt, expand, and then explode, explaining their apparent massive size (Marvin, 2007).

Response to Chladni immediately after the publication of his book was less than enthusiastic. Many believed that the assumptions of the presence of small bodies in outer space was too much supposition to be believed. Chladni also never witnessed a fall nor saw a meteorite firsthand so his evidence was solely based on the documentation of others (Marvin, 2007).

Old Biases and Alternate Hypotheses

During Chladni's day anything with any sort of mysticism surrounding it was dismissed immediately by scientists as old wives' tales. And, because so few witnesses ever saw meteorite falls, their existence was hotly debated before Chladni's time (Marvin, 2007). Scientists at this time did not believe there were any small objects in space with the exception of the moon, planets and comets. This idea was closely held by scientists of this era due to their immense respect for Isaac Newton, who postulated in 1704 that there were no small objects in outer space besides the moon, as they would interfere with the regular and observable motion of comets and planets (McCall, Bowden and Howarth, 2006).

There were many alternate theories as to what the origins of fireballs may have been, including the aurora borealis, streaks of zodiacal light or light reflected by dust clouds in the solar system, clouds of gases in the upper atmosphere, or an electrical phenomenon (Marvin, 2007). Dr. Edmund Halley proposed to the Royal Society, in 1714, after gathering three separate accounts of meteorites, that they were luminous vapours, formed in the upper atmosphere, that acquired their energy either from the Sun or the Earth's centre (Halley, 1714). John Pringle, a physician and fellow of the Royal Society, interviewed over twelve witnesses of a fireball in 1758 seen over Cambridge, England. He was astounded by the velocity of the fireball and proposed that it was some sort of comet revolving around an unknown centre (Burke, 1991).

After Chladni's publications there were two well documented meteorite falls. One in Sienna, Italy in 1795 and the other in Wold Cottage, England that same year. The following year Edward King published a short book discussing these two events (Marvin, 2007) with the above picture presented on the page before the title. Edward King described the fall in Sienna as coming from a cloud with red streaks that were too slow to be lightning based on many eyewitness accounts. The sound of explosions was also heard at that time by the eyewitnesses. He also discussed the discovery

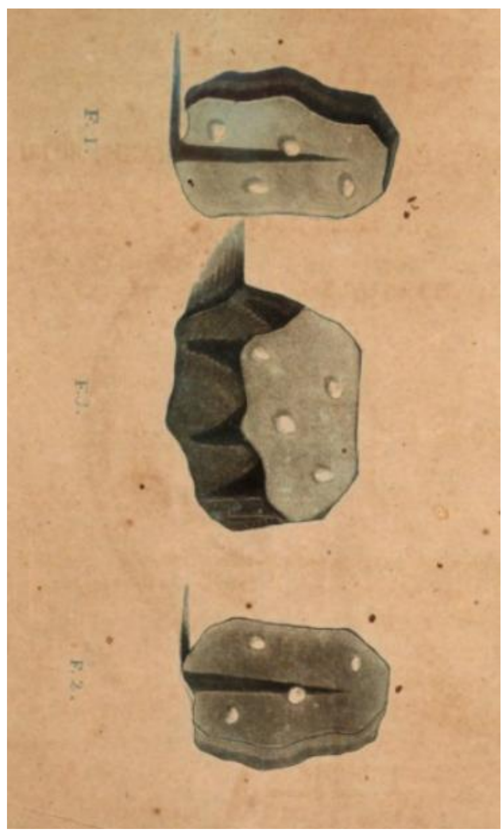


Figure 5.21. An artistic rendition of the meteorites discussed in Edward King's book on the Sienna and Wold Cottage falls, presumably created by the author. This image is relatively orderly and unrealistic, showing the author's bias towards the organized and understandable over the chaotic and strange.

of 19 of the stones that had fallen and compared the physical characteristics that had been described to him (hard, black, and with a glossy sheen). King also commented on the similarity in appearance between all the stones and described the teardrop shape of one of them.

King postulates that these stones were formed in midair from particulates rising from the Earth and correlated their fall to a recent volcanic eruption over 400 km away. He suggested that the cloud of particles from the eruption could have been compressed by the atmosphere in midair and crystallized quickly due to the presence of iron (King, 1796).

King then described a fall at Wold Cottage in England, from which he was able to obtain a meteorite (King, 1796). King was ready to publish his book when he received a copy of Chladni's book on meteorites. He discussed many of the falls contained in Chladni's book but did not agree with Chladni's explanation of the phenomena, instead maintaining his previous opinion that the stones were formed in the atmosphere. However, in a postscript King describes that he also received one of the stones from the Vienna fall and is beginning to compare the stones that he had obtained (King, 1796). It is unknown whether King's opinions on the subject ever changed.

Seven years later there was a large fireball observed over England and France on a northern trajectory. Based on witness testimony of this event, Sir Charles Blagdan, a British scientist and doctor, proposed that fireballs were caused by electric fluid in the atmosphere that was being drawn towards the North Pole. He had heard several other stories of fireballs where they had been travelling northward and due to the speed of the dissemination of knowledge he was unaware of the fireballs that Chladni wrote about how meteorites travelled in multiple directions. (Burke, 1991).

Proving Chladni Right

Opinions on Chladni's ideas began to change when nearly 3000 meteorites fell in L'Aigle, Normandy in 1803. A young, French scientist by the name of Jean-Baptiste Biot travelled to the area to make observations on the nature of these stones. He returned to Paris to read his report to the Classe de Sciences, after which the story of stones that fell from the sky was suddenly and widely publicized in various newspapers. Biot's report contained his description of many accounts of the fall from unrelated witnesses, describing the character of each. It also contained a description of the composition of the local rocks in comparison to the meteorites as well as a discussion of how there was no volcanic activity anywhere near the region of the fall. Biot even visited local smelters in order to compare the meteorites to the waste produced by smelting. In a matter of months after Biot's report the scientific consensus on the origin of meteorites completely shifted to a near total agreement on their extraterrestrial origin (Gounelle, 2006).

However, Chladni and Biot alone did not change the scientific community's opinions of meteorites. Just a year before the L'Aigle fall an important paper was published, without which Biot's report may not have had such a strong impact on the scientific community. This paper was written by Englishman Edward Charles Howard. Howard was a chemist who was known for his discovery of mercury fulminate. He embarked, in 1800, upon a study quite different from that which he was previously known for at the urgings of the President of the Royal Society, Sir Joseph Banks. Howard had access to eight meteorites, half of which were metallic with the rest being mineral meteorites (Kurzer, 1999). The four mineral meteorites came from vastly different areas of the globe: England, India, Italy, and Bohemia. They were discovered to be incredibly similar despite the disparity in source and dissimilarities between the areas from which they were recovered (Kurzer, 1999). The meteorites all had a grey matrix surrounding metallic particles, red-orange pyrites, and an opaque grey-green mineral. Howard investigated the composition of all of these minerals as well as the matrix. All of the parts of the meteorites contained higher percentages of nickel than any terrestrial source besides nickel ore. The grey-green mineral had hitherto been unseen and contained high levels of silica and iron oxide as well as magnesium and nickel oxide. The pyrite was also distinct when compared to its terrestrial cousin, as it produced hydrogen sulphide when treated with acid and was magnetic (Kurzer, 1999). Finally, the metallic particles were found to be an iron and nickel alloy (Wisniak, 2012). The four metallic meteorites were almost entirely iron and nickel and contained multiple small cavities, some of which were filled with green, glass-like globules. The globules were found to have some nickel in them as well as magnesium and ferrous orthosilicates in varying ratios.

These minerals are now called olivine (Kurzer, 1999). All of the meteorites were also observed to have a hard, black glaze of iron oxide coating the surface (Wisniak, 2012). The reason that this work alone did not change the opinions of the scientific community was that Howard, chemist that he was, stuck to interpreting his data, only implying possible extraterrestrial origins but not going so far as to state that he believed they came from outer space. Although, based on the implications of some of his comments, the authors suggest that he did personally subscribe to Chladni's position on the matter (Wisniak, 2012). Despite Howard's aversion to hasty conclusions, his work was crucial in the scientific community's imminent acceptance of the extraterrestrial origin of meteorites (Kurzer, 1999).

Farrington, Nininger and Maskelyne: Classification and Formation Events

Scientists who first began piecing together meteorite origin did this by correlating fireballs to fallen stones, requiring both eyewitnesses to the event and evidence gathered from after the fall to get a full picture. However, most meteorites found on Earth do not have such public origin stories, and are instead classified as finds, as the initial fall was never recorded or observed. Once their origin had been established these finds can be classified as meteorites without any witnesses to the actual fall. The categories they are later placed in are based on unique characteristics including shape, colour, and chemical composition. These distinctions are necessary as achondrite stone meteorites, the most common kind of meteorite found, are nearly indistinguishable from terrestrially formed rocks (Clayton, 2003). Oliver Farrington was the curator of the Geology Field Museum of Natural History. During his time at the institution he wrote *Meteorites; their structure, composition, and terrestrial relations*, where he discussed, among other things, the three most common shapes observed: cone-shaped (conoid), shield-shaped (peltoid), and angular forms (cuboidal, pyramidal) (Farrington, 1915). He stated that shape largely depended on their passage through Earth's atmosphere which is heavily influenced by the speed and length of time of the fall. Shaping is mainly independent of size and substance, meaning both large and small meteorites display similar characteristics based on their passage. However, there are some characteristics of iron meteorites not seen in stone meteorites (Farrington, 1915).

Building upon Farrington, and many others' research, was work done by famed meteorist Harvey H. Nininger. His work was invaluable for the categorization of meteorites, as his collection of 3000 meteorites allowed for observations and classifications of surface features, structure, and shape to be made. He proposed that other characteristics to look for were angular and irregular forms indicating that the meteorites broke apart before reaching Earth. (Nininger, 1972). In *Find a Falling Star*, Nininger also noted that the crust at the front of the meteorite is typically thin and dark, caused by melting during entry, while the rear is typically reddish brown and dented from oxidation (Nininger, 1972).

As stated above however, meteorites are not all the same. British geologist Nevil Story Maskelyne was the first to divide meteorites into three categories, based on the content of iron-nickel that they contained (Shepard, 2015).

The first is iron meteorites, composed mainly of iron with the remainder consisting of nickel and other trace elements (Shepard, 2015). During a planet's life iron's density causes it to settle in the center of the body resulting in iron meteorites with high iron composition. The structural classes of these iron meteorites are determined by studying the composition of the two iron-nickel alloys within them, kamacite and taenite (Frost, 1983). In 1804 and 1808 two different scientists, G. Thompson and Count Alois von Beckh

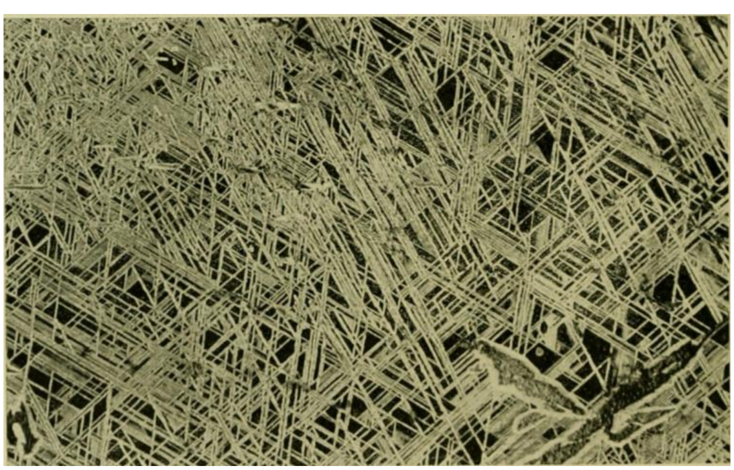


Figure 5.22. Photo of Widmanstätten pattern displaying the Carleton Iron Meteorite with interlocking crystal patterns.

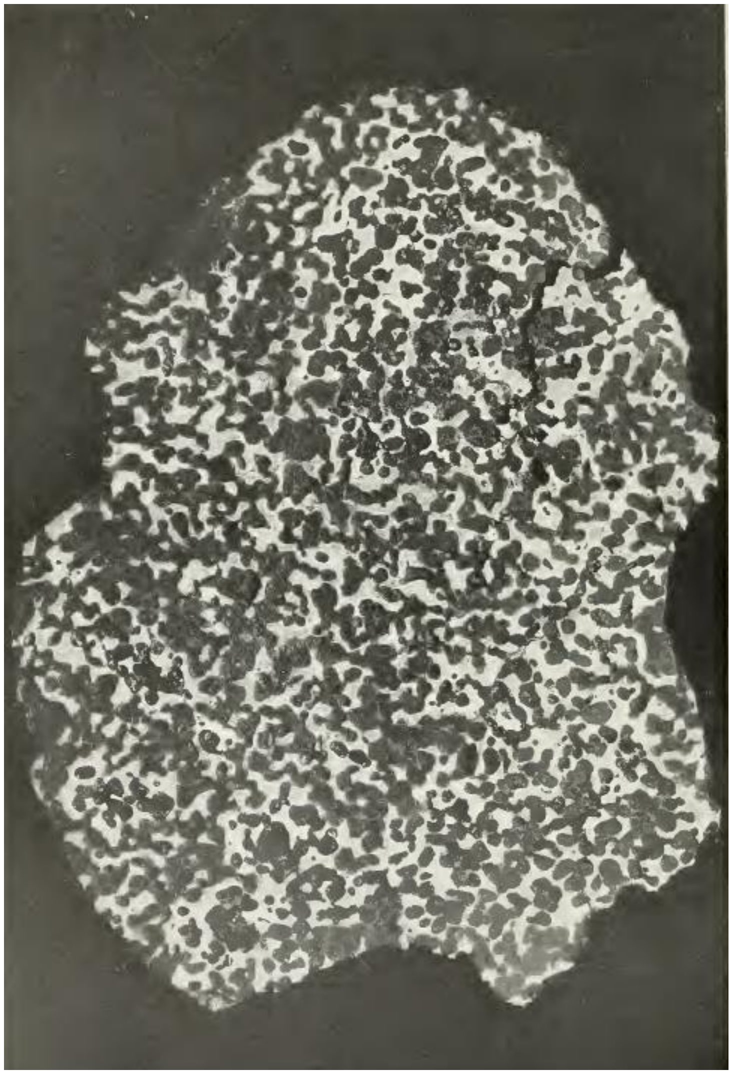


Figure 5.23. Image of Pallasite meteorite discovered in Pallasite Brenham, Kansas.

Widmanstätten, respectively, discovered a distinctive, lattice-like pattern on these iron meteorites which was termed the Widmanstätten pattern (Figure 5.22) (Goldstein, Scott and Chabot, 2009). To see these patterns meteorites are cut, polished, and treated with nitric acid to bring out the pattern of the Kamacite crystals; the gaps between are filled with taenite and remain dark. These bands are then measured and averaged to subdivide the meteorites into different structural classes, narrow (bands less then 1 mm) being classified as a fine octahedrite and wide bands being classified as coarse octahedrite (Frost, 1983).

The second class, aerolites or stone meteorites, have the lowest percent metal composition. They are the most common and make up 86% of all discovered meteorites (Farrington, 1915). Within this class there are two subclasses, achondrites and chondrites. Chondrites are named for the chondrules they contain, which originated from the solar nebula (Farrington, 1915). Chondrules, the opaque, grey-green mineral noticed by Edward Howard, was first studied microscopically by Henry Sorby in 1864. The two subclasses were first described by German mineralogist Gustav Rose that same year (McCall, 2006). The classification method for chondrites was later changed in 1916 by George Prior in order to make it simpler (McCall, 2006). Chondrites range in age from 4.5-4.4 billion years old and are some of the oldest materials in the universe having never experienced modification through melting (Wadhwa, 2007). For this reason, they are very rare and the majority of meteorites are achondrites.

The third and final type is called stony-iron meteorites. They are the rarest meteorites. They have around an equal amount of nickel-iron and stone and can be further divided into pallasites and mesosiderites (Davis, 2005). Pallasites (Figure 5.23), have a nickel iron matrix with olivine crystals scattered among them and the first discovered by Peter Simon Pallas near Krasnoyarsk, Siberia in 1772 (Pedersen, 2017). When polished they display an emerald green colour, making them a highly sought-after collectable. Mesosiderites do not have olivine but they do contain both nickel-iron and silicates creating a silver and black matrix when cut, hence why their first discovery in the 1960s was caused by someone mistaking it for silver (McCall and Cleverly, 1965)

Meteorites: A Source of Life?

Scientists have known that meteorites contained water since 1998, with one of the leading theories for the origin of water on Earth based on the idea that it was introduced by asteroids and meteorites. However, more recently, meteorites have been found to contain amino acids and other necessary elements for life on Earth. As was seen in the carbonaceous Murchison, Murray, and Orgueil chondrites (Fountain, 1999; Botta et al., n.d.). There is precedent for the production of pyrimidine and polycyclic aromatic hydrocarbons (PAHs) in interstellar environments during the breakdown of stars (Marlaire, 2015). In these freezing environments gas molecules condense onto dust, forming ice-covered fragments. Although these ice fragments are exposed to radiation; by binding to ice the nitrogen atom in pyrimidine stabilized and thus the molecules were less likely to break apart.

A study done in 2012 by Nuevo et al., looked to expand on his previous works with UV photo processing on pyrimidine in water rich ice with trace amounts of NH_3 or CH_4 (Nuevo, Milam and Sandford, 2012). To do this, a mixture of H_2O, NH_3, and pyrimidine was placed on a sterile aluminum foil substrate attached to a cryo-vacuum chamber such as the one seen (Figure 5.24) and cooled to about 15-40 K (Nuevo, Milam and Sandford, 2012). Both the ice and pyrimidine mixture were then irradiated by a UV lamp with photons at an average wavelength of 160 nm (Nuevo, Milam and Sandford, 2012). Infrared (IR) spectrum was initially done at 14-15 K (Nuevo, Milam and Sandford, 2012).

Afterwards, samples were warmed to 220 K (Nuevo, Milam and Sandford, 2012). As the sample was gradually warmed to room temperature, IR spectrums were continuously taken (Nuevo, Milam and Sandford, 2012). A separation of the pyrimidine and its derivatives was then performed.

A large amount of pyrimidine and non-pyrimidic species were found in the H_2O, NH_3, and pyrimidine mixed samples including the nucleobases uracil and cytosine (Nuevo, Milam and Sandford, 2012).

While the exact mechanisms of formation are not known, assumptions based on the results of both this and previous experiments allow researchers to hypothesize the chemical pathways of their formation. It begins with the formation of 4(3H)-pyrimidone, another addition of an OH group added at position 2 to form uracil (Nuevo, Milam and Sandford, 2012).

The formation of cytosine is not well known although can be assumed to occur in a similar manner, with the addition of NH_2 and OH groups to pyrimidine (Nuevo, Milam and Sandford, 2012).

This experiment provides invaluable information on how chemical reactions can occur in space, and how they link to the formation of life on our own planet. By having proof that the building blocks of life can form in such hostile conditions it opens up new doors for extraterrestrial life under conditions we had not previously explored. Further understanding of how life came to be on this planet can allow scientists to have more success in both looking for and creating extraterrestrial life.

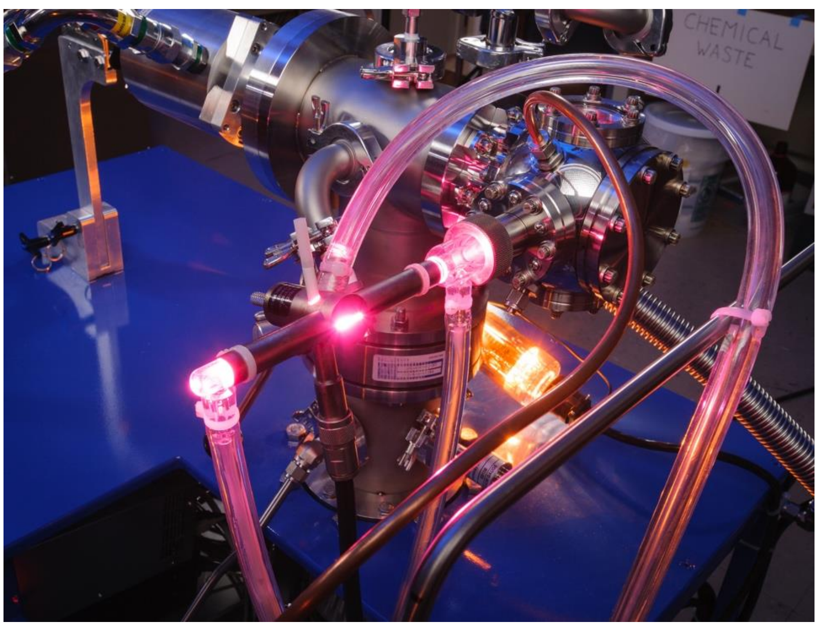


Figure 5.24. Image of Cryo vacuum cooled to ~440 °F with UV photons being supplied by a hydrogen lamp which break the bonds in pyrimidine and form compounds such as uracil.

Basalt Columns: Pillars of Contention

"Dark o'er the foam-white waves,
The Giant's Pier the war of tempests braves,
A far-projecting, firm, basaltic way,
Of clustering columns wedged in dense array;
With skill so like, yet so surpassing art,
With such design, so just in every part,
That reason pauses doubtful if it stand
The work of mortal or immortal hand."

- Anonymous, The Illustrated Magazine of Art, 1853

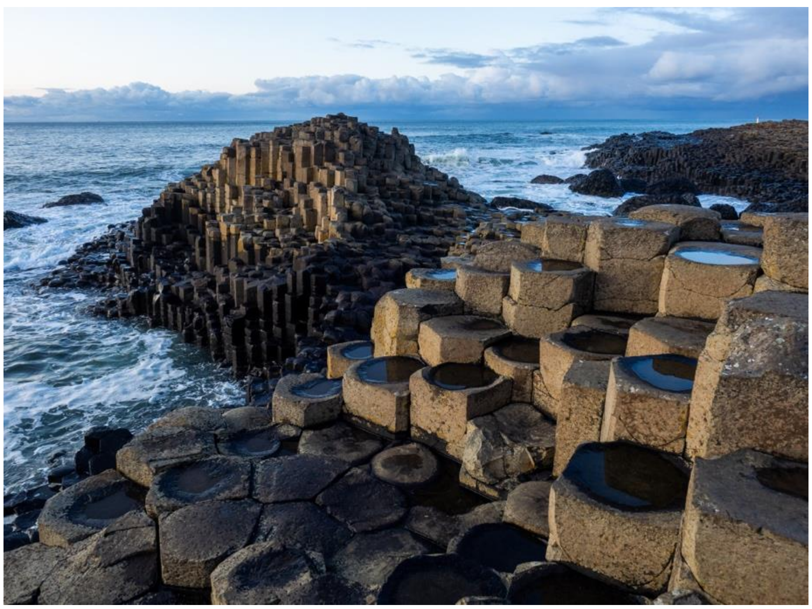


Figure 5.25. The Giant's Causeway has captivated people's attention for centuries. It is now classified as a UNESCO World Heritage Site and an Area of Special Scientific Interest (UNESCO, 2020).

The "basaltic way" in this poem refers to the Giant's Causeway on the Antrim Coast in Northern Ireland. This is one of the most famous sites of basaltic columns found around the world. Black-grey pillars of rocks, mostly hexagonal, form a platform stretching out into the sea. The scale and peculiar geometry of this awe-inspiring formation has garnered attention over the past few hundred years from locals, artists, early scientists and finally, tourists… all pondering how this dark Causeway could have formed.

Peoples' understanding of basalt column formation was closely intertwined with the development of the geological sciences in the seventeenth and eighteenth centuries. Basalt columns were interpreted according to the prevailing cultural and scientific perspectives, but investigation into their formation also provided evidence for a major paradigm shift in the field of geology.

Initially people turned to the supernatural to explain these impressive phenomena. Then, as modern science was born, the perspectives through which basaltic columns were viewed shifted. The scientific revolution and enlightenment placed new importance on applying reason to generate knowledge and understanding. In the late 1600s, natural philosophers began making detailed descriptions of the columnar basalt formations, which were then presented at Scientific Societies along with artists' renditions of the field sites. As the discipline of science evolved, simple observations and conjectures about the natural world made way to experimentation. Amidst this shift, columnar basalt formations got caught up in a major debate between the early geologists in Europe that raged through the 1700s.

Basalt Columns in Folklore

From ancient times, humans have turned to stories and legends to explain the unknown, and the historical views of basaltic columns were no exception. The regularity of the hexagonal pillars of rock evoked a sense of mystery and awe that called for supernatural explanations. The Irish name of the Giant's Causeway is "Clochan na bhFómharach" which translates to "Stones of the Fomorians," the evil deities of pre-Christian Celtic mythology (MacKillop, 2004; Ellis, 1987). The modern English name of "Giant's Causeway" is derived from a body of mythology originating in the early middle ages regarding the giant Fionn mac Cumhaill (generally anglicized to Finn Mac Cool) (MacKillop, 2004; Ellis, 1987). According to legend, the Giant's Causeway was created by Finn Mac Cool as a bridge between Ireland and Scotland, where another giant by the name of Benandonner dwelt. Wanting to challenge Benandonner to a duel, Finn Mac Cool built a bridge of stone for Benandonner to cross over on. The winner of the duel in this story depends entirely on whether one asks a Scotsman or an Irishman, but regardless, the basaltic promontory is interpreted as all that remains of a once formidable giants' bridge. Building upon this story, other basaltic formations along the Antrim coast are known as the Giant's Well, the

Giant's Chair and the Giant's Bagpipes (The Giant's Causeway, 1832). Comparisons between the mysterious basalt columns to known objects within the framework of mythology can be seen as early attempts to provide an explanation to the unexplainable.

The Natural Philosopher's View

The Scientific Revolution and the Enlightenment, which together spanned from the sixteenth to the eighteenth centuries, brought about new perspectives through which to understand the world. Reason was championed over faith-based knowledge, and a new class of 'Natural philosophers' emerged. These early scientists—including Thomas Molyneux, one of the initial investigators of the Giant's Causeway—looked down on "the Superstitious People of the Country [...] who through Ignorance, do usually ascribe whatever is strange and extraordinary, though Natural, to the working of Giants, Fairies, Dæmons, and such like Imaginary Causes" (Foley and Molyneux, 1694).

A big step forward in our understanding of basalt columns came with the establishment of Scientific Societies. These were organizations, independent of universities, which brought together natural philosophers and scholars to share and freely discuss scientific knowledge. The Royal Society of London, founded in 1661, was one of the most influential. Its regular publication of "Letters" in the *Transactions of the Royal Society* provides a record of the early exploration and interpretation of basalt columns, particularly those from the Giant's Causeway (Huff, 2010). The basalt columns of the Giant's Causeway were first introduced to the Royal Society by Sir Robert Redding in 1689 (Kennedy, 2008). Over the following decade, a handful of other reports were also submitted to the Society regarding this site (Bulkeley, 1693; Foley and Molyneux, 1694; Molyneux, 1698). The descriptions of natural philosophers reporting on the basalt columns were characterized by pages and pages of extremely detailed observations. These included debates over the number of sides in each pillar, whether or not the pillars were 'jointed' and what type of rock they consisted of (Bulkeley, 1693; Foley and Molyneux, 1694; Hamilton, 1790). By comparing rock samples to other known sites, natural philosophers were able to identify the columns as basalt by the late 1690s (Molyneux, 1698). However, the way in which columnar basalt—and even basalt in general—formed was still a complete mystery. The question of whether basalt formed under the influence of water or volcanism became a major point of contention between the geologists in the years that followed.

To accompany the natural philosphers' descriptions to the Royal Society, a number of maps and artists' illustrations of columnar basalt were made. The earliest illustrations of the Giant's Causeway include Christopher Cole's "A Draught of the Gyants Cawsway" submitted to the Royal Society in 1694, and then Edwin Sandys's "A True Prospect of the Giants Cawsway" (Figure 5.26), commissioned by the

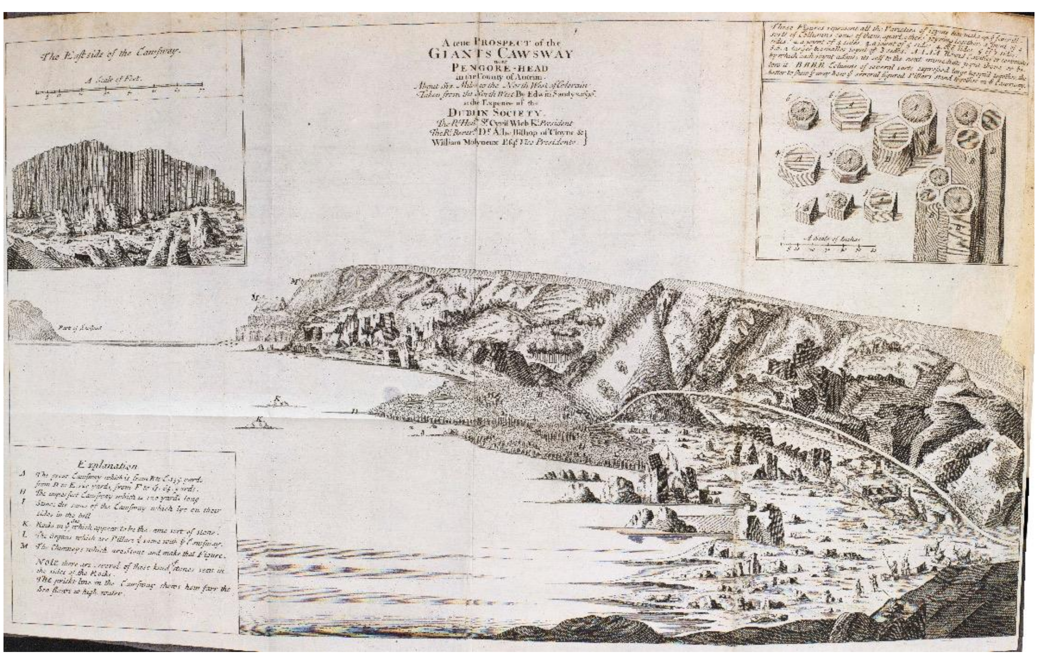


Figure 5.26. "A True Prospect of the Giants Cawsway", drawing by Edwin Sandy commissioned by the Dublin Philosophical Society in 1696.

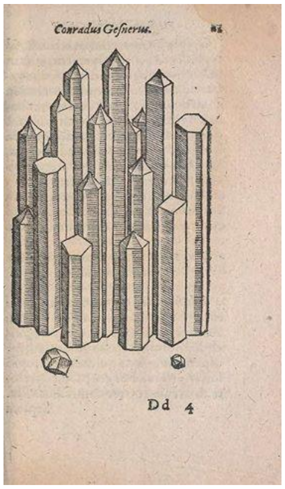


Figure 5.27. An early drawing of columnar basalt from Conrad Gesner's De Rerum Fossilium, Lapidium et Gemmarum *(1565), showing his 'mineralogical' interpretation of the column structures as quartz-type crystals (Montgomery, 1996).*

Dublin Philosophical Society in 1696 to overcome some of the flaws of Cole's initial drawing. Despite the fact that geological drawings were still very new and non-standardized, these early illustrations formed the basis of a growing discussion about basalt columns among natural philosophers, including many who had not witnessed them in person (Kennedy, 2008).

While some were fairly accurate depictions limited merely by the artist's skill, others appeared to have been biased by the new theories circulating about how basalt columns were formed. The most striking example of this came from a very early depiction of basalt columns in continental Europe from 1565 (Figure 5.27) (Montgomery, 1996). The drawing represented the columnar basalt as having pointy crystal-like tops and being spaced apart as individual crystals. This was consistent with the artist's belief that all rock had crystallized from water. These sorts of artistic interpretations were problematic, as the illustrations were then used as evidence to support the natural philosophers' arguments about the formation of basalt (Hamilton, 1790). It was not until 1739 that an artist by the name of Susanna Drury made what were considered to be the first accurate paintings of the Giant's Causeway (Figure 5.28) (Hamilton, 1790). Drury's objective depiction, including details such as the horizontal striations on the basalt pillars, paved the way for a better understanding of whether these enigmatic formations were born of water or of fire.

Neptunist vs. Vulcanist Controversy

The discovery of the origin of columnar basalt was tightly intertwined with a great scientific controversy of the eighteenth century. At this time, there was an unsettled dispute between mineralogists regarding the origins of Earth's rocks and sediments, which reflected two major schools of thought (Hallam, 1983).

The Neptunist school of thought was founded by Abrahab Gottlob Werner, a beloved and inspirational teacher who helped describe a new classification system for all existing rocks and mineral substances (Hallam, 1983). Werner proposed that all rocks had precipitated out of a primeval and retreating ocean 'soup', which laid down a succession of deposits through chemical precipitation and mechanical deposition as time passed. 'Primitive Rocks', such as mineral-rich granites and basalt were deposited first, followed by sandstones and limestones, and finally muds and alluvium into lowland areas. This retreating ocean did not subside quietly and slowly, but was originally very turbulent, with powerful currents carving the shapes of modern mountains and valleys until the water level had dropped significantly. A variation of Werner's theory included Diluvialism, a religious belief that it was Noah's flood, and not a universal ocean, which produced all observable rocks and fossils (Leddra, 2010).

Werner's theory was highly popular in the early eighteenth century, appearing to account in a simple and satisfying way for a wide range of geological phenomena (Hallam, 1983). Other 'Wernerians' included German geologists, mining engineers, and miners, who used Neptunist theories to predict where particular minerals might be found (Leddra, 2010). The Neptunist influence on the developing field of geology was strong, and at first overshadowed the pioneer work of mineralogists advocating for the uplift of land due to volcanic activity as

Figure 5.28. "East Prospect of the Giant's Causeway" by Susanna Drury (c. 1739), gouache on vellum, 34x67.6 cm.

the cause for the geological phenomena in question, instead of the fall of the ocean (Hallam, 1983). These (mainly French and Italian) scientists became known as Vulcanists, and eventually found their voice in the mid-eighteenth century in the major dispute over the origin of basalt.

While Werner was aware that others accepted basalt to be volcanic in origin, he disregarded their views and maintained that it was a chemical precipitate from the universal ocean. The basalt rocks he had studied lacked lava-associated scoriae, displayed columnar jointing (which was common in desiccated clay deposits), and were intercalated in sequences of sediments that were indisputably aqueous in origin (Hallam, 1983; den Tex, 1996). He did not believe that the Earth contained 'interior fire' and rationalized that the activity of modern volcanoes was limited to very recent times, with basalt and other rocks having been instead melted by the spontaneous combustion of subterraneous coal (Hallam, 1983). It was not a new idea that combustible substances were all that were required to account for the production of volcanoes—this had been proposed mid-century by the French geologist Jean Etienne Guittard (who also believed basalt had formed by crystallization from a fluid) (Hallam, 1983).

It was Nicholas Desmarest, however, who should perhaps be considered the true 'father' of Vulcanism. He conducted highly detailed, painstaking research in a small area of Auvergne, France and detected columnar jointing in volcanic rocks in 1763 which he traced back to an old lava stream and to volcanic cones (Desmarest, 1774). On that basis, he claimed basalts were volcanic in origin, and that basalt outcrops isolated from the rest of flow were resultant from erosion of the intervening basalt. These marked some of the first attempts to trace back the history of a landscape by comparing different erosional stages (Hallam, 1983), laying the beginnings of the conceptual groundwork for the future Uniformitarianism theory.

The criticisms of the Vulcanists were never openly addressed in publication by Werner, but seemed to have provoked him to seek further evidence for his theories. In 1788, he found an upward sequence of sandstones, clay, mudstone and basalt which appeared to grade smoothly into one another, which he believed to be a fundamental piece of evidence that basalt was indistinguishable from precipitated sediments, and therefore also aqueous in origin (Hallam, 1983). Surprisingly, however, this 'discovery' was challenged by J. K. W. Voigt, Werner's favourite and most able student, who insisted that the basalt found was in fact an ancient lava flow (Hallam, 1983). The lengthy ensuing arguments convinced neither party and eventually destroyed their friendship.

Figure 5.29. Panel from the 1768 edition of Diderot's famed Encyclopédie. *It features basalt columns from the Auvergne region, studied by Desmarest. This panel is part of the collection on volcanoes, testifying to the shift towards Vulcanism in 1760s France.*

Although rock correlation and classification in the 1770s and 1780s was primarily based upon fieldwork, this emphasis on research soon shifted to include results from chemical laboratory experiments (Lauden, 1987). In the late eighteenth century, mineralogists began to explore and compare several cause-effect relationships, including conditions required for crystal growth in aqueous solution (an undisturbed, quiet solution was found to be critical, quite unlike the suggested turbulent waters of Werner's universal ocean) (Lauden, 1987). Meanwhile, in 1776, chemist James Keir experimented with the melting and cooling of glass, testing whether cooling rates might influence the glass's final structure (Keir, 1776). He observed that glass that cooled quickly would mainly revert to its original state, while slowly-cooled glass would often crystallize (Figure 5.30). This suggested that crystals could grow equally well from heat as from water, lending support to Vulcanist theories. Keir also compared his crystallized glass to the columnar basalts of the Giant's Causeway, and argued that the spectacular column structures were large crystals that had formed during a melt, and not from water (Keir, 1776):

"Does not this discovery, of a property in glass to crystallize, reflect a high degree of probability on the opinion, that the great native crystals of basaltes, such as those which form the Giant's Causeway, or the pillars of Staffa, have been produced by the crystallization of a vitreous lava, rendered fluid by the fire of volcanos?" (Keir, 1776)

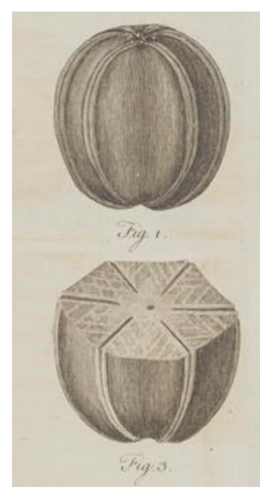


Figure 5.30. A selection of James Keir's drawings from his glass cooling experiments, showing that slow cooling rates produced crystallization of his glass structures.

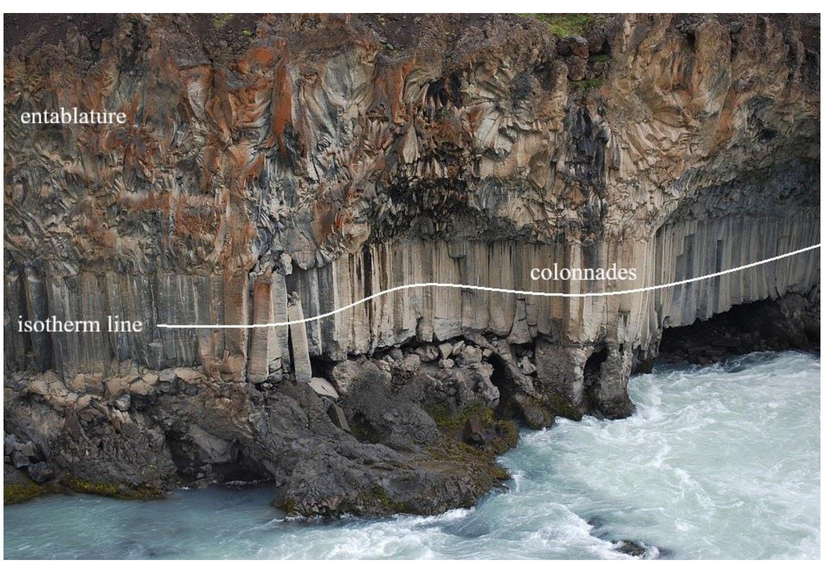
As new pieces of evidence emerged, support for Neptunist theories waned in favour of the Vuclanists (Figure 5.29). In 1829, the polarizing light microscope was invented, allowing geologists to examine rocks in thin section (Newcomb, 2009). It was this technique that revealed the inner microcrystalline structures of basalt rocks, representing clear mineralogical evidence that basalts were indeed igneous in origin (and therefore that basalt columns were a product of slow-cooling lavas) (Lauden, 1987; Newcomb, 2009). These events effectively marked the death of Neptunism, and the end of a chapter in the great basalt controversy. Meanwhile, Vulcanism persisted into the new century, continuing to alter modern understandings of geological phenomena and shape people's investigations into basaltic formations.

A New Curve on Columns

The Vulcanists were correct in their original suspicions that basalt columns had formed from cooling lava. Basalts are now known to be a type of igneous rock rich in iron and magnesium, having extruded as a molten liquid and cooled on or near the Earth's surface (Haldar and Tišljar, 2014). The new rock contracts and reduces in volume as it cools, building up tensional stress within the rock body. The rock then cracks to relieve this stress, forming the regular patterns of polygonal columns that have been so ardently admired throughout history (Goehring and Morris, 2008; Christensen et al., 2016).

The various properties of basalt columns observed by the natural philosophers of the seventeenth and eighteenth centuries—such as the polygonal patterns, striations and jointing—can be understood by analyzing the cooling lava as a thermodynamic process. When basaltic lava is exposed to a flat cooling surface (such as air, water, or a cooler host rock), a temperature gradient is formed. The lava in contact with this cooling surface solidifies first, and then the rest of the lava body is slowly lithified in turn as the heat gradually dissipates. Planes of equal temperature, called isotherms, form parallel to the cooling surface. As each layer of rock in an isotherm cools to a critical temperature, it contracts, generating polygonal fractures. These fractures allow the underlying rock to cool, causing the next isotherm layer to contract along the same fracture lines. Since these fractures propagate deeper into the body of rock as it cools, basalt columns are said to 'grow' perpendicular to their cooling surface (Christensen et al., 2016). As a result, the orientation of these columns provides information about whether the basalt was extruded as a lava flow (vertical columns), as a vertical dike (horizontal columns) or as a horizontal sill (vertical columns) (Gudmundsson, 2017).

Figure 5.31. Photograph of entablature and colonnade regions showing the direction of a hypothetical isotherm line at Aldeyjarfoss, Iceland.



If a layer of water floods the surface of a cooling lava flow, it can generate two distinct facies of basalt columns (Figure 5.31). The lower region, called the colonnade, consists of regular polygonal columns of basalt cooled slowly from the pre-existing host rock below. The upper region consists of jumbled, irregular, and curved columns called the entablature. Water causes rapid cooling and tends to penetrate into the cracks formed by the cooling surfaces to further cool underlying rock. This process generates new cooling fronts, where perpendicular columns grow in a disarray of thinner columns branching off in varying directions (Phillips et al., 2013; Christensen et al., 2016). In the absence of water, the entablature may also form sandwiched between an upper colonnade and a lower colonnade region. In this case, the curved tangle of columns may result from different stresses where the two sets of growing columns meet (Phillips et al., 2013). As a result of its non-linear cooling fronts, the entablature often contains interesting column patterns, such as rosettes, fans and chevrons (Figures 5.31, 5.32).

Figure 5.32. Image of a basalt rosette (left), with columns radiating outwards from a central point. This pattern was formed as lava flowed around a tree trunk, which helped draw heat from the forming rock, causing it to cool outwards in progressively larger rings (Garratt, 2006).

There is a critical temperature threshold (between 700-800°C) for the formation of basalt columns, known as the glass transition temperature (Ryan and Sammis, 1981; Goehring and Morris, 2008). Above this temperature, tensional stress in the rock is relieved through plastic deformation or viscous flow, instead of through cracking. Below this temperature threshold, the forming rock is brittle, and thermal contraction results in the characteristic fractures of basalt columns (Geohring and Morris, 2008). However, a 2018 study by Lamur et al. proposed that the initial crack formation could possibly occur at much higher temperatures (890-840°C) than predicted. As the cooling front penetrates deeper into the forming rock, each isotherm reaches the critical temperature one after the other. The striations along the outside of the columns, so faithfully portrayed by Susanna Drury in her 1739 paintings of the Giant's Causeway (Figure 5.28), indicate the distance advanced by the cracks in each of these steps (through each isotherm) (Goehring and Morris, 2008; Christensen et al., 2016). Thus, striations are an indicator of the rate of rock cooling. The size of the columns is also indicative of the rock's cooling rate. It is generally accepted that faster cooling rates correlate with thinner columns (such as those in the entablature region), although the underlying mechanism of this phenomenon is not yet fully understood (Goehring and Morris, 2008; Christensen et al., 2016). Hetényi et al. (2012) suggest that the chemical properties of the lava and the geologic environment could also influence how the rock cools, and consequently, the size of columns formed.

The study of basalt column formation is important and relevant to a wide number of geological applications. First, as previously mentioned, the size, shape, and orientation of the columns provide information about the conditions in which the lava cooled, which is useful in paleoenvironmental studies (Gudmundsson, 2017; Lamur et al., 2018). Secondly, studying basalt columns provides information about the thermodynamics of global heat transfer in cooling lava systems. Columnar joints create permeable structures in bodies of basalt, which can affect fluid circulation within the Earth's crust. This information is also useful for understanding the distribution of resources, such as sites of rich geothermal energy and ore deposition (Lamur et al., 2018). Furthermore, patterns of polygonal jointing are not exclusive to basalt columns but are common in other environments, including desiccated mud crack terrains and regions of abundant permafrost (Goehring, 2013). Finally, the study of columnar jointing is also useful in the context of planetary exploration, when interpreting the geologic histories of other planets. In October 2007, HiRISE images of Mars's surface revealed outcrops of columnar jointing in an unnamed crater in Marte Vallis (Figure 5.33). Some of these columns were greater than 30 m in height and ranged from less than a metre to greater than 2 m in diameter. Regions of entablature, similar to various Earth analogues, were also observed (Milazzo et al., 2009). Milazzo et al. (2009) hypothesized that these extraterrestrial columnar joints were produced by flood lavas that were inundated by liquid water, resulting in large-scale rapid cooling. The Marte Vallis region is thought to have been part of a drainage channel, and a location where volcanic and fluvial activity might have coincided. This theory is supported by other geologic formations observed in the HiRISE images, such as pillow lavas and hyaloclastite, which are structures produced by the contact of lavas with water (Milazzo et al., 2009).

Figure 5.33. Image of the columnar jointing in Marte Vallis, Mars. It shows layers of solidified lava flows exposed on a crater rim, with columns between 30-40 m tall and about 1-2 m wide.

The study of basalt columns remains relevant in the modern context, benefitting from technological advances to provide answers to new geological questions.

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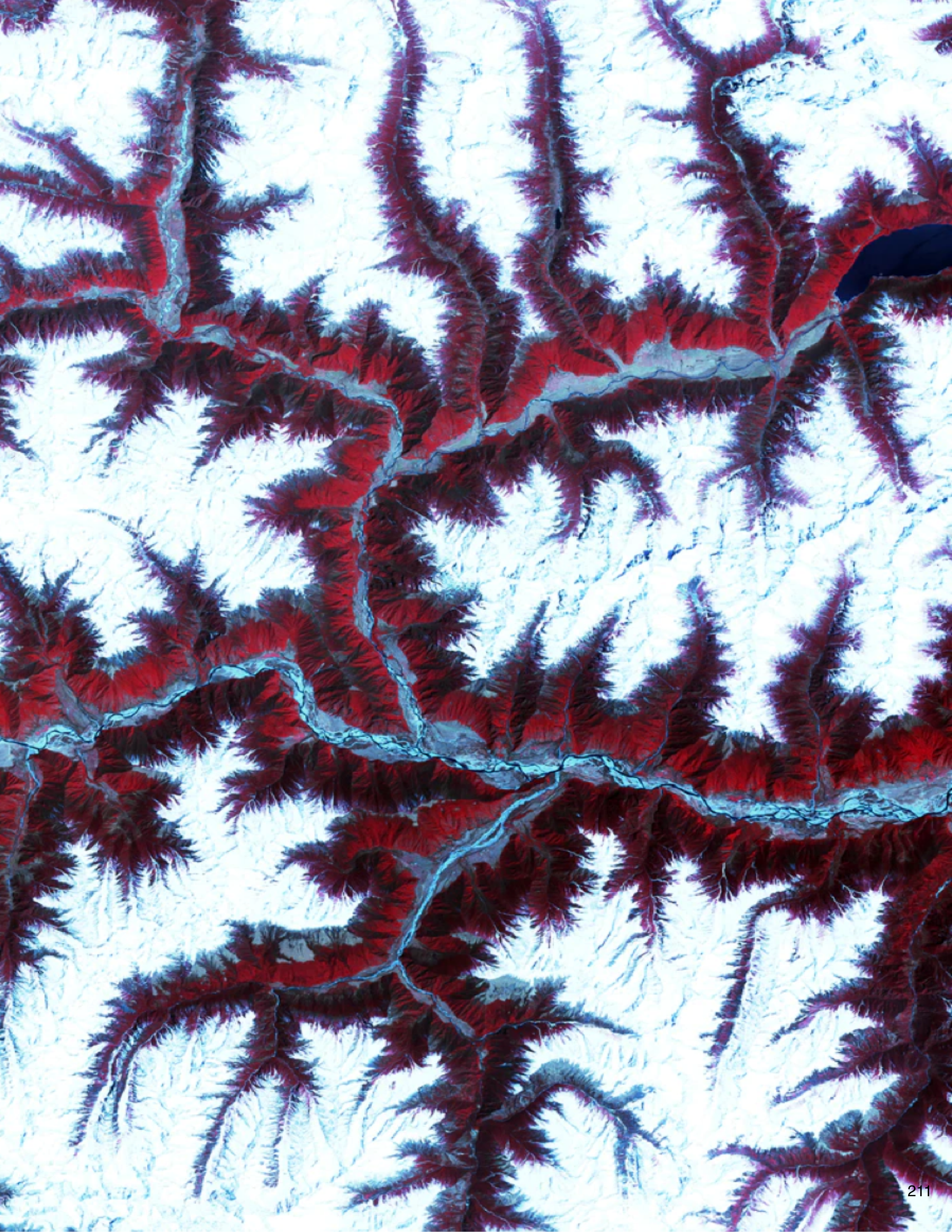
Conclusion

Science, at its pinnacle, has always been centered on three pillars: curiosity, exploration, and discovery. Curiosity motivates and drives the mind, exploration fulfills the desired need for adventure, and discoveries provide us reason to reembark on this journey again and again. From the processes that shape our Earth, the evolution of life, and the uncovering enigmatic discoveries, these are a small sample of stories that continue to evolve with time. Time is the river that meanders and provides us with opportunities to learn more about the world around us. As this river continues to flow forward, countless great minds have stepped up to the challenge and answered the call of studying the unknown. From single, great philosophers to groups of charismatic researchers, the world is full of individuals willing to endeavour above and beyond the norm. Once seemingly abstract, absurd, and aberrant hypotheses now shape our understanding of the Earth and her stories, blazing the path for others to follow. The torch continues to be handed from generation to generation, inspiring new minds to pick up where others have left off. At its core, the history of the Earth provides the framework through which all other discoveries are made possible. It is a place where rivalries, controversies, and brilliant ideas remain firmly imprinted in stone. These discoveries sculpted our past, inspire the present, and will continue to revolutionize the future. *The History of the Earth* is not a random collection of small stories, but one grand tale meant to be told as a holistic sum.

The pale blue dot in the vast expanse of the universe is the storyteller humans have been searching for since the dawn of time. Humans yearn for complete stories; they drive our existence and search for greater knowledge. The Earth is complex yet unquestionably beautiful. It is through the sharing of her stories that we can develop a more intimate connection with the environment around us. The truth about stories is that they are all we have. They are a method of communication from one generation to the next. The *History of the Earth Volume X* is nothing more than a selected compilation of stories that we find most fascinating. Take it. Run with it. Reread it. Explore it. Share it. Ignore it. It is all up to you. These are the stories we have selected to share. These are the stories that will impact the future. In time, perhaps a complete story can be told, one that puts an admirable conclusion to a spectacular beginning. You have heard her story. Do with it what you will. Her time is now.



Glossary

Actualism — the idea that the facts of geology can and should be explained in terms of physical processes that actually happen.

Achondrite — a stony meteorite containing no chondrules.

Aerosol — a system of colloidal particles dispersed in the air or in a gas, such as mist, fog, or smoke.

Alchemy — the branch of study and practical craft in the Medieval and early Renaissance period concerned with the nature and transformation of physical substances, especially the transmutation of baser metals into gold.

Allele — each of two or more alternative forms of a gene that arise by mutation and are found at the same place on a homologous chromosome.

Alloy — a metal made by intimately combining two or more metals or (less commonly) metals and non-metallic elements, typically to improve a physical property (such as strength, hardness, or corrosion resistance).

Alluvial fan — a triangle-shaped deposit of gravel, sand, and smaller sediment that is formed by a river.

Alluvium — a deposit of earth, sand, and other transported matter left by water flowing over land not permanently submerged, especially in a river valley or a delta.

Amber — hard translucent fossilized resin originating from extinct coniferous trees, typically yellowish in colour and used in jewellery.

Amino acid — any of a class of about twenty simple organic compounds which form the basic constituents of proteins and contain both a carboxyl (–COOH) and an amino (–NH2) group.

Ammonite — an extinct sea creature in the cephalopod family, related to modern squids.

Ammonoid — a fossil cephalopod of the order Ammonoidea, comprising the ammonites and related genera.

Amphipods — a crustacean of the chiefly marine order Amphipoda, having a laterally compressed body and a large number of leg-like appendages.

Anatomy — the branch of biology and medicine concerned with bodily structure, especially as revealed by dissection.

Angiosperm — a plant of a large group (subdivision Angiospermae) that comprises those that have flowers and produce seeds enclosed within a carpel, including herbaceous plants, shrubs, grasses, and most trees.

Antarctic Circle — the line of latitude 66° 33' South.

Aqueous — containing water; like water.

Archean — relating to or denoting the eon that constitutes the earlier (or middle) part of the Precambrian, in which there was no life on the Earth.

Arctic Circle — the line of latitude 66° 33' North.

Aristotelianism — the philosophic system or any doctrine of Aristotle.

Astronomy — the scientific study of the sun, moon, stars, planets, etc.

Atom — the smallest particle of a chemical element that can exist.

Aurora borealis — an astronomical phenomenon, when colored lights occur near or radiate from the Earth's Northern or Southern magnetic pole, which is occasionally visible at night in the adjoining hemisphere.

Barometer — an instrument measuring atmospheric pressure, used in forecasting the weather and determining altitude.

Basalt — a greenish- or brownish-black rock, igneous in origin, of compact texture and considerable hardness, composed of augite or hornblende containing titaniferous magnetic iron and crystals of feldspar (labradorite).

Basin — a circumscribed rock formation where the strata dip towards the centre.

Belemnite — a fossil common in rocks of the Secondary formation.

Big Bang — in cosmological theory, the rapid expansion of the universe from the extremely dense and hot initial state which marked its origin approximately 13.7 billion years ago.

Biodiversity — diversity of plant and animal life, as represented by the number of extant species.

Bioindicator — an organism used as an indicator of the quality of an ecosystem, especially with respect to pollution.

Biology — the scientific study of the life and structure of different organisms.

Biostratigraphy — the branch of stratigraphy that uses fossils to establish relative ages of rock and correlate successions of sedimentary rocks within and between depositional basins.

Biotic — relating to or resulting from living organisms.

Biotic stress — stress caused by interactions with other living organisms.

Bioturbation — the disturbance of sedimentary deposits by living organisms.

Biped — an animal which walks on two feet.

Burgess shale — a mudstone formation in the Rocky Mountains of western Canada, containing a wide range of well-preserved invertebrate fossils (including those of soft-bodied animals) from the Cambrian period.

Calcium — a chemical element; a soft silver-white metal found in bones, teeth, and chalk.

Cambrian — a name given by Sedgwick in 1836 to a group or 'system' of Palæozoic rocks lying below the Silurian, in Wales and Cumbria.

Carbonate — a salt containing either of the anions CO_3^{2-} or HCO_3^{-}, typically formed by the action of carbon dioxide or carbonic acid on a base.

Carbon dating — the determination of the age of an organic object from the relative proportions of the isotopes carbon-12 and carbon-14 that it contains.

Carnivore — an animal that feeds on flesh.

Cartography — the art or process of drawing or making maps.

Cataclysmic — relating to or denoting a violent natural event.

Catastrophism — the theory that changes in the Earth's crust during geological history were caused by catastrophes (sudden, violent, and unusual events) rather than by continuous and uniform processes.

Celestial body — any natural body outside of the Earth's atmosphere.

Celestial meridian — the line crossed by the sun at noon; the point on this line where it is crossed by the sun or a star at its highest point.

Chemistry — the scientific study of the structure of substances, how they react when combined or in contact with one another, and how they behave under different conditions.

Chlorella — a genus of unicellular green alga.

Chondrite — a stony meteorite containing small mineral granules (chondrules).

Chondrule — a small spherical grain of mineral embedded in varying numbers in the matrix of chondritic meteorites.

Chronology — the study of records to establish the dates of past events.

Chronometer — an instrument for measuring time, adjusted to keep accurate time in all variations of temperature.

Circumnavigation — the act of sailing all the way around something, especially all the way around the world.

Cladogenesis — a process of adaptive evolution that leads to the development of a greater variety of animals or plants.

Clathrate — rock that forms a lattice that traps methane.

Clay — a type of stiff, viscous soil found in beds or other deposits near the surface of the ground and at various depths below it, which forms a malleable paste when mixed with water.

Coal — a hard black mineral that is found below the ground and burnt to produce heat.

Comparative anatomy — compares the structure of different classes or groups of animals.

Condor — a very large American vulture with a bare head and mainly black plumage.

Conglomerate — describes material composed of the fragments of pre-existing rocks cemented together.

Core — a cylindrical sample of rock, ice, or other material obtained by boring with a hollow drill.

Continental drift — the gradual movement of the continents across the Earth's surface through geological time.

Cosmogonist — one who studies cosmogony, or offers an account of the origin or creation of the world.

Cosmology — the scientific study of the universe and its origin and development.

Craton — a large stable block of the Earth's crust that has resisted deformation over a long period of time.

Creationism — the belief that mankind and all living organisms, as well as the physical universe, originated in specific acts of divine creation as related in the Bible or other sacred book rather than by natural processes as described by science.

Cretaceous — describes the period between 146 and 65 million years ago.

Crust — the solid outer layer of rock that forms the surface of a planet, such as Earth.

Crystal — any naturally occurring mineral substance which is clear and transparent like ice; especially a form of quartz.

Crystallography — the branch of science concerned with the structure and properties of crystals.

Cytosine — a crystalline pyrimidine derivative, 4-amino-2-hydroxypyrimidine, which is one of the five main bases occurring in nucleic acids, and pairs with the purine base guanine in double-stranded DNA.

Dating — a method of calculating the age of very old objects by measuring the amounts of different chemical isotopes in them.

Deity — godhood, or the rank of a god.

Deposition — the natural process of leaving a layer of a substance on rocks or soil.

Diamondiferous — diamond-producing.

Diluvialism — the theory, largely abandoned in the mid-19th century, that the Earth's surface was shaped by the biblical flood.

Diversity-dependence — describes how diversity has demonstrated a negative feedback loop effect on diversification rates.

DNA — deoxyribonucleic acid, a substance present in nearly all living organisms as the carrier of genetic information, and consisting of a very long double-stranded helical chain of sugars joined by phosphate bonds and cross-linked by pairs of organic bases.

Dynamism — a philosophical system, theory, or doctrine, which seeks to explain the phenomena of the universe by some immanent force or energy.

Ecosystem — a biological community of interacting organisms and their physical environment.

Elastic wave — motion in a medium in which, when particles are displaced, a force proportional to the displacement acts on the particles to restore them to their original position.

Electrosensory — pertaining to the ability of a biological organism to perceive electrical impulses.

Enlightenment — the dominant European intellectual culture in the 18th century which typically emphasized freedom of thought and action without reference to religious and other traditional authority.

Entomology — the branch of zoology concerned with the study of insects.

Environment — the natural world in which people, animals and plants live.

Epicenter — the point on the Earth's surface vertically above the focus of an earthquake.

Epoch — a division of time that is a subdivision of a period and is itself subdivided into ages, corresponding to a series.

Equator — the line around the world dividing North and South.

Erosion — the process by which the surface of something is gradually destroyed through the action of wind, water, or other forces.

Evolution — the process by which different kinds of living organism are believed to have developed from earlier forms, especially by natural selection.

Exoplanet — a planet that orbits a star outside the solar system.

Extant — describes a species or other large group that is still in existence.

Extinct — describes a species or other large group that has no living (extant) members.

Fauna — a collective term for the animals or animal life of any particular region, habitat, or geological period.

Felsic — describes rocks relating to or containing a group of light-colored minerals, including feldspar, feldspathoids, quartz, and muscovite.

Fission — a reaction in which a heavy atomic nucleus splits in two, releasing much energy.

Fissure — a long, narrow crack.

Flora — a collective term for the plants or plant life of any particular region, habitat, or geological period.

Fluorescence — bright light produced by some forms of radiation.

Fluvial — relating to or found in a river

Foraminifera — phylum of amoeboid marine protozoa, characterized by reticulating pseudopodia and a minute perforated shell comprising one or more chambers.

Fossil — the remains or impression of a prehistoric organism, embedded in rock and preserved in petrified form.

Fossilized — preserved as a fossil.

Fossil record — a series or sequence of fossils which, dated in correlation with the strata in which they are found, provide material evidence of evolutionary or geological history, especially that of a particular group of organisms.

French Revolution — the overthrow of the monarchy and establishment of republican government in France during the period 1789–1795.

Genesis — the beginning or origin of something.

Genetics — the study of heredity and the variation of inherited characteristics.

Genome — the complete set of genetic material of an organism.

Geochronology — the science of determining the age of rocks, fossils, and sediments using chemical signatures found within the rocks themselves.

Geographic Information Systems — a conceptualized framework that provides the ability to capture and analyze spatial and geographic data.

Geography — the scientific study of the Earth's surface, physical features, divisions, products, or population.

Geology — the scientific study of the physical structure of the Earth, including the origin and history of the rocks and soil of which the Earth is made.

Geomagnetism — the branch of geology concerned with the magnetic properties of the Earth.

Geothermal — relating to or resulting from the internal heat of the Earth; also describes a locality or region having hot springs, geysers, or other features heated by underlying magma.

Geyser — a hot spring in which water intermittently boils, sending a tall column of water and steam into the air.

Glacial period — a period in the Earth's history when ice sheets were unusually extensive; an ice age.

Gondwana — a large landmass that existed in the southern hemisphere millions of years ago. It was made up of land that now forms Arabia, Africa, South America, Antarctica, Australia and India.

Granite — a granular crystalline rock consisting essentially of quartz, orthoclase-feldspar, and mica, much used in building.

Gymnosperm — a plant of a group (subdivision Gymnospermae) that comprises those that have seeds unprotected by an ovary or fruit, including conifers and cycads.

Gypsum — a natural, soft white chalk-like mineral that is used to make plaster.

Hemisphere — one half of the Earth, especially the half above or below the equator.

Herbivore — an animal that feeds on plants.

Heritability — the quality of being heritable, or capable of being inherited.

Hermeticism — Hermetic or theosophical philosophy, an ancient occult tradition which encompasses alchemy, astrology, and theosophy.

Huttonian — relating to the geologist James Hutton, a proponent of the igneous or 'plutonic' origin of unstratified rocks.

Hydrocarbon — a compound of hydrogen and carbon, such as any of those which are the chief components of petroleum and natural gas.

Hydrolysis — the chemical breakdown of a compound due to reaction with water.

Hydrophobic — tending to repel or unable to mix with water.

Ice core — a cylinder of ice drilled out of a glacier or ice sheet, typically analysed to obtain information about atmospheric change over time.

Igneous — describes rocks formed when magma solidifies, especially near a volcano.

Iron — a hard, strong metal element used to make steel, which is also found in small quantities in blood and food.

Inclusion — a body or particle of distinct composition embedded in a rock or other material.

Infrared — describes radiation with a wavelength greater than that of red light, but less than that of microwave radiation.

Interbed — To embed amongst or between, to interstratify.

Intermediate — describes rocks relating to or containing a mix of minerals found in mafic and felsic rocks.

International Biosphere Reserves — UNESCO protected areas intended for the conservation of plants and animals.

Interstellar — occupying or passing through the regions of space between the stars.

Invertebrate — an animal which lacks a backbone, such as an arthropod, mollusc, or annelid.

In vivo — describes processes taking place within a living organism.

Isopods — a crustacean of the order Isopoda, which includes the woodlice and many aquatic forms.

Isotope — one of multiple forms of a chemical element that have the same number of protons but a different number of neutrons in their atoms. They have different physical properties but the same chemical properties.

Isthmus — a narrow piece of land with water on each side, that joins two larger pieces of land; also known as a land bridge.

Jurassic — describes the period between 208 and 146 million years ago, when the largest known dinosaurs lived.

Kamacite — a variety of meteoric iron, exhibiting certain peculiar figures in its structure.

Kimberlite — the eruptive rock, or 'blue ground', which is the matrix of the diamond at Kimberley and elsewhere in South Africa; it occurs in cylindrical 'pipes', often having a diameter of several hundred feet, and of unknown depth.

Lacustrine — relating to lakes.

Lamarckian evolution — a theory of the origin of species proposed by Jean Baptiste de Lamarck, who suggested that species could have evolved from each other by small changes in their structure, and that characteristics acquired by an individual in order to survive could be passed on to offspring.

Latitude — the distance of a place north or south of the equator, measured in degrees.

Lattice — the space lattice underlying the arrangement of atoms or molecules in a crystal; also, the arrangement of points occupied by the atoms or molecules or of the atoms or molecules themselves.

Lava — hot liquid rock that exits a volcano.

Limestone — a rock which consists chiefly of carbonate of lime, and yields lime when burnt.

Lineage — a sequence of species each of which is considered to have evolved from its predecessor.

Lithic — relating to stone.

Longitude — the distance of a place east or west of the Greenwich meridian, measured in degrees.

Lutheranism — the body of doctrine taught by Luther and his followers; the holding of Lutheran opinions.

Macroevolution — major evolutionary change, usually over a long period; the evolution of genera or higher taxa.

Mafic — describes rocks relating to or containing a group of dark-colored, mainly ferromagnesian minerals, such as pyroxene and olivine.

Magma — hot fluid or semi-fluid material found below the Earth's crust.

Magnetic field line — a visual tool used to represent magnetic fields.

Magnetic meridian — a continuous, imaginary line around the surface of the Earth passing through both magnetic poles.

Marine — relating to or produced by the sea.

Marl — an earthy deposit, typically loose and unconsolidated, consisting chiefly of clay mixed with calcium carbonate, formed in prehistoric seas and lakes that is used to improve the texture of sandy or light soil.

Mass extinction — an episode of extinction involving numerous species or higher taxa.

Mass spectrometer — an apparatus for separating isotopes, molecules, and molecular fragments according to mass.

Mastodon — a large extinct elephant-like mammal of the Miocene to Pleistocene epochs.

Matrix — a mass of fine-grained rock in which gems, crystals, or fossils are embedded.

Mercury fulminate — a grey crystalline powder, $Hg(CNO)_2$, used as an explosive in caps and detonators.

Mesosiderite — a stony-iron meteorite in which the principal silicates are pyroxene and plagioclase.

Mesozoic — relating to or denoting the era between the Paleozoic and Cenozoic eras, comprising the Triassic, Jurassic, and Cretaceous periods, marked by the rise of dinosaurs and the appearance of the first birds, mammals, and flowering plants.

Metabolism — the chemical processes that occur within a living organism to maintain life.

Metallogenic — describes a crustal region characterized by a particular association of ores or mineral deposits.

Metamorphic — describes rocks formed by the action of heat or pressure.

Meteor — a small body of matter from outer space that becomes incandescent as a result of friction with the Earth's atmosphere, and appears as a streak of light in the sky.

Meteorology — the branch of science that deals with atmospheric phenomena and processes, especially with a view to forecasting the weather.

Mid-Ocean Ridge (MOR) — any of the mountainous ridges (several kilometres high and over a thousand wide) that rise abruptly from the abyssal plain in the middle of each ocean basin and form a connected worldwide system, marking the site of magmatic upwelling associated with sea-floor spreading and having a central rift that overlies earthquake foci along much of their length.

Mineral — a solid, naturally occurring, usually inorganic substance with a definite chemical composition and characteristic physical structure and properties.

Mineralogy — the branch of science that deals with minerals.

Miocene — relating to or denoting the fourth epoch of the Tertiary period (between the Oligocene and Pliocene epochs, 23.3 to 5.2 million years ago), a time when the first apes appeared.

Mohs hardness scale — a qualitative ordinal scale characterizing scratch resistance of various minerals through the ability of harder material to scratch softer material.

Mollusk — an invertebrate animal within the phylum Mollusca, such as a snail, oyster, or octopus.

National Park — an area of land protected by the government for people to visit because of its natural beauty and historical or scientific value.

Natural history — the study of animals and other living organisms, especially as presented in a popular rather than in a strictly scientific manner.

Naturalism — the perspective according to which everything arises from natural phenomena, and supernatural or spiritual explanations are excluded or discounted.

Natural selection — the evolutionary process whereby organisms that are better adapted to their environment tend to survive and produce more offspring.

Nautilus — any of several free-swimming cephalopods of the genus *Nautilus*, which have numerous short tentacles and a smooth coiled external shell.

Neolithic — describes the later part of the Stone Age.

Neptunism — the erroneous theory that rocks such as granite were formed by crystallization from the waters of a primeval ocean.

Niche — the actual or potential position of an organism within an ecosystem, as determined by its biological role together with the set of environmental conditions in which it lives.

Norse mythology — the body of myths of the North Germanic peoples, stemming from Norse paganism and continuing after the Christianization of Scandinavia, and into the Scandinavian folklore of the modern period.

North Pole — the point on the surface of the Earth that is the furthest North.

Ocean — the mass of salt water that covers most of the Earth's surface.

Octahedrite — a mineral consisting of titanium dioxide and forming octahedral crystals.

Olivine — an olive-green, grey-green, or brown orthorhombic silicate of magnesium and iron which is a common mineral in basic igneous rocks.

Ore — a naturally occurring solid material containing a precious or useful metal in such quantity and in such chemical combination as to make its extraction profitable.

Organism — an individual animal, plant, fungus, or single-celled life form.

Organic — relating to or derived from living matter.

Orthosilicate — any mineral or other compound containing discrete tetrahedral SiO_4 anions.

Oxidation — the action or process of oxidizing; combination with oxygen; conversion into an oxide or oxygen-containing compound.

Paleoenvironment — an environment at a period in the past.

Paleomagnetism — the study of Earth's magnetic field in rocks.

Palaeontology — the branch of science concerned with fossil evidence of organic life during the geological past.

Pallasite — any of a class of stony-iron meteorites composed largely of olivine crystals enclosed in a network of nickel-iron.

Particulate — a particulate substance, especially as a contaminant; particulate material.

Pedology — the study and characterization of soils.

Peninsula — an area of land that is almost entirely surrounded by water, but still joined to a larger piece of land.

Permafrost — soil, subsoil, or other surface or subsurface material that is at a temperature of less than 0°C throughout the year, as in Arctic regions.

Petroleum — a hydrocarbon oil found in suitable rock strata, extracted and refined to produce fuels including petrol, paraffin, and diesel oil.

Phenotype — the observable characteristics of an individual resulting from the interaction of its genotype with the environment.

Photon — a quantum of light or other electromagnetic radiation, the energy of which is proportional to the frequency of the radiation.

Photosynthesis — the process by which the energy of light absorbed by chlorophyll is utilized by plants for the synthesis of complex organic compounds from carbon dioxide, with the accompanying oxidation of water to form oxygen.

Phylogeny — a diagram or theoretical model of the sequence of evolutionary divergence of species or other groups of organisms from their common ancestors.

Physics — the scientific study of matter and energy and the relationships between them, including the study of forces, heat, light, sound, electricity, and the structure of atoms.

Pietism — a movement within the German Lutheran Church in the 17th and 18th centuries, concerned with practical devotion and ethics as opposed to dogma, prioritizing the religious experiences of the individual over institutional authority.

Plate tectonics — a theory in which the interactions of moving tectonic plates and the spreading of the sea floor are used to explain features of the Earth, and which provides a mechanism for the theory of continental drift.

Plesiomorphy — the ancestral or primitive condition or trait, as compared to a later, derived character state.

Pleistocene — relating to or denoting the first epoch of the Quaternary period (between the Pliocene and Holocene epochs, from 1.64 million to about 10,000 years ago), a time which included the ice ages and the appearance of humans.

Plumb line — an instrument consisting of a line attached to a weight, used to determine depth.

Plutonism — the theory that crystalline igneous rocks, such as granite and basalt, were formed by solidification from magma originating deep within the Earth.

Polycyclic aromatic hydrocarbon (PAH) — any of a group of toxic contaminants formed during the incomplete burning of organic substances.

Polymerase Chain Reaction (PCR) — a method of making multiple copies of a DNA sequence, involving repeated reactions with a polymerase.

Precambrian — relating to or denoting the earliest eon of the Earth's history, preceding the Cambrian period and the Phanerozoic eon.

Precipitate — a compound deposited in solid form from a solution.

Promontory — A point of high land which juts out into the sea or another expanse of water; a headland.

Protein — any of a class of organic compounds consisting of long chains of amino acids, having structural and functional roles in organisms and constituting an important part of the diet.

Protozoan — a single-celled microscopic animal within the kingdom Protista, which includes amoebas, flagellates, ciliates, and sporozoans.

Proxy — a figure used to represent the value of something in a calculation.

Pterodactyl — a pterosaur (flying reptile) with a long, slender head and neck and a very short tail, known from fossil remains of the late Jurassic period.

Puritan — a member of a group of English Protestants of the late 16th and 17th centuries, who sought to remove elements of church practice which they considered corrupt, idolatrous, or unscriptural.

Pyrimidine — a basic, crystalline, heteroaromatic compound which is a diazine with the nitrogen atoms in the ring separated by one carbon atom.

Pyrite — an iron sulphide mineral occurring very widely in many types of rock, often as brassy-yellow crystals with a metallic lustre, or in massive, globular, or granular aggregates.

Quadruped — an animal which has four feet, especially an ungulate mammal.

Radiometric dating — dating that makes use of the varying relative abundances over time of radioactive parent and daughter isotopes.

Renaissance period — the revival of the arts and high culture under the influence of classical models, which began in Italy in the 14th cent. and spread throughout most of Europe by the end of the 16th; (also) the period during which this was in progress.

Richter Scale — a numerical scale for expressing the magnitude of an earthquake on the basis of seismograph oscillations. The scale is logarithmic, such that an increase of 1 represents an approximate thirty-fold difference in magnitude. Destructive earthquakes typically score between 5.5 and 8.9 on the Richter Scale.

Rock — the hard, solid material that forms part of the surface of the Earth and other planets.

Romantic movement — a movement marked by an emphasis on feeling, individuality, and passion rather than classical form and order, and typically preferring grandeur, picturesqueness, or naturalness to finish and proportion.

Sandstone — a rock composed of consolidated sand.

Scientific revolution — the developments occurring in the early modern period in many branches of science and regarded as having a significant influence on European intellectual culture, considered as a discrete historical process.

Sediment — particulate matter carried by water or wind and deposited on the land surface or seabed.

Sedimentary — describes rocks formed from sand, stones, mud, or other precipitates that settle in the beds of bodies of water.

Seismology — the scientific study of earthquakes, and their causes and effects.

Selection pressure — differential mortality or fertility that tends to make a population adapt genetically.

Sequencing — to ascertain the sequence of monomers in (a biological polymer such as a polypeptide or a nucleic acid).

Shale — soft finely stratified sedimentary rock formed from consolidated mud or clay.

Silica — a mineral substance containing silicon, found in sand and in rocks such as quartz, which is used in making glass and cement.

Smelt — To fuse or melt a material, such as ore, in order to extract metal.

Soil horizon — a soil layer parallel to the soil surface whose physical, chemical and biological characteristics differ from the layers above and beneath.

Solar nebula — a mass of gas or dust within a galaxy, typically visible either as a luminous patch or as a dark silhouette against a brighter background.

South pole — the point on the surface of the Earth that is the furthest South.

Speciation — the formation of new and distinct species in the course of evolution.

Species — a group of living organisms consisting of similar individuals capable of exchanging genes or of interbreeding, considered to be the basic unit of taxonomy.

Specific gravity — the degree of relative heaviness characteristic of any kind or portion of matter; commonly expressed by the ratio of the weight of a given volume to that of an equal volume of some substance taken as a standard.

Spectroscopy — the study of forming and looking at spectra using spectrometers, spectroscopes, or other tools.

Speleogenesis — the origin and development of caves, the primary process that determines essential features of the hydrogeology of karst and guides its evolution.

Speleology — the study or exploration of caves.

Stalactite — a tapering structure hanging from the roof of a cave, formed of calcium salts deposited by dripping water.

Stoicism — The philosophy of the Stoics.

Stratification — the formation of strata in rock.

Stratigraphic succession — a number of strata following one after the other

Stratigraphy — the branch of geology concerned with the order and relative dating of strata.

Stratum — a natural layer or series of layers of rock, sediment, or other material, typically representing an approximately continuous period of deposition.

Stress — physical strain or pressure exerted upon a material object; the strain of a load or weight.

Striation — one of a set of streaks or markings, which may refer to grooves found on rock surfaces, or the fine parallel lines on a crystalline face.

Substrate — the surface or material on which an organism lives, grows, or feeds.

Subterranean — existing, situated, or operating below the surface of the Earth.

Supercontinent — a large continent that, according to the theory of plate tectonics, is thought to have split into smaller continents in the geologic past.

Supersonic — involving or denoting a speed greater than that of sound.

Surveyor — a person whose job is to examine and record the details of a piece of land.

Taenite — a variety of feldspar occurring in striped crystals.

Taxonomy — the scientific process of classifying things.

Tectonic plate — one of several large pieces of crust that form the Earth's surface and move slowly.

Theology — the study or science of God, His nature and attributes, and His relations with man and the universe.

Thermoregulation — the regulation of body temperature.

Theropod — a dinosaur of a group including bipedal carnivores, such as the carnosaurs and dromaeosaurs.

Thrust fault — a reverse fault of low angle, with older strata displaced horizontally over younger strata.

Tomography — a process used to provide a three-dimensional image or cross-section of the internal structure of something by combining X-ray or ultrasound images.

Trace element — any element having an average concentration of less than about 100 parts per million atoms, or less than 100ug/g.

Trace fossil — a fossil of a footprint or other trace of an animal, rather than of the animal itself.

Tree of life — the evolving and diversifying totality of living organisms, likened to a branching tree; (hence) a branching diagram representing the evolutionary relationships between organisms; a phylogenetic tree.

Triassic — describes the period between 252 and 208 million years ago.

Trophic — relating to feeding and nutrition.

Tsunami — a long, high sea wave caused by an earthquake or other disturbance.

Unconformity —difference of plane.

Ultrafiltration — filtration using a medium fine enough to retain colloidal particles, viruses, or large molecules.

Uniformitarianism — the theory that changes in the Earth's crust during geological history have resulted from the action of continuous and uniform processes.

Uracil — a pyrimidine base, $C_4H_4N_2O_2$, which is a constituent of RNA.

Uranium — a chemical element. Uranium is a heavy, silver-white, radioactive metal, used mainly in producing nuclear energy.

Vertebrate — describes an animal distinguished by the possession of a backbone or spinal column, including mammals, birds, reptiles, amphibians, and fishes.

Viscous flow — smooth and regular flow with a constant direction of motion at any point as if the fluid were moving in a series of layers sliding over one another without mixing.

Volatile — describes a substance that is easily evaporated at normal temperatures.

Volcano — a mountain or hill having a crater or vent through which lava, rock fragments, hot vapour, and gas erupt from the Earth's crust.

Vulcanism — a theory attributing the origin of basalt and other crystalline rocks to volcanic action or to igneous processes in general.

Weathering — the action of sun, rain or wind on rocks, which makes them change shape or colour.

Widmanstätten pattern — designating a pattern or figure exhibited by some meteorites when a cross section is exposed to acid, consisting of thin interleaving bands of iron-nickel alloys.

World Heritage Site — a natural or man-made place that is recognized as having great international importance, and is therefore protected by UNESCO.

Xenotime — a rare-earth phosphate mineral, the major component of which is yttrium orthophosphate.

X-ray — a penetrating form of high-energy electromagnetic radiation.

Zircon — a mineral occurring as prismatic crystals, typically brown but sometimes in translucent varieties of gem quality. It consists of zirconium silicate and is the chief ore of zirconium.

Zoology — the scientific study of the morphology, classification, physiology, behaviour, and distribution of animals or of a specific group of animals.

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